



# eBook of the 2<sup>nd</sup> Workshop Meeting

Belgrade, March 30th – April 1st 2016

**Editors** : Jose Matos, Joan Casas, Rade Hajdin, Snežana Mašović, Nikola Tanasić, Alfred Strauss, Irina Stipanović

**Publisher** : Faculty of Civil Engineering, University of Belgrade, Serbia

**ISBN** : 978-86-7518-187-3



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COST is supported by  
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# Opening Note from the Chair

COST Action TU1406 aims to address the European economic and societal needs by standardizing the condition assessment and maintenance level of roadway bridges. Currently, bridge quality control plans vary from country to country and, in some cases, within the same country. This therefore urges the establishment of a European guideline to surpass the lack of a standard methodology to assess bridge condition and to define quality control plans for roadway bridges.



Prof. Jose Matos

Such a guideline will comprise specific recommendations for assessing performance indicators as well as for the definition of performance goals, bringing together different stakeholders (e.g. universities, institutes, operators, consultants and owners) from various scientific disciplines (e.g. on-site testing, visual inspection, structural engineering, sustainability, etc.) in order to establish a common trans-national language.

COST Action TU1406 Workshops aim to facilitate the exchange of ideas and experiences between active researchers and practitioners as well as to stimulate discussions on new and emerging issues in line with the conference topics. This second Workshop addresses the WG1, performance indicators, WG2, performance goals, and WG3, establishment of a Quality Control plan, developments. The main outcome, given in this eBook, is really important, not only for those directly involved in this Action, but also for the whole bridge engineering community.

[COST TU1406 Action Presentation](#)

A handwritten signature in blue ink, appearing to read 'Jose C. Matos'.

Jose C. Matos

Chair COST Action TU1406



# Note from the Vice Chair

The working group meetings and 2<sup>nd</sup> Workshop of COST Action TU1406 in Belgrade has seen the continuation of the work developed within WG1 and the first working sessions for WG2 and WG3. The state-of-the-art and the different approaches along Europe on the performance indicators used by the different owners and operators to meet the quality expectations of the users is close to its completion. A huge amount of information has been collected and the posterior processing will become a relevant input for the rest of the WG's. Also the collecting of research performance indicators was presented. This will serve as the basis for the proposal of new indicators that will allow a more optimized definition of future quality control plans for highway bridges.



Prof. Joan R. Casas

An important number of papers were also presented during the Workshop related to all WG's. The key-note presentations explaining the experience from previous COST actions, on sustainability indicators and pavement performance indicators, will be very helpful for the Action in seeking the best methodology and approaches to gather the most relevant and representative data from the large data base that is in our hands by now.

Lively discussions after the presentations and in the WG's meetings has made possible to get an agreement and deliver a clear route map among the different WG conforming the Action on how and what to focus in the coming years, looking at their specific goals and close interactions and avoiding overlapping of activities. In summary, looking to the success of this second workshop, and the future activities planned, we may be confident on the achievement of the required standardization of the quality specifications for highway bridges in Europe.

A handwritten signature in blue ink, appearing to read 'Joan R. Casas', with a stylized flourish underneath.

Joan R. Casas

Vice-Chair COST Action TU1406

## *Note from the Local Organizers*

As the Work Group 3 Leader and a member of the Local Organizing committee, it has been a pleasure to host the 2<sup>nd</sup> Workshop of the COST TU1406 Action in Belgrade, Serbia. The principal aim of the COST Action is to facilitate the identification of maintenance needs within the roadway bridge management process. The main output of the action are adequate quality control plans for bridges which comprise performance indicators. The value of this Action therefore lies beyond its obvious academic merit, delivering a framework which is at this point in time urgently needed in bridge management by practitioners worldwide. Apart from the main goal of the meeting which is presenting of the results of WG1 - the survey on performance indicators, the kickoff meetings of WG2 and WG3 here take place.

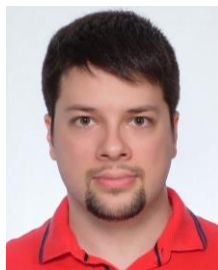


Prof. Rade Hajdin



Prof. Snežana Mašović

The COST Action TU1406 comprises members from nearly all European Countries, as well as countries outside Europe. Wide participation is an important feature of these actions, whose scope is to form a European research area across borders and interlink high-quality research and practice communities in Europe and worldwide. The location of the last conference at the end of the first year of the action is well chosen. The Serbian capital - Belgrade (Beograd) is situated in South-Eastern Europe, on the Balkan Peninsula, at the confluence of the Sava and Danube rivers. It has been always on the crossroads of many cultures and nations. Today, it is the capital of Serbian education, science, economy and culture. Here located are the most significant works of architecture, monuments, cultural treasures and numerous archaeological sites from prehistory to today.



Prof. Nikola Tanasić

With these words: It is a pleasure to welcome the WG Meetings and the second Workshop of the COST TU1406 Action in Belgrade !

# ***Acknowledgment***

The editors would like to thankfully acknowledge the contribution of those who supported the execution of this event:

**Faculty of Civil Engineering, University of Belgrade, Serbia**

*- PhD Candidates & Teaching assistants –*

**Ana Nikolić**

**Jelena Nikolić**

**Marija Petrović**

**Nevena Simić**

**Jelena Dragaš**

**Nikola Tošić**

**Marina Aškračić**

**Aleksandar Radević**

**&**

**Eleni Chatzi,**

*Technical Secretariat of COST Action TU1406*

**Sérgio Fernandes,**

*Technical Support of COST Action TU1406*

**Lara Leite**

*Administrative Secretariat of COST Action TU1406*

# Acknowledgment

The editors would like to thankfully acknowledge the contribution of Local organizers and sponsors who supported the execution of this event:

**Faculty of Civil Engineering, University of Belgrade, Serbia**

[www.grf.rs](http://www.grf.rs)



**&**

**IMC, Switzerland**

[www.imc-ch.com](http://www.imc-ch.com)



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## Opening Session

[Welcome word from Prof. Rade Hajdin](#), Local organizer & WG3 leader

[Welcome word from Prof. José C. Matos](#), Chairman COST TU1406

## Session 1

Keynote speech: [„Indicators for Sustainability Assessment“](#) by Prof. Luis Bragança, University of Minho, Portugal

Keynote speech: ["State of Art of Bridges Maintenance Programs in South America. Experience on seismic hazards and scour"](#) by dr Matias Valenzuela, Chile Ministry of Public Works

[“Performance Indicators as Basis for Life-Cycle-Considerations“](#), by Mr. Ralph Holst, Federal Highway Research Institute (BAST), Germany

[“Structural robustness of bridges based on redistribution of internal forces“](#), by dr Tomasz Kamiński, Assistant prof. at Wroclaw University of Technology, Poland

[“Robustness as performance indicator for masonry arch bridges“](#), by dr José C. Matos, Assistant prof. at University of Minho, Portugal

[“Performance indicators for road bridges – categorization overview“](#), by dr Ana Mandić Ivanković, Associate prof. at Faculty of Civil engineering, University of Zagreb, Croatia

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## Session 2

[“Structural behaviour of stone arch bridges”](#), by dr. Cristina Costa, Assistant prof. at Instituto Politécnico de Tomar, Portugal

[“Forecasting of performance indicators”](#), by dr Snežana Mašović, Assistant prof. at Faculty of Civil engineering, University of Belgrade, Serbia

[“Interface for collection of performance indicators for roadway bridges– STSM experiences”](#), by Ivan Zambon, PhD candidate at BOKU Wien, Austria

[“A new perspective for robustness assessment of framed structures”](#), by Hugo Guimarães, PhD. candidate at University of Minho, Portugal

[“Lifecycle-based discretization of bridge performance indicators”](#), by Mr. Dimosthenis Kifokeris, PhD candidate, Aristotle University of Thessaloniki. Greece

## Session 3

[“The impact of the severe damage on the dynamic behavior of the composite road bridge”](#), by Dr Pavel Ryjáček, Associate prof. at Faculty of Civil Engineering, Czech Technical University in Prague

[“Effect of vehicle travelling velocity on bridge lateral dynamic response”](#), Dr Luke Prendergast, Postdoctoral research associate at University College Dublin, Ireland



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## Session 3 (continued)

[“Damage detection for bridge structures based on dynamic and static measurements”](#), by Dr Viet Ha Nguyen, Postdoctoral research associate at Faculty of Science, Technology and Communication, University of Luxembourg

[“Qualitative performance indicators for bridge management in Italy”](#), by Dr Mariano Zanini, University of Padova, Italy

[“Using an air permeability test to assess curing influence on concrete durability”](#), by Dr Rui Neves, Assistant prof. at Instituto Politécnico de Setubal – ESTBarreiro, Portugal

## Session 4

Keynote speech: [“Data-driven Decision Making on Maintenance Activities in Serbia”](#) by Momčilo. Veljović, “Putevi Srbije” - Serbian public road enterprise

Keynote speech: [“COST354 – The way forward for pavement performance indicators across Europe”](#) by Dr Alfred Weninger-Vycudil, PMS-Consult, Austria

[“Sustainable Construction of Bridges in Kanton Zürich”](#), by Dr Martin Käser, Bridge Engineer at Bridge research workgroup - Swiss federal roads authority, Zurich, Switzerland

[“Consequence modelling for bridge failures”](#), by Dr Boulent Imam, Senior lecturer at University of Surrey, UK

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## Session 4 (continued)

[“Data collection on Bridge Management Systems”](#), by Dr Nikola Tanasić, Assistant prof. at Faculty of Civil engineering, University of Belgrade, Serbia

[“Scheduling bridge rehabilitations based on probabilistic life cycle condition information”](#), by Dr Dimos C. Charmpis, Associate prof. at University of Cyprus

## Session 5

[“Environmental effects on bridge durability based on existing inspection data”](#), by Dr Ioannis Balafa, Special teaching staff at University of Cyprus

[“Development of the bridge management system under the project BridgeSMS”](#), by Mr Igor Kerin, Research Assistant at UCC / MaREI, Ireland

[“The assessment method of Hungarian documents on bridge inspection”](#), by Mrs. Zsuzsanna Pisch, Hungarian Transport Administration, Hungary

[“Development of a Quality Management Plan for Timber Bridges”](#), by Dr Steffen Franke, Assistant prof. at Bern University of Applied Sciences, Switzerland

[“Guide for the Assessment of Masonry Bridges – Technical Parameters”](#), by Mr. João Amado, Infraestruturas de Portugal, S.A.

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## Session 6

Guest lecture: [“Introduction of COST Action TU1402 on Quantifying the Value of Structural Health Monitoring”](#), by Prof. Sebastian Thöns, Chair of COST TU 1402, Technical University of Denmark

Reports from Working Groups:

[Report from WG1](#), by Prof. Alfred Strauss

[Report from WG2](#), by Prof. Irina Stipanović

[Report from WG3](#), by Prof. Rade Hajdin

## Closing Session

[“State of the Action TU1406”](#) by Prof. Joan Casas, Vice chair of the COST TU 1406, BarcelonaTech, Spain

[Closing remarks](#) by Prof. José Matos, Chair of the COST TU 1406, University of Minho, Portugal

## [CONTRIBUTIONS](#)

# WG Meetings and Workshop objectives

The goals of WG meetings and Workshop are to develop a common understanding of the aims and ideas of COST Action TU1406 within the Action network and their dissemination.

This meeting has several objectives:

- to initiate a discussion upon the systematizing of knowledge on quality control plans for bridges in order to achieve an overall state-of-art report;
- to establish a wide set of quality specifications aiming to assure an expected performance level;
- to collect and contribute to up-to-date knowledge on PI-s, including technical, environmental, economic and social indicators;
- to develop detailed examples for practicing engineers on the assessment of PI-s as well as in the establishment of performance goals, to be integrated in the developed guidelines;
- to make a scientific discussion on proposed PI-s and criteria, for clustering and organizing the PI-s with respect to the different life phases and assessment levels of road bridges and to provide final comments/suggestions by participants;
- to present the results of WG1, in particular the results of survey on performance indicators;
- to present the comparison of PI-s throughout Europe and suggest a common set of PI-s;
- to present the results of WG2, in particular the definitions of PG-s and their relations to PI-s;
- to present the results of WG3, in particular the general framework for QC plans and the corresponding questionnaire focusing on triggering criteria for maintenance actions throughout Europe;
- to allow participants to present some contributions relevant for a specific WG (e.g. their experiences related to other PI research activities, etc.).



Prof. Rade Hajdin  
WG 3 Leader



Prof. Irina Stipanović  
WG 2 Leader



Prof. Alfred Strauss  
WG 1 Leader



### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **Welcome to Belgrade!**

Rade Hajdin - University of Belgrade, Serbia



Грађевински факултет

Универзитет  
у Београду

30<sup>th</sup> March - 1<sup>st</sup> April 2016  
Belgrade, Serbia

# OUR HOST

- **The Faculty of Civil Engineering at the University of Belgrade** is the oldest and largest educational and scientific institution in the field of civil engineering and surveying in Serbia.
- The beginning of teaching and education in the field of civil engineering and surveying at university level dates back to June, 19 1846, when the School of Engineering was formed at Lyceum in Belgrade.
- The founder and creator of The Engineering school was Atanasije Nikolic (1803-1882), an engineer and the first rector of Lyceum and later, the initiator of Serbian Academy.
- The studies lasted for three years, and in the Foundation Decree on it was stated: "Subjects (students) will be lectured theoretically in this school during winter and, in summer, they will be trained in field, alongside engineers, in design and construction of buildings and roads in order to supervise and construct various structures according to plans."



Singidunum

Castelbianco

Βελιγράδι

Alba Greca

Београд  
Belgrade

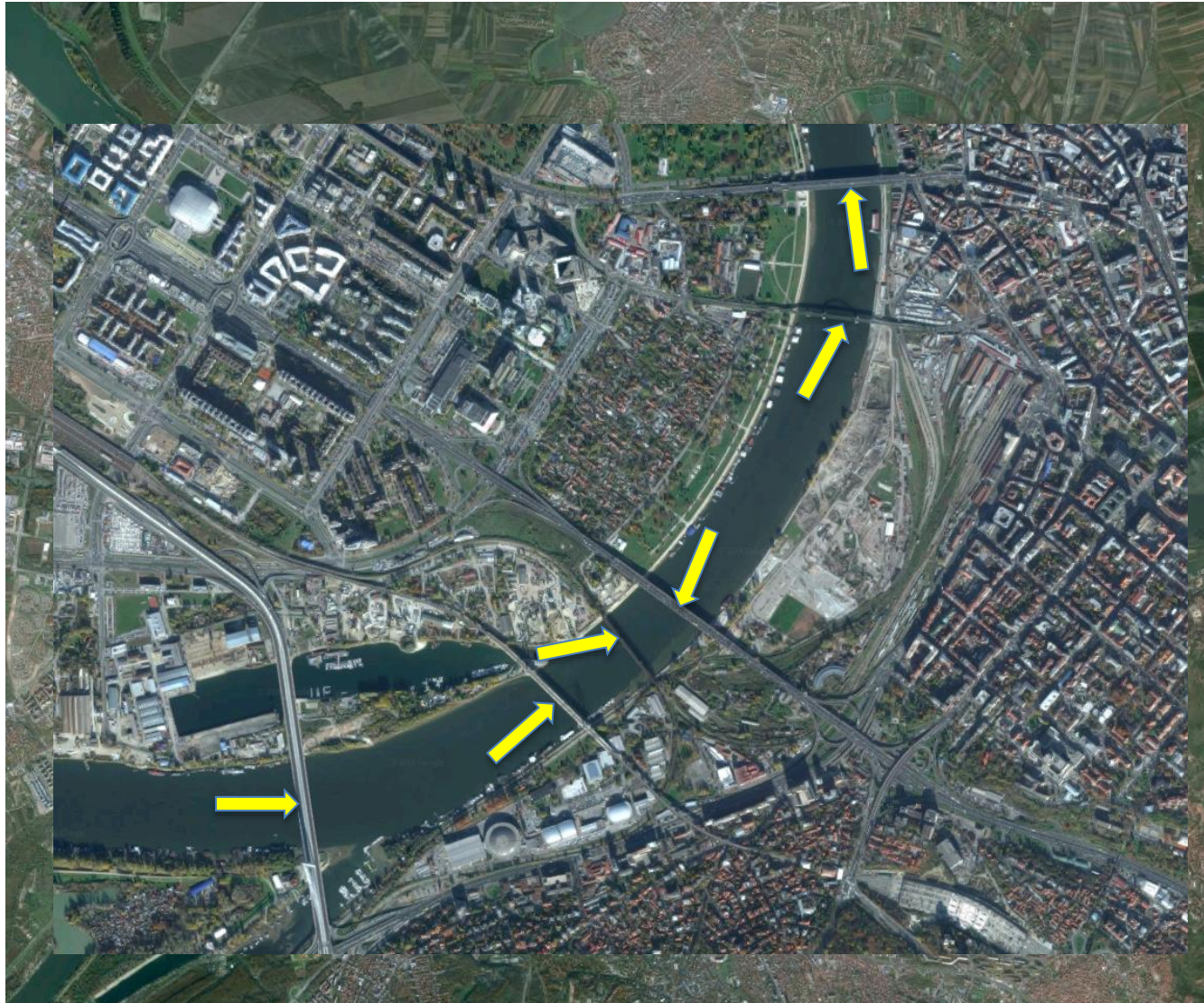
Nándor-Fejérvár

Alba Bulgarica

Griechisch Weissenburg

# ORIGIN OF THE NAME

- The first mentioning as Singidūn inhabited by the Celtic tribe Scordisci in 279 BC
  - Dūn(on) means in enclosure, fortress
  - Singi means circle but can stem from the Sings, a Thracian tribe that occupied the area prior to the arrival of the Scordisci.
- Roman conquered Singidūn in 75 BC and called it Singidunum
- The name remained until the beginning of the 7<sup>th</sup> century and after its fall to Avars its fate of the city is obscure.
- The Slavs called it Beligrad “white city” (named for the color of the stone it was built from), first mentioned in a letter written on 16 April 878 by Pope John VIII to Bulgarian prince Boris I Mihail.
- The foreign names are either phonetically (Belgrade) or semantically (Weissenburg) related to the current name.





# THE FIRST BRIDGE

- Railway bridge opened 1884
- The bridge was a part of the famous Orient Express line.
- Destroyed twice: 1914 and 1941



# KING ALEKSANDAR I BRIDGE

- Road bridge opened 1934
- Destroyed in 1941



# BRANKOV MOST (BRANKO'S BRIDGE)

- Built over the substructure of king Aleksandar I bridge in 1956
- The largest span at that time (261 m) open box continuous girder







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Грађевински факултет

Универзитет  
у Београду

**THANKS FOR YOUR ATTENTION!**

WG MEETINGS & WORKSHOP  
30<sup>th</sup> March - 1<sup>st</sup> April 2016  
Belgrade, Serbia



# Quality Specifications for Roadway Bridges, Standardization at a European Level (*BridgeSpec*)

**José C Matos** – Chair COST TU1406, ISE - University of Minho,  
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**Good morning to everybody !**

Acknowledgments to Local Organizers and to Metropole Palace Hotel (Belgrade, SR).

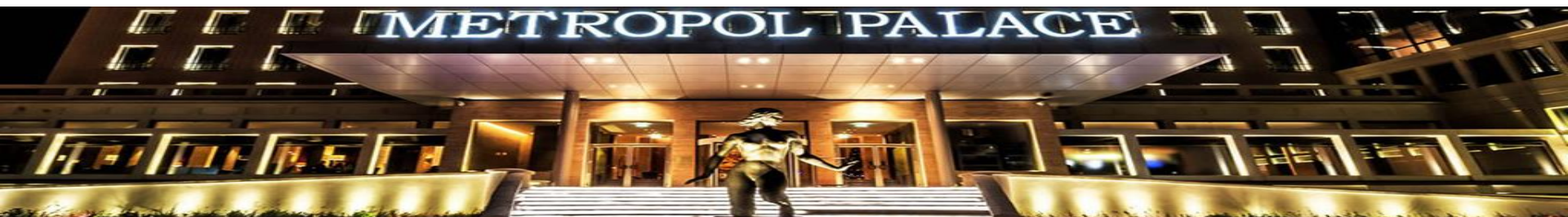
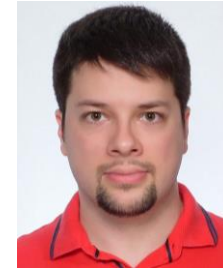
Rade Hajdin  
(UBelgrade)



Snežana Masović  
(UBelgrade)



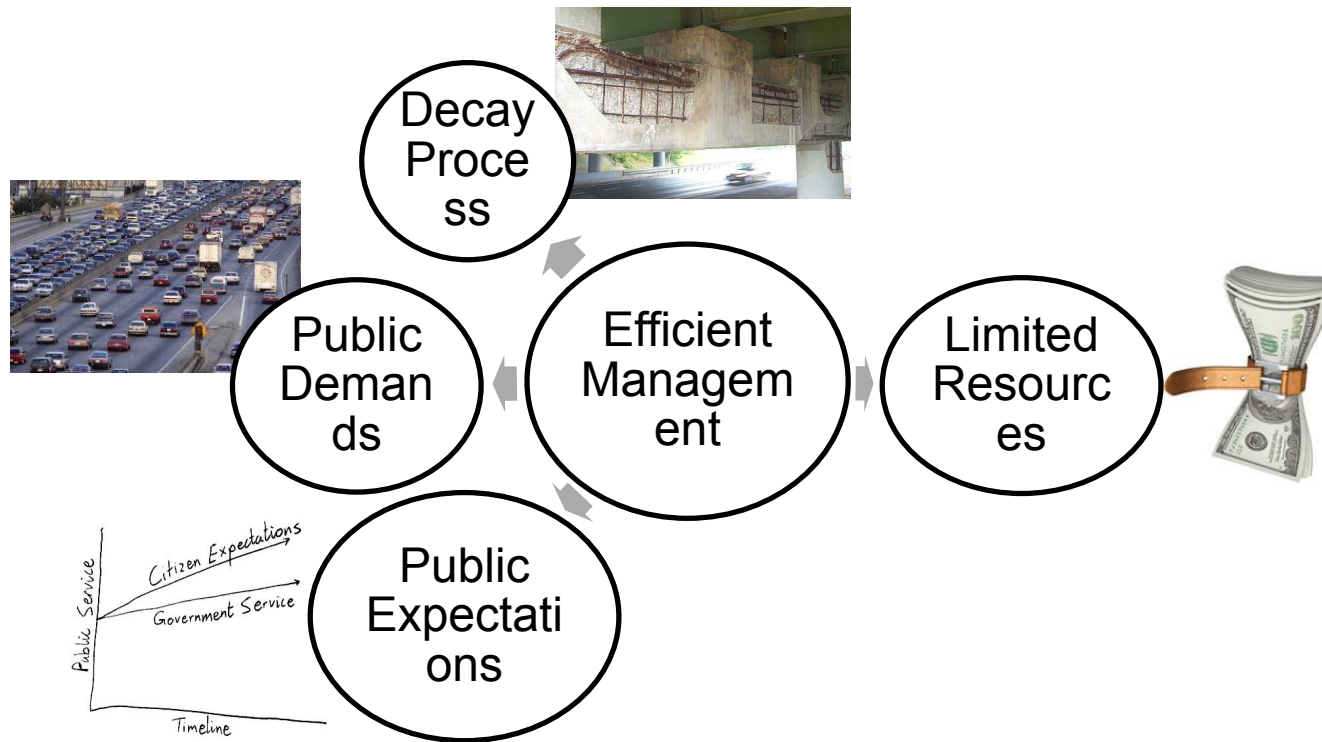
Nikola Tanasić  
(UBelgrade)



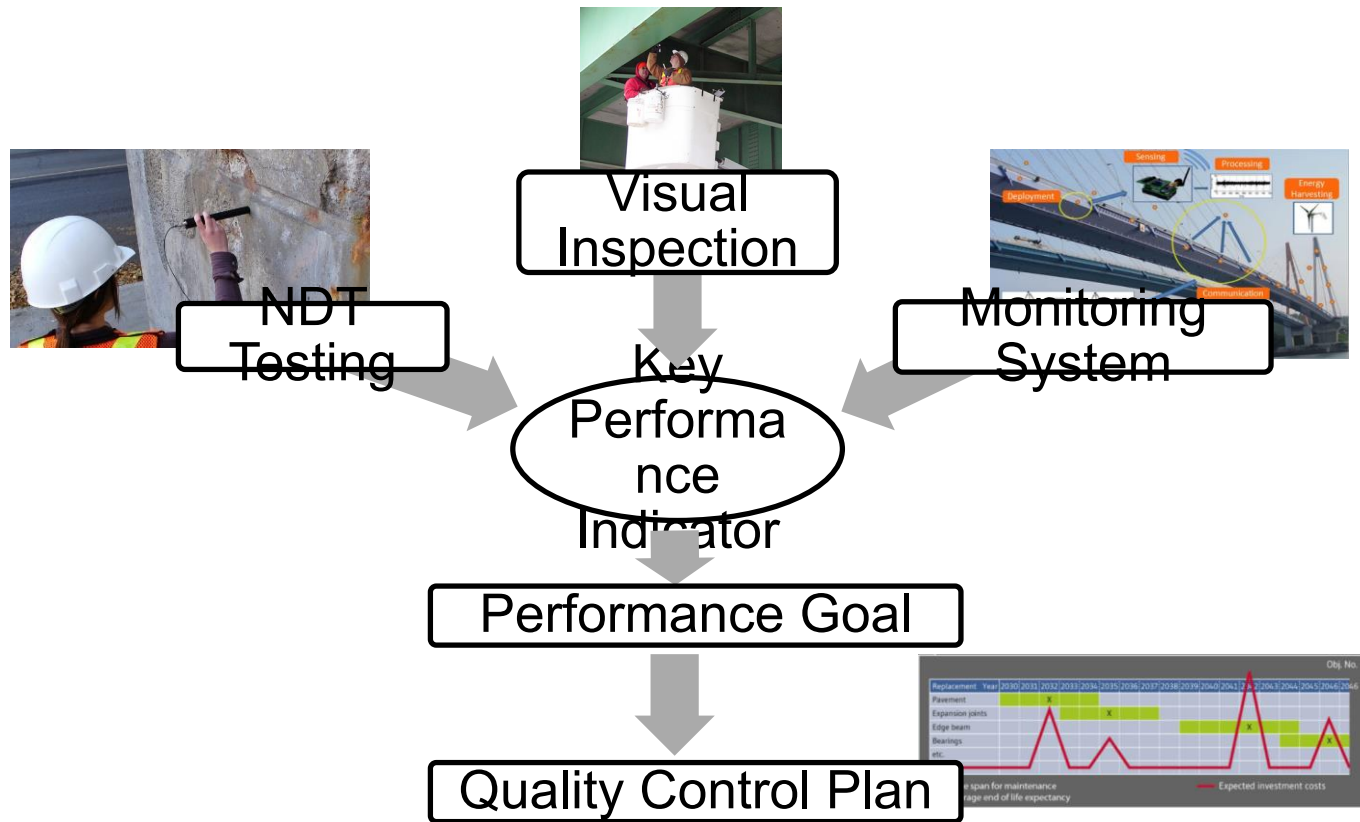
## OUTLOOK

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3. OBJECTIVES AND MILESTONES
4. HORIZONTAL ROLES
5. INVOLVED COUNTRIES
6. INVOLVED SME
7. KPI DATABASE
8. PROCESSING THE KPI SURVEY
9. KPI GLOSSARY
10. OPERATORS KPI DATABASE
11. RESEARCHERS KPI DATABASE
12. FUTURE DEVELOPMENTS

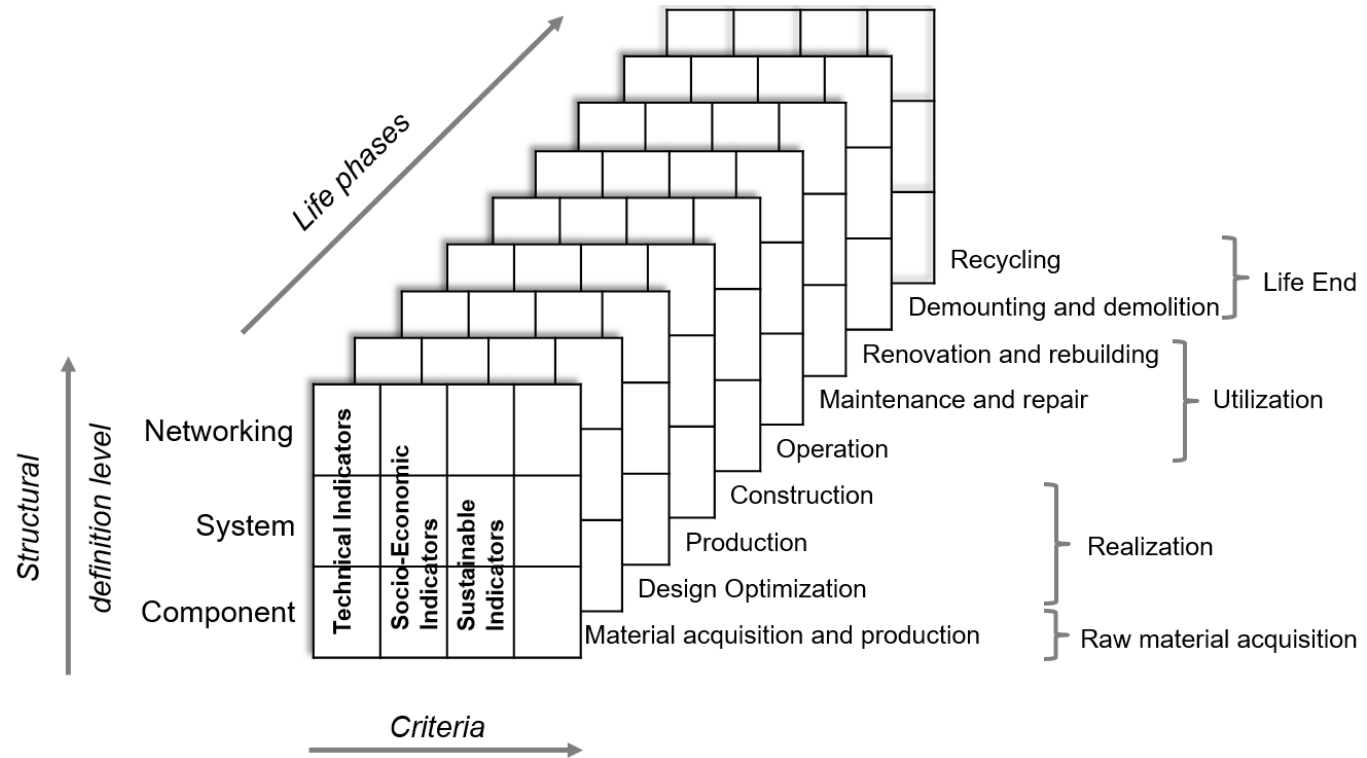
# 1. BACKGROUND



# 1. BACKGROUND

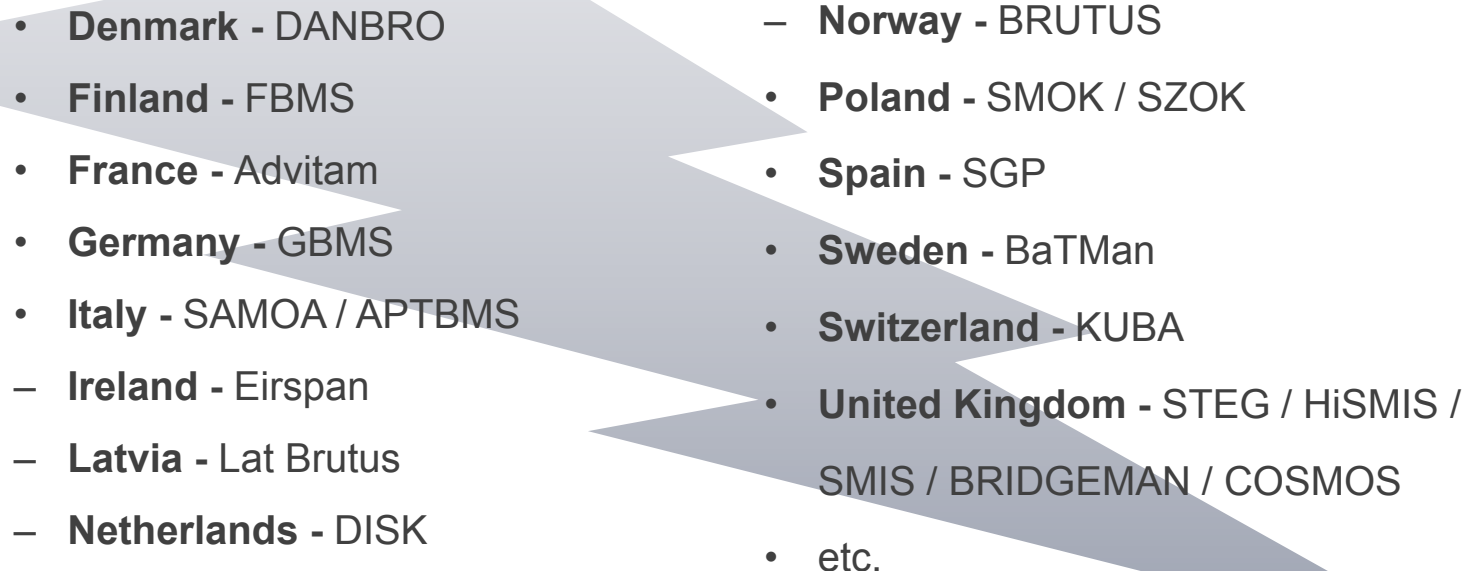


# 1. BACKGROUND





## 2. REASONS FOR THE ACTION

- 
- **Denmark** - DANBRO
  - **Finland** - FBMS
  - **France** - Advitam
  - **Germany** - GBMS
  - **Italy** - SAMOA / APTBMS
  - **Ireland** - Eirspan
  - **Latvia** - Lat Brutus
  - **Netherlands** - DISK
  - **Norway** - BRUTUS
  - **Poland** - SMOK / SZOK
  - **Spain** - SGP
  - **Sweden** - BaTMan
  - **Switzerland** - KUBA
  - **United Kingdom** - STEG / HiSMIS / SMIS / BRIDGEMAN / COSMOS
  - etc.

## 2. REASONS FOR THE ACTION



There is a **REAL NEED** to standardize the quality control of roadway bridges at an European Level

### 3. OBJECTIVES AND MILESTONES

The main objective of the Action is to:

**develop a guideline for the establishment of QC plans in roadway bridges.**

This guideline will focus on bridge maintenance and life-cycle performance at two levels:

- (i) key performance indicators.
- (i) performance goals.

### 3. OBJECTIVES AND MILESTONES

**WG1 : Key Performance indicators:**

- M1 - Report of Key Performance Indicators (incorporating new indicators).

**WG2: Performance goals:**

- M2 - Report of Performance Goals (incorporating new indicators).

**WG3: Establishment of a QC plan:**

- M3 - Recommendations for the Establishment of a QC plan (with detailed examples for practicing engineers).

**WG4: Implementation in a Case Study:**

- M4 - Database from Benchmarking (from COST countries).

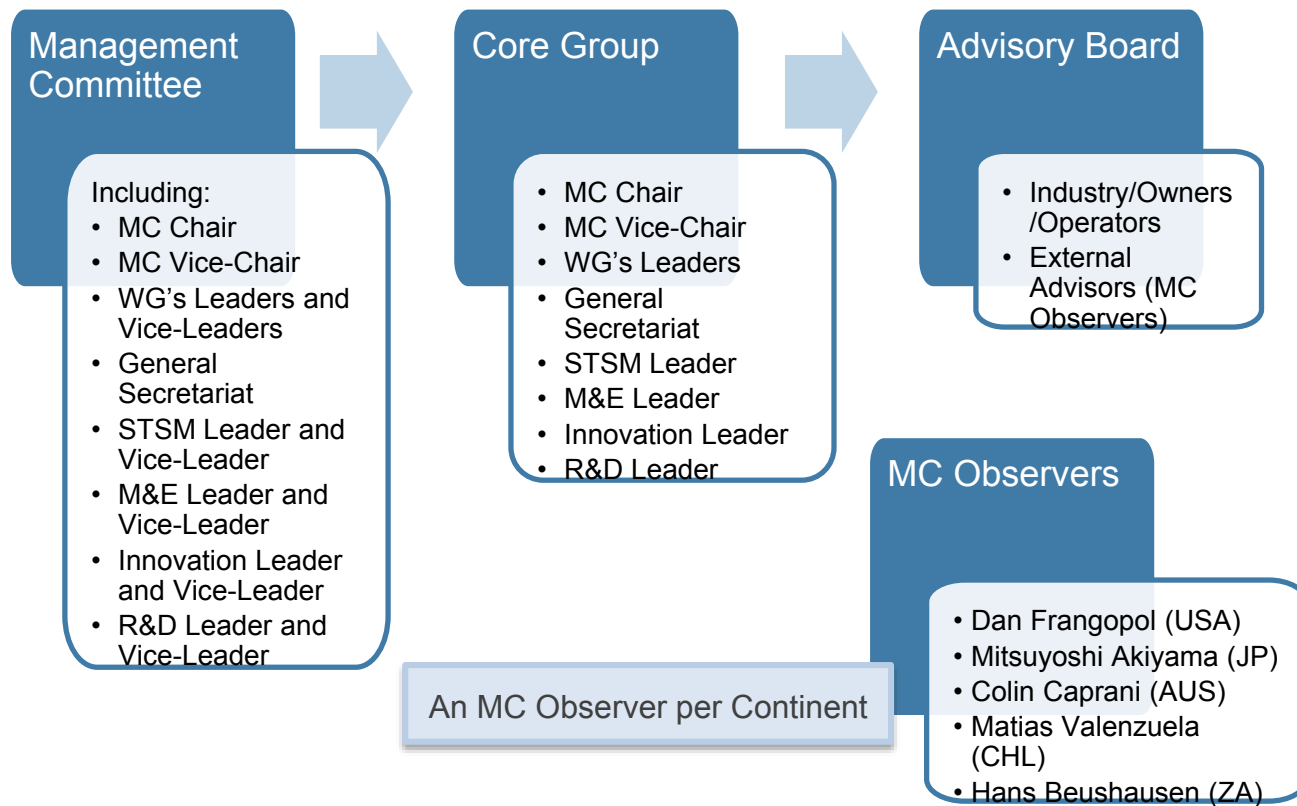
**WG5: Drafting of guideline / recommendations:**

- M5 - Guideline for the Establishment of a QC plan.

## 4. HORIZONTAL ROLES

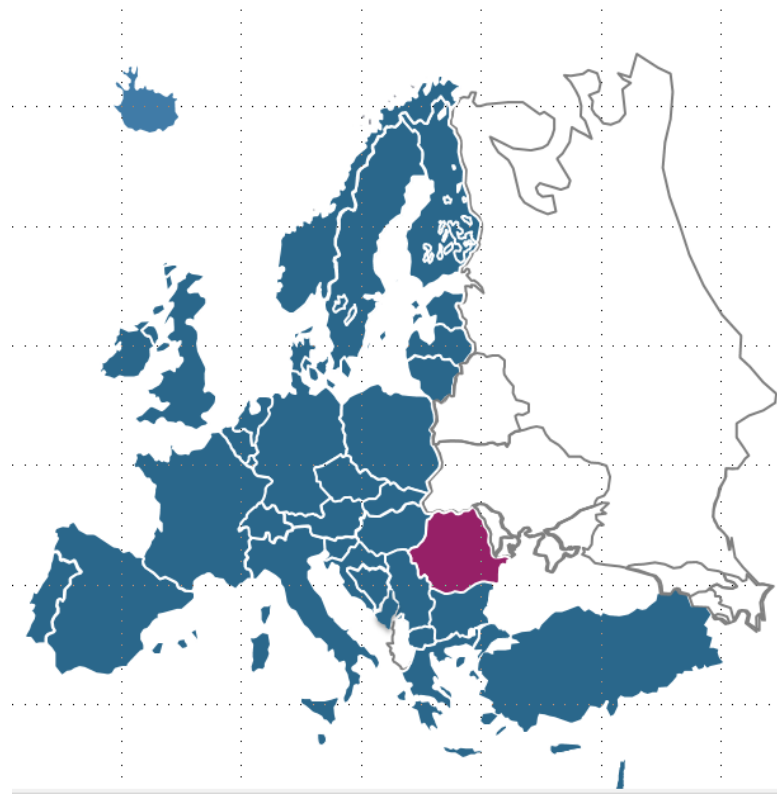
Position	Name
WG1: Key Performance Indicators	Leader: Alfred Strauss (AT) Vice Leader: Ana Mandić (HR)
WG2: Performance Goals	Leader: Irina Stipanović (NL) Vice Leader: Lojze Bevc (SL)
WG3: Establishment of a QC Plan	Leader: Rade Hajdin (SB) Vice Leader: Matej Kušar (SL)
WG4: Implementation in a Case Study	Leader: Amir Kedar (IL) Vice Leader: Sander Sein (EE)
WG5: Drafting of guideline/recommendations	Leader: Vikram Pakrashi (IR) Vice Leader: Helmut Wenzel (AT)
WG6: Dissemination	Leader: Gudmundur Gudmundsson (IS) Vice Leader: Stavroula Pantazopoulou (CY)

## 4. HORIZONTAL ROLES





## 5. INVOLVED COUNTRIES

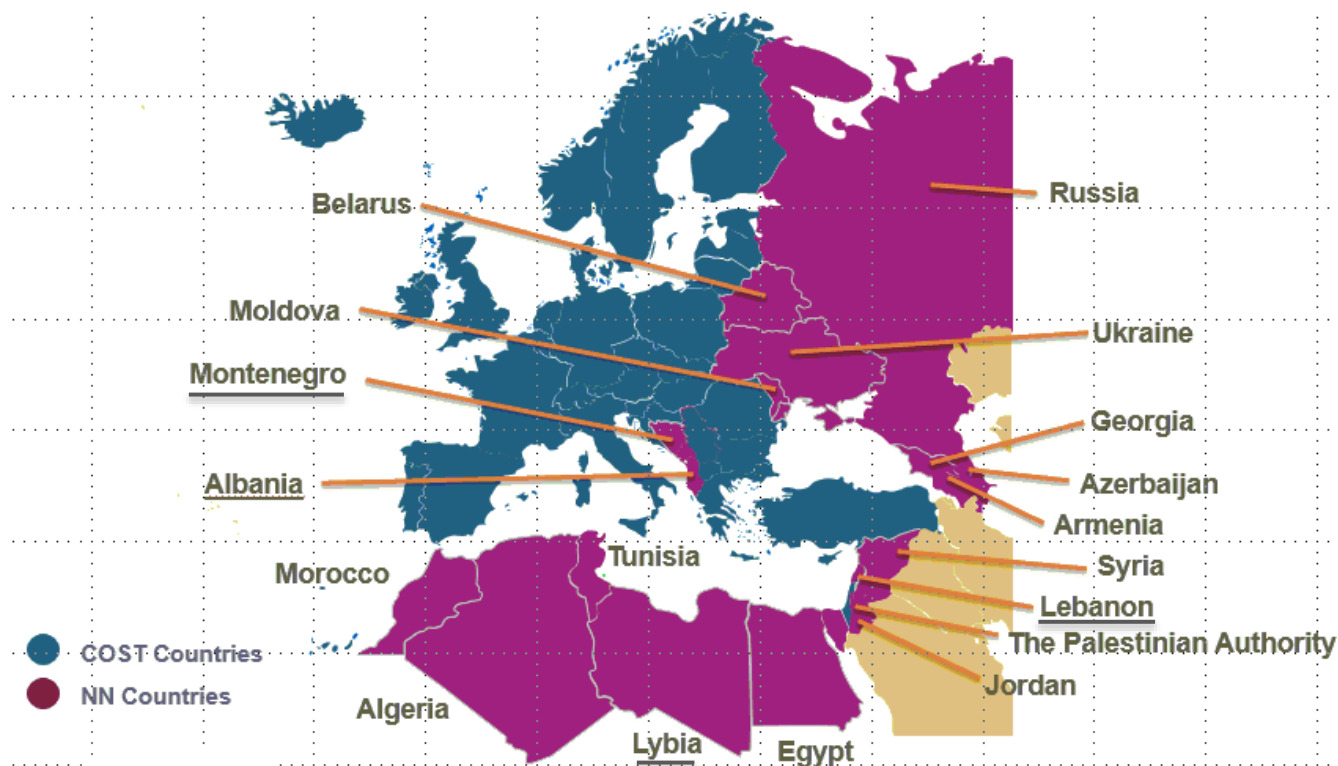


■ Action represented countries

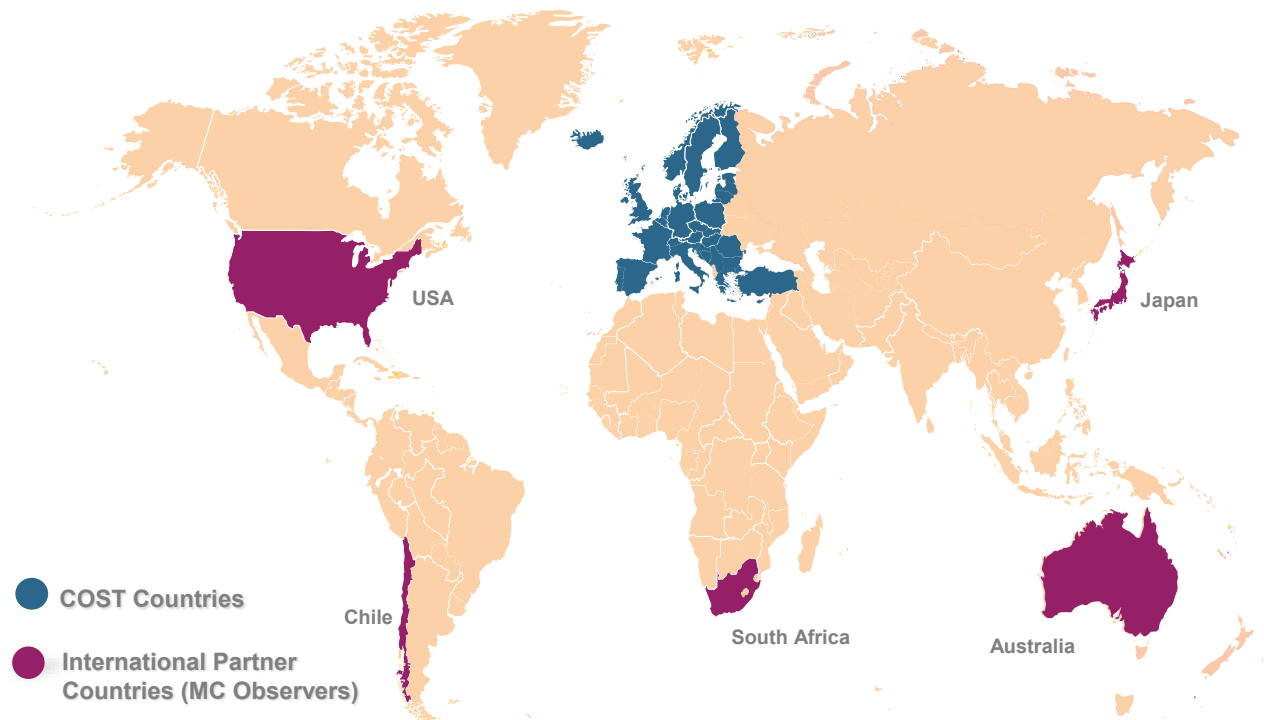
■ Missing Countries

► Romania

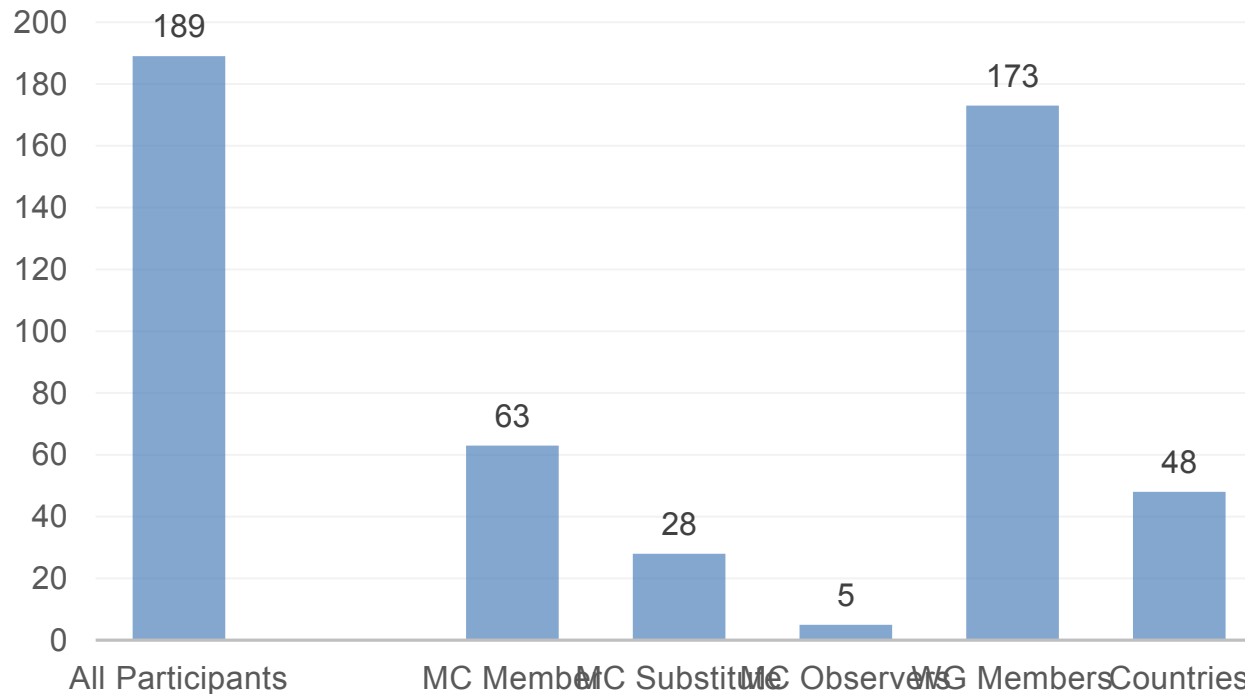
## 5. INVOLVED COUNTRIES



## 5. INVOLVED COUNTRIES



## 5. INVOLVED COUNTRIES



## 6. INVOLVED SME



## 7. KPI DATABASE



*COST TU1406 KPI  
Database*  
@ [www.tu1406.eu](http://www.tu1406.eu)





## 8. PROCESSING THE KPI SURVEY

- It was decided to incorporate information from two document types :
  - *Operator documents*:
    - Actually in use by different Agencies in the form of guidelines or recommendations.
  - *Research documents*:
    - Showing the recent advances in the field by people from Academia and Research Institutes.
- The survey is structured in two important stages:
  - *Screening*:
    - Aims to upload the relevant parts of the document.
  - *Glossary*:
    - With the objective of collecting several terms definition.

## 8. PROCESSING THE KPI SURVEY

- It was decided to nominate in each country several persons with different tasks:
  - *Member of the Management Committee:*
    - Responsible to contact owners and operators of roadway bridges asking for available documents in practice.
  - *Country responsible person:*
    - Screening and processing national operator documents.
  - \* ) The screening of research documents will be made by *Researchers participating in different WGs.*
  - *Core Group among each WG members:*
    - Preparation of tutorials for the screening of documents and analyze the database to obtain the main results and conclusions.

## 8. PROCESSING THE KPI SURVEY

### Countries screening operator documents ...

Bosnia and Herzegovina

Croatia

Czech Republic

Denmark

FYRO Macedonia

Greece

Israel

Netherlands

Portugal

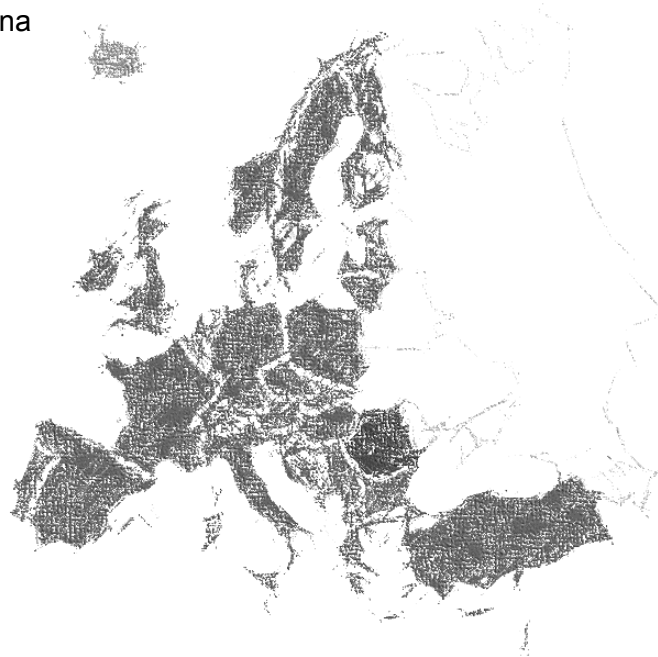
Serbia

Slovakia

Slovenia

Spain

United Kingdom



Austria

Belgium

Estonia

France

Germany

Ireland

Lithuania

Luxembourg

Poland

Switzerland

Bulgaria

Finland

Hungary

Iceland

Italy

Latvia

Malta

Montenegro

Norway

Sweden

Turkey

Romania

## 8. PROCESSING THE KPI SURVEY

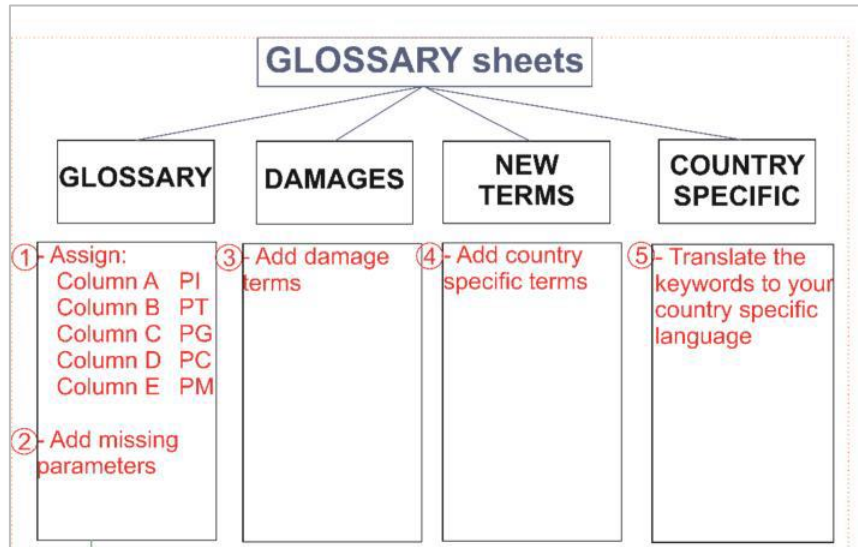


Country	Document	Doc. Type	Author	Year
Slovenia	Bridge condition assessment	Evaluation	Žnidarič, Terčelj, Marolt	1990
	Damage types numerical evaluation	Evaluation	Žnidarič et al.	1992
	Expansion joints inspection report	Inspection	?	2005
Spain	Guía para la realización de inspecciones principales de obras de paso en el Rinspección	Inspection	Ministerio de Fomento	2012
	Guía para la redacción			
Country	Document	Doc. Type	Author	Year
Switzerland	ASTRA 82001 - Überprüfungen	Inspection	Vejdirektoratet	2014
	ASTRA 12002 - Überprüfungen	Evaluation	Vejdirektoratet	2015
	ASTRA 12010 - Massnahmen	Evaluation	Vejdirektoratet	2004
	ASTRA 12011 - Fahrplan	Inspection	Republic Agency for Roads	2003
	ASTRA 12009 - Oberfläch			
	ASTRA 19003 - Managem			
	ASTRA 62014 - KUBA			
	Beurteilung der Erdb			
	SIA Norm 469 - Erhalt			
	SIA Norm 269 - Grund			
United Kingdom	ADDENDUM TO CSS G			
Country	Document	Doc. Type	Author	Year
Denmark	Eftersyn af bygværker	Inspection	Vejdirektoratet	2014
	Vejledning til belastnings- og beregningsgrundlag for broer	Evaluation	Vejdirektoratet	2015
	Reliability-Based classification of the Load Carrying Capacity of Existing Bridges	Evaluation	Vejdirektoratet	2004
FYRO Macedonia	Roobook for technical inspection of culverts and bridges on road network	Inspection	Republic Agency for Roads	2003
Greece	Bridge Inspection Manual			
	Bridge Evaluation Manual			
	Bridges structural and operational adequacy			
	Visual inspection manual for bridges			
Israel	"Guidance document for evaluation of s			
	"Seismic performance evaluation for Bri			
	"Guide for Documenting Bridges and Ro			
	"Guidance documents for bridge inspect			
	"Israeli bridges and road structures defe			
	"Identification, Numbering and Marking			
	"Bridge inspector's qualification guide"			
Netherlands	Analysekader vaste kunstwerken			
	Referentiedocument Viaduct			
	Referentiedocument Vaste Brug			
Portugal	Screening1 - Quality Control Plan			
	Screening3 - Technical Specifications fo			
Serbia	Tehničko rešenje baze podataka o most			
	Pravilnik o utvrđivanju nosivosti postoje			
	Vulnerability assessment of bridges exp			
Slovakia	TP 13/2013 Technical Specifications. Roa			
	USM 1/2012 Regulation. Load-carrying ca			
	TP 07/2012 Technical Specifications. Insp			
	TP 08/2012 Technical Specifications. Insp			
	TP 09/2012 Technical Specifications. Dan			
	TP 14/2013 Technical Specifications. Brid			
	STN 73 6209 Loading tests of bridges (ST			
Country	Document	Doc. Type	Author	Year
Austria	Quality Assurance for Structural Maintenance - Suveillance, Checking and As	Inspection	BMVIT	2011
Bosnia and Herz.	ZAKON O CESTAMA FEDERACIJE BOSNE I HERCEGOVINE / LAW ON ROADS OF	Inspection	Parlament Federacije BiH / Federation Parli	2010
	Odluka o kategorizaciji cesta u autoceste i brze ceste, magistralne ceste i re	Inspection	Vlada FBiH / Government of FBiH	2014
	Pravilnik o održavanju javnih cesta / Regulations the maintenance of public	Inspection	Federalnom ministarstvu prometa i komuni	2010
	SMJERNICE ZA PROJEKTOVANJE, GRAĐENJE, ODRŽAVANJE I NADZOR NA CEST	Inspection	RS-FB&H/3CS – DDC	2005
	UPUTSTVO ZA INSPEKTORE MOSTOVA / INSTRUCTIONS FOR INSPECTORS OF	Evaluation	BCEOM Societe Francaise D'ingenere	2004
	MOSTOVI / BRIDGES	Research	Prof. Boris Koboević, Prof. Bisera Kara	1994
	Ispekciski formular za prolede mosta / The inspection form for an overp	Inspection	Prof. Bisera Karalić, Hromić	2004
Croatia	Handbook of damages on bridge elements	Evaluation	Hrvatske ceste d.o.o., dr.sc. Danijel Tenžera	2014
	Guidelines for bridge inspections	Inspection	Hrvatske ceste d.o.o.	2014
	HRMOS manual – Bridge management	Inspection	Hrvatske ceste d.o.o.	1999
	HRMOS manual – Bridge management – General bridge inspection	Inspection	Hrvatske ceste d.o.o.	1999
	Handbook of damages on bridges	Inspection/evaluati	Hrvatske Autocese d.o.o.	2010
	Guideline for bridge evaluation	Evaluation	Hrvatske Autocese d.o.o.	2010
	Bridge Management Planning	Background docum	Hrvatske Autocese d.o.o.	2008
Czech Republic	CSN 73 6221 Inspection of road bridges	Inspection	UNMZ Ústav pro technickou normalizaci, me	2011
	CSN 73 6222 Load capacity of road bridges	Evaluation	UNMZ Ústav pro technickou normalizaci, me	2009
	Catalogue of the bridge damages and defects	Inspection	Pontex spol. s r.o.	2008
	TP22 Diagnostics of road bridges	Inspection	Pontex spol. s r.o.	2008
	TRP201 Measuring and monitoring of the cracks in the concrete bridges	Inspection	CTU in Prague, Klokner institute	2008
	CSN 73 6209 Load tests of bridges	Evaluation	UNMZ Ústav pro technickou normalizaci, me	1996
	Damages of railway bridges	Inspection	SZDC TUDC	2009
	Rules for the assessment of the load capacity of railway bridges	Evaluation	SZDC TUDC	2014
	SZDC S5 management of bridges(railway)	Inspection	SZDC TUDC	2012
	TP120 Maintenance, repairs and refurbishment of concrete road bridges	Inspection	Pontex spol. s r.o.	2010
	TP175 Evaluation of the remaining life of concrete road structures	Evaluation	SVUOM s.r.o.	2006
	TP215 The application of the modal analysis for the road bridges evaluation	Evaluation	CTU in Prague, Faculty of civil eng.	2009



## 9. KPI GLOSSARY

Goal: Collecting the terms connected with key performance indicators and goals for roadway bridges across different participating countries.



## TUTORIAL

= provides the explanations of the data surveying procedure and illustrates the process of filling up the database

= explains how should one use *DATABASE* and *GLOSSARY* files

= provides examples for screening

An exact Section of the document has been assigned and the new Paragraph

Document	Quality Assurance for Structural Maintenance Surveillance, Checking and Assessment of Bridges and Tunnels Road Bridges	Add Chapter/Paragraph
Chapter/ Paragraph/ Section	6.5 Unterbau - 6.5.1 Lagerartige Veränderung der Pfeiler, Wiederlager und Flügel	Hide/show Chapter

Figure 6. First example – Austrian document – beginning of the screening

Figure 7 is portraying how the table was fulfilled with the information from the

(a)

6.5 **Unterbau**

Der Zustand ist zu erheben, zu dokumentieren und zu bewerten.

6.5.1 Lagemäßige Veränderung der Pfeiler, Widerlager und Flügel

Werden Setzungen, Verdrrehungen oder Verschöbungen des Unterbaues festgestellt, sind diese einzumessen, zu protokollieren und ihr Einfluss auf das Bauwerk zu bewerten.

Einer Prüfung der Möglichkeit der Beweglichkeit von Lagern und Fahrbahnübergängen ist besonderer Beachtung zu bedürfen.

(b)

AI Performance Level					AI Damage			
	Level	System	Component	Parameter	Type	Characteristics	Indicator	IR
+	Sub_System	AI Bridge	SubStructure		Damage_State	Settlements		
+	Sub_System	AI Bridge	SubStructure		Damage_State	Rotation		
+	Sub_System	AI Bridge	SubStructure		Damage_State	Displacement		

AI auxiliary defined in the aid above

## 9. KPI GLOSSARY

Performance Indicator	Performance Threshold	Performance Goal	Performance Criteria	Performance Method	Begriff (Deutsch)	Term (English)	Source	Definition	Source	Keywords	Projekt Relevance
X					Abnutzung	Wearout		Degradation of external coatings caused by chemical and/or physical processes.	[DIN 31051]	Building conservation	FE 15.0510 (Schädigungspotenziale)
	X				Abnutzungsgrenze	Wearout Limit		The accepted or specified minimum value of degradation levels.	[DIN 31051]	Building conservation	
					Abnutzungsprognose	Wearout Prognosis		Assessment of the service behavior of a Component (Unit), at the aim to predict future demand requirements on the basis of the known or assumed loads, starting from an actual state of the Component.	[DIN 31051]	Building conservation	
	X	X			Abnutzungsvorrat	Wearout Reserve		Stock of the possible function executions under specified conditions, of a unit due to the manufacture, repair or inherent improvement.	[DIN 31051]	Building conservation	
					Abschnitt (ASB)	Section / Segment		As a section directed part of the road network is called, which lies between two consecutive nodes. It is limited by the conditions laid down in the network nodes.	[ASBNetzdaten]	Transportation and Transportation Infrastructures	
					Adaption	Adaption		In the art "adaptation" means the ability of a mechanical or electrical system, to respond intelligently and adapt (Adaptive Systems). The adaptation or updating of the status review of a component or structure (system), including any information obtained by a structure, is also referred to as adaptation. In a model adaptation (model updating) the unknown parameters of a model of this structure are calibrated so long until the static or dynamic behavior of the model corresponds to the actual measured on.	[ScKK12, FSTS12]	Modeling	FE 15.0509 (Machbarkeitsstudie) FE 15.0508 (Bewertung)

- Glossary Sheets presents the key concepts, definitions and keywords in relation to key performance indicators (PI), thresholds (PT), goals (PG), criteria (PC) and methods (PM).
- Users should **assign these expression using mark "X" to terms** in Glossary. This characterization in PI, PT, PG, PC and PM is essential information for the Database.
- Country specific terms serves for translation of contents of the sheet Glossary (terms, definitions, keywords ...) to the user's native language.
- Glossary offers a list of terms with **source (reference), definition and keywords**. Users should fill in Glossary parallel with Database while screening their national documents.

# 10. OPERATORS KPI DATABASE

## List of documents

SURVEY OF PERFORMANCE INDICATORS					
Country		Croatia		New Document	
num	Responsible Person	Document	Doc. Type	Author	Year
1	Ana Mandić Ivanković	Handbook of damages on bridge elements	Evaluation	Hrvatske ceste d.o.o., dr.sc. Danijel	2014
2	Ana Mandić Ivanković	Guidelines for bridge inspections	Inspection	Hrvatske ceste d.o.o.	2014
3	Ana Mandić Ivanković	HRMOS manual – Bridge management	Inspection	Hrvatske ceste d.o.o.	1999
4	Dominik Skokandić	HRMOS manual – Bridge management – General bridge inspection	Inspection	Hrvatske ceste d.o.o.	1999
5	Dominik Skokandić	Handbook of damages on bridges	Inspection/evaluation	Hrvatske Autoceste d.o.o.	2010
6	Ana Mandić Ivanković	Guideline for bridge evaluation	Evaluation	Autoceste d.o.o.	2010
7	Ana Mandić Ivanković	Bridge Management Planning	Background document	Hrvatske Autoceste d.o.o.	2008
8					
9					
10					
11					
12					



## Handbook of damages on bridge elements

elements

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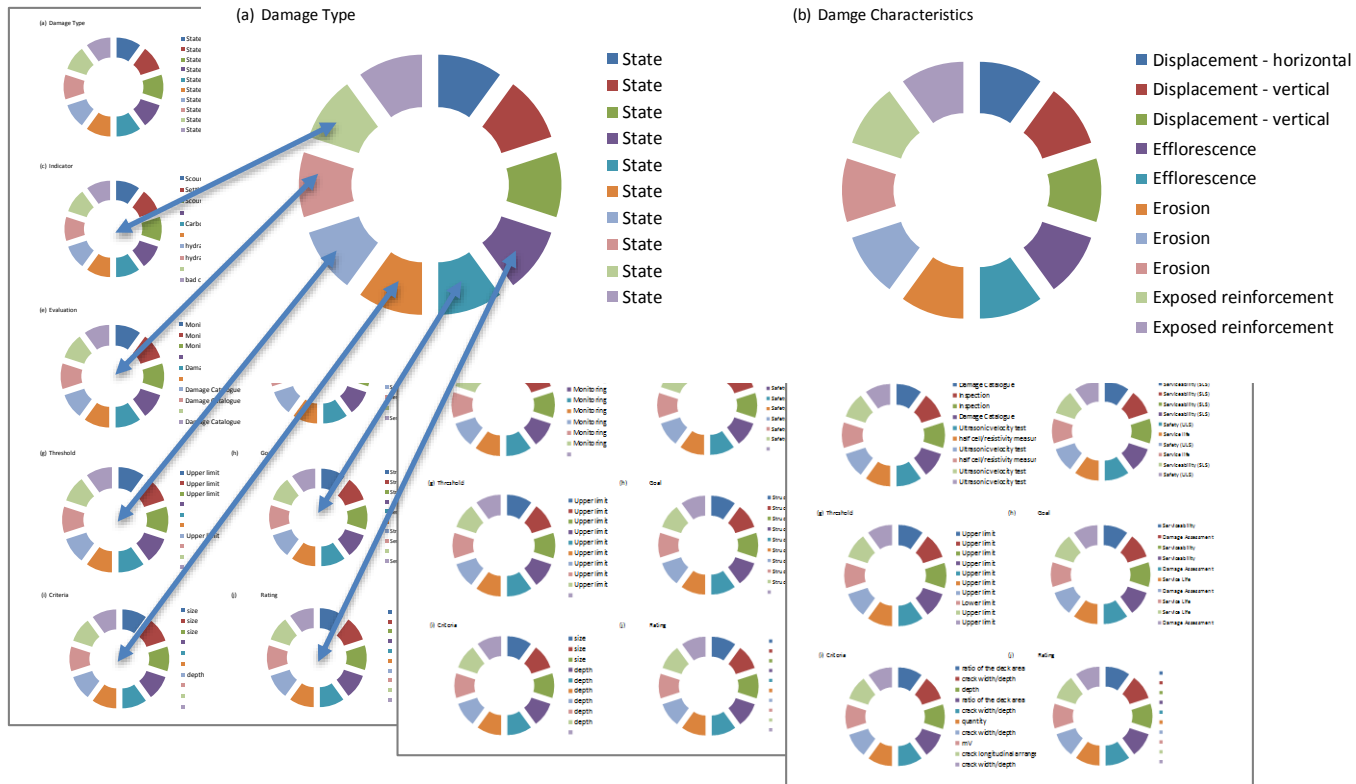
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## 10. OPERATORS KPI DATABASE



Example  
of  
Greece

**PI, PT, PG, PC  
and PM for  
roadway bridges  
abutments in  
each specific  
country.**

# 10. OPERATORS KPI DATABASE

Damages indicated for RC abutments in different countries

	Au	Be	Bosnia and H	Bu	Croatia	Cy	Cz	Denmark	Es	Fin	Fr	Gr	Ge	Greece	Hu	It	Ir	Is	Ita	Lat	Lit	Lux	Ma	Mc	Netherlands	No	Po	Portugal	Serbia	Slovakia	Slovenia	Spain	Sw	Sw	Tu	Un
Abrasion			x																																	
Alkali aggregate reaction														x																						
Breaking away					x																															
Cavities																																				
Concrete cover insufficient					x																															
Concrete quality insufficient																																				
Corrosion																																				
Cracks					x			x																												
Cracks - longitudinal														x																						
Cracks - mapping														x																						
Cracks - mapping														x																						
Cracks - skew														x																						
Cracks - transversal														x																						
Cracks - vertical														x																						
Cracks in the bearing beams			x																																	
Cracks on the front face of the v			x																																	
Debris																																				
Deformation					x																															
Delamination					x									x																						
Deterioration														x																						
Differential rotation																																				
Displacement																																				
Displacement - horizontal														x																						
Displacement - vertical														x																						
Drainage deficiency																																				
Efflorescence																																				
Erosion			x																																	
Erosion around and under the pi			x																																	
Erosion in front abutments			x																																	
Exposed foundations																																				
Exposed reinforcement																																				
Flooding																																				
Formwork residuals																																				
Hydraulic protection deficiency																																				
Joint deficiency																																				
Landslide - transmission embank																																				
Loose stones																																				
Mortar flaking																																				
Move the abutment			x																																	
Peeling off																																				
Position fixing deficiency																																				
Protection cover deficiency																																				
Reinforcement corrosion																																				
Riverbed protection elements de																																				
Rotation / Leaning																																				
Sag																																				
Scour																																				
Scour under abutment																																				

Example of damages indicated for roadway bridges abutments in all the countries.

Damages indicated for RC abutments in different countries

	Au	Be	Bosnia and H	Bu	Croatia	Cy	Cz	Denmark	Es	Fin	Fr	Gr	Ge	Greece	Hu	It	Ir	Is	Ita	Lat	Lit	Lux	Ma	Mc	Netherlands	No	Po	Portugal	Serbia	Slovakia	Slovenia	Spain	Sw	Sw	Tu	Un
Scour under abutment																																				
Segregation of concrete					x									x																						
Settlement cracks																																				
Settlements									x																											
Soil failure																																				
Spalling														x																						
Spalling with exposed reinforcement														x																						
Split-off																																				
Stagnant water in abutment insp														x																						
Strike																																				
Subterranean waterflow														x																						
Sulphate action														x																						
Vegetation														x																						
Water drainage deficiency														x																						
Water penetrability																																				
Wet spots																																				



## 10. OPERATORS KPI DATABASE

### *Categorization of Performance indicators for roadwa bridges*

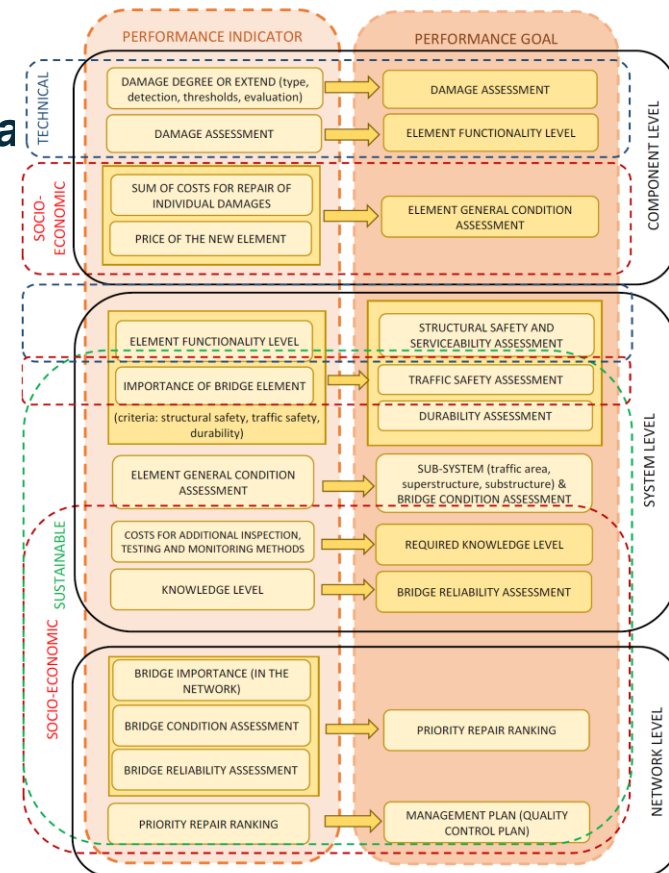
(i) Performance indicators at the *component level*:

- Technical indicators.
- Socio-Economic indicators.

(ii) Performance indicators at the *system level*:

- Technical indicators.
- Socio-Economic indicators.
- Sustainable indicators.

(iii) Performance indicators at the *network level*.



# 11. RESEARCHERS KPI DATABASE

SURVEY OF RESEARCH PERFORMANCE INDICATORS

Article	Performance assessment of concrete structures based on probabilistic prediction models and monitoring information
Author	Strauss, Zambon, Vidovic, Grossberger, Bergmeister
Year	2015
Abstract	An efficient evaluation and prediction of time variable mechanical and chemical degradation processes is fundamental requirement for life-cycle analysis as well as for the complete assessment of concrete structures. Important tools and valuable support in these tasks are inspection systems and methods. Unfortunately, due to their practical feasibility and costs they entail, their utility and information gathered with inspection and monitoring methods need to be used in the most efficient way possible. The aim of this contribution is to present a framework for the prediction of time-dependent performance indicators of concrete structures prone to fatigue, with emphasis on a wind tunnel test. A theoretical background with selected indicators is presented through associated life-cycle methods including inspection and monitoring information with incorporated reliability.
Journal	IABSE Conference – Structural Engineering: Providing Solutions to Global Challenges; September 2015, Geneva, Switzerland
Keywords	life-cycle analysis; performance indicators; probabilistic performance prediction; efficient

Performance Indicator	Young modulus
Type of Indicator	Material property
Mathematical Formulation	
Threshold	
Intentions (where to apply)	In order to evaluate the fatigue performance of the critical cross-sections
Level of maturity	Research stage
Case study	STRABAG test foundation in Cuxhaven
Performance Indicator	Reliability Index
Type of Indicator	Reliability
Mathematical Formulation	
Threshold	
Intentions (where to apply)	In order to evaluate the fatigue performance of the critical cross-sections
Level of maturity	Research stage
Case study	STRABAG test foundation in Cuxhaven

References

- [1] Zhao, Y.-G., Zhong, W.-Q., Ang, A.H.-S., 2007. Estimating joint failure probability of series structural systems. J. Eng. Mech. 133, 588–596.
- [2] Strauss A, Vidovic A, Zambon I, Grossberger H, Bergmeister K. Monitoring information and probabilistic based prediction models for the
- [3] Mark, P., Stangenberg, F., Bergmeister, K., Strauss, A., Ahrens, M.A., 2013. Lebensdauerorientierter Entwurf, Konstruktion, Nachrechnung

SURVEY OF PERFORMANCE INDICATORS

Country	Austria			Add Article
num	Responsible Person	Article	Author	Year
1	Ivan Zambon	<i>Performance assessment of concrete structures based on probabilistic prediction models and monitoring information</i>	Strauss, Zambon, Vidovic, Grossberger, Bergmeister	2015
2				
3				
4				

## 12. FUTURE DEVELOPMENTS



WG		Year 1				Year 2				Year 3				Year 4			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
WG1	Technical indicators	✖	✖	✖	✖												
	Environmental indicators	✖	✖	✖	✖												
	Other indicators	✖	✖	✖	✖												
WG2	Technical goals					X	X	X	X								
	Environmental goals					X	X	X	X								
	Other goals					X	X	X	X								
WG3	Survey of European roadway QC plans	✖	✖	✖	✖	X	X										
	Procedures for the establishment of a QC plan							X	X	X	X						
	Selection of case studies							X	X	X							
WG4	Benchmarking										X	X	X	X	X		
	Application on a QC plan											X	X	X	X		
	Standardized performance indicators				✖	X	X	X									
WG5	Standardized goals								X	X	X	X					
	Standardized QC plan										X	X	X	X	X	X	X
WG6	Dissemination	✖	✖	✖	✖	X	X	X	X	X	X	X	X	X	X	X	X

## 12. FUTURE DEVELOPMENTS

- WG1 report in Key Performance Indicators, including Operators and Researchers KPI Database (*developments during Belgrade meeting*):
  - **Predicted date - end of April 2016.**
- WG5 will start to work in cooperation with WG1, using the main results for standardization purposes. WG1 final report, with WG5 inputs with respect to standardization of KPI:
  - **Predicted date - end of December 2016.**
- WG2 and WG3 just started their works, focusing on add-ons to the existing database and a questionnaire for different stakeholders (*developments during Belgrade meeting*).



*wish you a pleasant stay in Serbia ...*





Belgrade, 30.03.2016

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## **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **Indicators for Sustainability Assessment**

**Luís Bragança**  
**University of Minho, Portugal**



**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**

# Content

- Objective of the Sustainable Construction
- COST Action C25 - Sustainability of Constructions
- Indicators for Sustainability Assessment
- Development of sustainability assessment systems
- Development of SBTool<sup>PT</sup> for building sustainability assessment

# Objective of the Sustainable Construction

**Creating and operating  
a healthy built environment**

**based on**

**resource-efficiency and ecological principles**



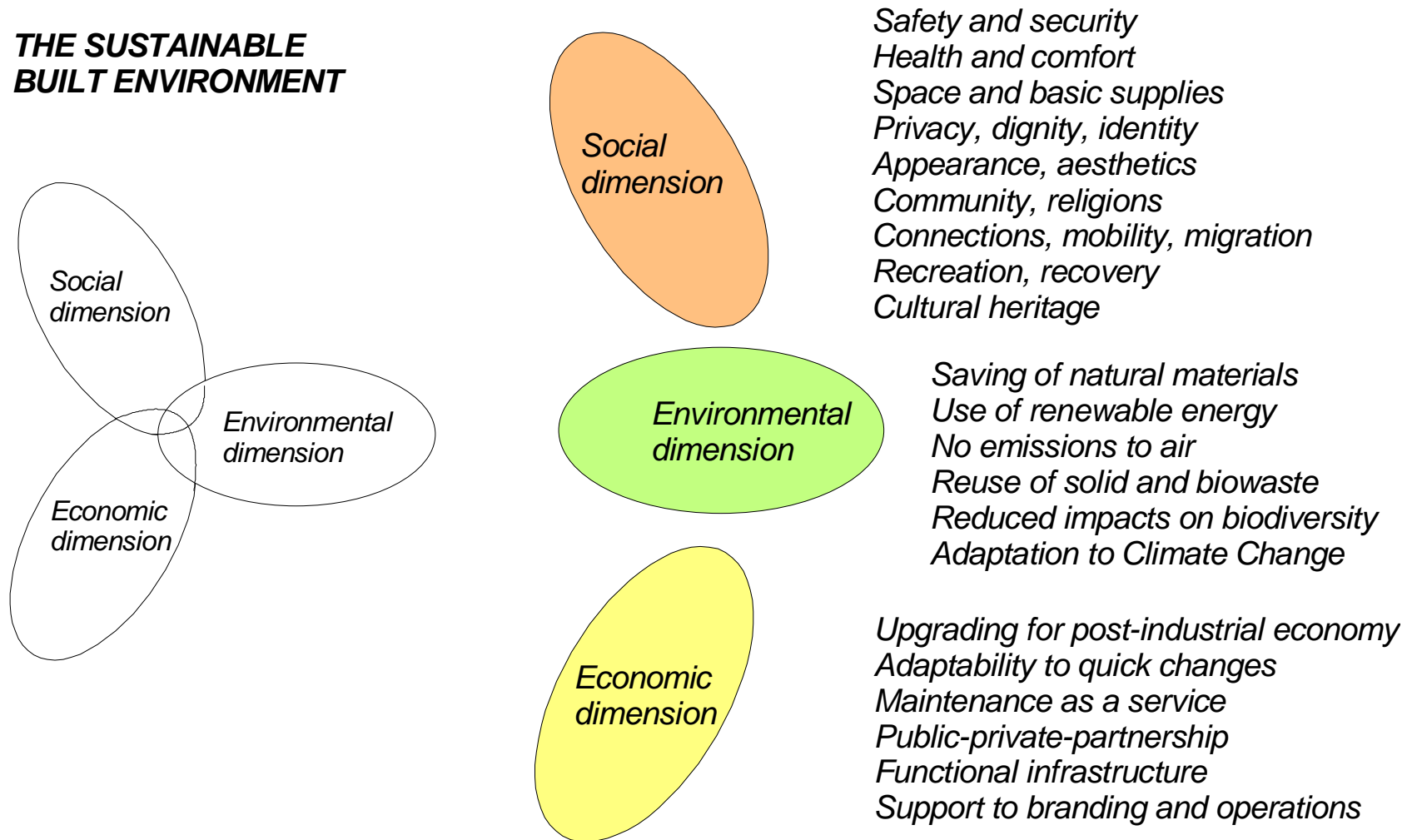
## Agenda 21

on sustainable construction

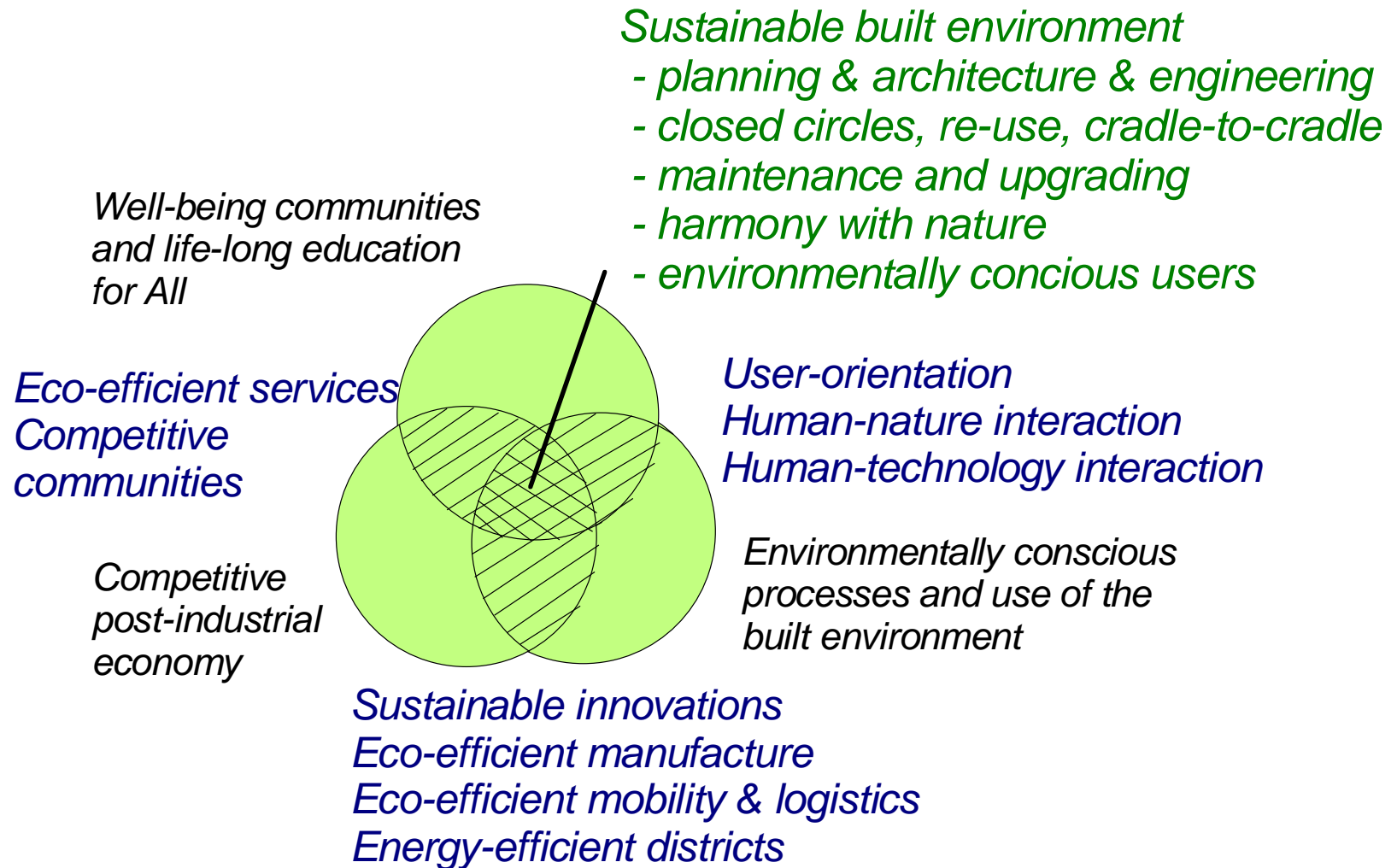
CIB Report Publication 237

# Dimensions of the sustainable built environment

## THE SUSTAINABLE BUILT ENVIRONMENT







# Life-time engineering

**aims**  
**to ensure that the requirements**  
**of stake-holders of the sector are fulfilled**  
**in technical terms**  
**during the whole life-cycle of a structure or building.**

**It is an integrated approach.**

**It benefits from several theoretical disciplines to produce**  
**service-life design methods and tools.**

# **COST Action C25**

## **Sustainability of Constructions**

### **- Integrated Approach to Life-time Structural Engineering**

The Action was established to promote science-based and research-based approaches for sustainable construction in Europe through the collection, development, research and collaborative analysis of scientific results concerning life-time structural engineering and especially the integration of environmental assessment methods and tools of structural engineering.

# COST Action Sustainability of Constructions

The ideas and the knowledge have matured throughout the Action, from the initial brainstorming of the proposal, in 2005, until the production of its final outcome and organization of the Final Conference in Innsbruck in February 2011.

The Action has successfully contributed to the scientific advancement of the methods of life-time structural engineering and to the implementation of sustainable construction approaches.

The achievements are mainly published in 4 Books of Proceedings, in relation to the Action events, 2 Training School Books and the 2 Volumes of the Final Conference Proceedings.

# COST Action Sustainability of Constructions

Main achievements:

- Sustainability assessment guidelines for both bridges and buildings
- A methodology to assess sustainability of bridges
- Integrated methodology for lifetime engineering including risk analysis and maintenance scenarios
- A Special Issue on “Sustainability of Constructions - Integrated Approach to Life-time Structural Engineering” in the Sustainability Journal (ISSN: 2071-1050)

[http://www.mdpi.com/journal/sustainability/special\\_issues/sustainability-constructions](http://www.mdpi.com/journal/sustainability/special_issues/sustainability-constructions)

- A Special Issue on “Sustainability Assessment of Buildings” in the International Journal of Sustainable Building Technology and Urban Development (ISSN: 2093-761X Print, 2093-7628 Online)

<http://www.tandfonline.com/toc/tsub20/3/4>



# COST Action Sustainability of Constructions

## Publications

Book 1 - 1st Workshop, Lisbon, 2007

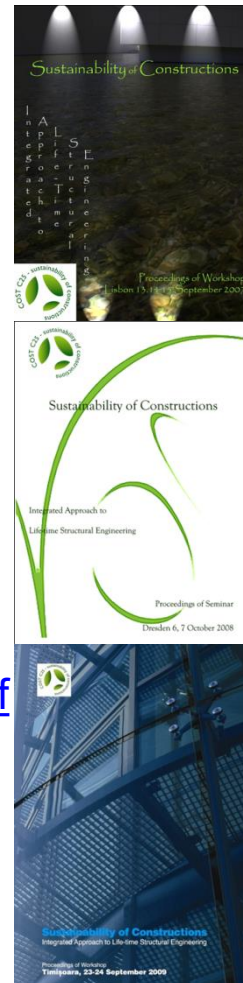
[http://dl.dropbox.com/u/7498807/C25\\_Book1\\_1st\\_Workshop\\_Lisbon\\_2007.pdf](http://dl.dropbox.com/u/7498807/C25_Book1_1st_Workshop_Lisbon_2007.pdf)

Book 2 - Midterm Conference, Dresden, 2008

[http://dl.dropbox.com/u/7498807/C25\\_Book2\\_Midterm\\_Conference\\_Dresden\\_2008.pdf](http://dl.dropbox.com/u/7498807/C25_Book2_Midterm_Conference_Dresden_2008.pdf)

Book 3 - 2nd Workshop, Timisoara, 2009

[http://dl.dropbox.com/u/7498807/C25\\_Book3\\_2nd\\_Workshop\\_Timisoara\\_2009.pdf](http://dl.dropbox.com/u/7498807/C25_Book3_2nd_Workshop_Timisoara_2009.pdf)

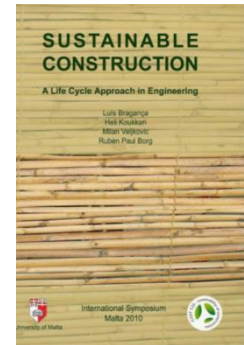


# COST Action Sustainability of Constructions

## Publications (cont.)

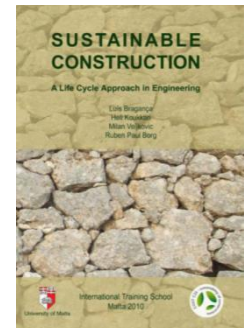
Book 4 - ESR Symposium, Malta, 2010

[http://dl.dropbox.com/u/7498807/C25\\_Book4\\_ESR\\_Symposium\\_Malta\\_2010.pdf](http://dl.dropbox.com/u/7498807/C25_Book4_ESR_Symposium_Malta_2010.pdf)



Book 5 - 3rd Training School, Malta 2010

[http://dl.dropbox.com/u/7498807/C25\\_Book5\\_Training\\_School\\_Malta\\_2010.pdf](http://dl.dropbox.com/u/7498807/C25_Book5_Training_School_Malta_2010.pdf)



# COST Action Sustainability of Constructions

## Publications (cont.)

Book 6 - Final Outcome Volume 1, 2010

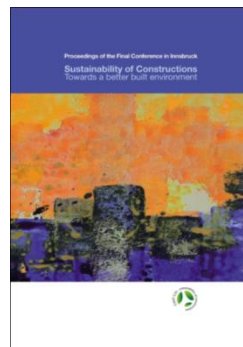
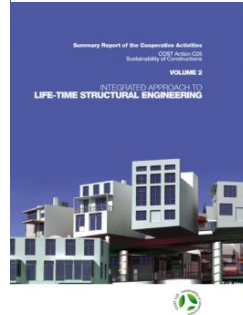
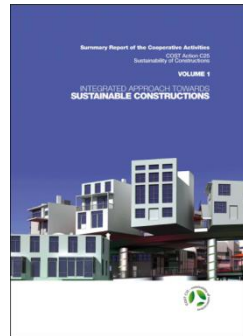
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Book 7 - Final Outcome Volume 2, 2010

[http://dl.dropbox.com/u/7498807/C25\\_Book7\\_Final\\_Outcome\\_Volume\\_2\\_2010.pdf](http://dl.dropbox.com/u/7498807/C25_Book7_Final_Outcome_Volume_2_2010.pdf)

Book 8 - Final Conference Proceedings, Innsbruck, 2011

[http://dl.dropbox.com/u/7498807/C25\\_Book8\\_Final\\_Conference\\_Proceedings\\_Innsbruck\\_2011.pdf](http://dl.dropbox.com/u/7498807/C25_Book8_Final_Conference_Proceedings_Innsbruck_2011.pdf)



# *Why indicators*

- Optimizing sustainability involves various relations between built, natural and social systems. Therefore it comprises the analysis of **hundreds of variables**, most of them interrelated and partly contradictory.
- Sustainability assessment tools are useful to **gather** and **report** information for **decision-making** during different phases of construction, design and use of a structure (holistic approach).
- This way, this process is only possible through a **systematic approach**.



- Therefore sustainability assessment is generally based on a **list of indicators**

*An sustainability **indicator**.*

- **provide information about the main influences** of the industry as a whole and about the impacts of construction and operation of buildings, structures and other built assets
- **is expressed by a value derived from a combination of different measurable parameters** (variables)

- **Different indicators have been developed** by institutions, organizations and industries locally, nationally and globally.



Main reasons...

- Political, Technological and Cultural differences between countries
- Lack of normalization and common understanding

**Different indicators (methods) = Different results**

## Master List of SBTool Parameters

		Phase active			
		P-Dsn	Dsn	C&C	Ops
<b>A Site Selection, Project Planning and Development</b>					
<b>A1 Site Selection</b>					
A1.1	Pre-development ecological value or sensitivity of land.				
A1.2	Pre-development agricultural value of land.				
A1.3	Vulnerability of land to flooding.				
A1.4	Potential for development to contaminate nearby bodies of water.				
A1.5	Pre-development contamination status of land.				
A1.6	Proximity of site to public transportation.				
A1.7	Distance between site and centres of employment or residential occupancies.				
A1.8	Proximity to commercial and cultural facilities.				
A1.9	Proximity to public recreation and facilities.				
<b>A2 Project Planning</b>					
A2.1	Feasibility of use of renewables.				
A2.2	Use of Integrated Design Process.				
A2.3	Potential environmental impact of development or re-development.				
A2.4	Provision of surface water management system.				
A2.5	Availability of potable water treatment system.				
A2.6	Availability of a split grey / potable water system.				
A2.7	Collection and recycling of solid wastes in the community or project.				
A2.8	Composting and re-use of sludge in the community or project.				
A2.9	Site orientation to maximize passive solar potential.				
<b>A3 Urban Design and Site Development</b>					
A3.1	Development density.				
A3.2	Provision of mixed uses within the project.				
A3.3	Encouragement of walking.				
A3.4	Support for bicycle use.				
A3.5	Policies governing use of private vehicles.				
A3.6	Provision of project green space.				
A3.7	Use of native plantings.				
A3.8	Provision of trees with shading potential.				
A3.9	Development or maintenance of wildlife corridors.				
<b>B Energy and Resource Consumption</b>					
<b>B1 Total Life Cycle Non-Renewable Energy</b>					
B1.1	Annualized non-renewable primary energy embodied in construction materials.				
B1.2	Annual non-renewable primary energy used for facility operations.				
<b>B2 Electrical peak demand for facility operations</b>					
<b>B3 Renewable Energy</b>					
B3.1	Use of off-site energy that is generated from renewable sources.				

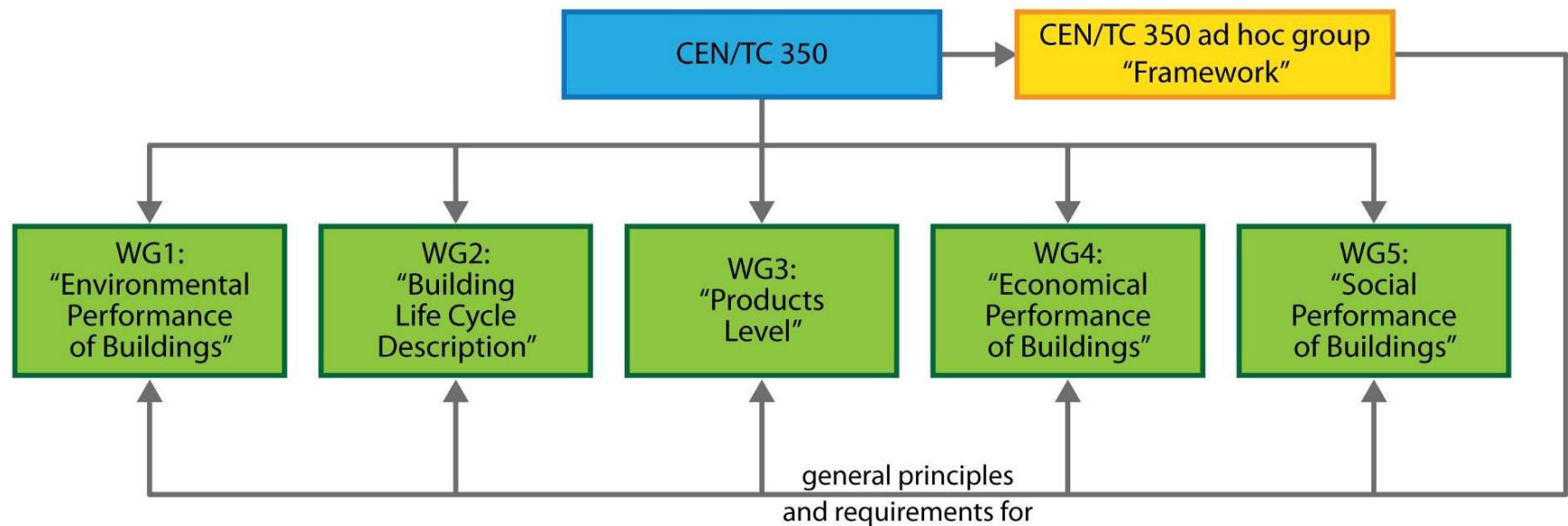
The full list of sustainability indicators is quite long...

For example, SBTool 2016 has a total of potentially active 191 indicators

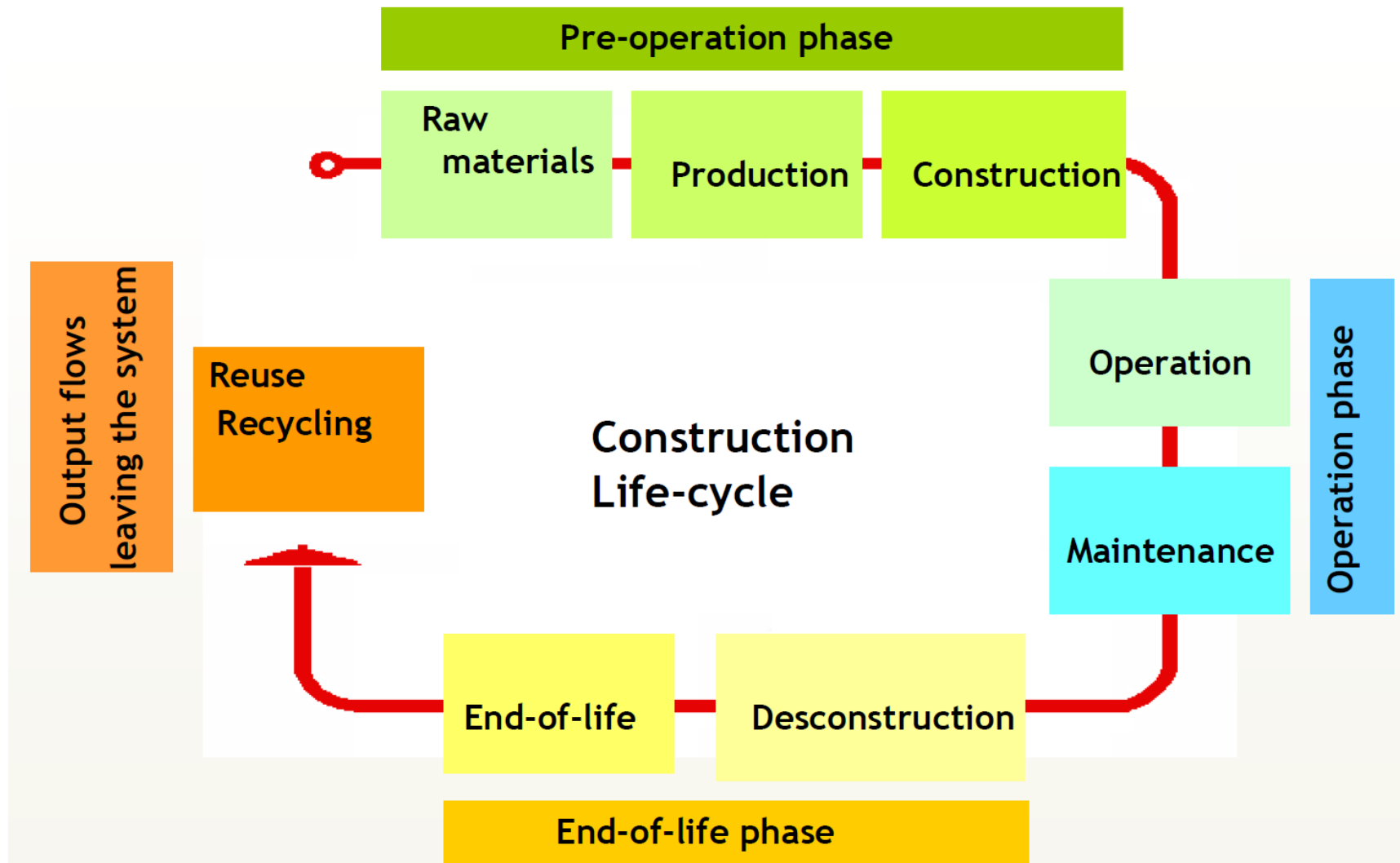


# Development of sustainability assessment systems

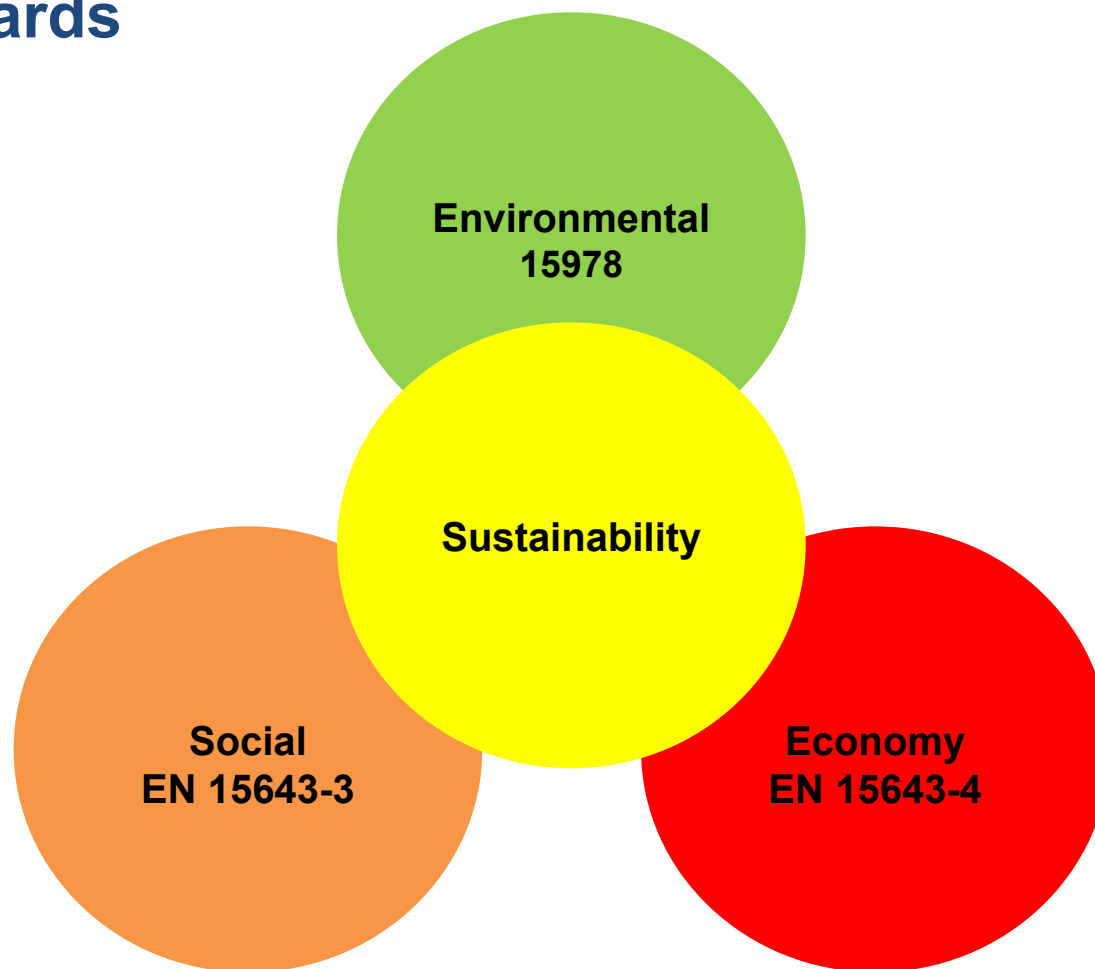
- In order to **standardize** and **promote** the **interpretation and comparison of results** from different assessment methods developed in Europe, the European Committee for Standardization (CEN) launched the Technical Committee 350 (CEN/TC 350).



# *Life-cycle boundaries*



# CEN/TC 350 - Sustainability of Construction Works - Standards



- According to standard **EN 15978:2012** the assessment of the environmental performance of a building is based in **4 types of environmental indicators (total of 22)**:

### ***1 - Indicators describing environmental impacts:***

Indicator	Unit
Global warming potential, GWP	kg CO <sub>2</sub> equiv
Depletion potential of the stratospheric ozone layer, ODP;	kg CFC 11 equiv
Acidification potential of land and water; AP;	kg SO <sub>2</sub> <sup>-</sup> equiv
Eutrophication potential, EP;	kg (PO <sub>4</sub> ) <sup>3-</sup> equiv
Formation potential of tropospheric ozone photochemical oxidants, POCP;	kg Ethene equiv
Abiotic Resource Depletion Potential for elements; ADP_elements	kg Sb equiv
Abiotic Resource Depletion Potential of fossil fuels ADP_fossil fuels	MJ

**2 - Indicators describing resource use:**

Indicator	Unit
Use of renewable primary energy excluding energy resources used as raw material	MJ, net calorific value
Use of renewable primary energy resources used as raw material	MJ, net calorific value
Use of non-renewable primary energy excluding primary energy resources used as raw material	MJ, net calorific value
Use of non-renewable primary energy resources used as raw material	MJ, net calorific value
Use of secondary material	kg
Use of renewable secondary fuels	MJ
Use of non-renewable secondary fuels	MJ
Use of net fresh water	m <sup>3</sup>

**3 - Indicators describing additional environmental information:**

Indicator	Unit
Hazardous waste disposed;	kg
Non-hazardous waste disposed	kg
Radioactive waste disposed	kg

**4 - Indicators describing the output flows leaving the system:**

Indicator	Unit
Components for re-use	kg
Materials for recycling	kg
Materials for energy recovery (not being waste incineration)	kg
Exported energy	MJ for each energy carrier



➤ Some of the established **social indicators** are:

***Indicators describing social impacts:***

- Accessibility;
- Adaptability / Flexibility;
- Health and comfort;
- Cultural identity;
- Neighborhood pressure;
- Maintenance;
- Safety/security.

➤ Economy aspects should **include life-cycle costs related to:**

- Operation;
- Maintenance;
- Refurbishment and replacement of components;
- Deconstruction;
- Recycling / End-of-life scenario.

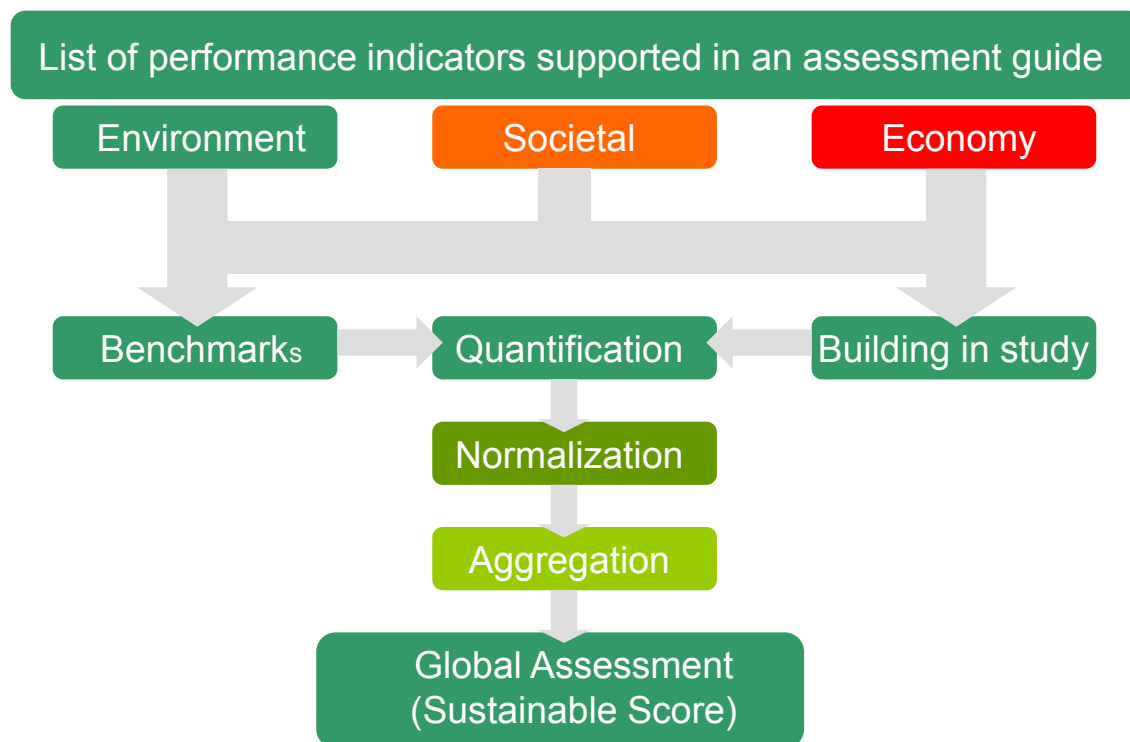
# ***Use of CEN/TC 350 indicators on Building Sustainability Assessment methods (example of SBTool<sup>PT</sup>)***

- Based on global methodology SBTool and on the ongoing work in CEN/TC 350, there are a number of sustainability assessment and certification tools that are appropriate to the national contexts (standards and regulations, weather, technologies and sociocultural issues)



**Example: Module for assessment of housing buildings (SBTool<sup>PT</sup>)**

## Structure of the Methodology SBTool<sup>PT</sup>



## Dimensions, Categories and Parameters

### CATEGORIES UNDER ASSESSMENT

#### Environment

- C1) Climate change and outdoor air quality;**
- C2) Land use and biodiversity;**
- C3) Energy efficiency;**
- C4) Materials use and solid waste;**
- C5) Water use and effluents.**

#### Society

- C6) Occupants health and comfort;**
- C7) Accessibilities;**
- C8) User's awareness and education.**

#### Economy

- C9) Life-cycle costs.**

## Categories and environmental parameters (15)

Dimension	Categories	Parameters	P <sub>ID</sub>
Environmental	C1 – Climate change and outdoor air quality	<ul style="list-style-type: none"> <li>• Embodied environmental impacts</li> </ul>	P1
	C2 – Land use and biodiversity	<ul style="list-style-type: none"> <li>• Urban soil use</li> </ul>	P2
		<ul style="list-style-type: none"> <li>• Land waterproofed index</li> </ul>	P3
		<ul style="list-style-type: none"> <li>• Pre-developed land use</li> </ul>	P4
		<ul style="list-style-type: none"> <li>• Use of local plants</li> </ul>	P5
		<ul style="list-style-type: none"> <li>• Heat-island effect</li> </ul>	P6



## Categories and environmental parameters (cont.)

Dimensão	Categorias	Parâmetros	P <sub>ID</sub>
Environmental	C3 - Energy Efficiency	• Primary energy consumption	P7
		• In-situ energy production from renewables	P8
	C4 – Materials and solid waste	• Building materials re-use	P9
		• Building materials recycling content	P10
		• Use of certified organic materials	P11
		• Use of cement substitutes materials on concrete	P12
		• Household waste management	P13
	C5 – Water efficiency and effluents	• Fresh water consumption	P14
		• Water reuse and recycling	P15

## Categories and societal parameters (8)

Dimension	Categories	Parameters	P <sub>ID</sub>
Societal	C6 – Occupant's health and comfort	• Natural ventilation potential	P16
		• Embodied VOC content	P17
		• Thermal comfort	P18
		• Natural lighting potential	P19
		• Acoustic comfort	P20
	C7 - Accessibilities	• Accessability to public transportation	P21
		• Accessibilities to urban amenities	P22
	C8 – Users education and awareness	• Availability and content of the Building User's Manual	P23

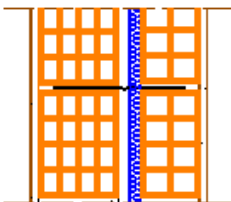
## Categories and economic parameters (2)

Dimension	Categories	Parameters	P <sub>ID</sub>
Economy	▪ Life-cycle cost	• Capital costs	P24
		• Operation costs	P25

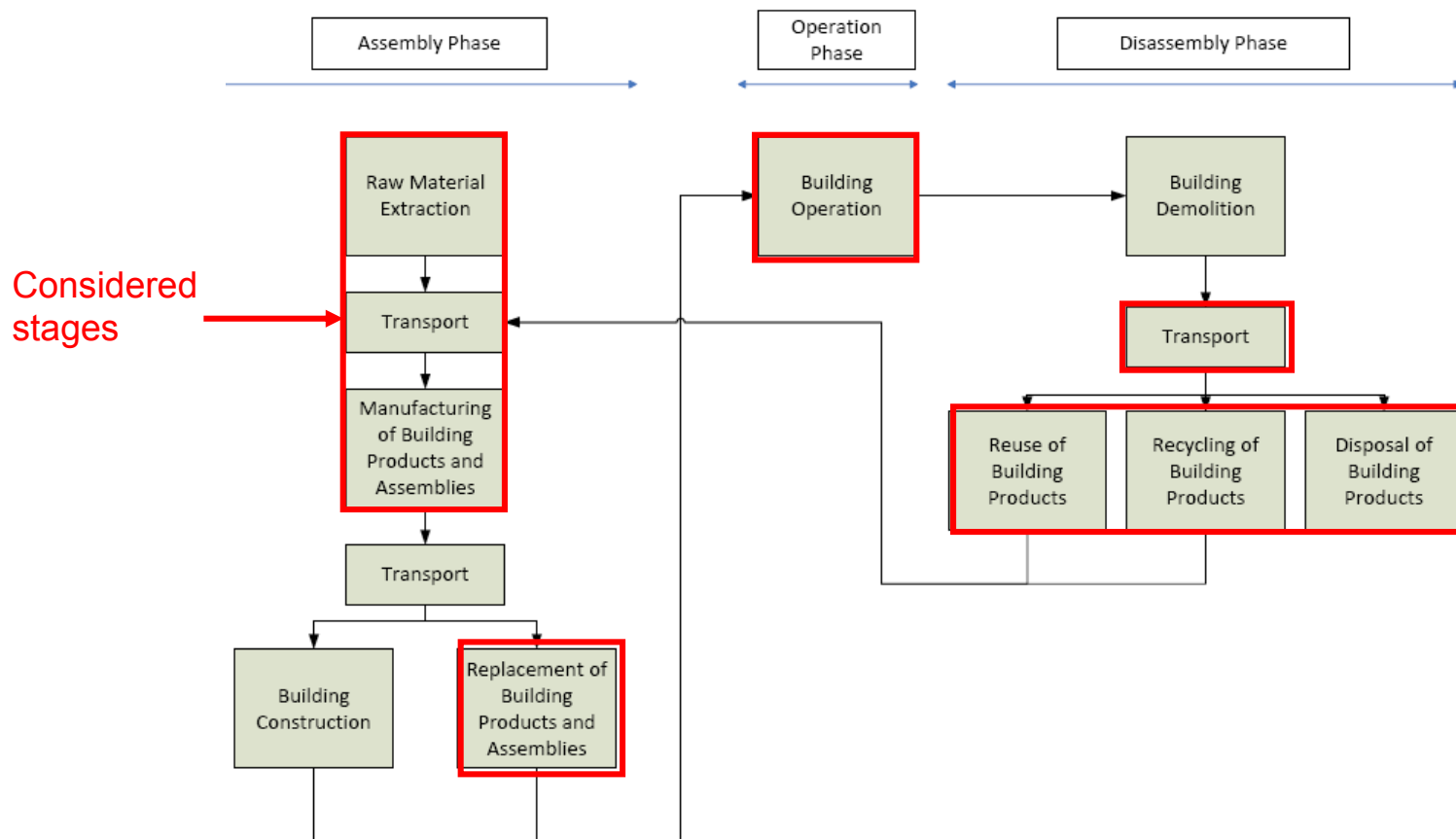
## QUANTIFICATION OF PARAMETERS

### ➤ ENVIRONMENTAL

#### LCA database (example)

Solução construtiva	Parede dupla de alvenaria de tijolo furado (15cm+11cm) com isolamento térmico em EPS							Ref: Par 1	
	Fase de ciclo de vida	Categorias de impacto ambiental de LCA						Energia incorporada	
		ADP	GWP	ODP	AP	POCP	EP	ENR	ER
	<b>Cradle-to-gate</b>	3.70E-01	9.53E+01	1.02E-04	1.91E-01	1.13E-02	2.54E-02	8.68E+02	1.01E+02
	<b>Fim de vida</b>	2.08E-01	3.17E+01	5.00E-06	1.42E-01	5.40E-03	2.95E-02	4.75E+02	2.83E+00
	<b>Total</b>	5.78E-01	1.27E+02	1.07E-04	3.33E-01	1.67E-02	5.49E-02	1.34E+03	1.04E+02
<p><b>Comentários:</b> <b>Materiais Considerados:</b> Tijolo furado, poliestireno expandido extrudido (isolamento térmico), argamassa de assentamento e reboco (revestimento)</p> <p><b>Método(s) de LCA:</b> CML 2 baseline 2000 versão 2.04 (para avaliar o Impacto ambiental) e Cumulative Energy Demand versão 1.04 (Para avaliar a energia)</p> <p><b>Bibliotecas do LCI:</b> Ecoinvent system process</p>									

## ➤ Typical life-cycle of a building and considered stages



## ➤ SOCIETAL

Using one of the different **analytical methods** or **through experimental monitoring**.

## ➤ ECONOMIC

Using **costs databases** or through the use of external **Life-cycle costing (LCC)** tools.



# *Why Benchmarking?*

## Normalization of Parameters / Benchmarking

### ***Relevance of benchmarking:***

- **systematic process** for identifying and implementing **best or better practices**
- **sustainability is a relative matter** and therefore the performance of the structure under assessment should be compared with conventional and best/better practices (benchmarks)

➤ In SBTool<sup>PT</sup>, the adopted benchmarking process **compares the performance of a building with conventional and better practices.**

➤ In SBTool<sup>PT</sup> the following principles were used to set the benchmarks of the 25 indicators:

- **Conventional practice** – a building with the same geometry as the one under assessment but that uses the local's conventional building elements (for the embodied impacts) and that fulfills the minimum environmental legal requirements or that has a similar performance to the conventional practice (for other indicators)
- **Best/better practice** – a building that have 25% of the conventional impacts (for the embodied impacts) and that fulfils best/better practices (for other indicators)

- The adopted normalization system, converts the performance values obtained for each parameter on a scale between **0 (reference value /conventional)** and **1 (best/better performance)**:

$$\bar{P}_i = \frac{P_i - P_{*i}}{P_i^* - P_{*i}} \quad \forall_i$$

with,

$P_i$  – Value of  $i$ th parameter;

$P_{*i}$  – Conventional practice of  $i$ th parameter;

$P_i^*$  – Best practice of the  $i$ th parameter.

- The quantified values are converted in a **graded scale, from A+ to E**:

Best practice	A+	$\bar{P} > 1,00$
	A	$0,70 < \bar{P} \leq 1,00$
	B	$0,40 < \bar{P} \leq 0,70$
Conventional practice	C	$0,10 < \bar{P} \leq 0,40$
	D	$0,00 \leq \bar{P} \leq 0,10$
	E	$0,00 < \bar{P}$

## PARAMETERS AGREGATION - WEIGHTS

### ➤ Environmental (US EPA's TRACI method)

Table 1: Relative importance of each environmental impact according to EPA,U.S.A.

ID	Categorias de impacto ambiental	Pesos (%)
GWP	Potencial de Aquecimento Global	16
AP	Potencial de Acidificação	5
EP	Potencial de Eutrofização	5
FFDP	Potencial de Esgotamento das Reservas de Combustíveis Fósseis	5
IAQ	Qualidade do Ar Interior	11
HA	Alteração dos Habitats	16
WI	Consumo de Água	3
CAP	Poluição da Atmosfera	6
POCP	Potencial de Oxidação Fotoquímica (smog)	6
ODP	Potencial de Destruição da Camada de Ozono	5
ET	Toxicidade Ecológica	11
HT	Toxicidade Para o Ser Humano	11

- The weights of the environmental parameters considered in SBTool<sup>PT</sup> result from the distribution of the weights of the environmental categories of TRACI method (extent, intensity and duration of impact).

## PARAMETERS AGREGATION - WEIGHTS (cont.)

### ➤ Social

A **scientific based methodology** was developed to quantify the relative importance of each comfort and health parameter in global comfort perceived for building occupants.

The perceived global comfort ( $C_G$ ) result from the combination of various comfort parameters ( $P_i$ ):

$$C_G = P_1 \times W_1 + P_2 \times W_2 + P_3 \times W_3 + P_4 \times W_4$$

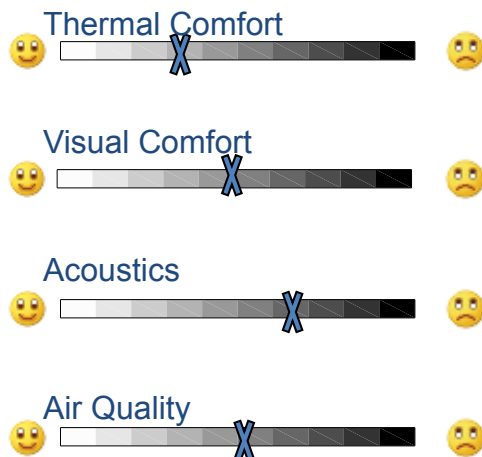
Each parameter affects differently the global comfort, since it presents a different **subjective weight** ( $W_i$ ).



# PARAMETERS AGREGATION – WEIGHTS (cont.)

## Methodology

### Subjective Evaluation

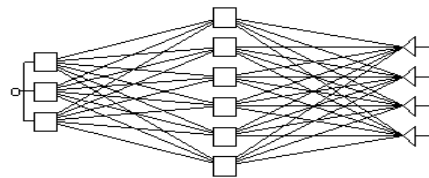


### Weight:

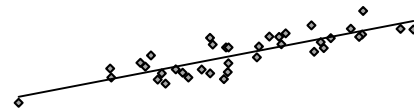
**Thermal Comfort: 32,5%**  
**Visual Comfort: 24,6%**  
**Indoor Air Quality: 23,8%**  
**Acoustics: 19,1%**

Conforto Global

### Neural Networks

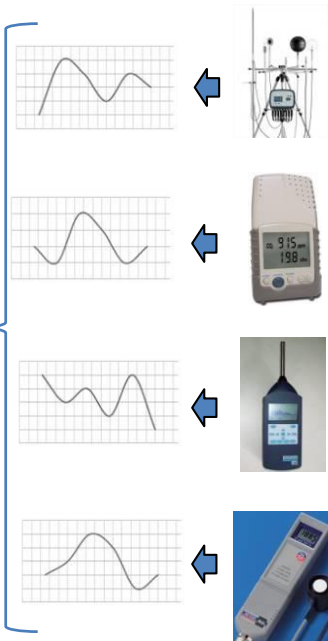


### Multivariate Regression – Linear Regression



Results:  $W_1, W_2,$   
 $W_3, W_4$

### Objective Evaluation



## WEIGHTS (Categories)

Dimension	Category		Weight (%)
Environmental	C1	Climate change and outdoor air quality	13
	C2	Land use and biodiversity	20
	C3	Energy efficiency	32
	C4	Materials and waste management	29
	C5	Water efficiency	6
Societal	C6	Occupant's health and comfort	60
	C7	Accessibilities	30
	C8	Awareness and education for sustainability	10
Economy	C9	Life-cycle costs	100



## WEIGHTS (Sustainability dimensions)

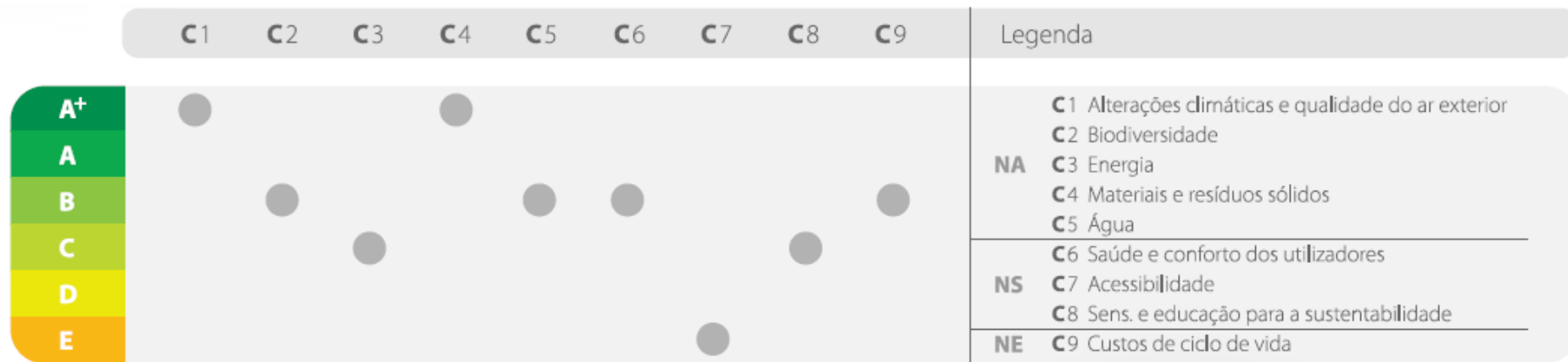
Dimension		Weight (%)
Environmental	DA	40
Societal	DS	30
Economy	DE	30

## REPRESENTATION AND GLOBAL ASSESSMENT OF A PROJECT

➤ The assessment output is presented at two levels:

### Level 1: Categories

**SBTool<sup>PT</sup>** – Example of the performance of a building solution presented at the level of the different categories



## REPRESENTATION AND GLOBAL ASSESSMENT OF A PROJECT (cont.)

### Level 2: Sustainable dimensions and sustainable score

- The assessment output is similar to the approach adopted by existing schemes such as EU Energy labelling scheme for white goods and European Display™ Campaign posters.

**SBTool<sup>PT</sup>** – Example of the performance of a solution at the level of each dimension and the overall score



# Certificado de Sustentabilidade

Nº Certificado



**SBTOOL**<sup>pt</sup>  
ferramenta para a construção sustentável

---

## 1 - IDENTIFICAÇÃO DO EDIFÍCIO

Form (Edifício principal)

TIPO ☐ Edif. Habitação Unifamiliar ☐ Edif. Habitação Multifamiliar

MORADA / SITUAÇÃO

Rua/Av/rua/Prça

Localidade	Freguesia
Concelho	Código Postal
Imóvel inscrito na	Cons. do Reg. Predial de
Sob o nº	Art. Matricial nº



---

## 2 - ETIQUETA DE SUSTENTABILIDADE

Desempenho ao nível de cada dimensão

Nota Global (NG)

Legenda da ferramenta SBTOOL<sup>pt</sup>



NA	NS	NE
Nota Ambiental	Nota Social	Nota Económica
- Alterações climáticas e qualidade do ar exterior	- Saúde e conforto dos utilizadores	- Custos de ciclo de vida
- Biodiversidade	- Acessibilidade	
- Energia	- Sensibilidade e educação para a sustentabilidade	
- Materiais e métodos de construção		
- Água		



NG Nota Global

---

## 3 - DESAGREGAÇÃO DO DESEMPENHO POR CADA CATEGORIA

	C1	C2	C3	C4	C5	C6	C7	C8	C9
A+									
A									
B									
C									
D									
E									

Legenda

C1 Alterações climáticas e qualidade do ar exterior

C2 Biodiversidade

NA Energia

C4 Materiais e métodos de construção

C5 Água

C6 Saúde e conforto dos utilizadores

NS Acessibilidade

C7 Sensibilidade e educação para a sustentabilidade

NE C9 Custos de ciclo de vida

---

Nome do responsável pela emissão do certificado

\_\_\_\_\_

Avaliador

\_\_\_\_\_

Data da emissão

\_\_\_\_\_

ENTIDADE SUPRADORA



International Initiative for a Sustainable Built Environment



## To discuss

1. How many indicators should be included for practical use of sustainability assessment tools?
2. Should all indicators be mandatory?
3. What should be the good practice for benchmarking the environmental performance of the several types of structures (in terms of LCA environmental impact categories) ?
4. Should the sustainability profiles be oriented only for designers or also to users?
5. What should be the communication format for users?



WG MEETINGS & WORKSHOP  
30<sup>th</sup> March - 1<sup>st</sup> April 2016  
Belgrade, Serbia





### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

## ***State of Art of Bridges Maintenance Programs in South America. Experience on seismic hazards and scour***

**Matías A. Valenzuela** – Public Work Department, Chile

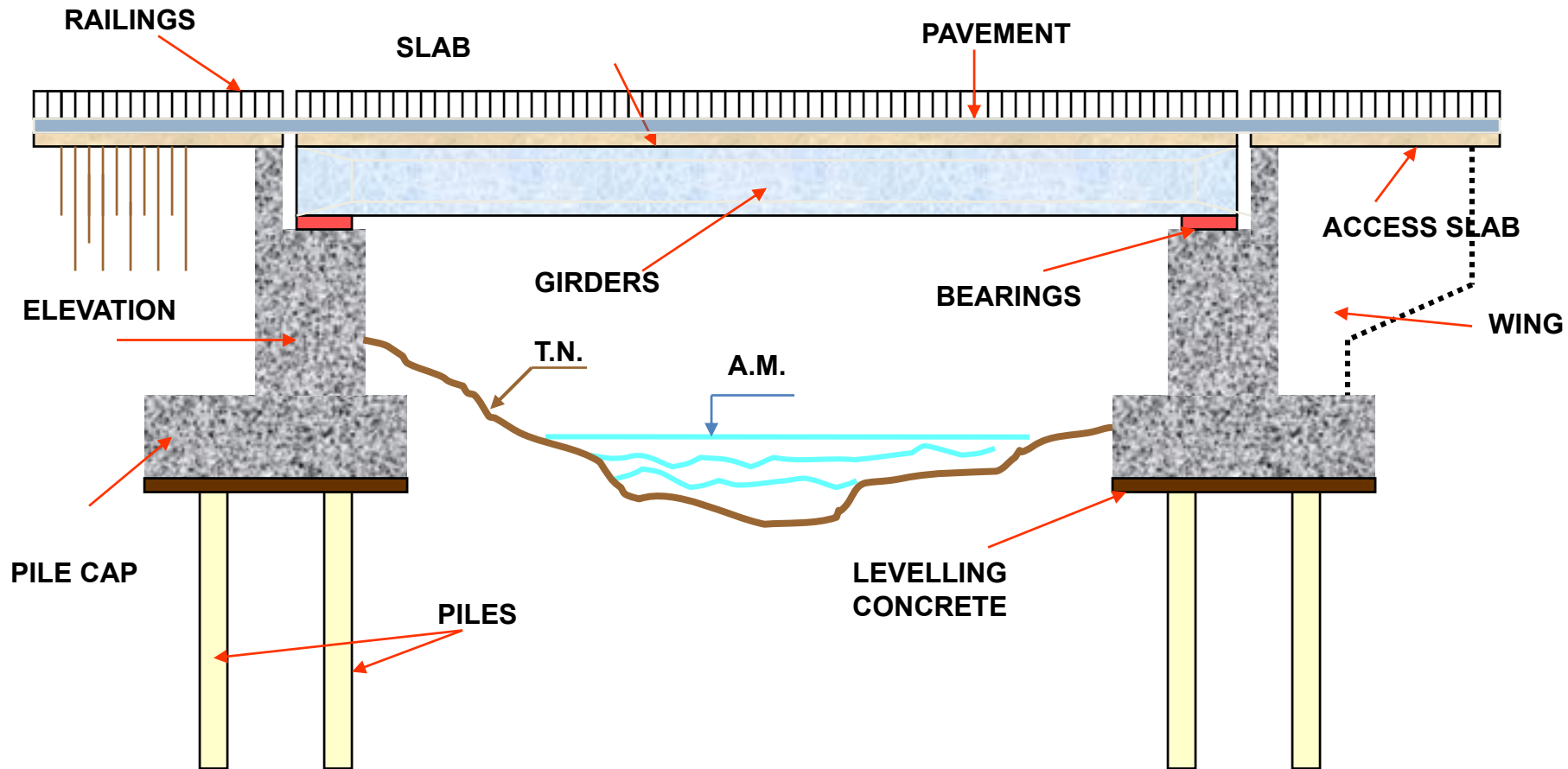


**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**

# Contents

- Maintenance Programs
- Pathologies
- Earthquake
- Tsunami
- Scour
- Final Comments

# Scheme of Traditional Bridge



# Traditional Bridge



# Chilean Bridge Cost

INFRA	BEAMS	DECK	Nº BRIDGE	LINEALS M.	US\$/M.L.	COST US\$
C	C	C	2.875	76.036	31.000	2.357.116.000
C	S	C	2.520	75.300	33.000	2.484.900.000
S	S	C	160	2.525	34.000	85.850.000
C	S	T	646	14.120	18.000	254.160.000
C	T	T	485	7.063	12.000	84.756.000
S	ST	T	130	2.025	14.000	28.350.000
T	T	T	870	8.036	9.000	72.324.000
			7.686	185.105		5.367.456.000

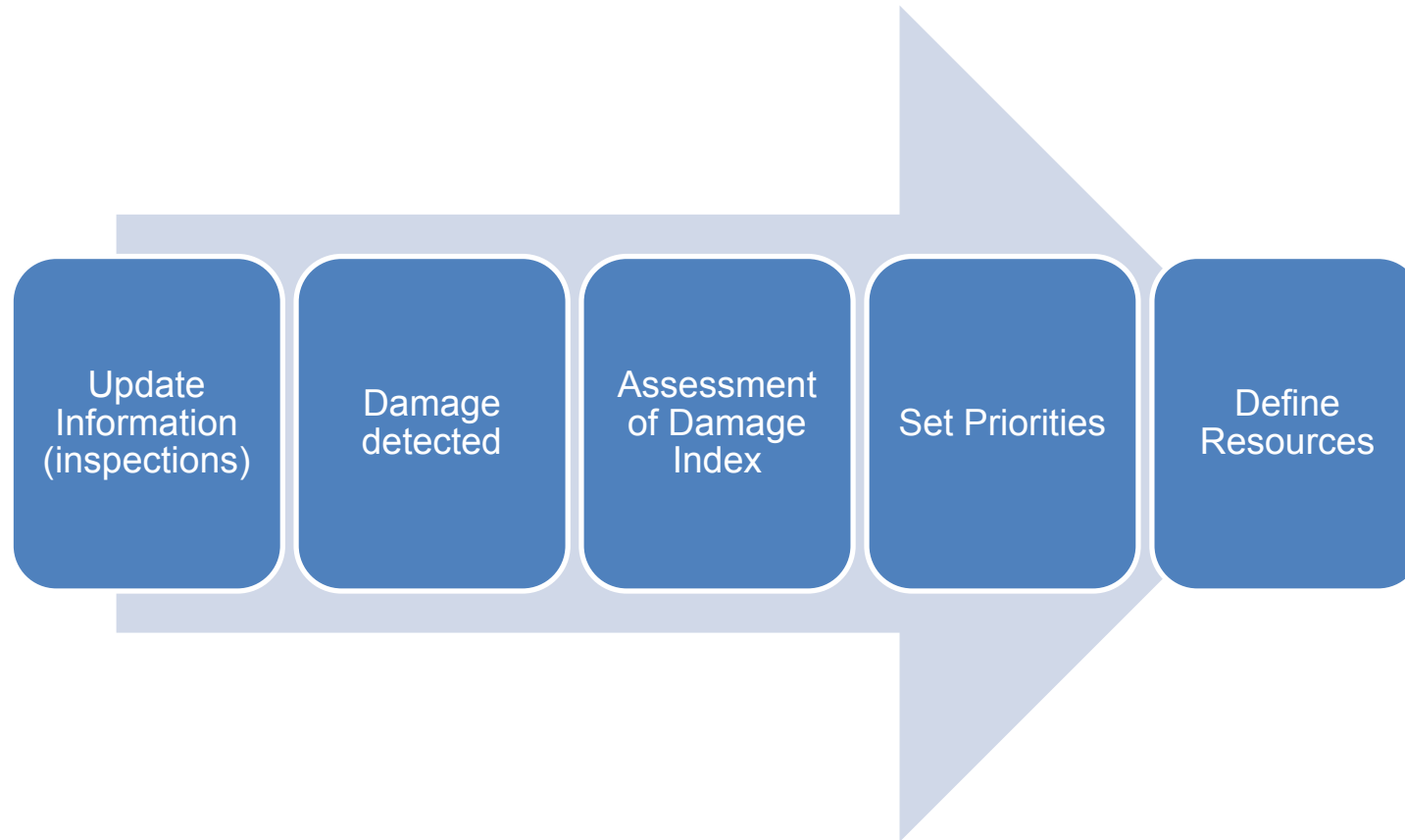
# Maintenance Concepts



## Current Situation

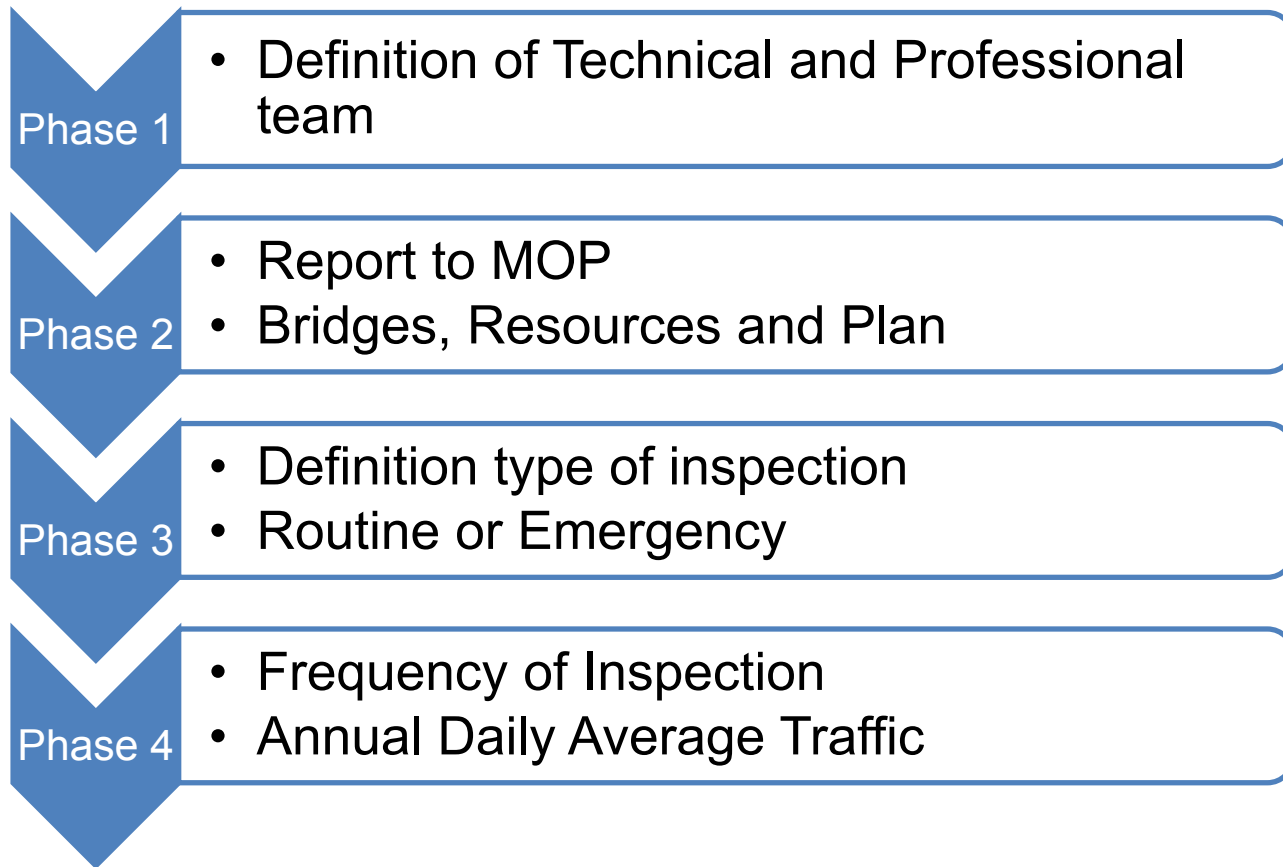
- Lack Policies for Maintenance → No Prevention
- No Interest to Community
- No Knowledge about the Benefit
- Inertia of common practice

# Current Situation





# Inspection Procedures (Road Manual V7)



# Inspection Procedures (Road Manual V7)

REPÚBLICA DE CHILE  
MINISTERIO DE OBRAS PÚBLICAS

NOMBRE DEL PUENTE

TIPO DE PUENTE

EN KM

ROL RUTA  
CODIGO DV

EN EL CAUCE

REGIÓN

PROV.

COMUNA

LONG TOTAL		ANCHO PASILLOS		LUZ MAYOR		NÚMERO DE VIGAS	
ANCHO TOTAL		ANCHO DE CALZADA		NÚMERO TRAMO		NÚMERO DE CEPAS	
GALIBO		ESPESOR DE LOSA		TIPO DE CARPETA		¿TIENE ESVAIAJE?	
OBRA FLUVIAL		TRÁNSITO (Pás/día)		GRADO DAÑO		CAPACIDAD DEL PUENTE	

General Description

Geometry

Fluvial Issues

Traffic

Damage Index

Code

# Inspection Procedures (Road Manual V7)

REPÚBLICA DE CHILE MINISTERIO DE OBRAS PÚBLICAS		NOMBRE DEL PUENTE		Puente Ventisquero		TIPO DE PUENTE	H-A	
A		EN KM	59.306	Carretera Austral Tramo Chaitén – La Junta				
ROL RUTA CODIGO DV		CH-7	EN EL CAUCE	Río Ventisquero				
REGION		X	PROV.	Palena	COMUNA	Chaitén		
LONG TOTAL		42.0 m	ANCHO PASILLOS	0.5 m	LUZ MAYOR	42.0 m	NÚMERO DE VIGAS	2
ANCHO TOTAL		8.0 m	ANCHO DE CALZADA	7 m	NÚMERO TRAMO	1	NÚMERO DE CEPAS	0
GALIBO		7.7 m	ESPESOR DE LOSA	0.25 m	TIPO DE CARPETA	HOR	¿TIENE ESVAJE?	NO
OBRA FLUVIAL		NO	TRÁNSITO (Pés/día)	NO *	GRADO DAÑO	3(4)	CAPACIDAD DEL PUENTE	NO *

The diagram illustrates the longitudinal profile of the bridge. It shows a total length of 42 m, with a central span of 1.9 m and a total height of 7.7 m. The bridge is supported by two piers. The diagram also shows the location of the bridge on the road, with a distance of 5.16 m from the start of the bridge to the first pier and 5.13 m from the second pier to the end of the bridge. The bridge is labeled 'PUENTE LONGITUDINAL' and 'UBICACION DE LOS ARRIOSTRIMIENTOS'.

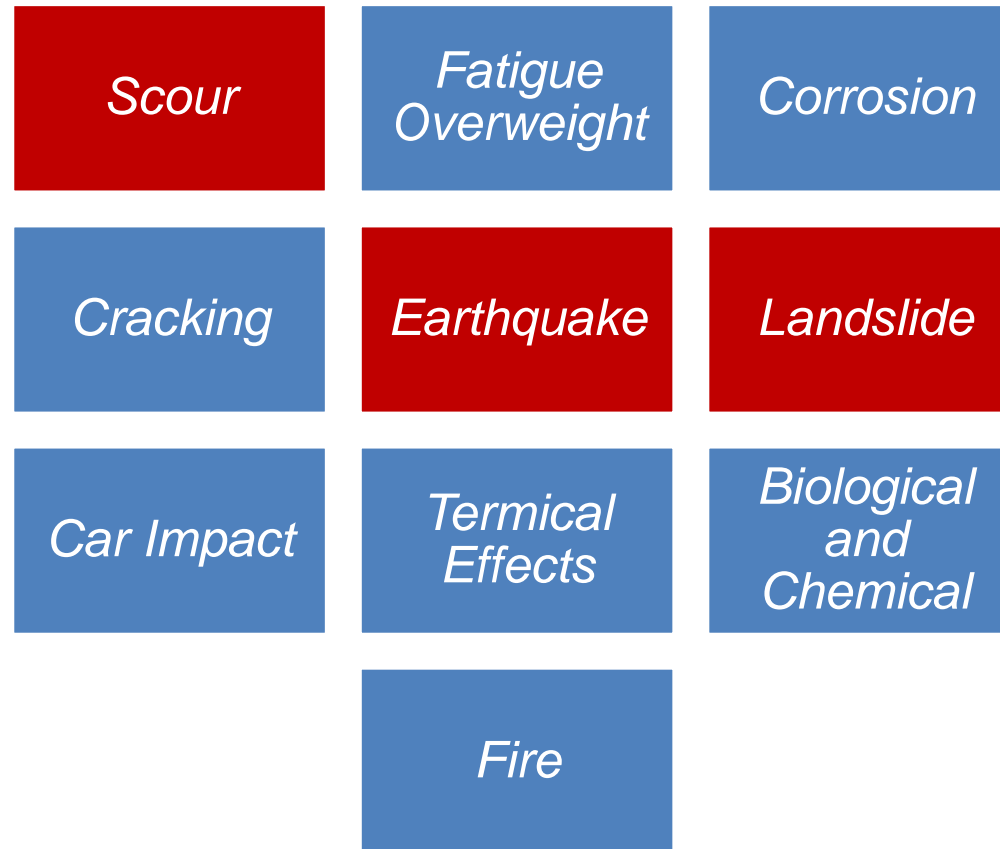
# Inspection Procedures (Road Manual V7)

FECHA DE CONSTRUCCIÓN		CONSTRUCTOR		<b>CORTE TRANSVERSAL</b>		
PROYECTISTAS				<input type="checkbox"/>		
AUTOS	CAMIONETAS	CAMIONES SIMPLES	CAMIONES TRAILER			BUSES
T.M.D.A. (Pas/día)		DEL AÑO		HUBO CORTE EN LOS AÑOS		
MATERIALES: A = Acero, M = Madera, HA = Hormigón Armado, PC = Precomprimido, LC = Ladrillo y/o Cantería						
PISO		VIGAS		ESTRIBOS		
				CEPAS		
				FUNDACIONES		
DESCRIPCION FUNDACIONES						
ALTERNATIVA EXISTENTE						
PLANOS EXISTENTES						
BREVE DIAGNÓSTICO DE SU ESTADO						
NOMBRE			NOMBRE			
CARGO			CARGO			
FECHA			FECHA			
<b>MAPA DE UBICACIÓN</b>						

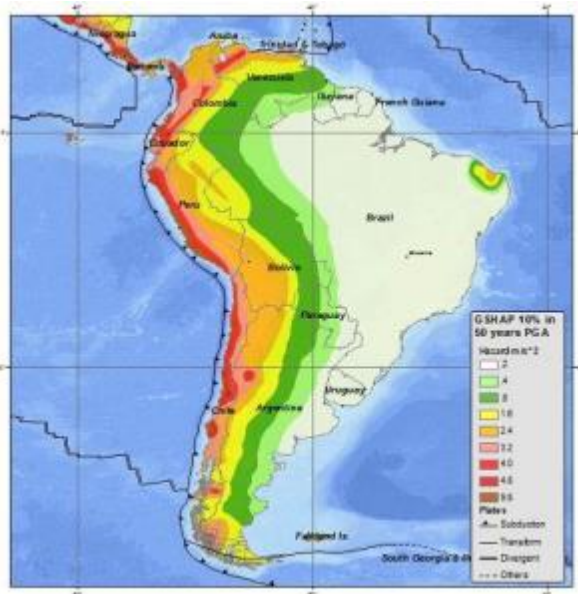
# Inspection Procedures (Road Manual V7)

Puentes Definitivo										Name and Location	
Nombre de la estructura		Kilometro		Nombre de la vía		Rol de la Ruta		Provincia		Codigo del Puente	
Puente :											
Estado del Sustrato de Pavimentación y de la Superficie											
1	Pavimento	ITEM	ALISO	EMBUCCADO O CARRILES	PRESTAMIENTO	ABERTAMIENTO	OTROS				
2	Pavimento	ITEM	ALISO	EMBUCCADO O CARRILES	PRESTAMIENTO	ABERTAMIENTO	OTROS				
3	Barandales Metálicos	ITEM	ALISO	EMBUCCADO O CARRILES	PRESTAMIENTO	ABERTAMIENTO	OTROS				
4	Barandales Metálicos	ITEM	ALISO	EMBUCCADO O CARRILES	PRESTAMIENTO	ABERTAMIENTO	OTROS				
5	Barandales Metálicos	ITEM	ALISO	EMBUCCADO O CARRILES	PRESTAMIENTO	ABERTAMIENTO	OTROS				
6	Barandales Metálicos	ITEM	ALISO	EMBUCCADO O CARRILES	PRESTAMIENTO	ABERTAMIENTO	OTROS				
EVALUACIÓN		Puntuación		Grado Deterioro				Socavación			
		5		NO EXISTE				NO EXISTE			
		4		EN UNO O DOS PUNTOS				TENDENCIA A SOCAVAR			
		3		EN MUCHOS PUNTOS				PELIGRO			
		2		MENOS DE LA MITAD				SOCAVACIÓN PELIGROSA			
		1		CASI TODO				SITUACIÓN DE EMERGENCIA			
SEÑALÉTICA		HAY		BUENAS <input type="checkbox"/>		REGULARES <input type="checkbox"/>		MALAS <input type="checkbox"/>			
		NO HAY <input type="checkbox"/>									
TACHAS REFLECTANTES		HAY		BUENAS <input type="checkbox"/>		REGULARES <input type="checkbox"/>		MALAS <input type="checkbox"/>			
		NO HAY <input type="checkbox"/>									
SEÑALÉTICA		HAY <input type="checkbox"/>		BUENAS <input type="checkbox"/>		REGULARES <input type="checkbox"/>		MALAS <input type="checkbox"/>			
		NO HAY <input type="checkbox"/>									
TACHAS REFLECTANTES		HAY <input type="checkbox"/>		BUENAS <input type="checkbox"/>		REGULARES <input type="checkbox"/>		MALAS <input type="checkbox"/>			
		NO HAY <input type="checkbox"/>									

# Main Pathologies

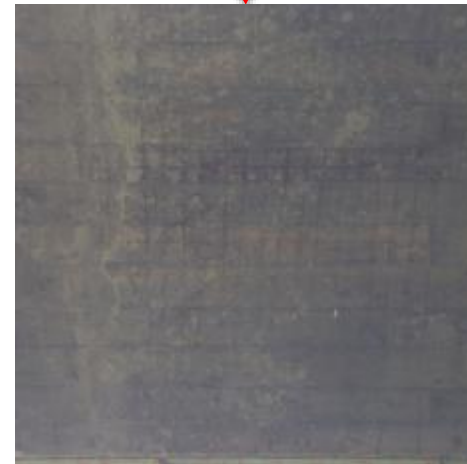


# Main Pathologies





# Main Pathologies – Minor Damage



# Main Pathologies – Gerber Bridges



- Concrete Damage
- Steel Support
- Construction pathologies

# Main Pathologies – Earthquake



- Approach Slab





# Main Pathologies – Earthquake



- Expansion Joints

# Main Pathologies – Earthquake



- Deck misalignment

# Main Pathologies – Earthquake



- Gerber
- Transverse Damage



# Main Pathologies – Earthquake



- Unseating
- Skew Bridges



# Main Pathologies – Earthquake



- Unseating
- Skew Bridges

# Main Pathologies – Earthquake



- Transverse Displacement
- Beam Damage



# Main Pathologies – Earthquake



- Local Buckling
- Steel Beams





# Main Pathologies – Earthquake



- Overturning Piers

# Main Pathologies – Earthquake



- Overstress Piers

# Main Pathologies – Earthquake



- Settlement Piers



# Main Pathologies – Earthquake



- Aftershock



# Main Pathologies – Earthquake



- Liquefaction

# Main Pathologies – Tsunami



- Deck



# Main Pathologies – Tsunami



- Non Structural

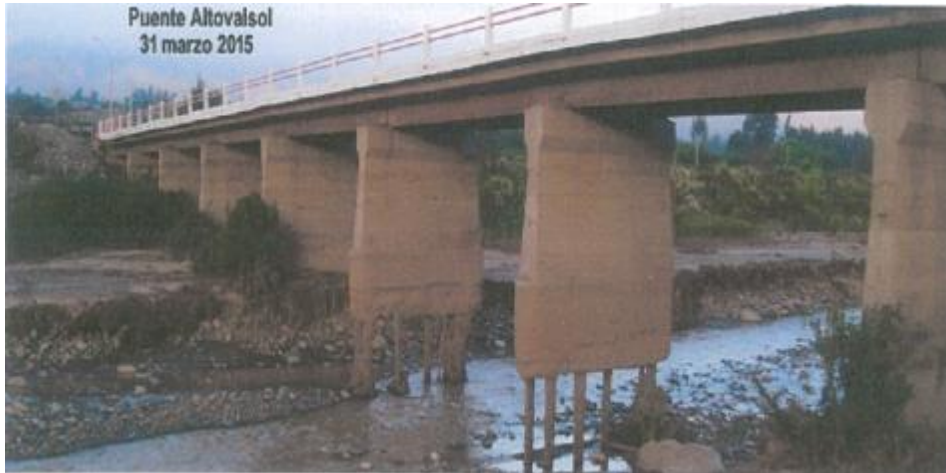
# Main Pathologies – Landslides



- March 2015
- Debris Impact



# Main Pathologies – Landslides / Scour



- Scour
- Steel piles





# Main Pathologies – Scour



- Scour
- San Luis - Strengthening





# Main Pathologies – Scour



- Scour
- Collapse Colombia
- New Bridge Perú



# Main Pathologies – Landslides / Volcano



- Deck missing





# Main Pathologies – Landslides / Volcano



- Deck missing

# Repair and Post Emergency – Modular Bridge



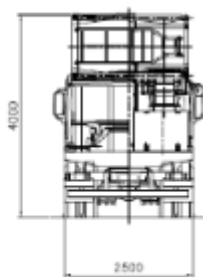
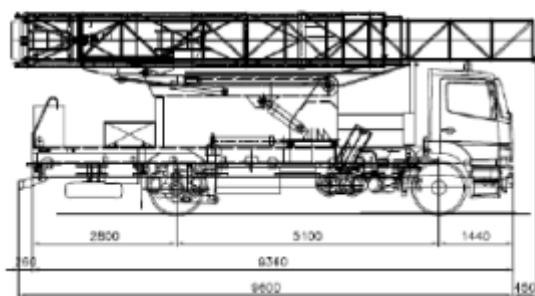


# Inspection Truck



ABC 130 / LS

OVERALL DIMENSIONS IN ROAD TRANSPORT POSITION

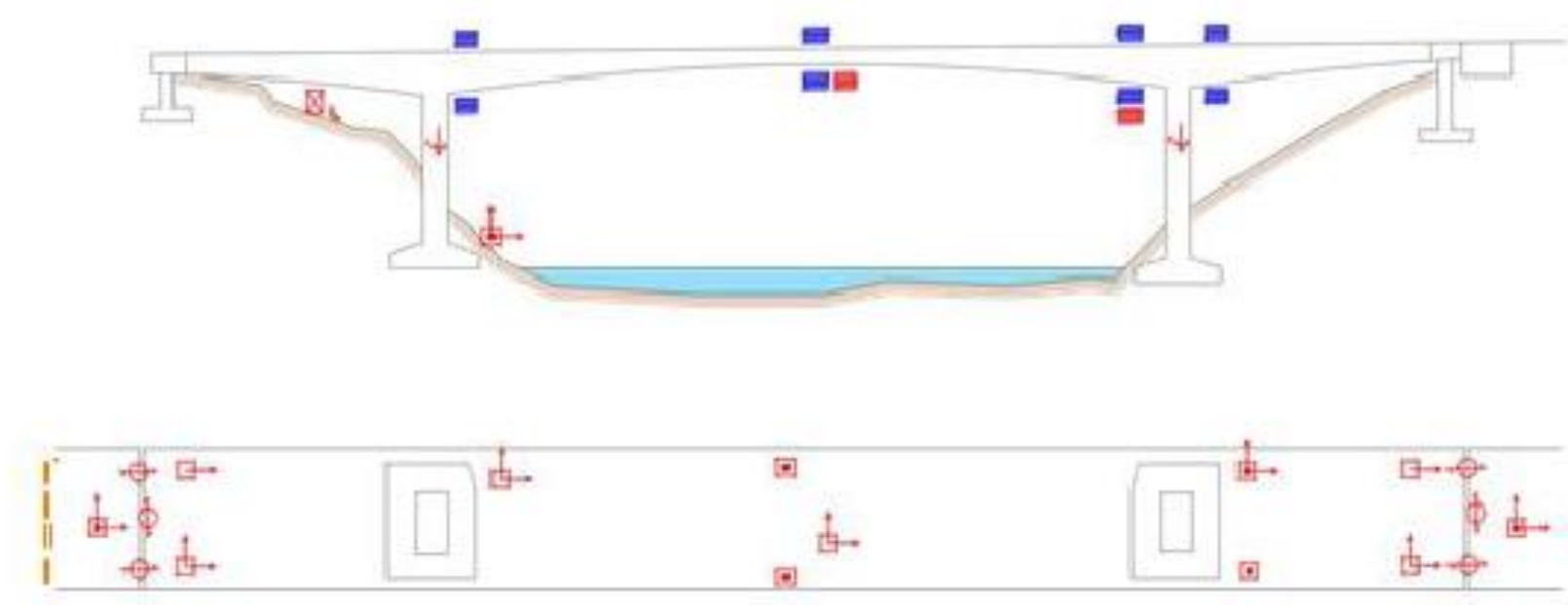


# Monitoring - Seismic





# Monitoring - Seismic



Accelerometers  
Displacement Sensors  
Inclinometers  
Deformation Sensors

# Final Comments

## Main Parameters

- Seismic Demand
- Skew index
- Length of support
- Longitudinal and transverse restrictions
- Soil Condition (liquefaction, in situ effects, scour, etc)
- Deck – up lifting
- Pre-cast bridges
- Curved bridges
- Foundation Torrential rivers
- Isolation bridges

# Final Comments

## Maintenance Program – Future South America

- Not enough visual inspections - subjective (the transference of experience not recorded).
- New Standard and Damage Index.
- Include the Life Cycle of the structure in the Design Programs.
- Preventive Repair and Maintenance Program (not only Emergency).
- Singular and Critical Structure have to include Maintenance Manuals.
- Instrumentation and Monitoring have to be included.
- Maintenance programa per each climate.
- Maintenance concepts applied to hazards.

# Acknowledge



Structure Department:	Ing. Sandra Achurra & Claudio Rivera
Bridge Department:	Ing. Marcelo Marquez
Regional Department:	Ing. Patricio Dinamarca
Emergency Department:	Ing. Marco Almonacid
Chacao Bridge:	Ing. Raul Vasquez



WG MEETINGS & WORKSHOP  
30<sup>th</sup> March - 1<sup>st</sup> April 2016  
Belgrade, Serbia



## **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **Performance Indicators as Basis for Life-Cycle-Considerations**

**Ralph Holst** – Federal Highway Research Institute (BAST), Germany

[link to paper](#)

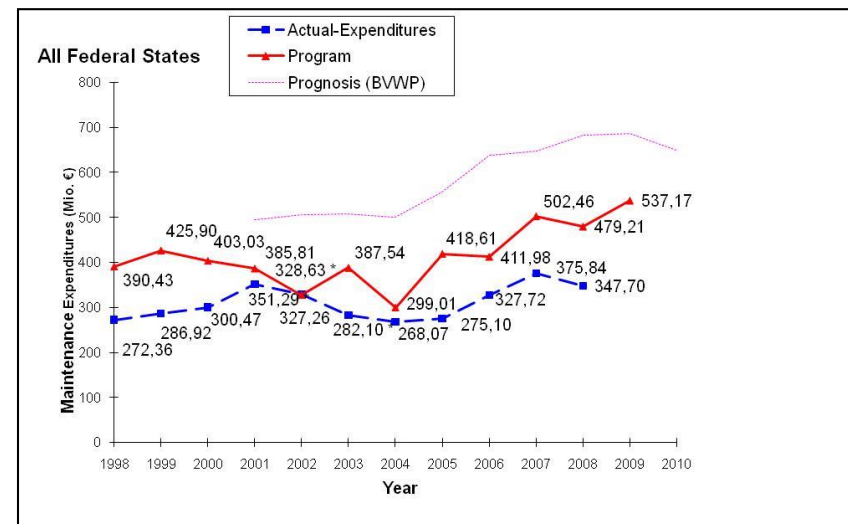
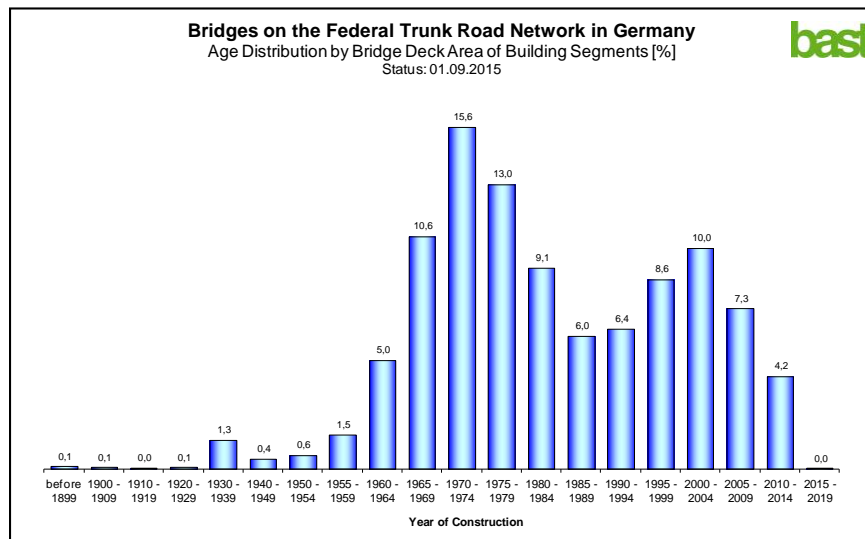


30<sup>th</sup> March - 1<sup>st</sup> April 2016



# BOUNDARY CONDITIONS

- Significant increase in traffic, particularly heavy goods traffic,
- Increase of total allowable weight of vehicles,
- Overloading of trucks,
- Increasing bridge ages



# LIFE-CYCLE-ASPECTS (I)

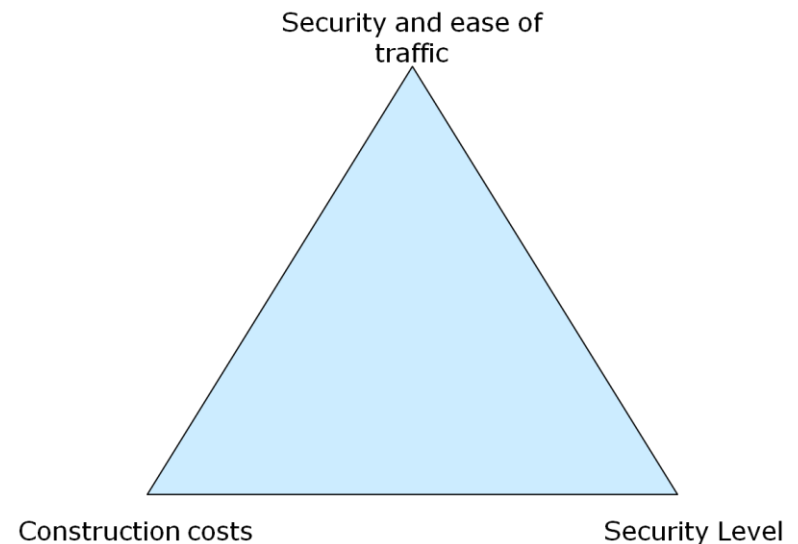
- LCA, Life Cycle Assessment is a systematic analysis of the environmental impacts of products.
- LCC, Life-cycle costing, is a cost management method that considers the whole life cycle of a building.
- LCP, the life cycle performance of mechanical systems describing the performance of a system.



Combination of environmental impact, costs and performance

# MAIN FACTORS FOR LC-OPTIMISATION

- Minimal direct costs,
- Necessary Level of Security,
- Minimal indirect costs, e.g.
  - Minimal disturbance of traffic over Life-Time,
  - Minimal environmental costs,



# NECESSARY LIFE-TIME-INFORMATION

- Construction data,
- Year of construction (Constructive deficits; used guidelines, age, ...),
- Dimensions/sizes/masses (Robustness),
- Position within the network (Corridor, alternative routes),
- Condition data (history; future behavior),
- Durability ((new)materials),
- Maintenance alternatives (Costs, influence regarding third parties, service life),
- Traffic data (Heavy traffic; today and for the future)

# AVAILABLE DATA (SIB-BAUWERKE)

- Length, width, bridge Deck area,
- Static system (longitudinal, transverse),
- Year of construction; Years of maintenance actions,
- Materials of Components/component groups,
- Condition data (last Bridge inspection(s)).



Not available

- Future behavior,
- Future traffic data/volume,
- Service life.

But these data can be created by evaluating of bridge data...

**SIB-BAUWERKE Verwaltungsprogramm**

**bast** Referat "Grundsatzfragen der Bauwerkserhaltung" **SIB-BAUWERKE** **Bridge**

Bauwerksnummer **5136528** **0** Interne Bwnr. **A 4 1781U**

Crossection of Superstructure: Zweistegiger Vollquerschnitt

Crossection mainstructure: Mit Querschnitt des Überbaus identisch

construction method: Auf Traggerüst hergestellt

Length: **54,00** m Konstruktionshöhe min. **0,25** m BW-Winkel **98,7** gon

Width: **11,75** m Konstruktionshöhe max. **1,40** m Winkelrichtung Links

Bridge area: **635** m<sup>2</sup> Längsneigung max. **3,2** % Lichte Weite bei Einfeld **0,00** m

**1** Stk Querneigung max. **2,5** % Lichte Höhe **4,73** m

**0,00** m Überschüttungshöhe max. **0,00** m

**12,25** m Überschüttungshöhe min. **0,00** m Anzahl der Felder **2** Stk

Nein

Comments: Nicht gekrümmt ( $R > 1500$  m), nicht aufgeweitet  
- Gründungssohle: 230,90 - 228,17 m über NN  
\*\*\*

Letzte Bearbeitung **07.01.2002 10:45:50** Bearbeiter **BERGER**

**Ändern**

**Zurück**

Static system/  
bearing load capacity

Bridge cable

Design

Joints

Lines (gas, water,...)

Water proofing

Crack repair

Spans/  
supportings

Foundation

Cover

Concrete replacements

Materials

Prestress

Safety barriers

surface protection

Anchor

Equipment

Overlayings

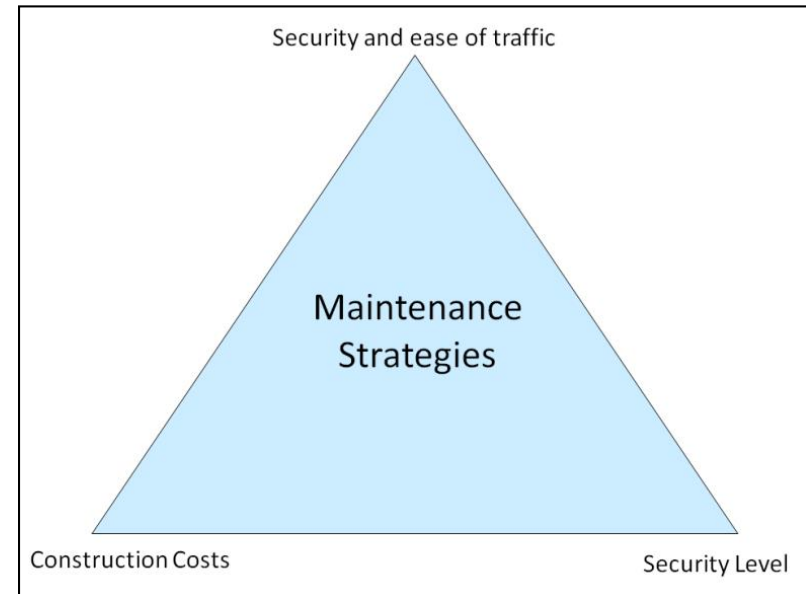


## LIFE-CYCLE-ASPECTS (II)

- Classification of the bridge components/groups (similar, future behavior),
- masses of components/groups (ecological, economic effects during Lifetime),
- Component or component group-related
  - damages (assessments, extent),
  - behavior models (right time for maintenance),
  - direct costs for maintenance measures,
- Indirect costs (environment, traffic).

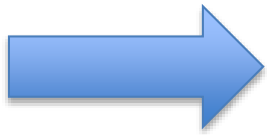
# MAINTENANCE STRATEGIES

- Preventive maintenance,
  - Systematic conservation and/or
  - "targeted aging".
- 
- Interventions in the road should be minimal,
  - Construction and maintenance costs should be minimized,
  - It's at any given time to ensure the required level of security and
  - The useful life should be guaranteed.



# SUMMARY AND OUTLOOK

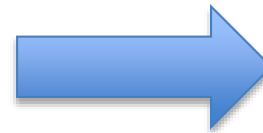
- Performance Indicators are necessary for
  - Evaluation of current condition,
  - Next maintenance actions,
  - Keep network at desired performance level



Short/Middle term

but in combination with

- Data of “Birth Certificate”,
- Future behavior,
- Service life and
- Maintenance strategies,



long term (Life-Time-Optimization)



**bast**

[link to paper](#)

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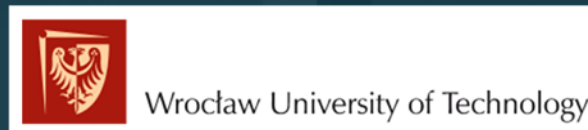
### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **STRUCTURAL ROBUSTNESS OF BRIDGES BASED ON REDISTRIBUTION OF INTERNAL FORCES**

**Tomasz Kamiński** – Wrocław University of Technology

[link to paper](#)



**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**



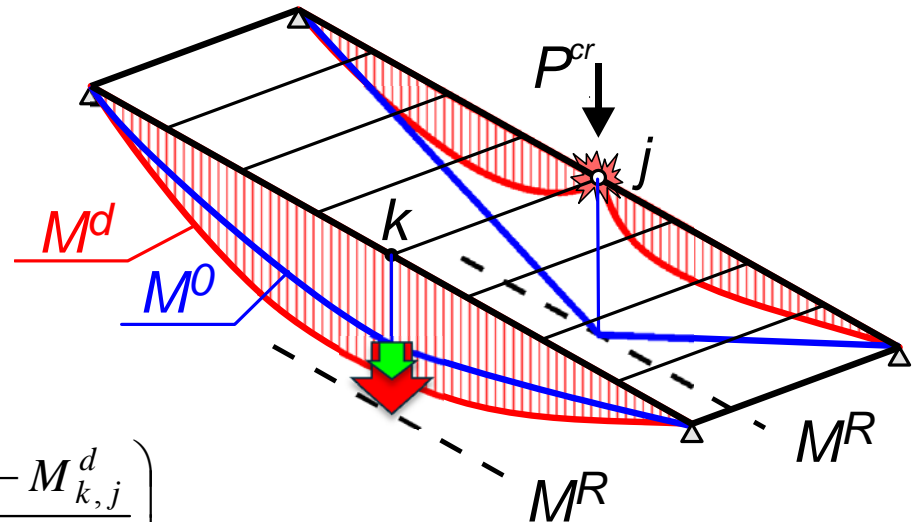
# STRUCTURAL ROBUSTNESS DEFINITION

- The method presented refers to an energetic approach defined by (Starossek & Haberland, 2008) where for simplification of calculations instead of energy the internal forces are used

## Approach I

$$R = 1 - \max_k \left( \frac{\Delta M_{k,j}}{\Delta M_k^R} \right)$$

$$R = 1 - \max_k \left( \frac{M_{k,j}^d - M_{k,j}^0}{M_k^R - M_{k,j}^0} \right) = \min_k \left( \frac{M_k^R - M_{k,j}^d}{M_k^R - M_{k,j}^0} \right)$$





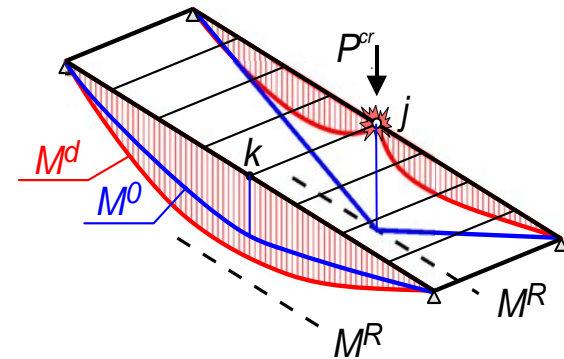


# STRUCTURAL ROBUSTNESS DEFINITION

- In linear-elastic models satisfying the superposition principle it is possible use moments triggered by a unit force:

$$R = 1 - \max_k \left( \frac{M_{k,j}^{d,1} \cdot k_j - M_{k,j}^1 \cdot k_j}{M_k^R - M_{k,j}^1 \cdot k_j} \right) = \min_k \left( \frac{M_k^R - M_{k,j}^{d,1} \cdot k_j}{M_k^R - M_{k,j}^1 \cdot k_j} \right)$$

$$k_j = \frac{M_j^R}{M_{j,j}^1}$$



- When the sections j and k are with the same properties and resistance then  $R$  may be independent of the section resistance:

$$R = 1 - \max_k \left( \frac{M_{k,j}^{d,1} - M_{k,j}^1}{M_{j,j}^1 - M_{k,j}^1} \right)$$



# STRUCTURAL ROBUSTNESS DEFINITION

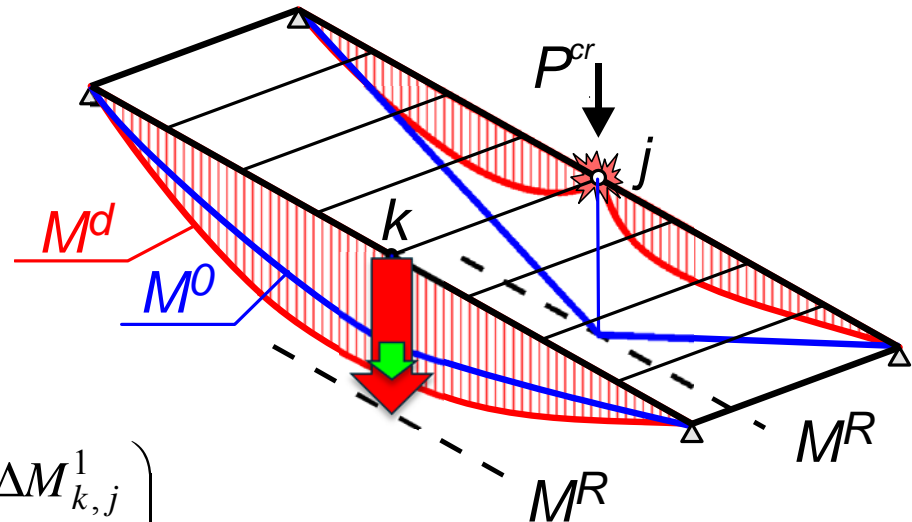
## Approach II

- The robustness  $R'$  is calculated according to formula:

$$R' = 1 - \max_k \left( \frac{M_{k,j}^d - M_{k,j}^0}{M_k^R} \right)$$

$$R' = 1 - \max_k \left( \frac{M_{k,j}^{d,1} \cdot k_j - M_{k,j}^1 \cdot k_j}{M_k^R} \right)$$

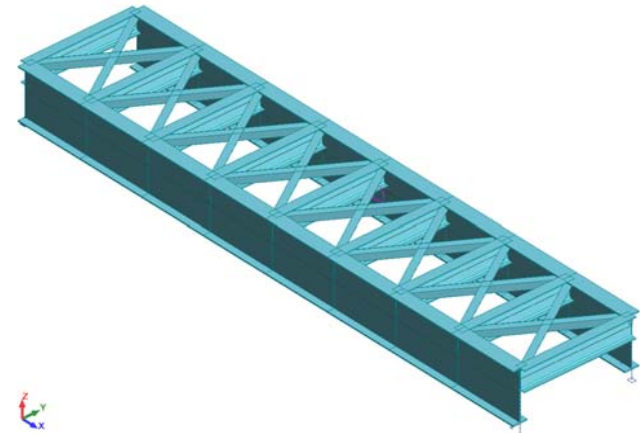
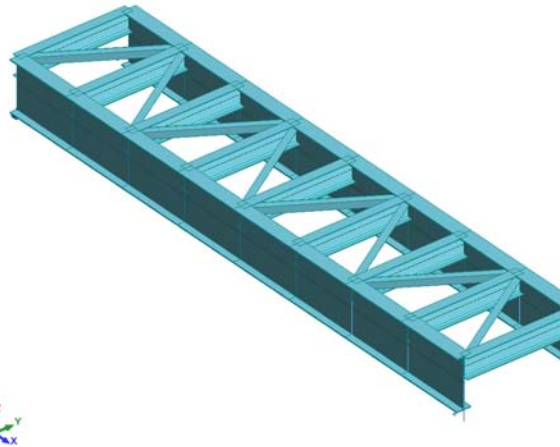
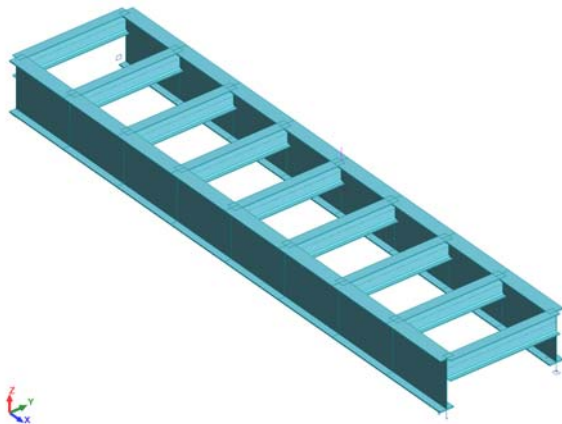
$$R' = 1 - \max_k \left( \frac{M_{k,j}^{d,1} - M_{k,j}^1}{M_{j,j}^1} \right) = 1 - \max_k \left( \frac{\Delta M_{k,j}^1}{M_{j,j}^1} \right)$$





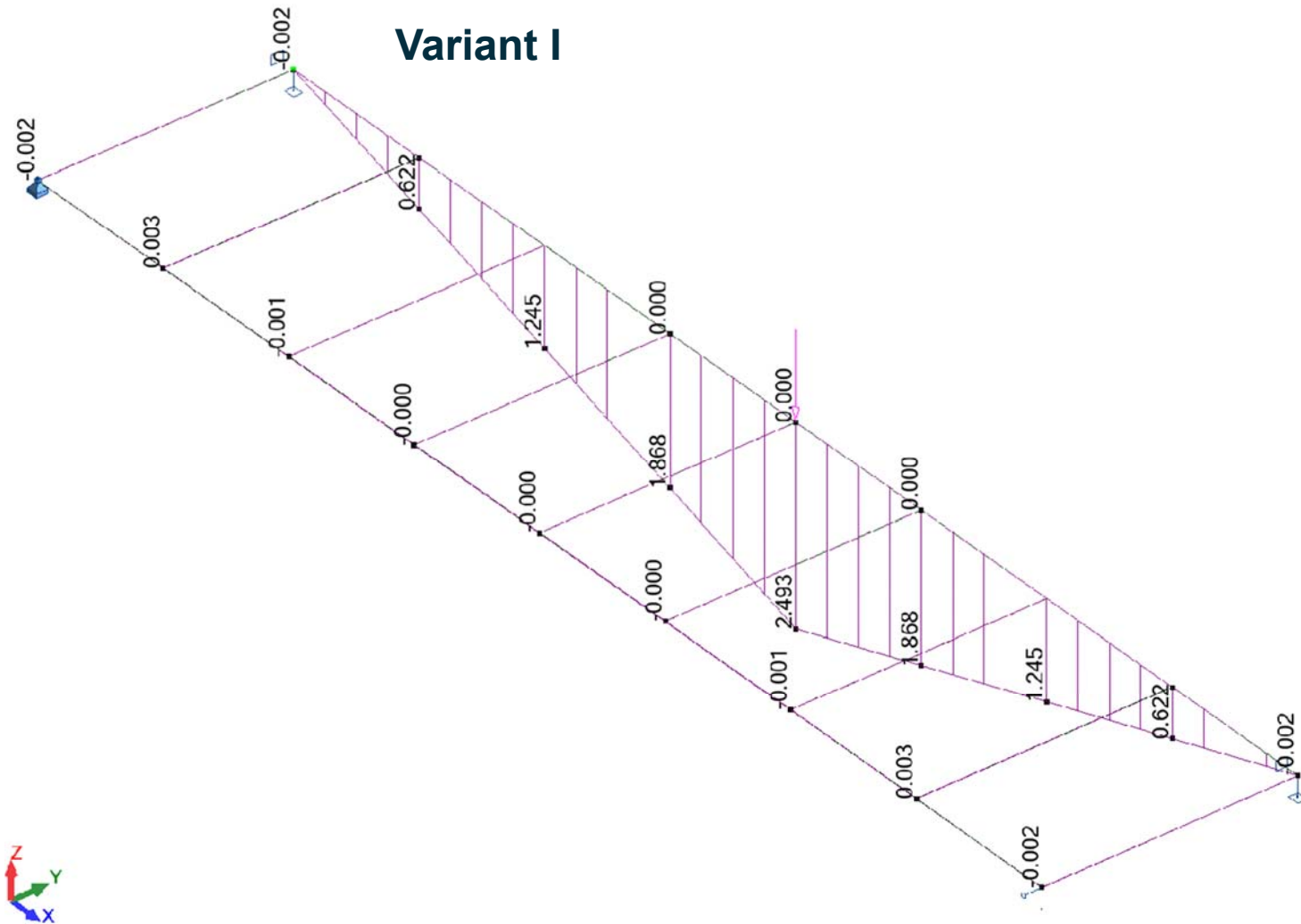
# CASE STUDIES - Simply supported 2-girder bridge

- Three variants considered:
  - cross-beams only (IPE 360)
  - cross-beams (IPE 360) with N-system of horizontal bracing (L120x120x10)
  - cross-beams (IPE 360) with X-system of horizontal bracing (L120x120x10)





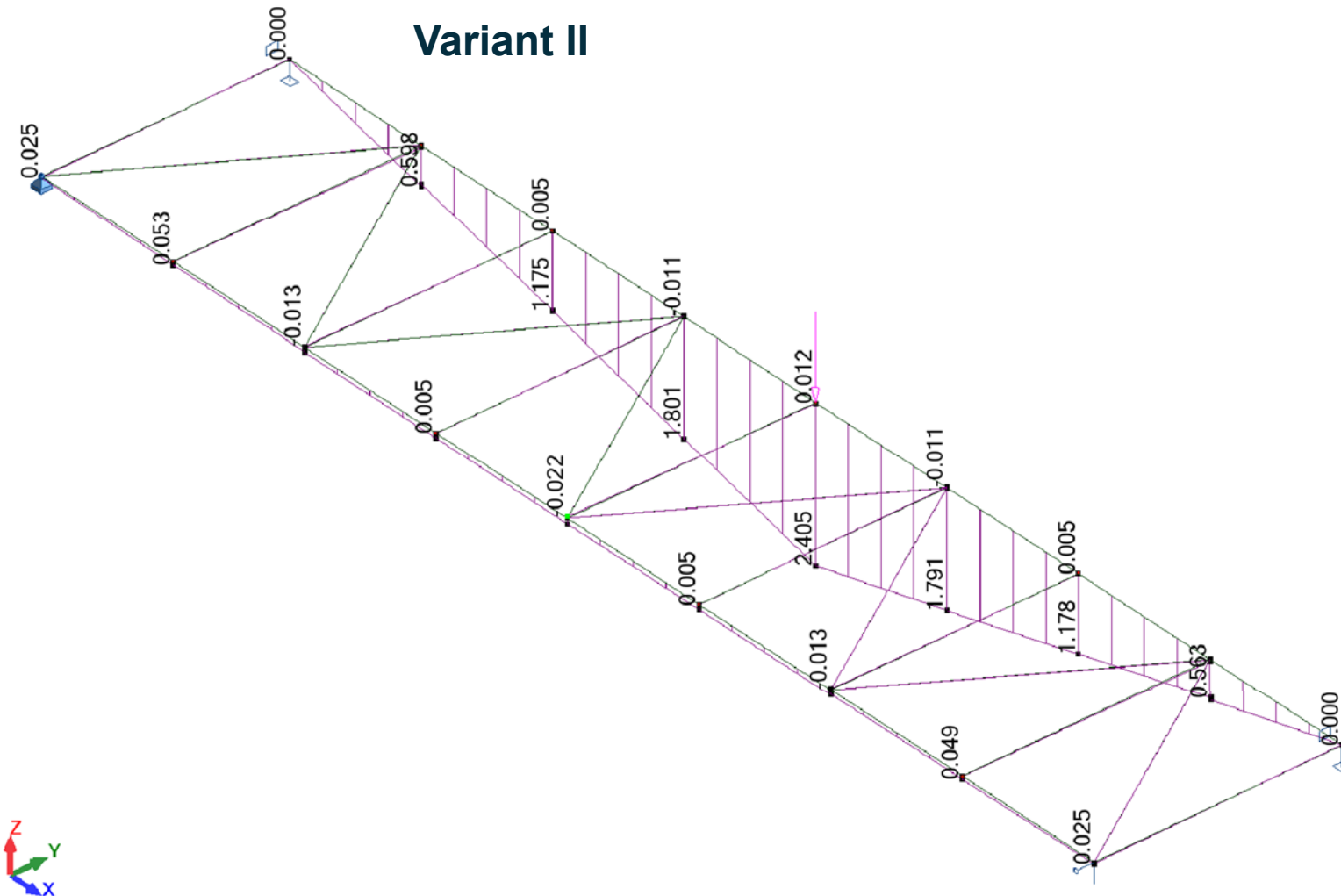
# CASE STUDIES - Simply supported 2-girder bridge





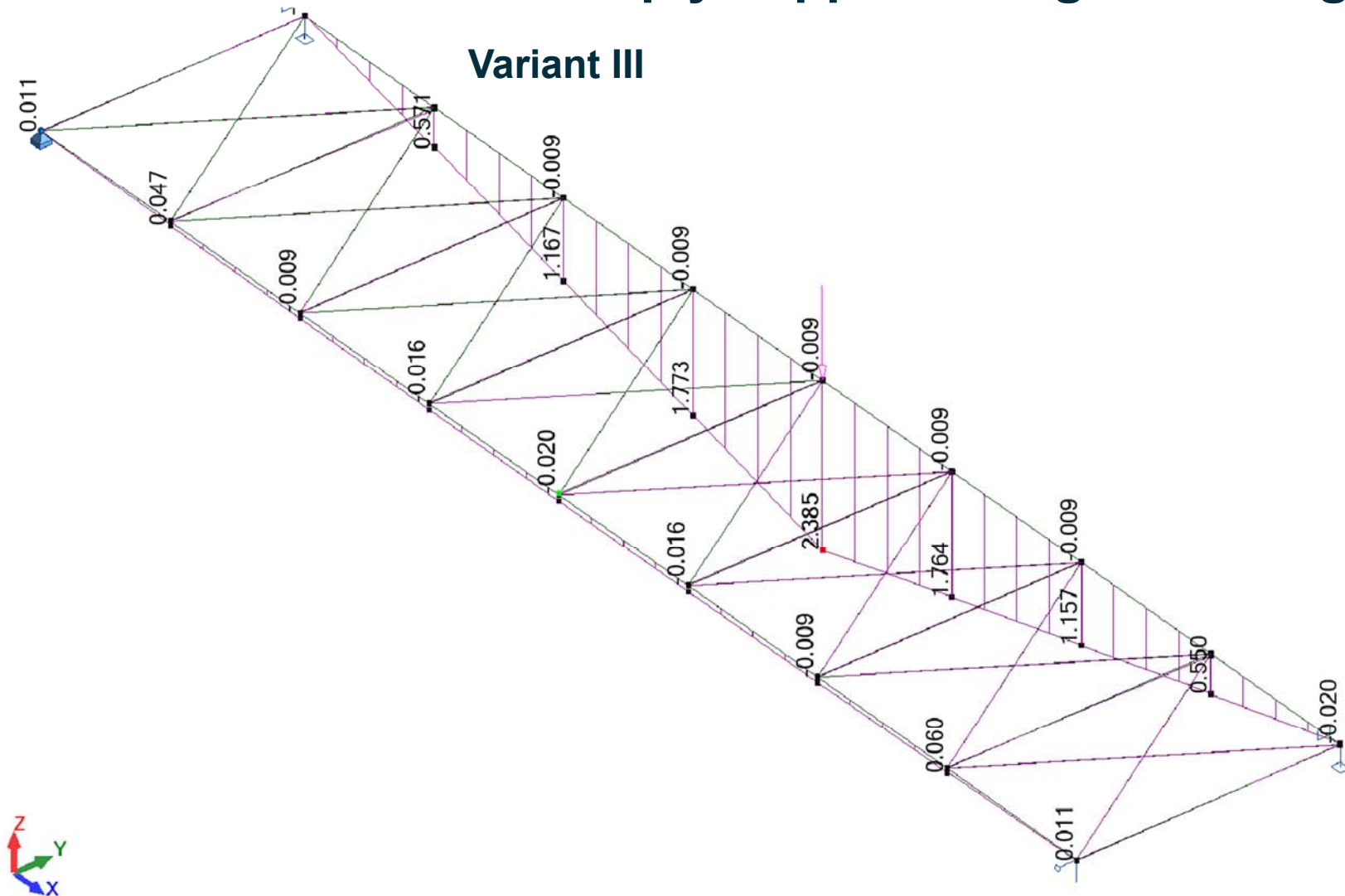
# CASE STUDIES - Simply supported 2-girder bridge

Variant II





# CASE STUDIES - Simply supported 2-girder bridge







## CASE STUDIES - Simply supported 2-girder bridge

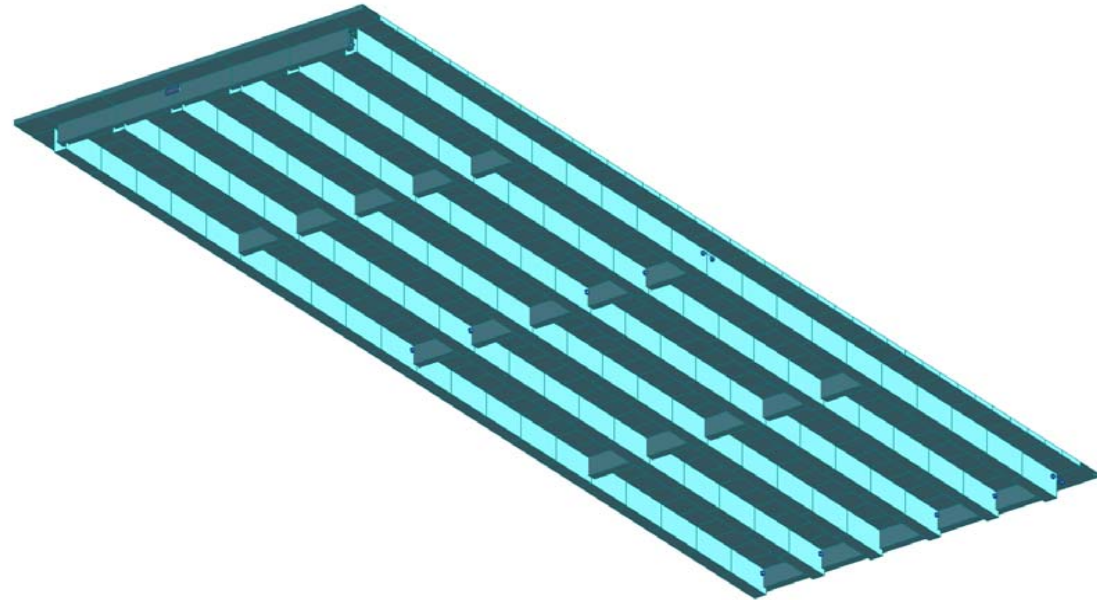
$$R = 1 - \max_k \left( \frac{M_{k,j}^{d1} - M_{k,j}^1}{M_{j,j}^1 - M_{k,j}^1} \right) = 1 - \frac{2.01 - 2.40}{2.40 - 0.08} = 0.168$$

$$R' = 1 - \max_k \left( \frac{M_{j,j}^{d1} - M_{k,j}^1}{M_{j,j}^1} \right) = 1 - \frac{2.01 - 2.40}{2.40} = 0.196$$

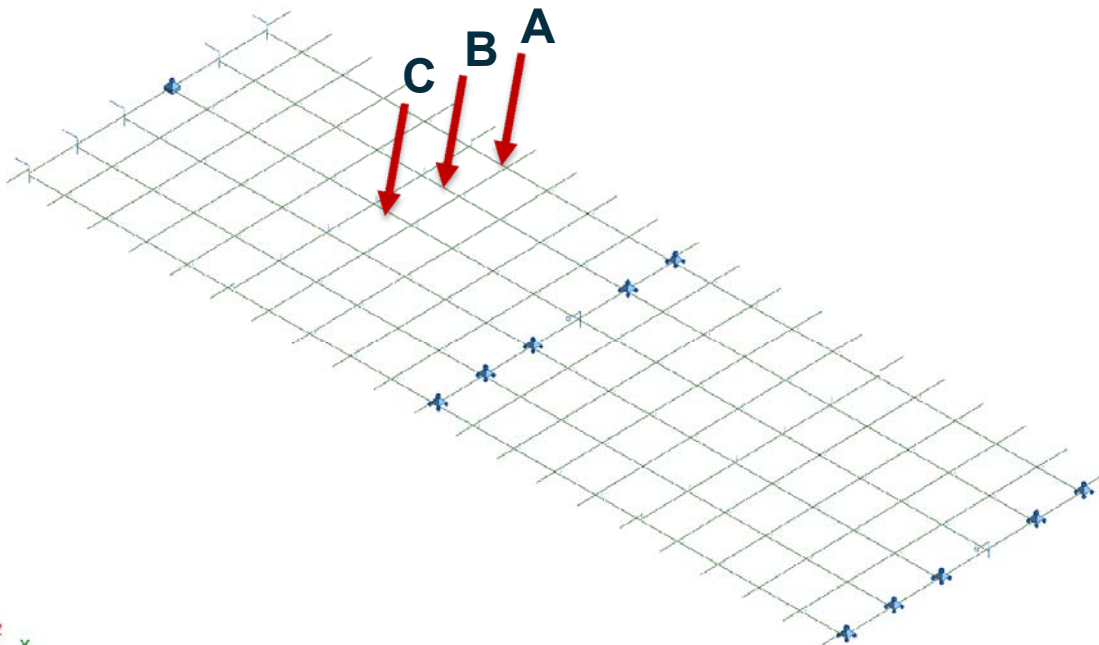
variant	$M_{j,j}^1$	$M_{k,j}^1$	$M_{k,j}^{d1}$	$R_j$	$R'_j$
	kNm	kNm	kNm		
I	2,50	0,00	2,50	0,000	0,000
II	2,40	0,08	2,01	0,168	0,196
III	2,38	0,09	1,43	0,415	0,437



# CASE STUDIES - Continuous 2-span 6-girder bridge



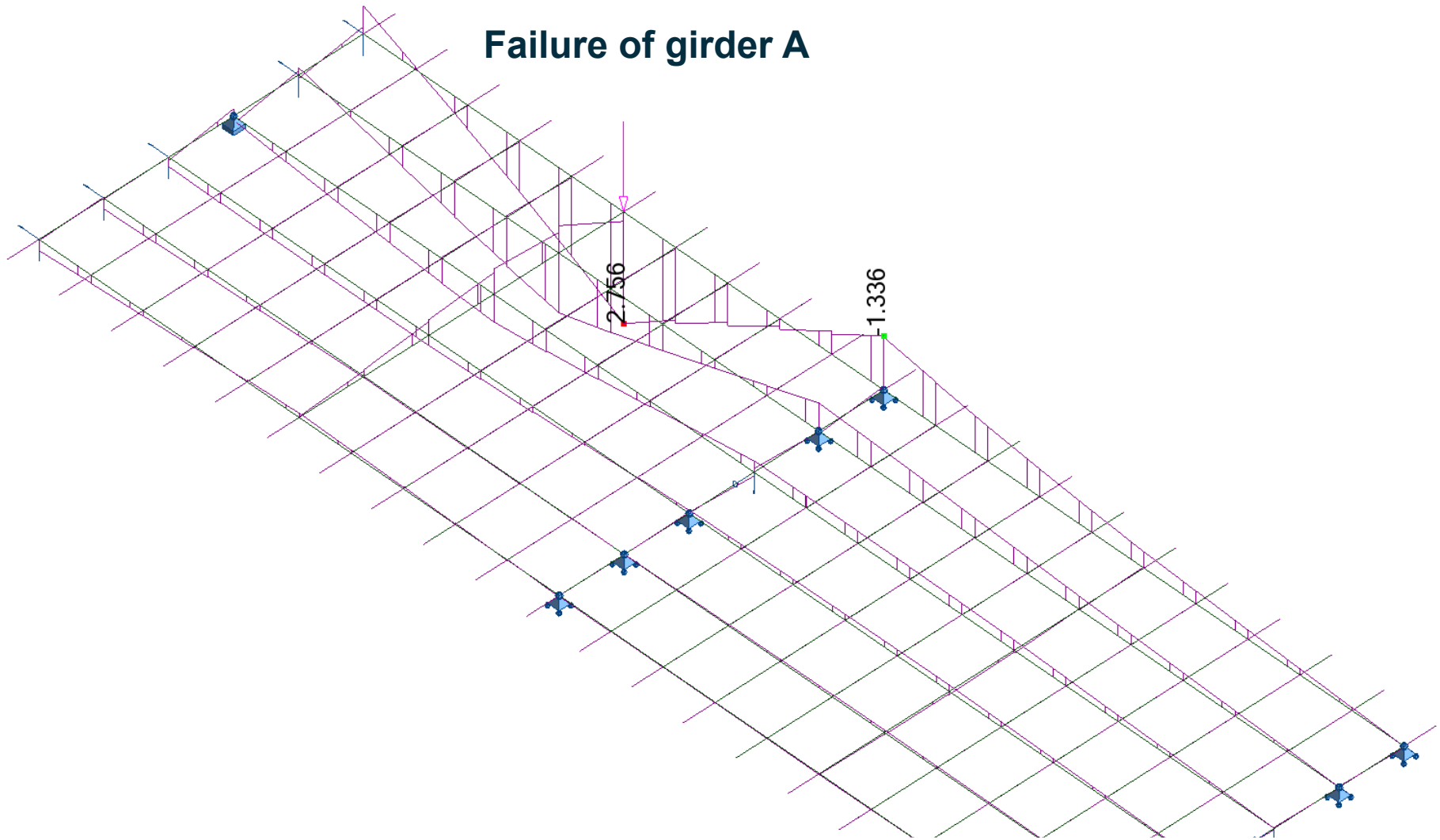
Analysed failures of girders:





# CASE STUDIES - Continuous 2-span 6-girder bridge

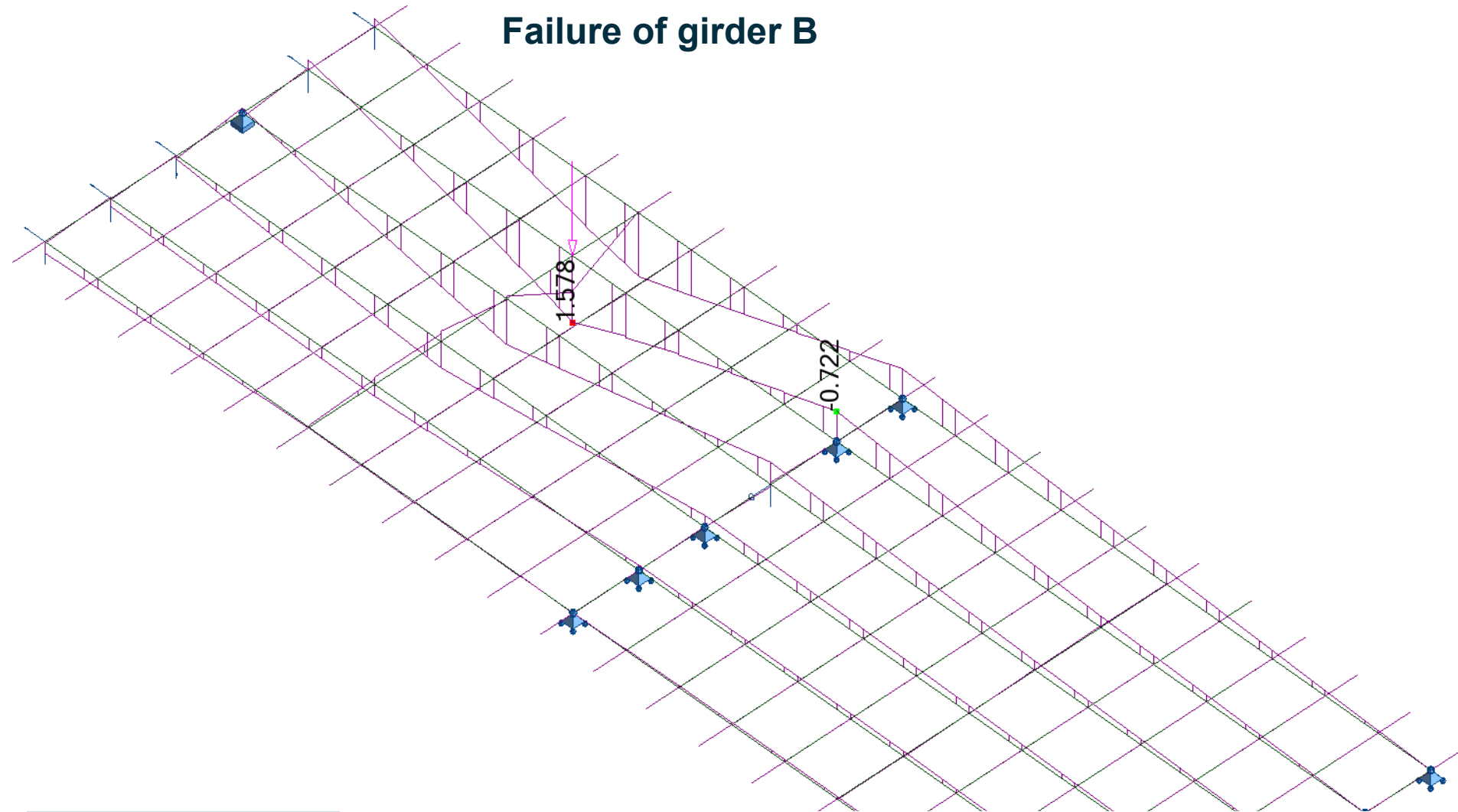
## Failure of girder A





# CASE STUDIES - Continuous 2-span 6-girder bridge

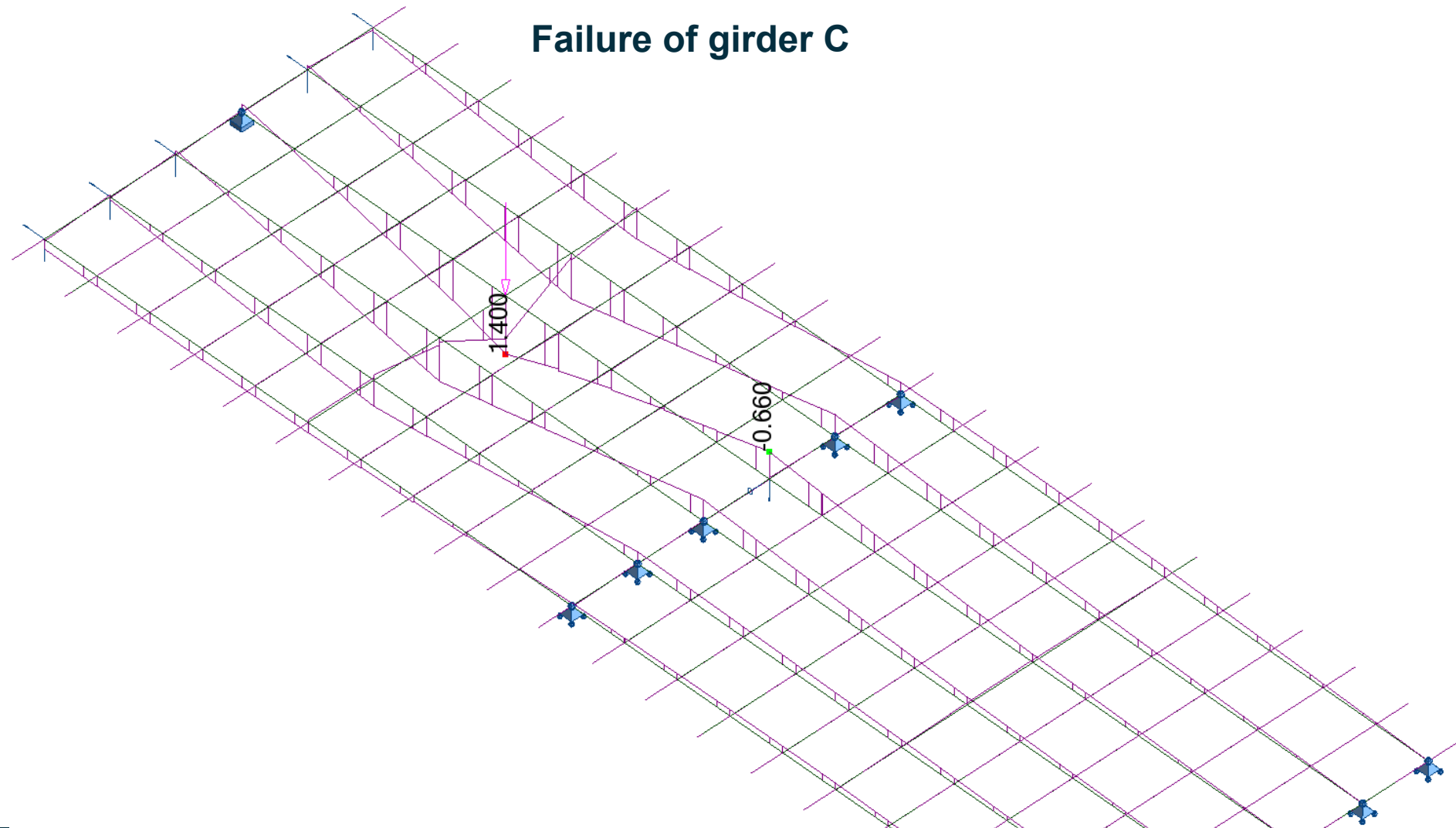
## Failure of girder B





# CASE STUDIES - Continuous 2-span 6-girder bridge

## Failure of girder C

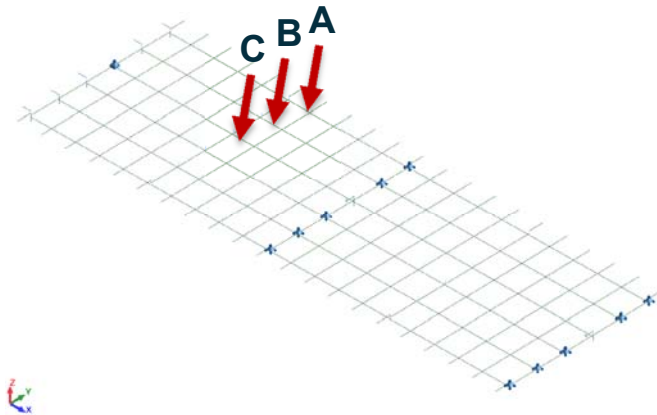




# CASE STUDIES - Continuous 2-span 6-girder bridge

$$R = R_{B,A} = 1 - \frac{M_{k,j}^{d1} - M_{k,j}^1}{M_{j,j}^1 - M_{k,j}^1} = \frac{3.319 - 1.474}{2.756 - 1.474} = -0,439 < 0$$

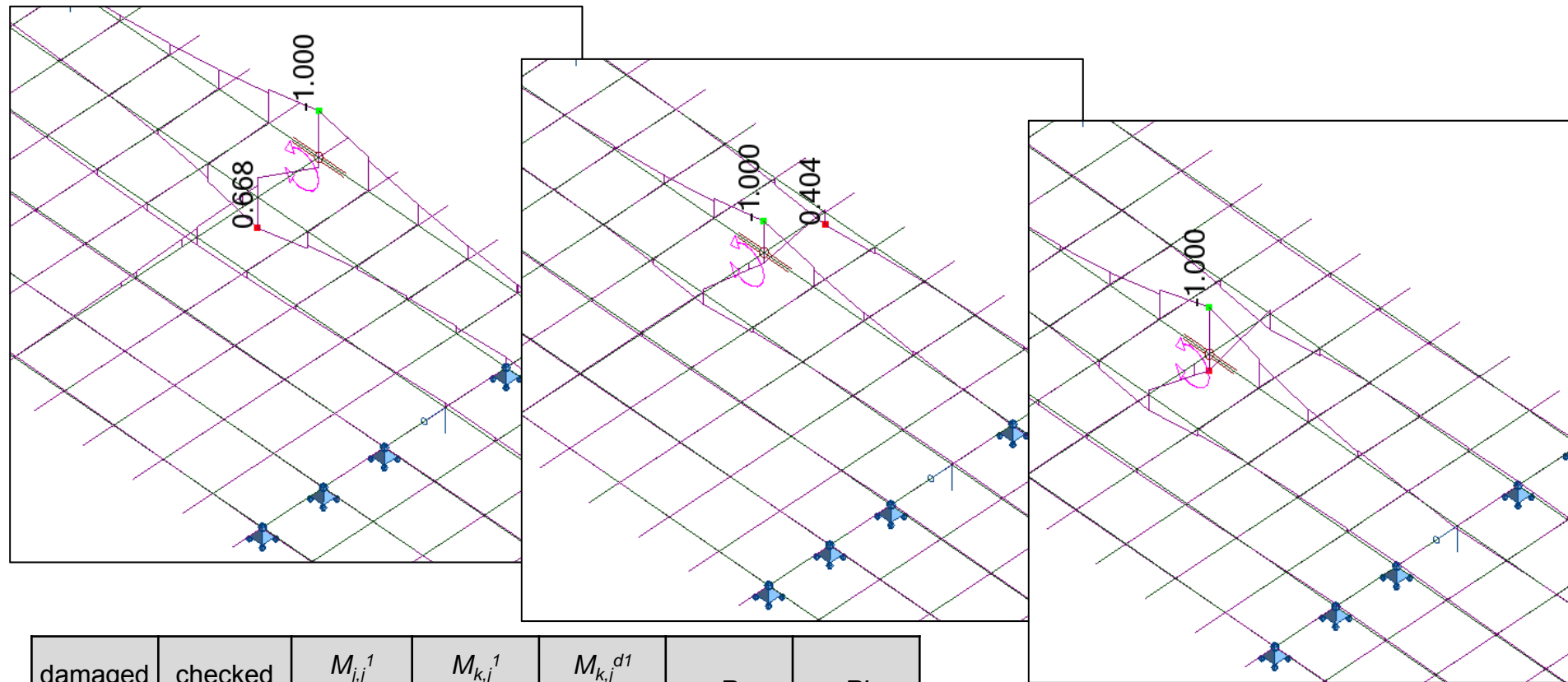
$$R' = R'_{B,A} = 1 - \frac{M_{k,j}^{d1} - M_{k,j}^1}{M_{j,j}^1} = \frac{3.319 - 1.474}{2.756} = 0,331$$



damaged section $j$	checked section $k$	$M_{j,j}^1$	$M_{k,j}^1$	$M_{k,j}^{d1}$	$R_j$	$R'_j$
		kNm	kNm	kNm		
A	B	2,756	1,474	3,319	-0,439	0,331
B	A	1,578	1,504	2,142	-7,622	0,596
C	B	1,400	1,097	1,575	-0,578	0,659



# CASE STUDIES - Continuous 2-span 6-girder bridge



damaged section $j$	checked section $k$	$M_{j,j}^1$	$M_{k,j}^1$	$M_{k,j}^{d1}$	$R_j$	$R'_j$
		kNm	kNm	kNm		
A	B	2,756	1,474	3,319	-0,439	0,331
B	A	1,578	1,504	2,142	-7,622	0,596
C	B	1,400	1,097	1,575	-0,578	0,659



# CONCLUSIONS

- The proposed method represents a consistent and complete approach applicable to any type of structure.
- Thanks to the applied measures the robustness can be quantified and compared for various cases.
- Given measures  $R$  and  $R'$  get values close to 1 for robust system and close to 0 for non-robust ones. In case of  $R$  the negative values can appear what indicates a threat of progressive collapse.
- Within the case studies two types of beam bridges are analysed. Robustness is checked for a hinge formation in the mid-span.
- In case of the 2-girder structure robustness evaluated by means of both  $R$  and  $R'$  measures reflects effectiveness of various layouts of the bracing systems in agreement with expectations and intuition.
- Analysis of the 6-girder structure reveals essential dependence of measures  $R$  and  $R'$  to the assumed loading scenario and to the initial level of internal forces in the checked section.



**8<sup>th</sup> International Conference  
on Arch Bridges**



**October 5-7, 2016, Wrocław, Poland**

[www.arch16.pwr.edu.pl](http://www.arch16.pwr.edu.pl)

[link to paper](#)

**THANKS FOR YOUR ATTENTION!**



## WG MEETINGS & WORKSHOP

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# Robustness as performance indicator for masonry arch bridges

Vicente N. Moreira, João Fernandes, José C. Matos, Daniel V. Oliveira  
University of Minho, Portugal

[link to paper](#)



Institute for Sustainability and Innovation in Structural Engineering



Universidade do Minho

30<sup>th</sup> March - 1<sup>st</sup> April 2016

# Conference paper presentation topics

- Introduction;
- Structural robustness;
- Framework for MAB structural robustness index;
- Damage scenarios;
- Case study: the Calharda Viaduct;
- Conclusions.

# Introduction

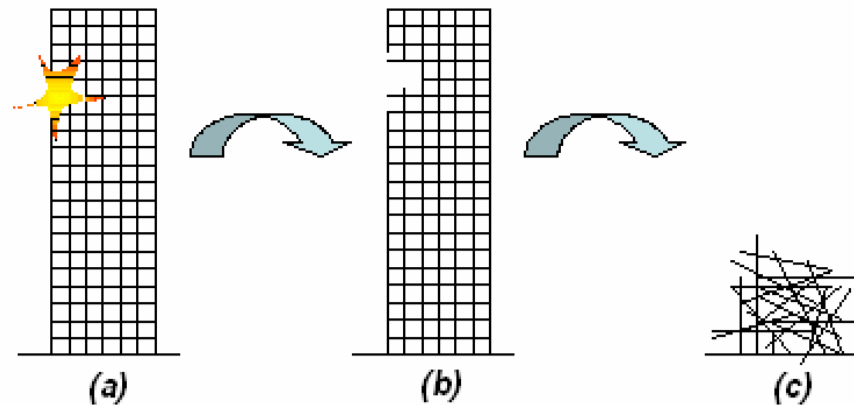
- Masonry arch bridges (MAB) play a significant role in the transportation network nowadays. These bridges have proven to possess excellent performances;
- Combining both degradation and damages over time, their safety condition may be affected and trigger global collapse;
- Thus, it is imperative to investigate their robustness under certain damage scenarios.





# Structural robustness

- Structural robustness is related to structural collapse, in which small damages ((a) and (b)) originate catastrophic consequences (disproportionate failure – (c));



- World Trade Centre collapse has triggered the renewed interest in the study of structural robustness.

# Framework for MAB structural robustness index

- According to Cavaco (2013), robustness is evaluated by the variation of structural performance indicator under a certain damage scenario, given by:

$$RI = \int_{D=0}^{D=1} f(D) dD$$

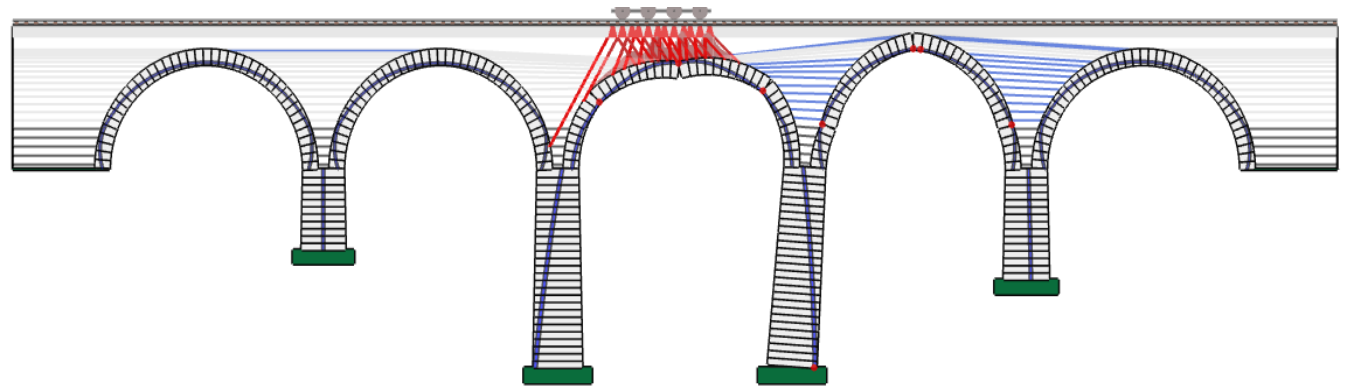
where  $D$  is the normalized damage and  $f(D)$  is the normalized structural performance, expressed by:

$$f = R - S$$

where  $R$  is the resistance curve, which is the MAB ultimate load-carrying capacity, and  $S$  is the applied loads .

# Framework for MAB structural robustness index

- Plastic theorems. Limit Analysis theory
  - Masonry arch bridge structure as an assemblage of rigid blocks;
  - Mechanical parameters:
    - Density ( $\gamma$ ), compressive strength ( $f_c$ ) and friction angle( $\mu$ );
    - Null tensile strength;
    - Sliding failure mechanism not admissible.



# Damage scenarios

- Longitudinal cracking
  - Decreasing the bearing capacity due to the reduction of the effective bridge width;
  - The detachment of spandrel walls diminishes the effective bridge width and arch support to bear applied loads.
- Transversal cracking
  - The detachment of spandrel walls or support settlement originate cracks;
  - Masonry arch voussoirs may loss its mortar, resulting in the displacement of it and to the deterioration of fill and surrounding voussoirs.

# Damage scenarios

- Spalled masonry arch voussoirs
  - Generally, spalled masonry arch voussoirs do not compromise structural integrity. However, in cases of mortar loss, mortar wash-out and/or widespread spalled voussoirs, the effective arch thickness may be severely reduced;
- Masonry deterioration and fatigue
  - Fatigue may reduce up to 50% of masonry's quasi-static compressive strength. In respect to deterioration, it is mainly related to environment, physical and chemical attacks. All these facts result in the reduction of its mechanical properties, especially in its compressive strength.

# Case study: the Calharda Viaduct

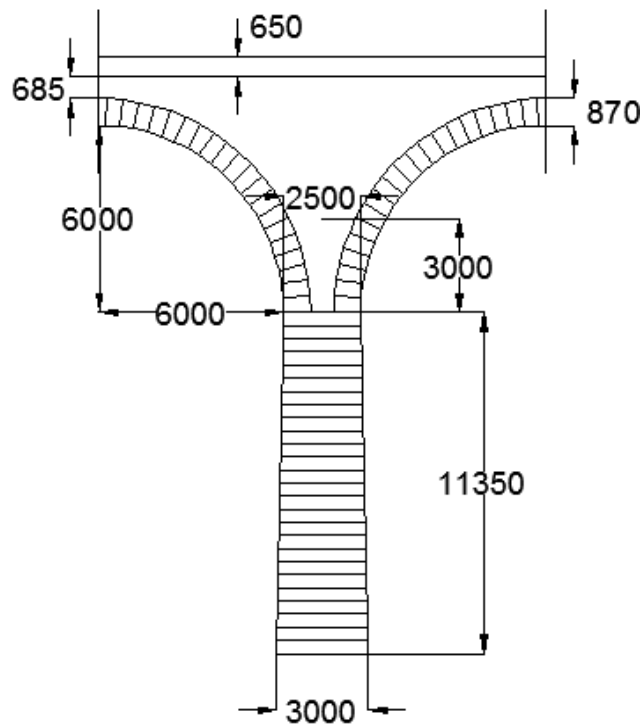
- Built in 1882;
- Located in the Beira Alta railway line;
- Composed by 5 full-centered arches;
- Granitic masonry;
- Rough dry joints.





# Case study: the Calharda Viaduct

- MAB characterization:



		$x_m$
<b>Masonry</b>	Density, $\gamma_m$ (kN/m <sup>3</sup> )	25
	Compressive strength, $f_c$ (MPa)	20
	Friction coefficient, $\mu$ (-)	0,58
<b>Fill</b>	Density, $\gamma_f$ (kN/m <sup>3</sup> )	20
	Angle of friction, $\phi$ (°)	30
	Cohesion, $c$ (kPa)	0
<b>Ballast</b>	Density, $\gamma_b$ (kN/m <sup>3</sup> )	17,66
<b>Track</b>	Track load per unit area, $T_L$ (kN/m <sup>2</sup> )	1,42

# Damage scenarios. Robustness index

- Damage Scenarios and corresponding failure load factors and RI:

DS	Max damage	0%	10%	25%	50%	100%	RI
1	500 mm	4.09 (1.00)	4.09 (1.00)	4.09 (1.00)	4.09 (1.00)	4.09 (1.00)	1.00
2	87 mm	4.09 (1.00)	4.07 (1.00)	4.03 (0.99)	3.77 (0.92)	3.61 (0.88)	0.94
3	87 mm	4.09 (1.00)	4.08 (1.00)	4.07 (1.00)	4.04 (0.99)	3.95 (0.97)	0.99
4	87 mm	4.09 (1.00)	4.06 (0.99)	4.01 (0.98)	3.89 (0.95)	3.57 (0.87)	0.94
5	5 MPa	4.09 (1.00)	4.08 (1.00)	4.07 (1.00)	4.04 (0.99)	3.99 (0.98)	0.99

# Conclusions

- Obtained RI for the different scenarios of damage indicate that all the five scenarios present a high robustness index:
  - In respect to bridges effective width for load transversal dispersion (DS1), it is verified that the bearing capacity has not been affected. Therefore, bridge width is not totally used for the dispersion of applied loads;
  - The reduction of the effective arch thickness, due to transversal cracking (DS2), reduces the bridges performance up to 12%, pointing out that the arch is a crucial element in MAB;

# Conclusions

- Obtained RI for the different scenarios of damage indicate that all the five scenarios present a high robustness index:
  - Localized cracking in the third section of the span-length (DS3) has practically no effect on Calharda viaduct overall safety;
  - For the situation of localized damaged in the middle span section (DS4) of the third span, the failure load factor is reduced in 13%, being the failure mechanism attained more easily;
  - The degradation of masonry due to fatigue and biological/chemical attacks (DS5) reaching 20% of its original value has minor influence in the overall performance.

# Thank you!

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# Acknowledgements

- The authors would like to thank:
  - ISISE – Institute for Sustainability and Innovation in Structural Engineering (PEst-C/ECI/UI4029/2011 (FCOM-01-0124-FEDER-022681)).
  - FCT for the funding through the project UID/ECI/04029/2013 and demonstration under grant agreement No 606229.
  - Portuguese railway network – REFER;
  - Mr. Eng. Rui Patrício.







Universidade do Minho

[link to paper](#)

WG MEETINGS & WORKSHOP  
30<sup>th</sup> March - 1<sup>st</sup> April 2016  
Belgrade, Serbia



### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **PERFORMANCE INDICATORS FOR ROAD BRIDGES – CATEGORIZATION OVERVIEW**

**Alfred Strauss** - University of Natural Resources and Life Sciences, Institute of Structural Engineering, Austria

**Ana Mandić Ivanković** - Faculty of Civil Engineering, University of Zagreb, Croatia

[link to paper](#)

**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**

# OVERVIEW

- PI ↔ PG

- Clustering and categorisation of PI

- Overview based on results of the screening process of the inspection and evaluation documents
- Collection and categorisation of PI is ongoing, particularly in the area of research-based indicators.
- Critical overview and feedback in the developed PI database is still under progress.

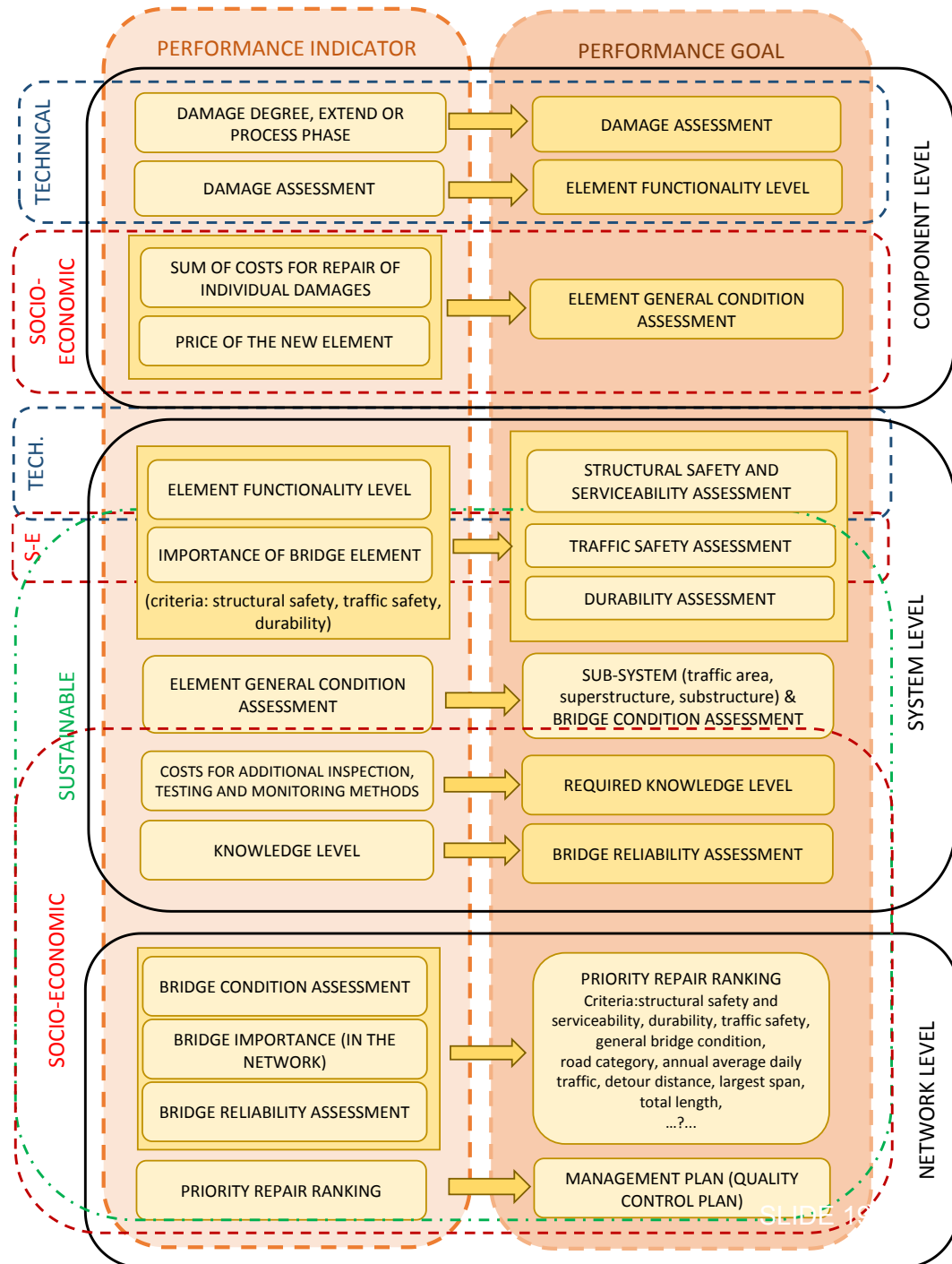
- Damage assessment

- Further steps

Document	Handbook of damages on bridge elements				Add Chapter/Paragraph									
Chapter/Paragraph/Section	A. Oštećenja prilaza i čunjeva - A-1				Hide/Show Chapter									
	Ref				Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
level	system	component	material	type	characteristic	indicator	detection	evaluation	index	threshold	goal	criteria		
Element	All bridge types	Embankment		Damage_State	Erosion	Damage degree	Direct_Measurement			affected ar	Damage Assessment			
Sub_System	All bridge types	Access roads		Damage_State	Asphalt pavement cracking	Damage degree	Direct_Measurement			crack width	Damage Assessment			
Chapter/Paragraph/Section	B. Donji ustroj - B.1. Oštećenja temelja upornjaka i stupova - B1-1				Hide/Show Chapter									
	Ref				Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
level	system	component	material	type	characteristic	indicator	detection	evaluation	index	threshold	goal	criteria		
Element	All bridge types	Foundations		Damage_State	Scour/Erosions	Damage degree	Direct_Measurement			affected ar	Damage Assessment			
Element	All bridge types	Foundations		Damage_State	Abrasion	Damage degree	Direct_Measurement			affected ar	Damage Assessment			
Element	All bridge types	Foundations		Damage_State	Abrasion	Damage degree	Direct_Measurement			affected de	Damage Assessment			
Element	All bridge types	Foundations		Damage_State	Settlements	Damage degree	Direct_Measurement			sag (cm)	Damage Assessment			
Element	All bridge types	Foundations		Damage_State	Degradation	Damage degree	Direct_Measurement			affected ar	Damage Assessment			

# PI ↔ PG

- interactions are contemplated, as they are crucial for optimal quality control and management of road bridges



# PI ↔ PG: COMPONENT LEVEL

- Inspection carried out by components forming three main sub-systems

Substructure	Superstructure	Roadway + equipment
Foundations (concrete)	Superstructure (reinforced concrete)	Pavement
Deep foundations, piles (concrete)	Superstructure (prestressed concrete)	Curb & Cornices
Deep foundations, piles (steel)	Superstructure (steel)	Railings & anchorage, barriers
Deep foundations, piles (timber)	Superstructure (composite)	Sidewalk (Pedestrian walkway)
Abutments (concrete)	Superstructure (timber)	Bearings
Abutments (masonry)	Superstructure (brick)	Expansion joints
Piers (concrete)	Superstructure (stone)	Drainage
Piers (steel)	Arch (concrete)	Lighting
Piers (masonry)	Arch (masonry)	Signalization
...	...	...



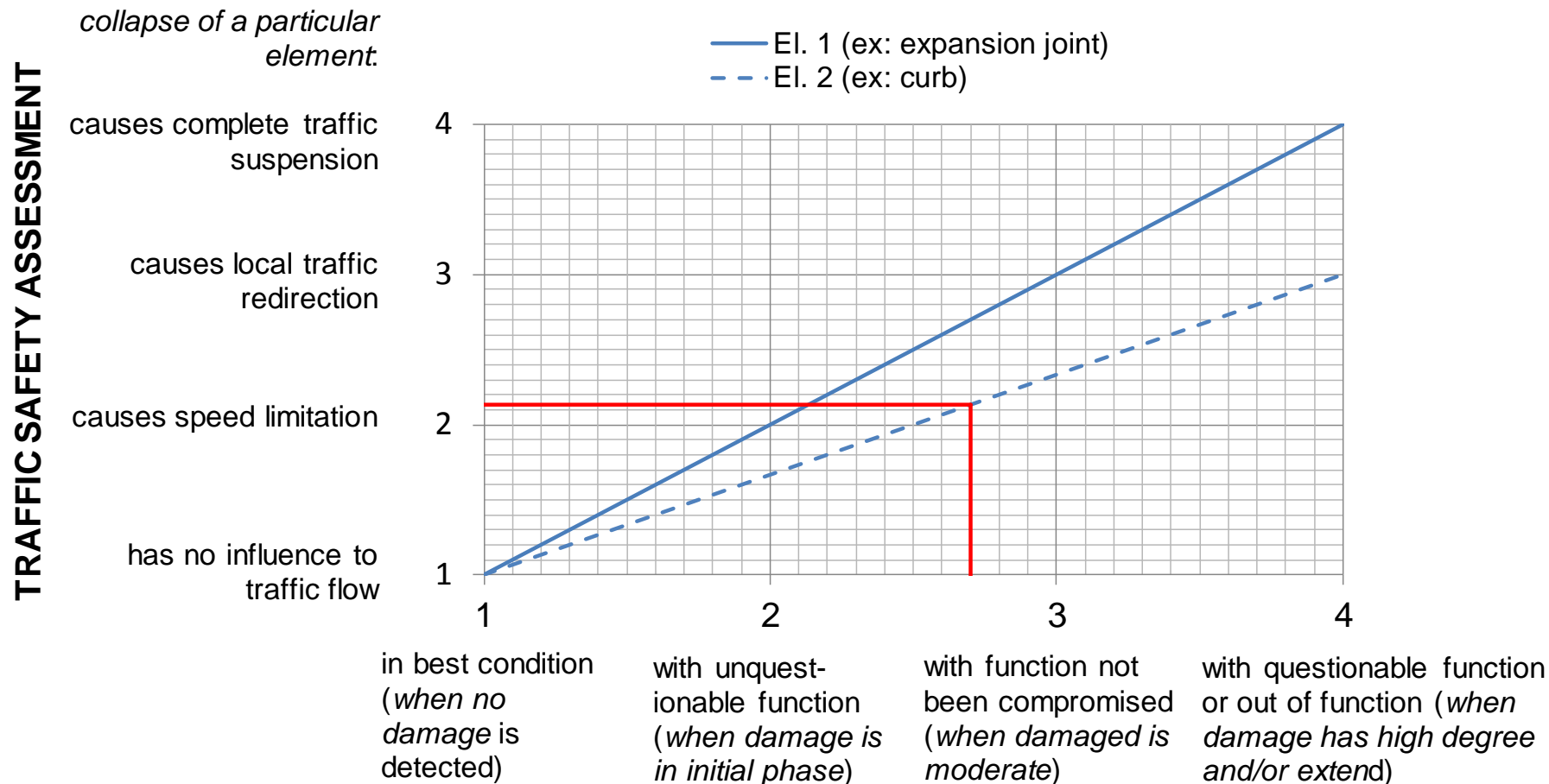
# PI ↔ PG: SYSTEM LEVEL

- Importance of the component to evaluate impact to the entire structure

Structural safety criteria	Traffic safety criteria	Durability criteria
collapse of particular element...		
have no influence to the bridge safety 1 <i>railing, curb, embankment, ...</i>	has no influence to traffic flow 1 <i>cornices, ...</i>	have no influence to durability of other components 1 <i>railing, main girder, arch, pier, foundation, ...</i>
has influence to a part of a bridge structure 2 <i>cornices, cross girders, bearing, wing, ...</i>	causes speed limitation 2 <i>sidewalk with barrier, ...</i>	will cause reduced durability of other components 2 <i>expansion joint, pavement, curb, drain, ...</i>
has influence to an entire bridge structure 3 <i>main girders, arch, pier, foundation, ...</i>	causes local traffic redirection 3 <i>sidewalk, embankment, curb, drainage,</i>	
	complete traffic suspension 4 <i>barriers, pavement, expansion joint, roadway slab, ...</i>	



# PI ↔ PG: SYSTEM LEVEL

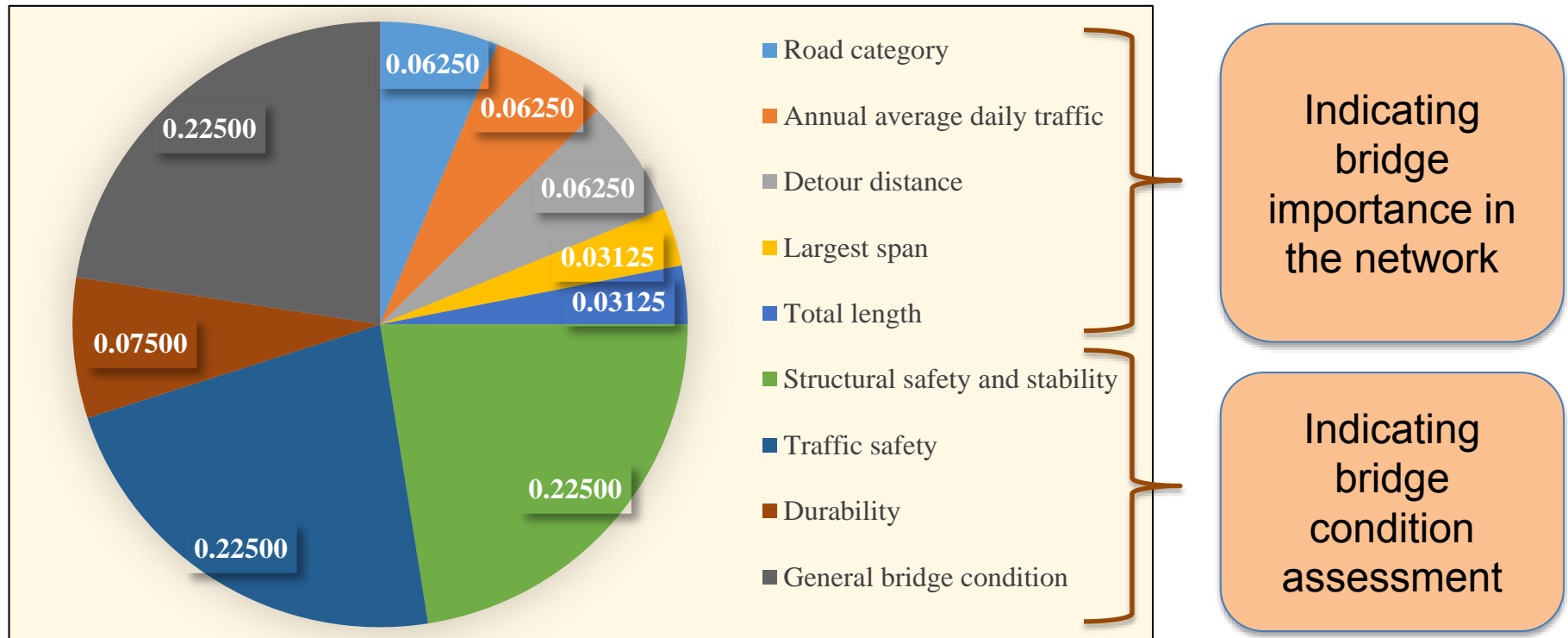


$$T=1+((EL-1)*(T_{MAX}-1)/3)$$

## ELEMENT FUNCTIONALITY LEVEL

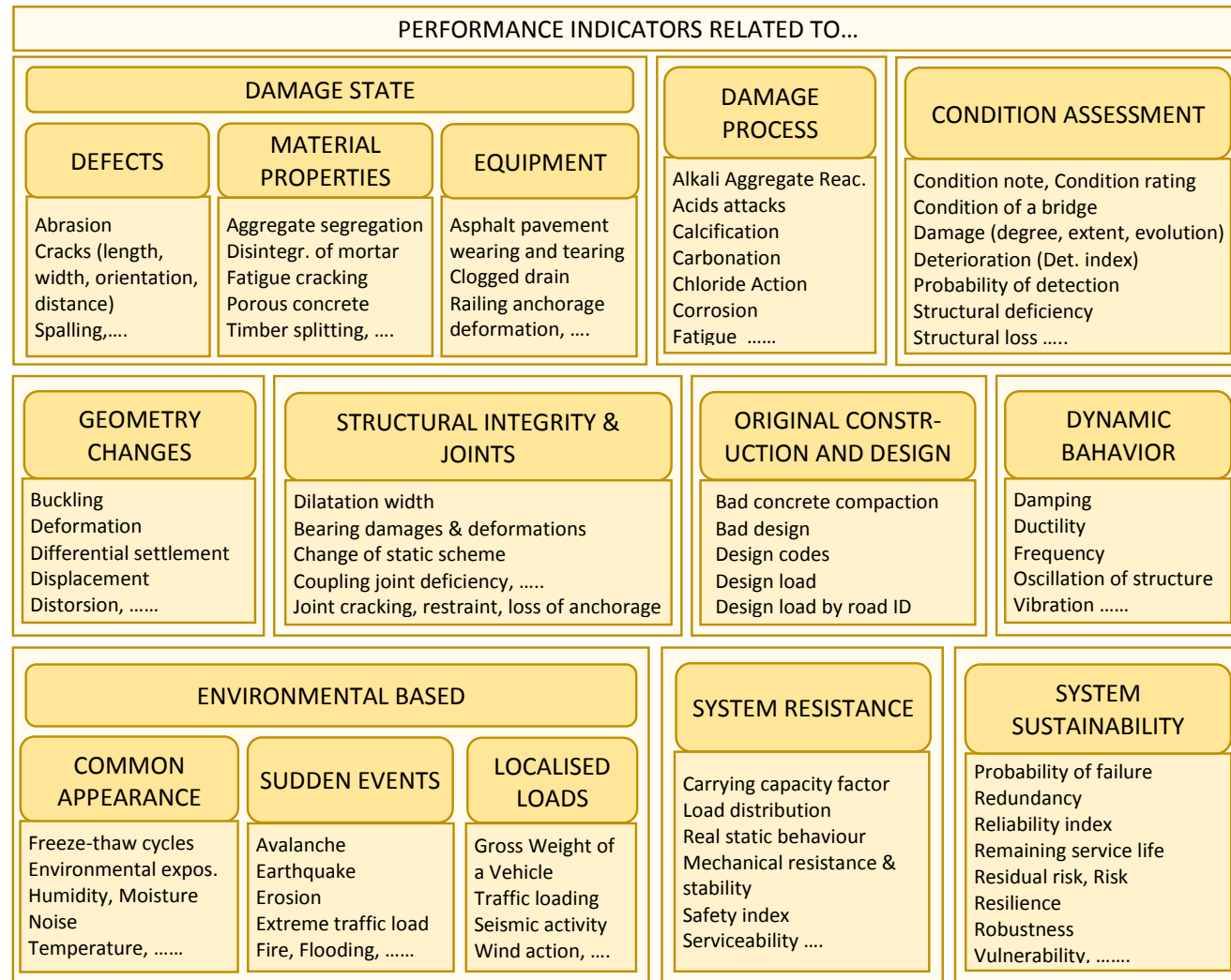
## PI ↔ PG: NETWORK LEVEL

- Example of weight of performance criteria for priority repair ranking



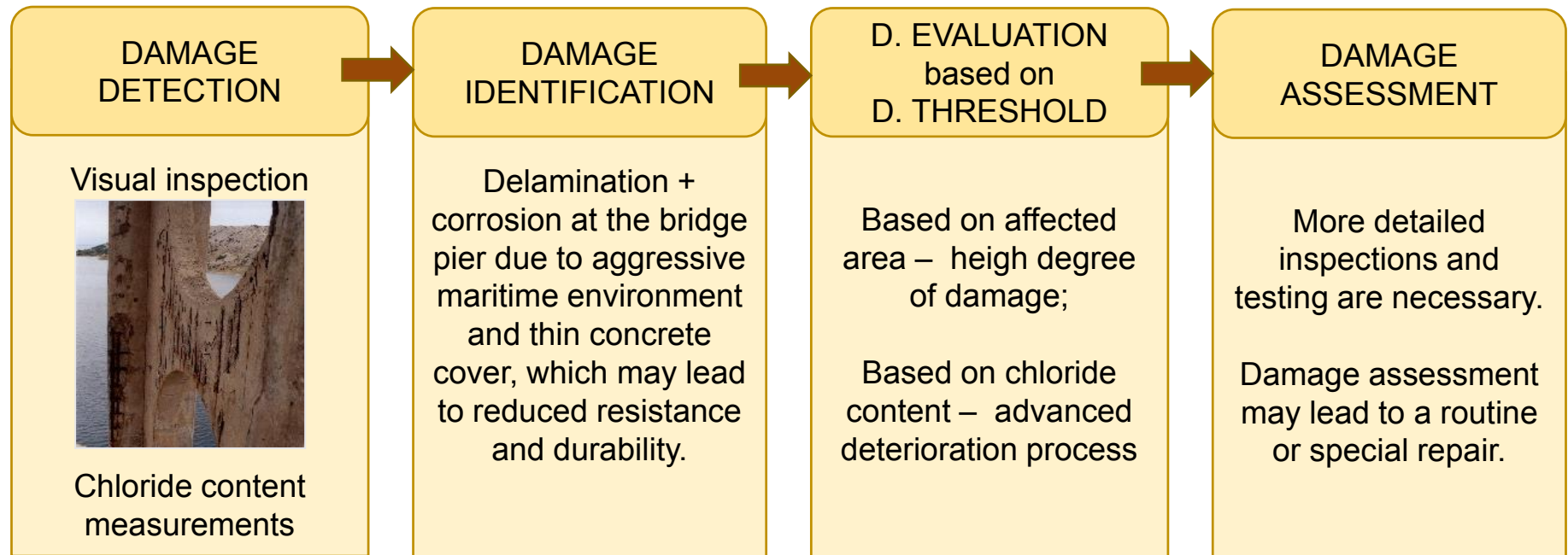
# CLUSTERING OF PI

- to more easily identify:
  - their origin,
  - methods and procedures for their revealing and quantification
  - level and extend of their influence to a certain structural performance type



# DAMAGE ASSESSMENT

- ... implies detection of damages as well as their identification and evaluation.



# DAMAGE ASSESSMENT

- Four main approaches in damage detection are:
  - visual inspection,
  - non-destructive testing,
  - probing and
  - SHM.

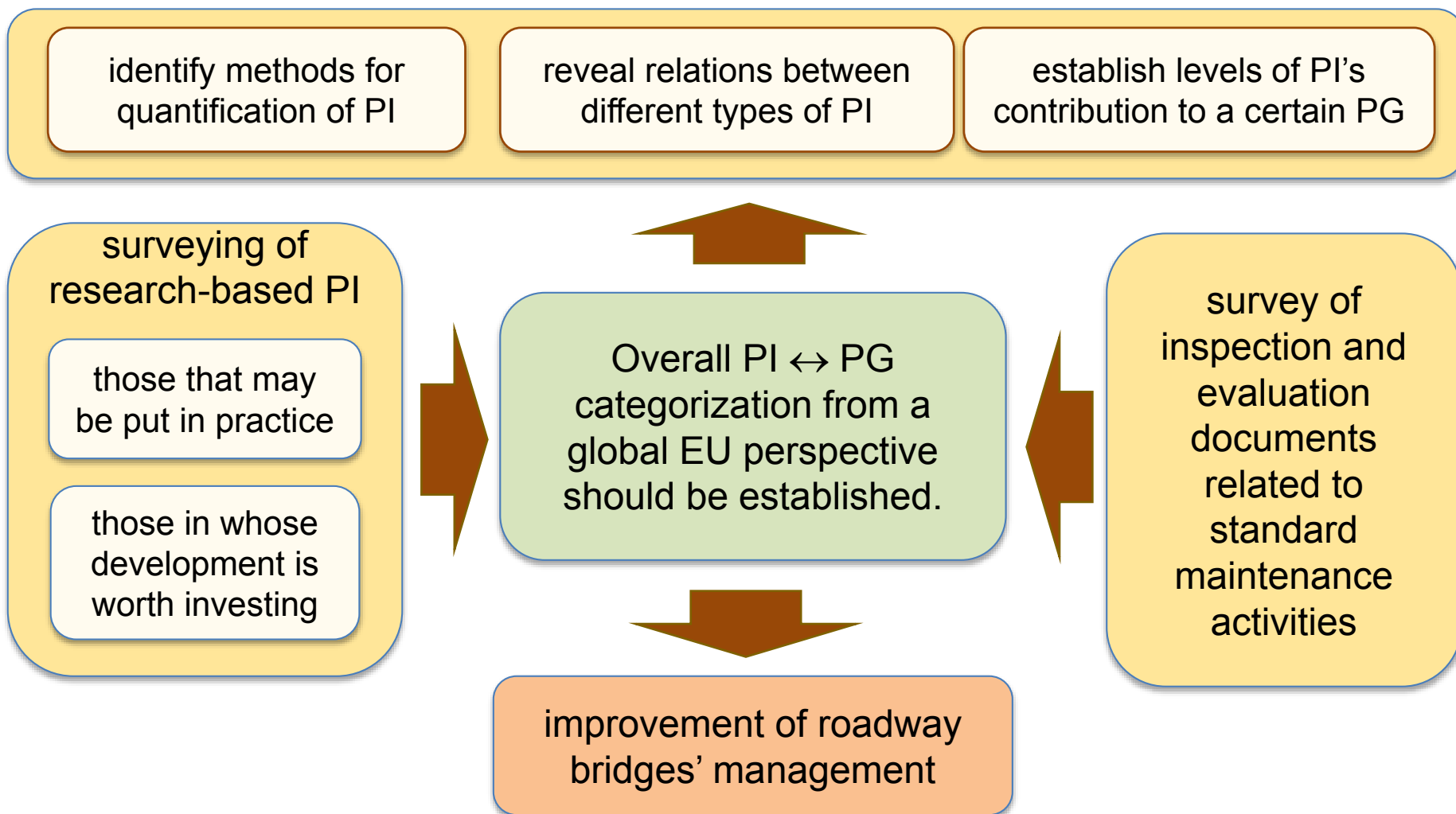


# EXAMPLE OF DAMAGE CATEGORISATION

Damage type (characteristics)	Damage indicator	Damage detection	Damage threshold	Damage evaluation
Abrasion	Affected area (m2) + Affected depth (cm)	Visual inspection + Direct measurement	Classes / upper value + damage phase duration	Grades according to handbook of damages
....				
Cavities	Speed of reflected signal	Acoustic emission		Results analysis
	Resonance in amplitude-frequency spectra	Impact-echo test		Results analysis
Corrosion	Affected area (m2)	Visual inspection + Direct measurement	Classes	Grades according to handbook of damages
	Percentage of damaged cross section of reinforcement (%)	Specialist detailed inspection	Upper values of the phase + damage phase duration	Grades according to handbook for assessment
	Physical parameter	In situ testing		Testing analysis
	Potential (mV)	Half cell potential measurements	Classes and lower limit	Evaluate risk of corrosion
	Chloride content (%)	Probing at concrete samples in laboratory	Critical value	Quantitative analysis
	Carbonization depth (mm)	Laboratory testing of collected material	carbonization depth limit	Evaluate risk of corrosion
		<i>Corrosion Monitoring systems</i>		<i>Monitoring of corrosion progress</i>
Cracks	Crack width (mm)	Visual inspection + Direct measurement	Classes / upper value + damage phase duration	Grades according to handbook of damages
	Crack width/depth	Ultrasonic velocity test	Upper limit	Testing analysis
	Existence	Hammer sounding		
		<i>SHM of cracking</i>		<i>Monitoring of cracks evolution</i>
Delamination	Affected area (m2) + Affected depth (cm or mm)	Visual inspection + Direct measurement	Classes	Grades according to handbook of damages
Deflection	Long-term deflection	Visual inspection + <i>Direct (periodic long lasting) measurement</i>	Upper limit	<i>Monitoring of deflection evolution</i>



# CONCLUSIONS & FUTURE ACTIVITIES





**THANK YOU FOR YOUR ATTENTION !**

**PERFORMANCE INDICATORS FOR ROAD BRIDGES – CATEGORIZATION OVERVIEW  
ALFRED STRAUSS & ANA MANDIĆ IVANKOVIĆ**

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Belgrade, Serbia



### WG MEETINGS & WORKSHOP

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# STRUCTURAL BEHAVIOR OF STONE ARCH BRIDGES

**Cristina Costa** - CONSTRUCT-LESE: Polytechnic of Tomar, Porto

**António Arêde** - CONSTRUCT-LESE: University of Porto, Portugal

[link to paper](#)



30<sup>th</sup> March - 1<sup>st</sup> April 2016

# Introduction

## **StonArcRail Project**

(PTDC/ECM-EST/1691/2012)

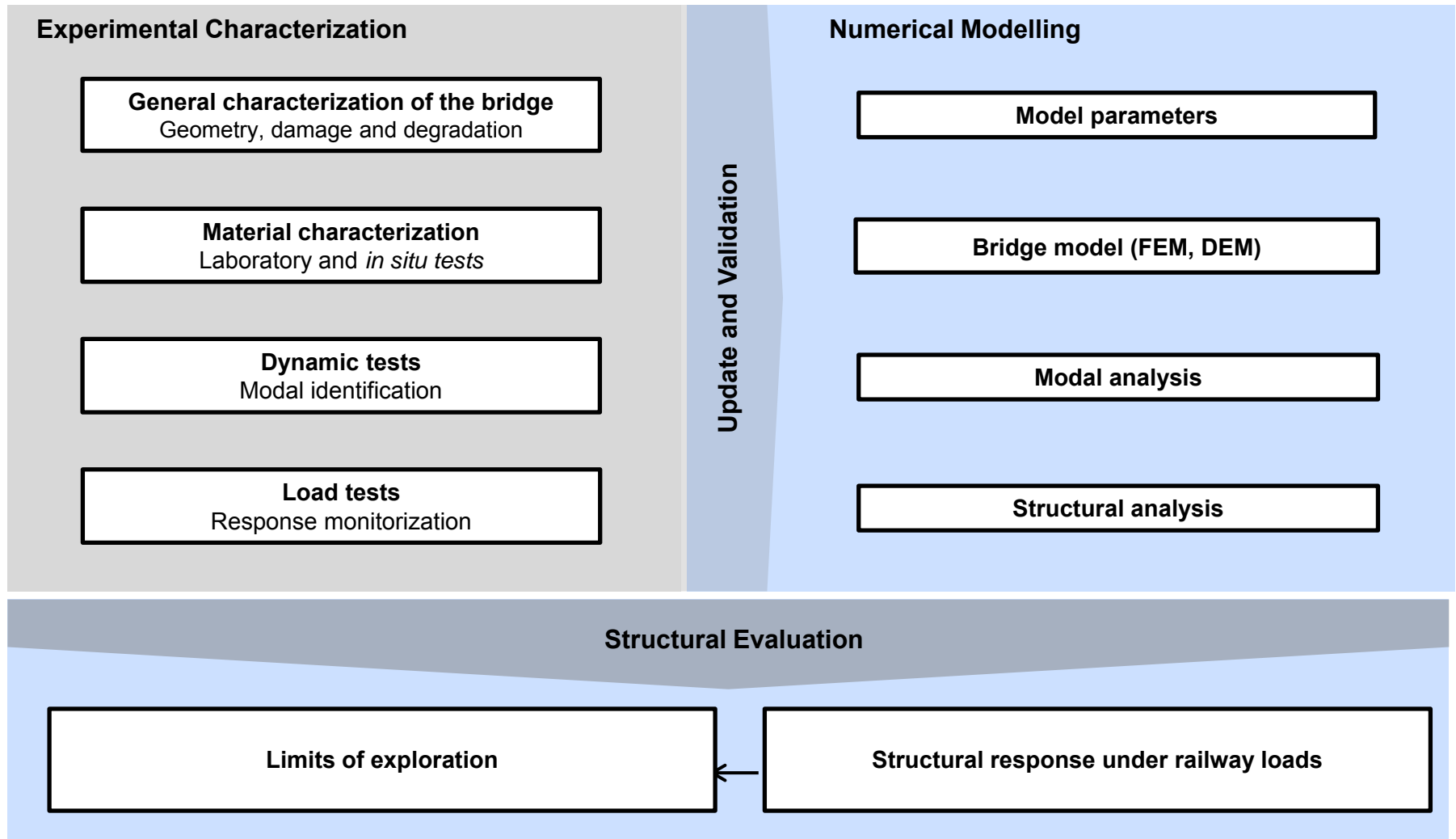


**Experimental and numerical characterization of the structural behaviour of stone arch bridges under railway traffic loading - Application to Existing Portuguese Bridges**

### **General objectives**

- Identify for bridges existing in the Portuguese rail network:
  - **limits of exploration** (loads and train speeds)
  - **effects that constrain the regular operation of these bridges**

# Methodology – StonArcRail Project



# Case studies



**Côa bridge, 1948**  
**Line of Beira Alta**  
**Vilar Formoso**  
**238 m**  
**8 arches**



**Durrães bridge, 1878**  
**Line of Minho**  
**Barroselas**  
**256 m**  
**16 arches**



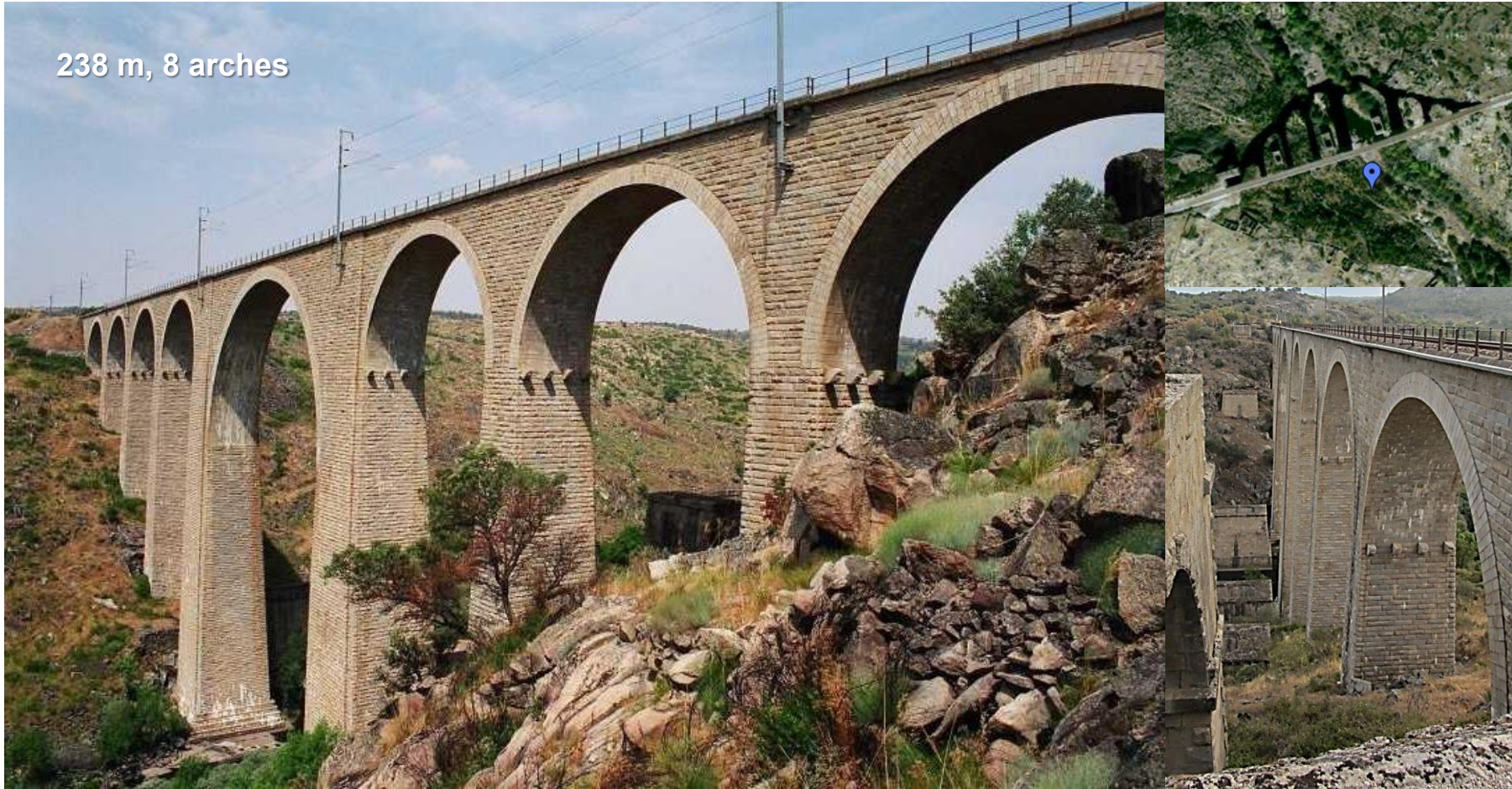
**PK124 bridge, 1879**  
**Line of Minho**  
**S. Pedro da Torre**  
**11 m**  
**1 arch**



# Case studies

## Côa bridge, Vilar Formoso, 1948

238 m, 8 arches





# Case studies

## Durrães bridge, Barcelos, 1878

256 m, 16 arches





# Case studies

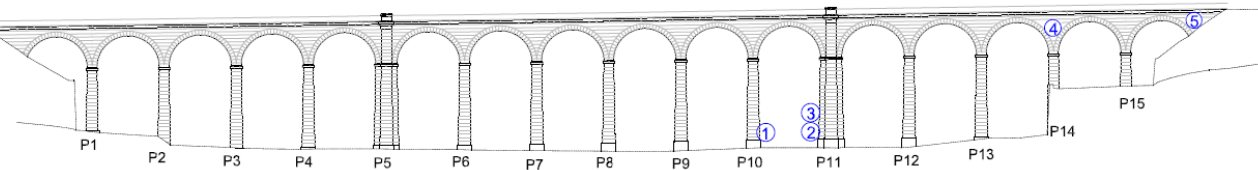
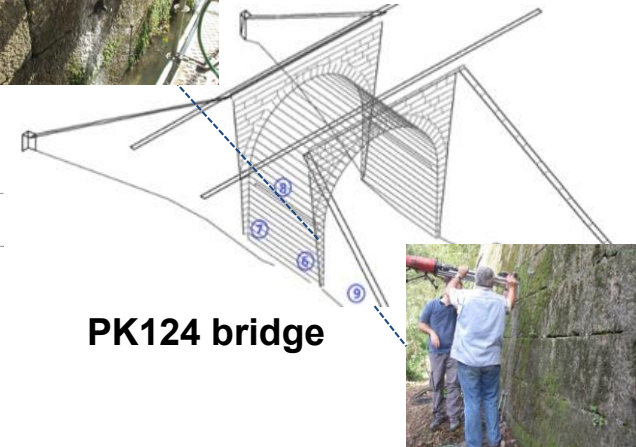
## São Pedro da Torre bridge, PK124, 1879

11 m, 1 arch



# Experimental campaign

## Coring



Durrães bridge

PK124 bridge

## Lab testing

### Stone tests

Diametrical compressive testing

Compressive testing

Elastic modulus testing



### Stone-to-stone joint tests

Shear tests

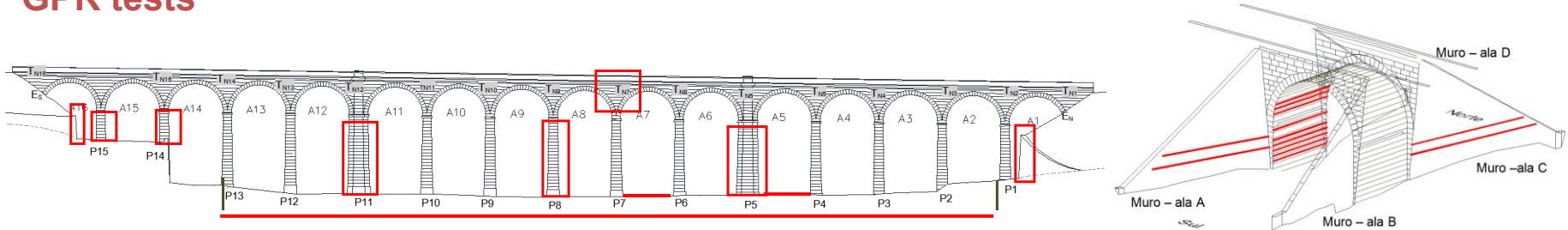
Compression tests





# Experimental campaign

## GPR tests



25 profiles in Durrães bridge and 15 profiles in PK124 bridge

- Thickness of the facing stones and infills of structural components
- Constituent layers of the foundation ground

## Test procedure

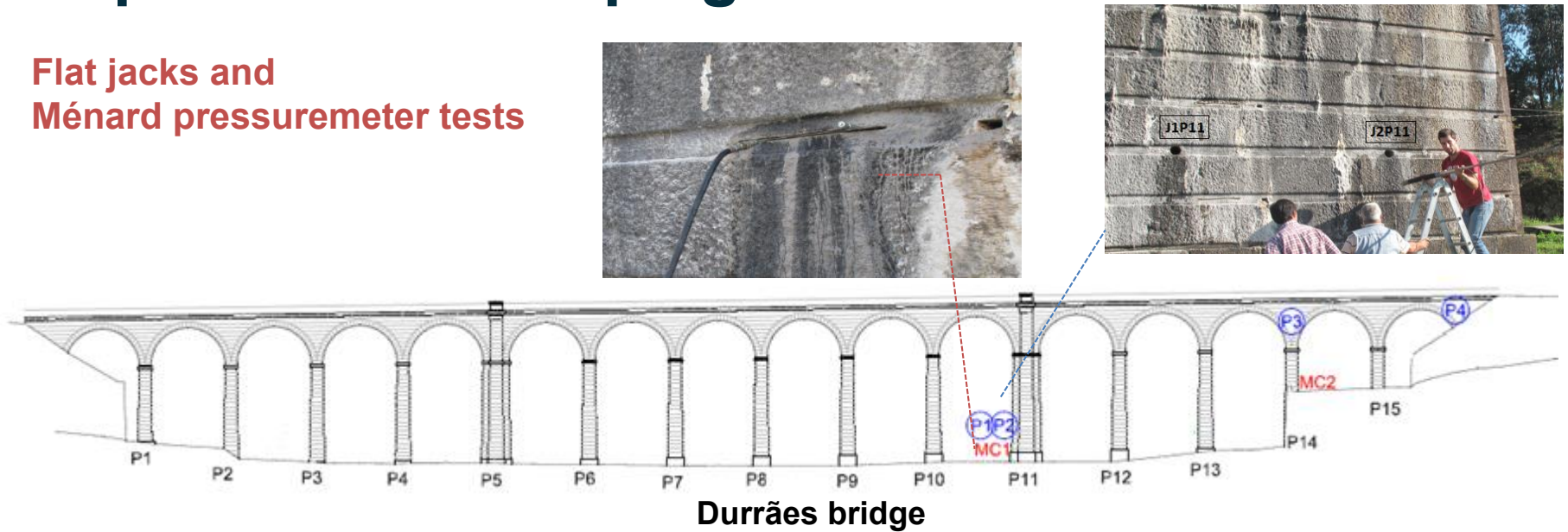


RAMAR, MALÅ Geoscience

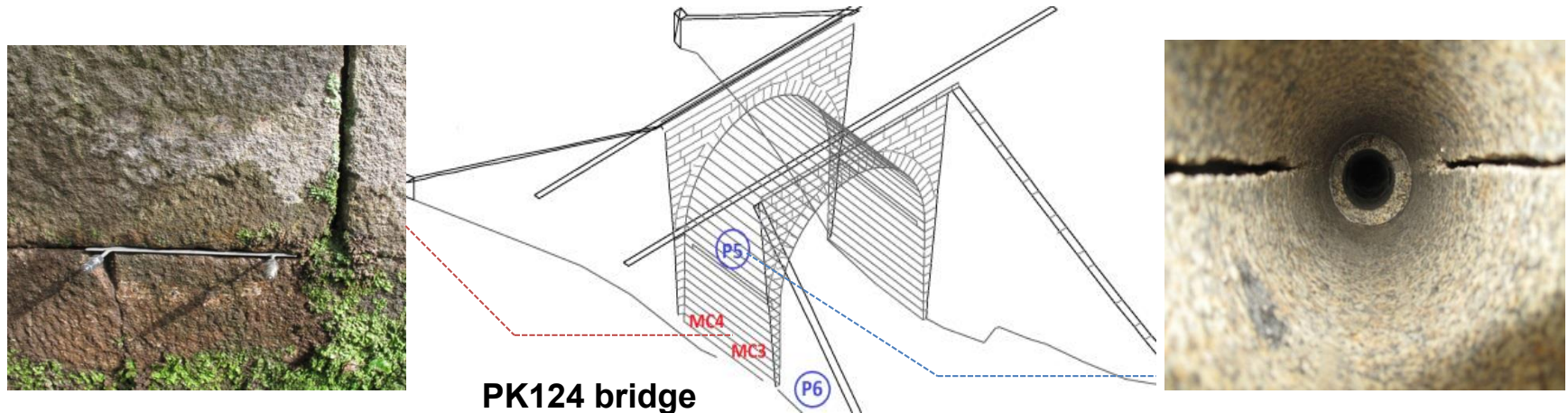
2 antenna types: 250 MHz and 500 MHz

# Experimental campaign

Flat jacks and  
Ménard pressuremeter tests



Durrães bridge



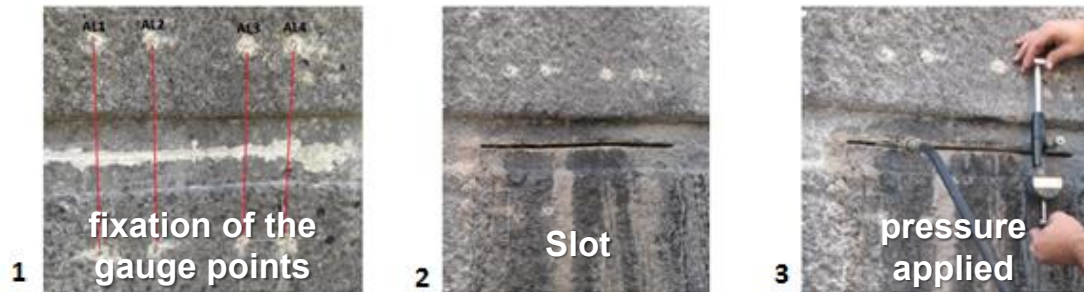
PK124 bridge



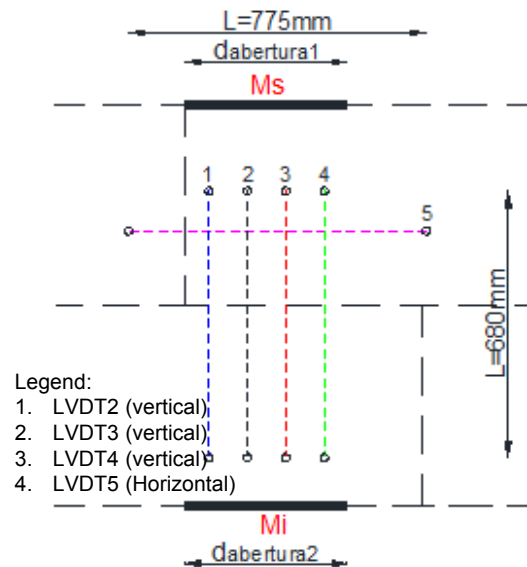
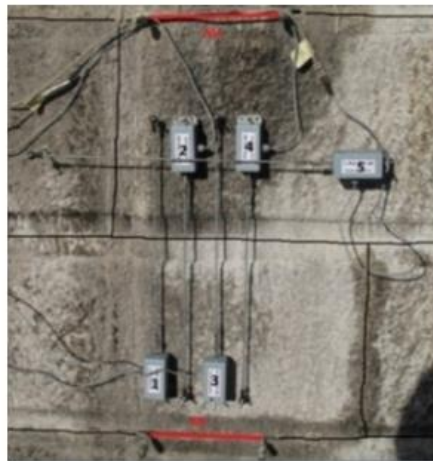
# Experimental campaign

## Flat jack testing

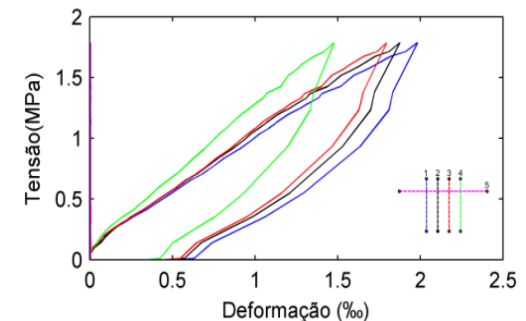
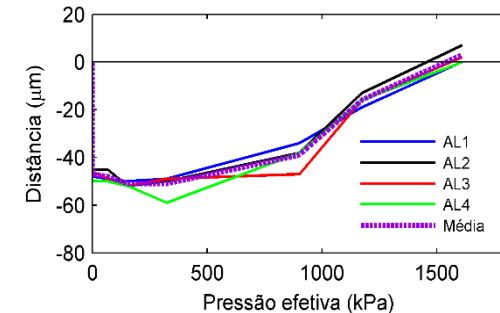
### Single tests



### Double tests



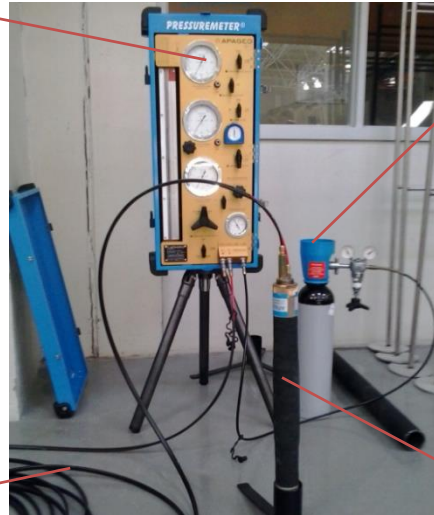
Model MP-A  
 Dimensions: 350x260x4 mm (761.5 cm<sup>2</sup>)  
 Parameter of calibration,  $K_m$ : 0,85  
 Maximum pressure: 60 bar (6MPa)  
 Effective pressure:  $P_{ef} = K_m K_a P$



# Experimental campaign

## Ménard pressuremeter tests

Control unit



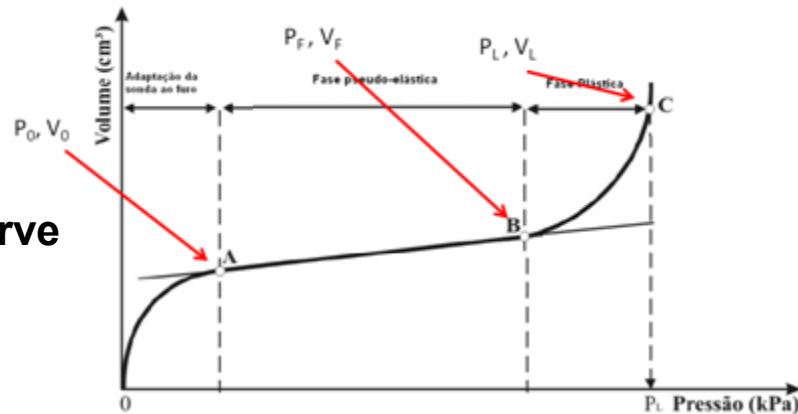
Compressed gas (Nitrogen)



Connecting hose (tube)

Cylindrical probe (d=62mm)

Typical  
Pressiometric curve



**Estimated parameters:**

Deformation modulus

$$G_{PMT} = V_{med} \frac{\Delta P}{\Delta V}$$

Ménard modulus

$$E_{PMT} = 2(1 + \nu)V_{med} \frac{\Delta P}{\Delta V}$$

# Experimental campaign

## Vibration testing

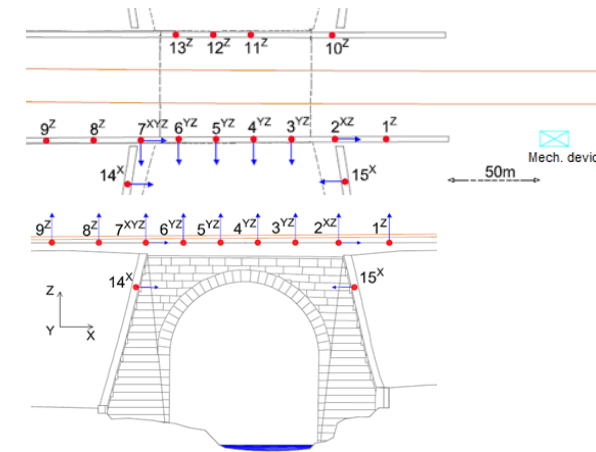
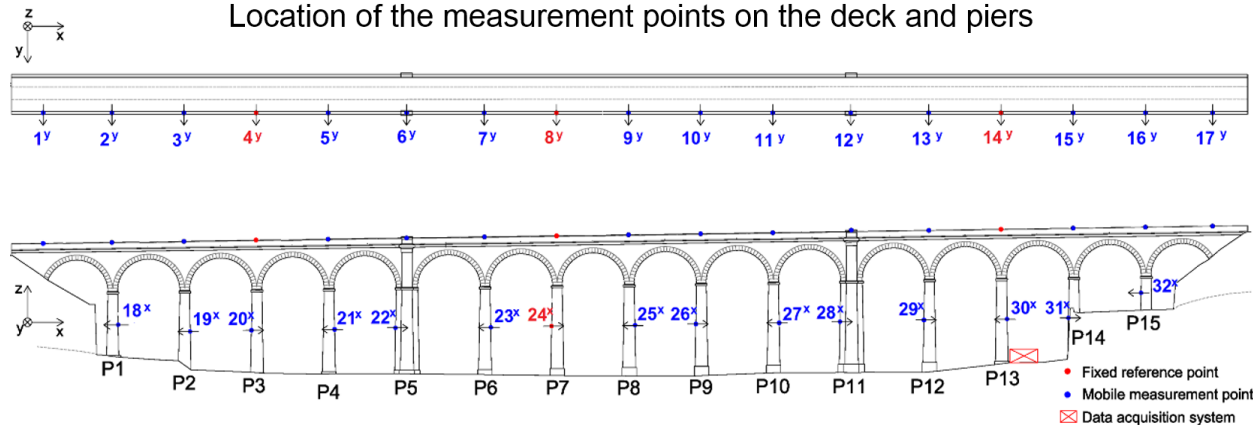
Response measurement of accelerations in a set of pre-selected locations

Ambient vibration of C $\hat{o}$ a and Durr $\hat{a}$ es bridges

Forced excitation of PK124 carried out by means of a mechanical device



Location of the measurement points on the deck and piers





# Experimental campaign - results

## Samples

### Durrães bridge



Stone

Joint

Infill

### PK124 bridge



Stone

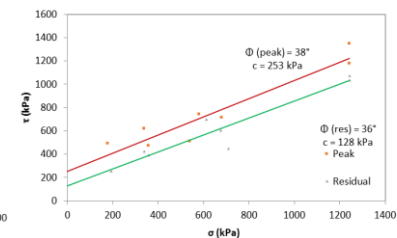
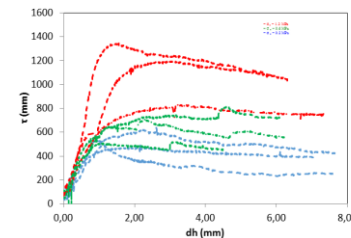
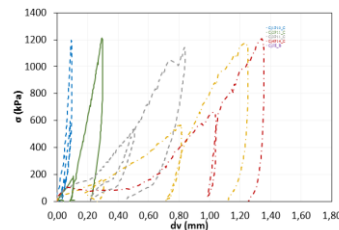
Joint

Infill

## Lab tests in stone samples

Parameter	Mean values	
	Durrães bridge	PK124 bridge
Specific weight (kN/m <sup>3</sup> )	25,9 – 26,5	25,2 – 25,7
Compressive strength (MPa)	34,8 – 59,4	35,9 – 81,4
Tensile strength (MPa)	3,7 – 5,4	2,3 – 5,2
Elastic modulus (GPa)	20,0 – 23,5	6,8 – 10,9

## Lab tests in stone-to-stone joint samples



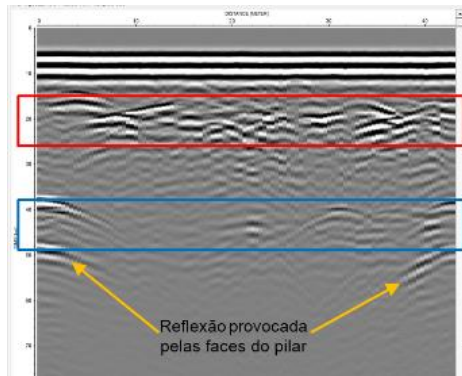
Parameter	Mean values	
	Durrães bridge	PK124 bridge
Normal stiffness (MPa/mm)	0,83 – 1,8	0,5 – 2,5
Shear stiffness (MPa/mm)	0,63 – 0,83	0,07 – 0,63

# Experimental campaign - results

## GPR testing

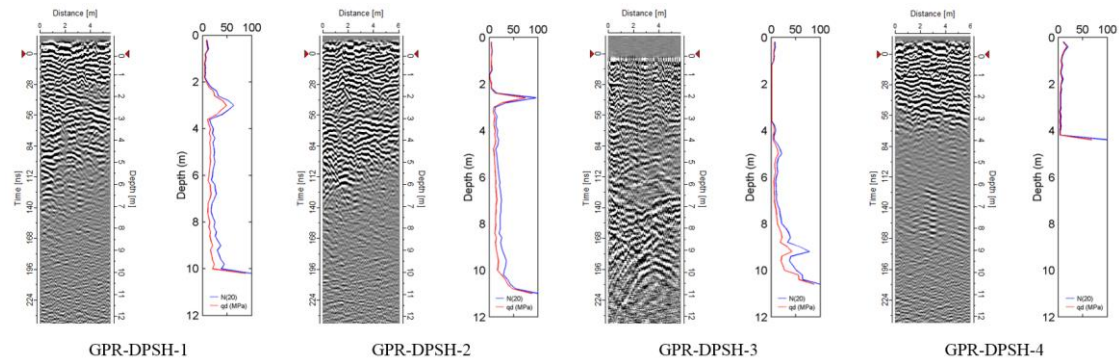
### Geometry of P8 cross section

Recorded radargram

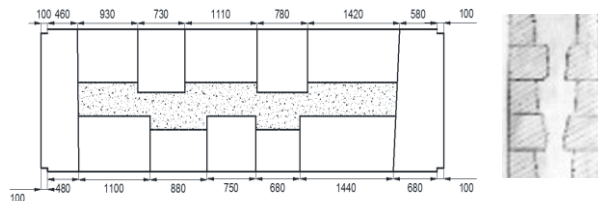


### Ground foundation profile, Durrães bridge,

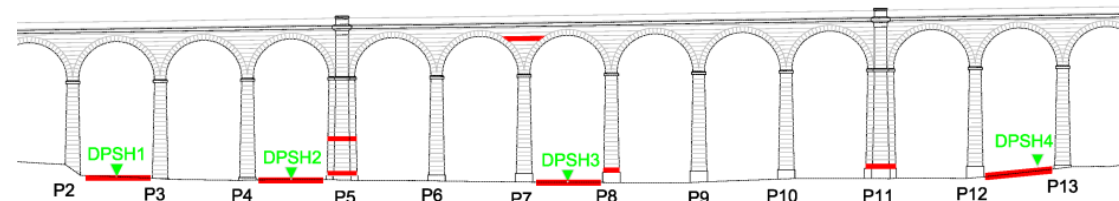
GPR and DPSH testing



...and geometry based on simulated radargrams using software GPRSIM



Depth of the firm: ~4 a 10m



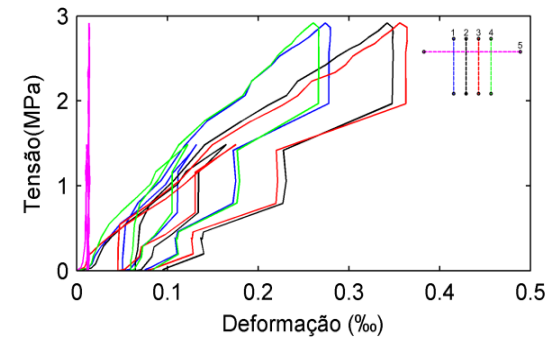
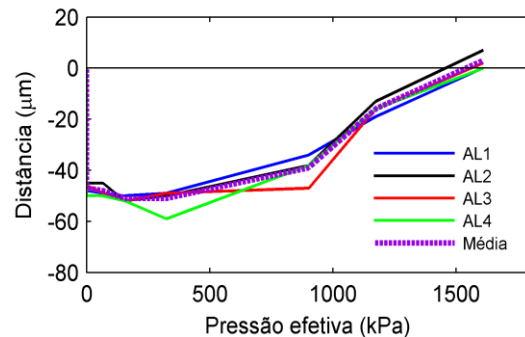
# Experimental campaign - results

Flat jack

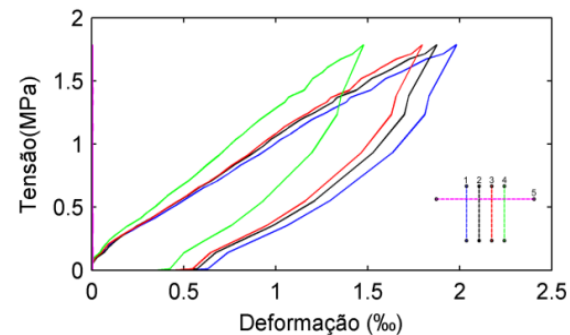
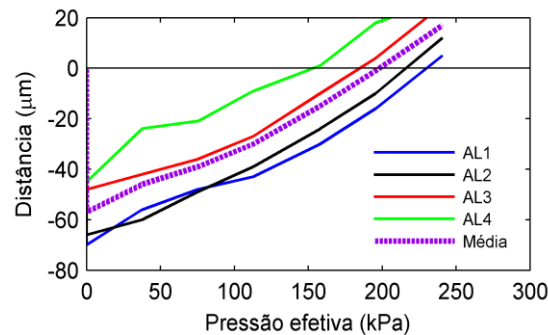
Single test

Double test

MC1  
Durrães



MC3  
PK124



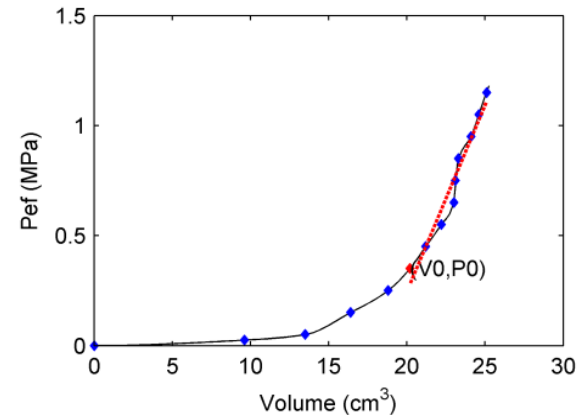
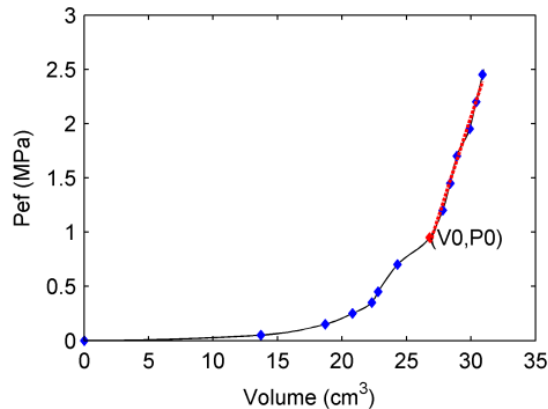
Test	In situ stress (kPa)	Módulo de Young (GPa)
MC1 - Durrães bridge	1534	16-23
MC2 - Durrães bridge	1540	7-11
MC3 - PK124 bridge	986	0,9-1,3
MC4 - PK124 bridge	198	0,9-1,2



# Experimental campaign - results

## Ménard pressuremeter tests

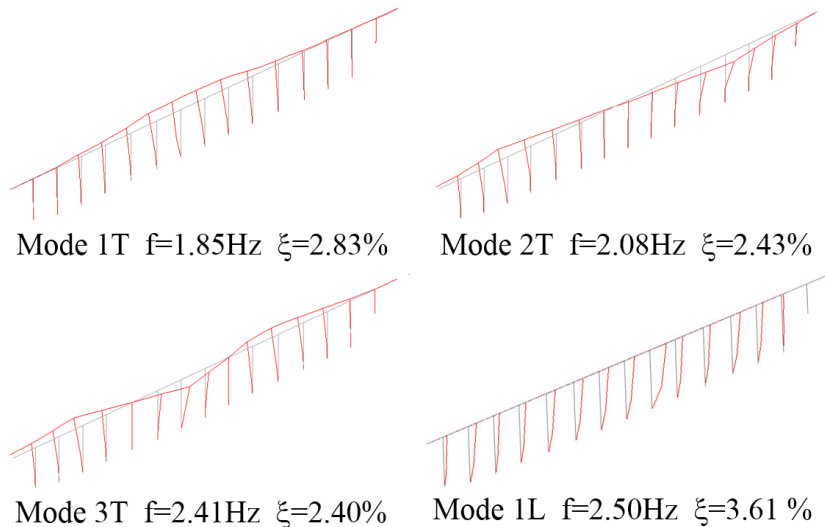
### Pressiometric curve



Core		$G_{PMT}$ Médio (MPa)	$E_{PMT}$ Médio (MPa)	$E_{PMT}$ [(Min-Máx)] (MPa)
<b>Durrães</b>				
Cj2P11	Pier P11	226	588	490-735
Cj3P11	Pier P11	206	537	524-550
Cj4P14	Spandrel P14	135	350	300-438
Cj5E	Abutment	140	363	208-513
<b>PK124</b>				
Cj8A	Arch	95	247	145-305
Cc9MA	Wing-wall	110	286	172-398

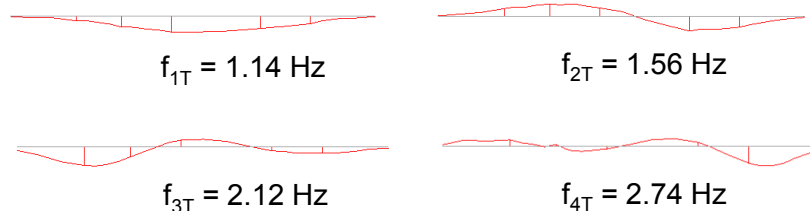
# Experimental campaign - results

## Modal identification

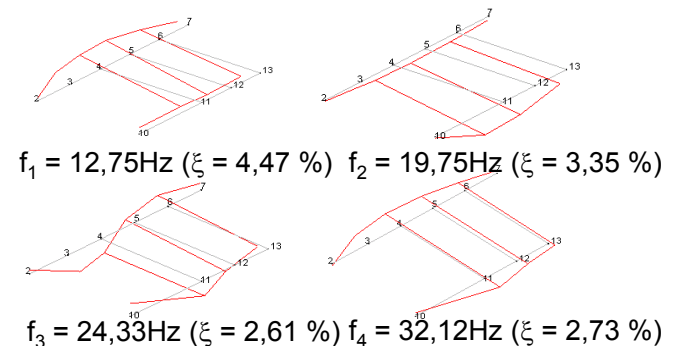


PK124 Bridge		Durrães Bridge		Côa Bridge	
Frequency [Hz]	Damping coef. [%]	Frequency [Hz]	Damping coef. [%]	Frequency [Hz]	Damping coef. [%]
10.45	4.91	1.85	2.83	1.14	3.64
12.75	4.47	2.08	2.43	1.56	3.16
15.08	4.56	2.41	2.40	2.12	2.32
19.75	3.35	2.50	3.61	2.74	1.75
21.97	2.88	2.79	3.37	3.39	1.36
24.33	2.61	3.31	2.23	7.01	1.38
26.88	2.77	3.83	1.67	7.75	0.87
32.12	2.73	4.11	1.94		
		4.33	1.72		
		5.17	1.00		
		5.92			

### Durrães bridge



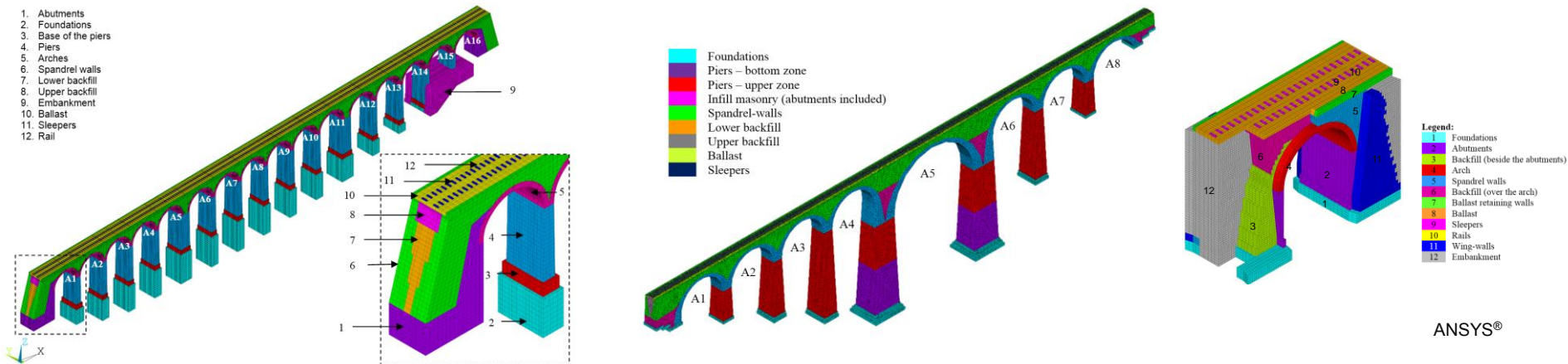
### Côa bridge



### Pk124 bridge

# Numerical modelling

## FE continuous models



**Solid elements** representing homogeneous elastic materials

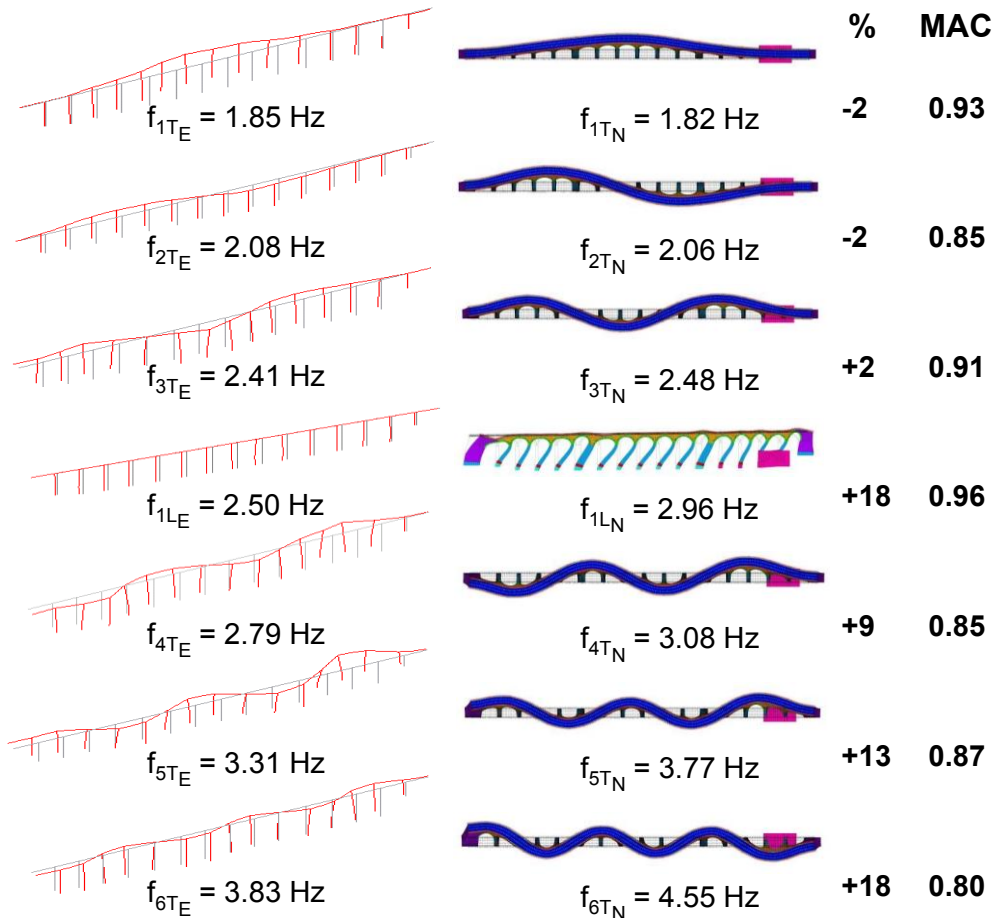
## Detailed FE and DE discrete models



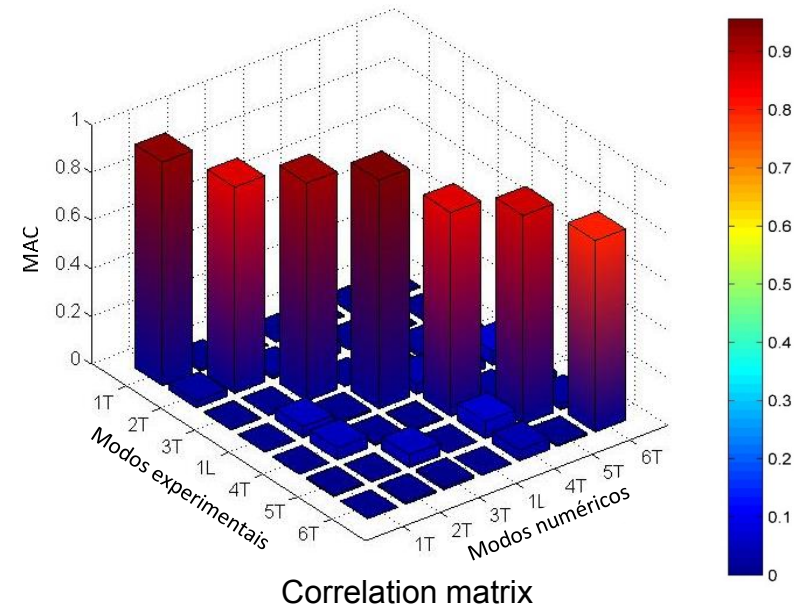
**Micro-modelling strategies** to represent nonlinear behaviour of masonry components

# Numerical modelling - modal updating

## Correlation of experimental and numerical modal parameters

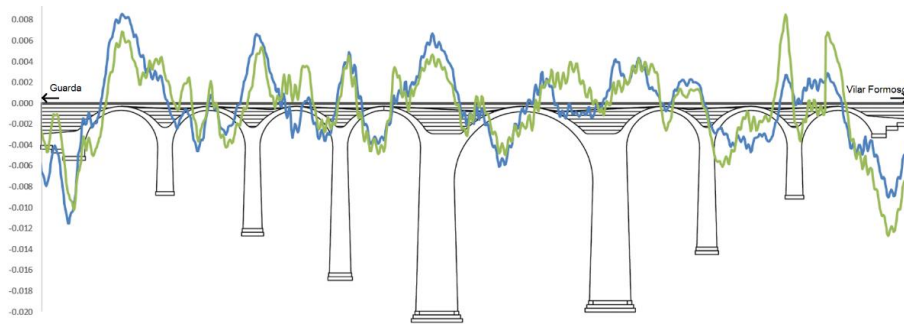


Modal Assurance Criteria (MAC) Durrães bridge

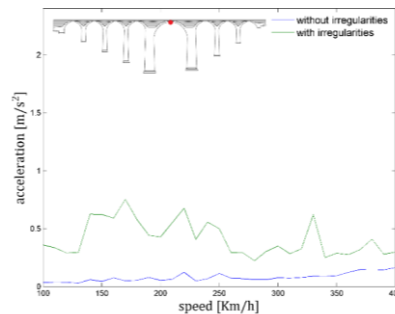
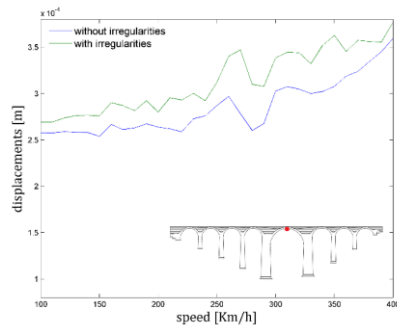


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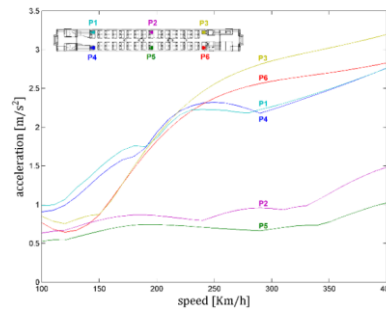
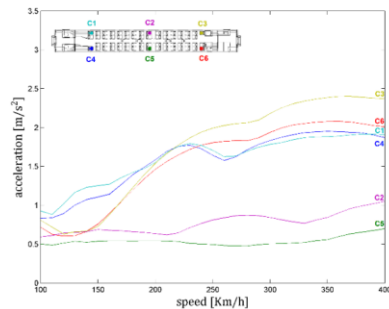
# Numerical modelling - dynamic effects



Cõa bridge levelling profiles, wavelengths 3 to 70 m, maximum amplitude 12.7 mm



Dynamic responses of the main arch of Cõa bridge due to Alfa Pendular train



Dynamic responses of the carbody and passenger of Alfa Pendular train

## Train speed ranges

**Alfa-Pendular trains:** 100 to 400 km/h

**Freight trains:** 80 to 220 km/h

**Track irregularities** based on in situ measurements

## Bridge acceleration ( $a_{EC0-A2}=3.5 \text{ m/s}^2$ )

**Durrães and PK124 bridges:** no vertical accelerations exceeding the code-standard limit with freight trains

**Cõa bridge:** the code-standard limit is exceeded in several locations; need to set a speed limit for Alfa-Pendular train

## Alfa Pendular train acceleration

**Very good passenger comfort level** for 120 km/h speed limit

**Good comfort levels** for 160 km/h speed limit

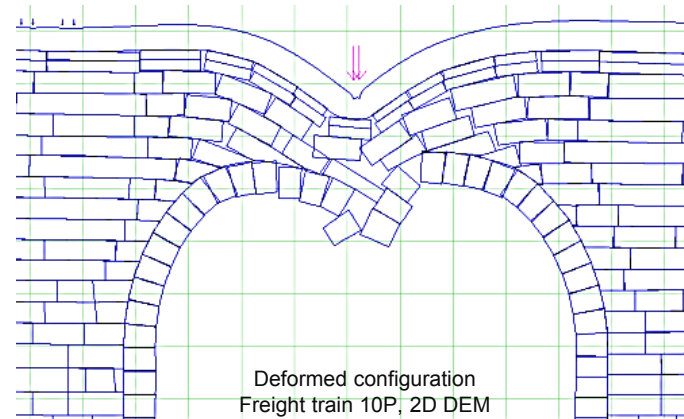
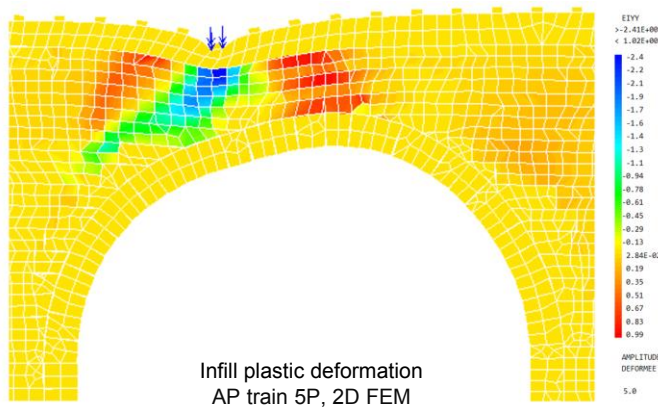
**Satisfactory comfort levels** for 240 km/h speed limit

## Freight train acceleration

**High values** are reached but no information is available on code-standard limit acceleration

# Numerical modelling - load carrying capacity

**Incremental static loading** of the Alfa Pendular and freight trains **at the most unfavourable train positions** to induce an **arch failure** associated with the formation of a **hinge mechanism**



**Very high values are required for the load factor** of the nominal train loading to develop a bridge collapse mechanism

3D model with freight train loading without the formation of any hinge in the arch until the intensity level of 10

2D model with the maximum multiplier applied with the Alfa Pendular loading ~70

2D model with the maximum multiplier applied with the freight train loading ~10





### Acknowledgements

This work includes research conducted with the **financial support of FCT** through the PTDC project/ECM-EST\_1691/2012- Experimental and Numerical Characterisation of the Structural Behaviour of Arch Stone Masonry Bridges under the Action of Railway Traffic - Application to Portuguese Existing Bridges (StonArcRail). The authors thank **engineers Ana Silva, Hugo Patrício and Nuno Lopes from IP-Infrastructures of Portugal** for all their collaboration and the information provided on the bridges and **professors Rui Calçada, Diogo Ribeiro, José Meneses, António Gomes and Rui Gonçalves and engineers Pedro Jorge, Ruben Silva, Maria Morais and Nuno Pinto and Mr. Valdemar** for all their collaboration as members of the researcher team.

[link to paper](#)

**THANKS FOR YOUR ATTENTION!**

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### WG MEETINGS & WORKSHOP

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# FORECASTING OF PERFORMANCE INDICATORS

**Snezana Masović** - *Faculty of Civil Engineering, University of Belgrade, Bul. kralja Aleksandra 73,  
11000, Serbia*

*E-Mail: [smasovic@grf.bg.ac.rs](mailto:smasovic@grf.bg.ac.rs)*

[link to paper](#)



# INTRODUCTION

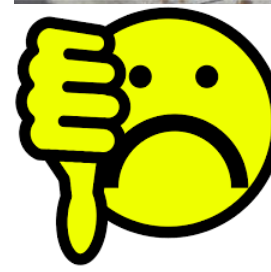
- To assure that bridge structure meets all performance requirements (performance goals) many different performance indicators are introduced.
- A performance indicator is a parameter that quantitatively describes a specific performance aspect.
- Thus, such indicators are measurable, testable and computable, i.e. they can be derived from the conditions of the structure and the environment.
- This performance indicators might be represented in a qualitative discrete scale.
- Condition rating – condition state takes an integer value



# BRIDGE MANAGEMENT



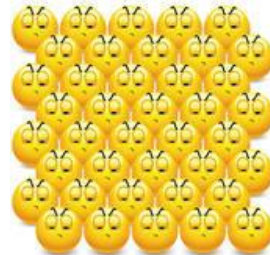
# WHAT?



Redirection of the budget towards great investments in infrastructure reduces funds for maintenance.



# WHEN?



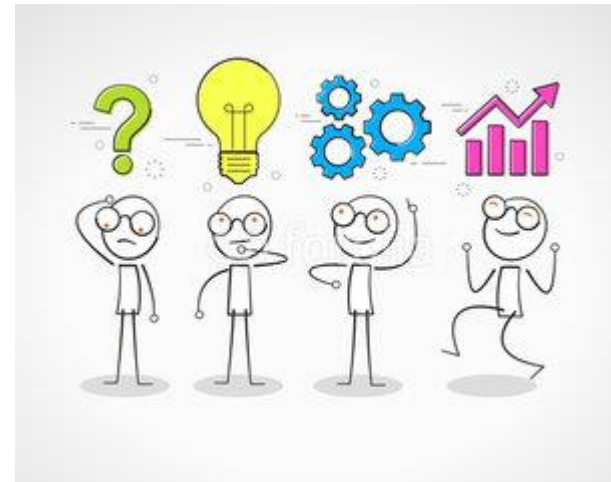


# PREDICT THE FUTURE !?



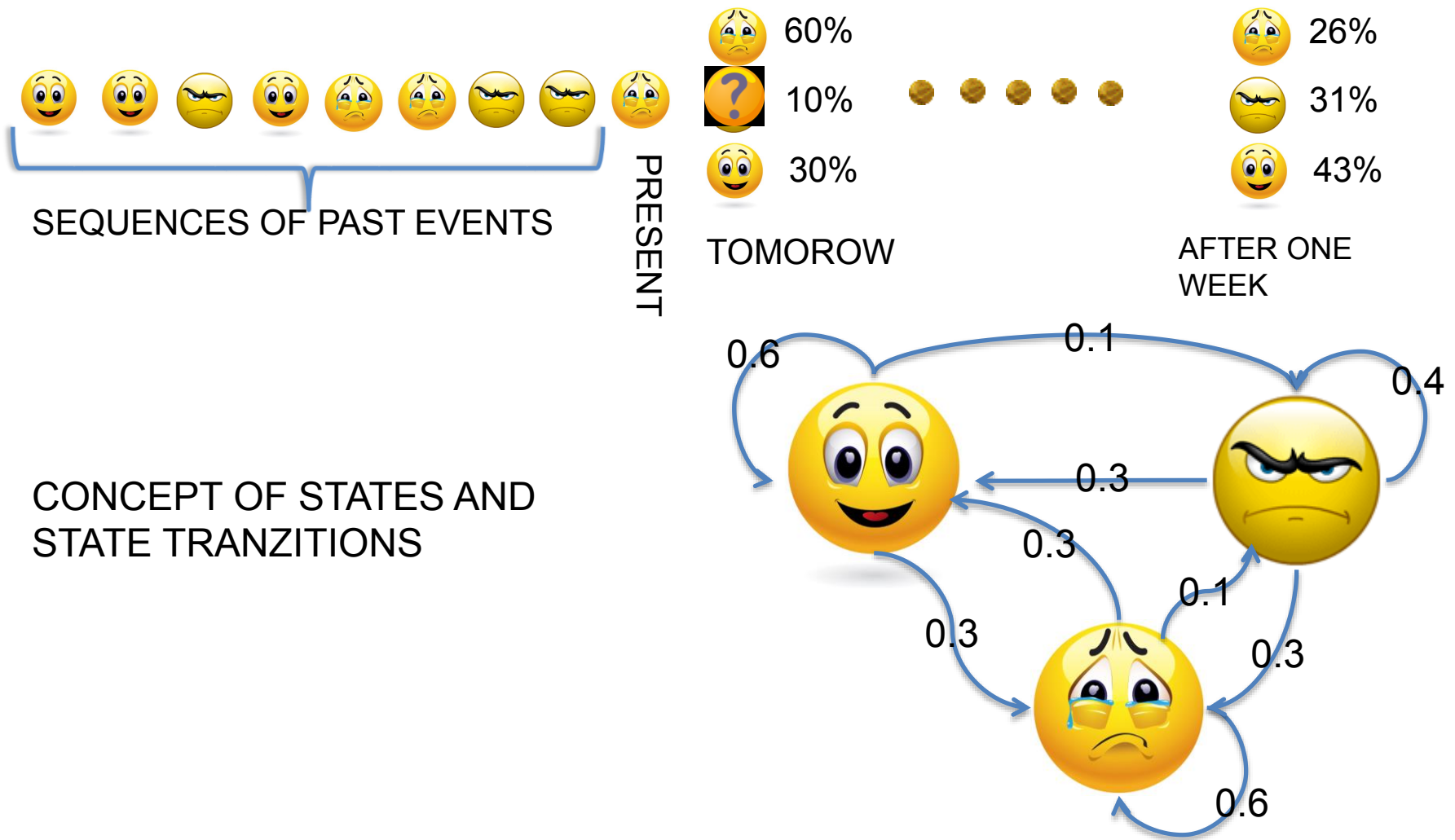
There might be something in the past that will predict the future – but the right questions are to be asked.

To predict future performance it is essential to explore how something has “behaved” in a similar set of circumstances.

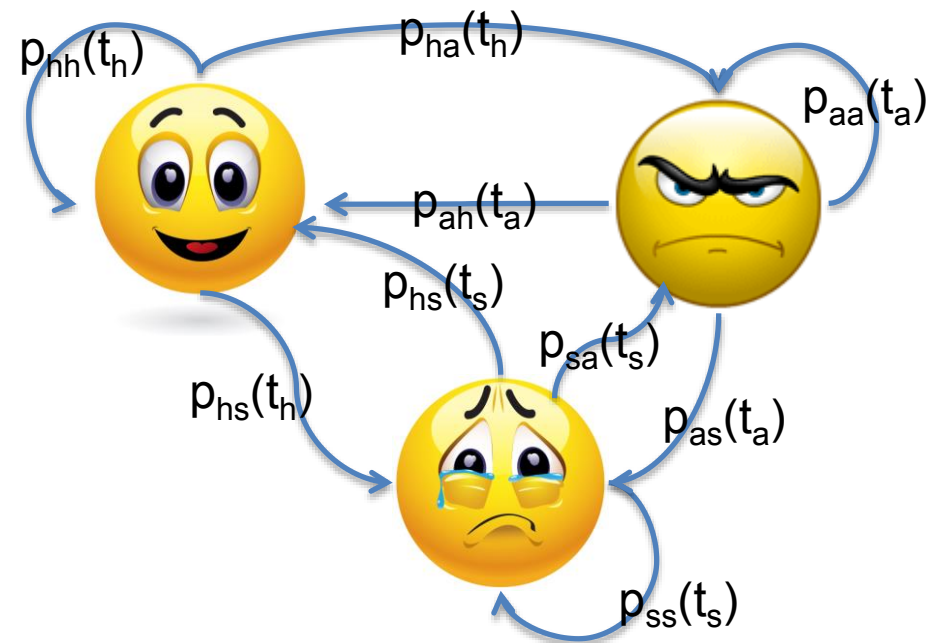
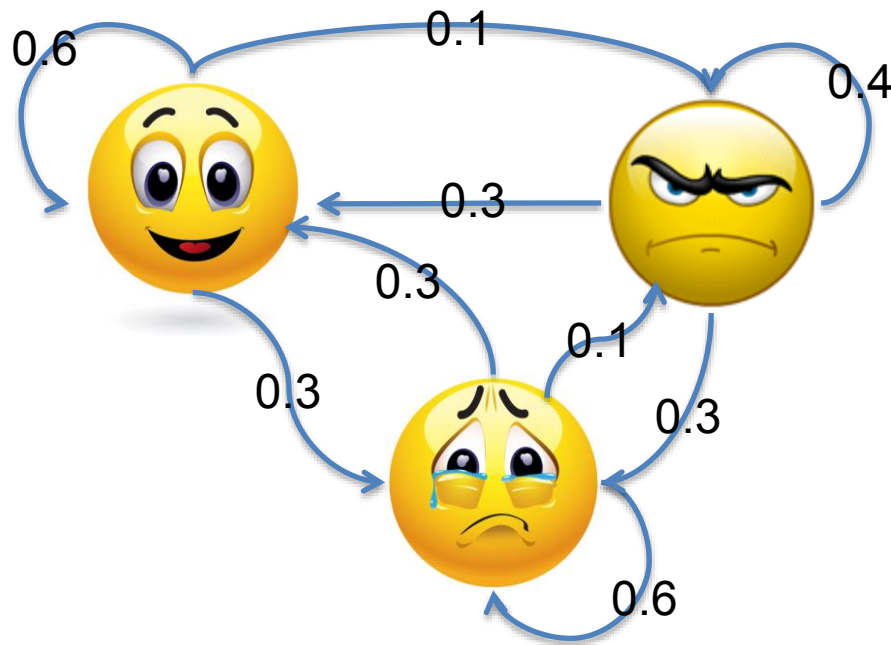


LOOK INTO THE PAST

# FORECASTING WITH MARKOV CHAIN



# MARKOV AND SEMI MARKOV MODEL

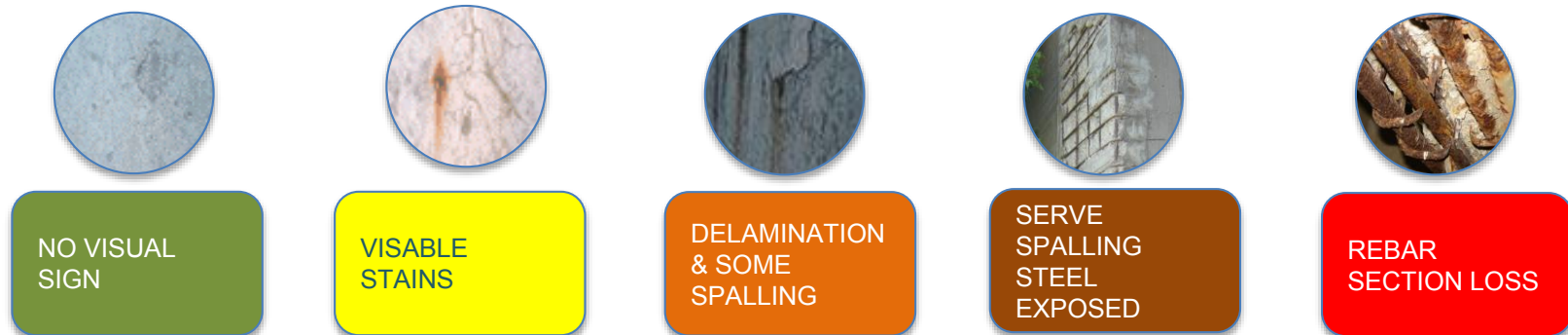


# MARKOV MODEL FOR AGEING STRUCURE

- Aging is the one way process



- Deterioration of the structures is somewhat similar



# SURVIVAL IN THE STATE

- Complementary cumulative distribution function of random variable  $T_i$  i.e.  $(p(T_i > t) = S_i(t))$  is called the survival function of  $T_i$  (survival in state  $i$ ).
- Memoryless property (Markovian property) in discrete case (unit time step) gives:

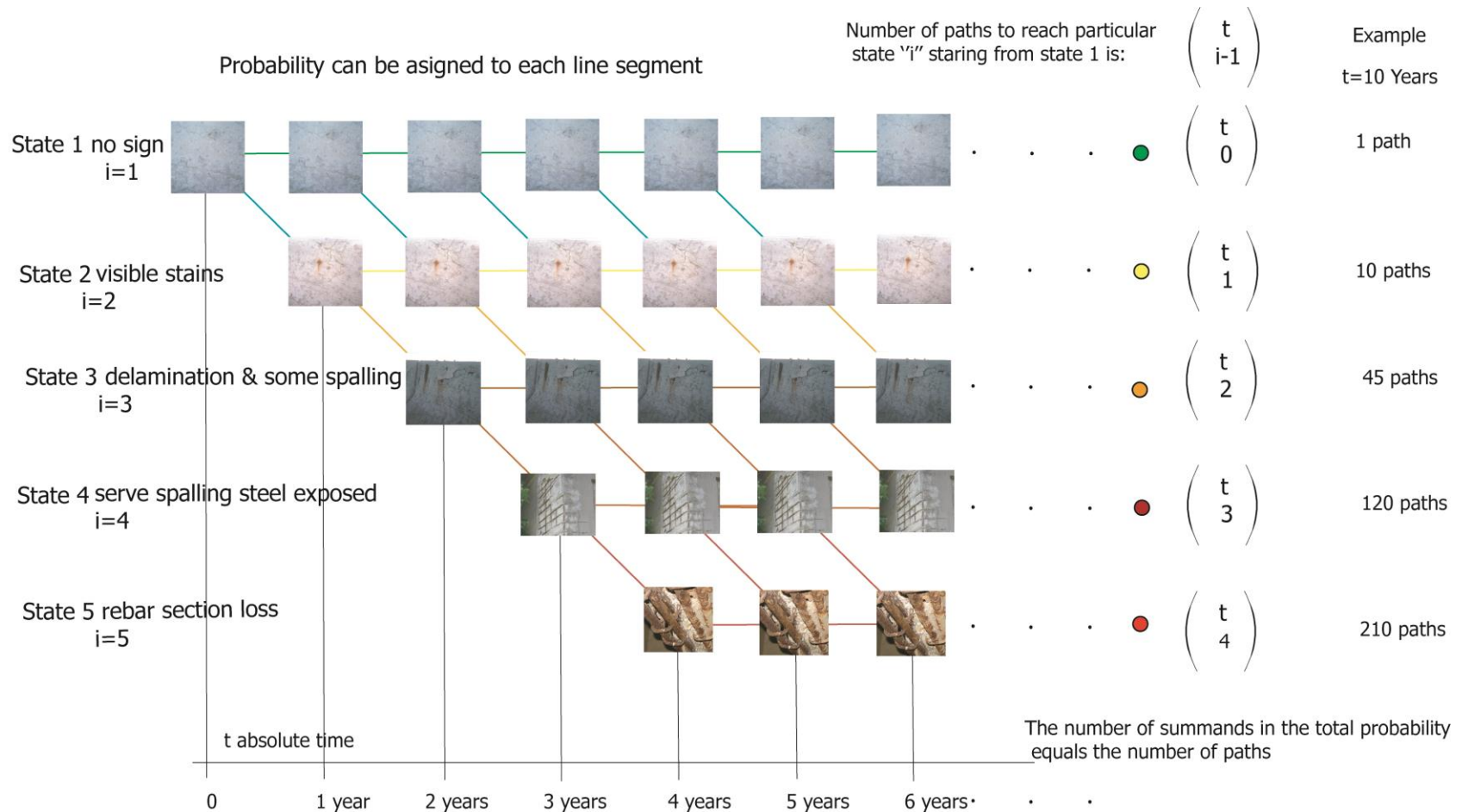
$$S_i(k) = 1 - F_i(k) = p_{ii}^k$$

- If sojourn time in state  $i$  follows Weibull distribution than survival function in state  $i$  is given by:

$$S_i(k) = e^{-(k/\mu_i)^{\beta_i}}$$

- The longer an element has been at a particular condition, it seems that is more likely it will transit to a lower condition in the next instant, i.e.  $\beta_i > 1$

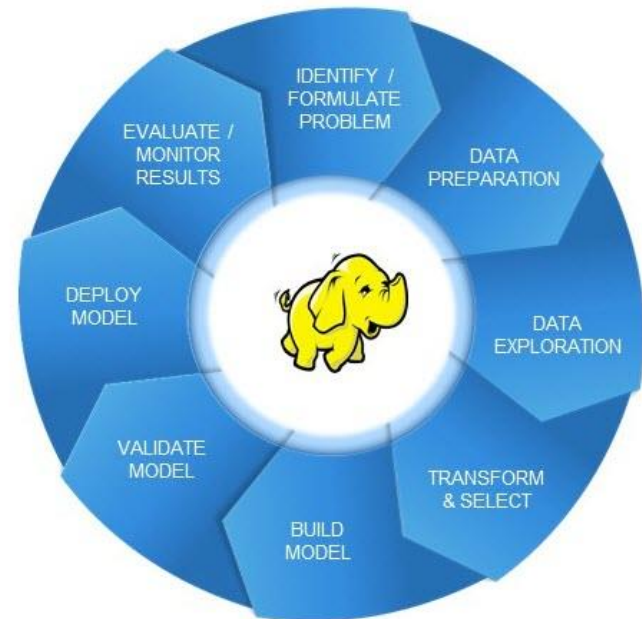
# EVENT TREE





# DATA

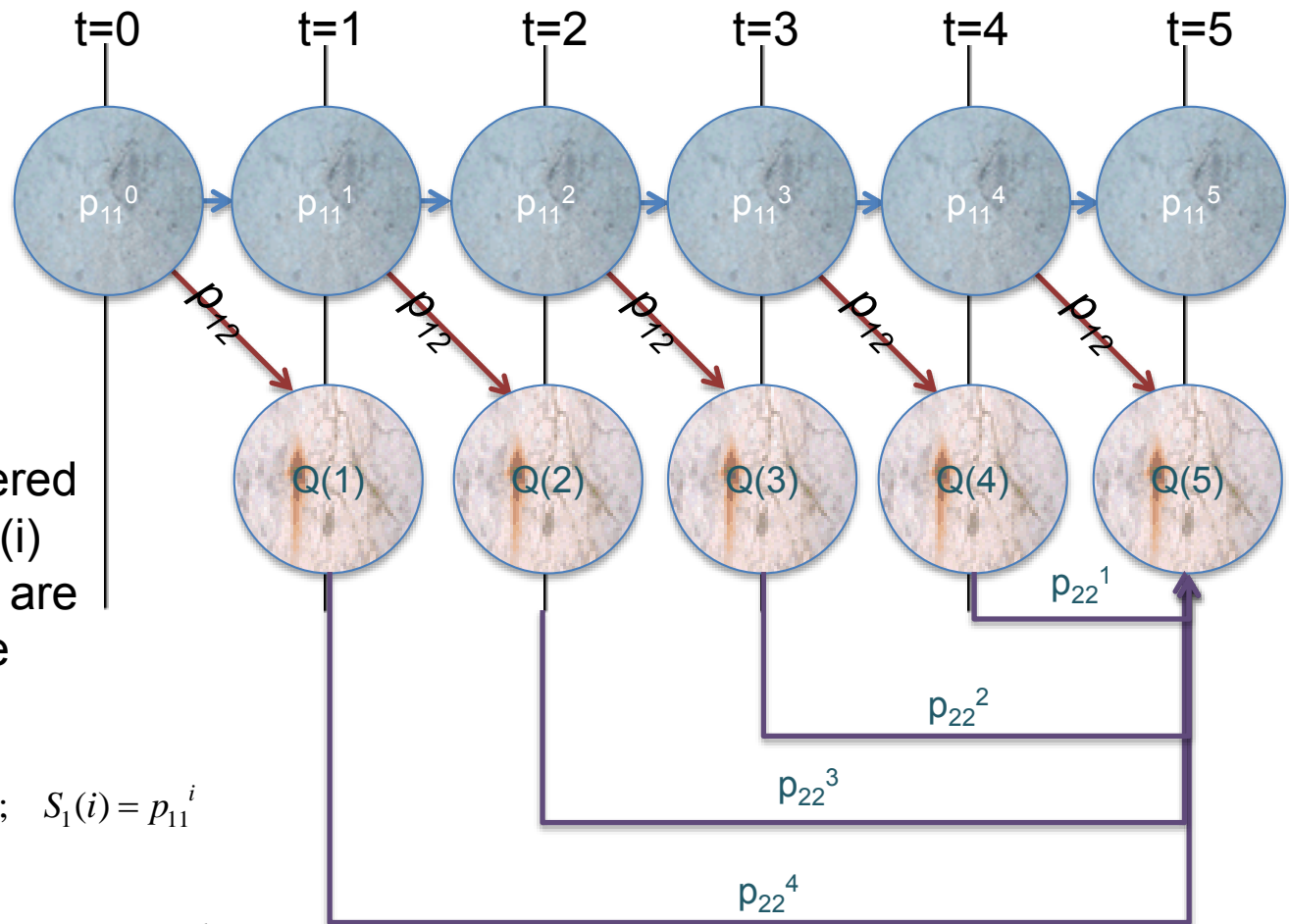
- Model is data driven
- Databases
- Quantity and quality of the data
- Visual inspection
- Visual inspection - Subjective data
- Data filtering – (possibility of manipulation)!
- Use the historical data to estimate transition probabilities ( $p_{i,i+1}$ ), employing statistics.
- Does the model fit to the data?
- Is the process stationary ?
- Does  $p_{i,i+1}$  depends on the sojourn time?
- Abundance of data for transition from the best (state 1) to the second best (state 2) indicates that **it does**.
- How to model sojourn time?
- Random variable  $\tau_i$  sojourn time in state  $i$ .
- Practical problem – determination of sojourn time distribution.



# MARKOV PROPERTY (MEMORYLESS)

Quantities that  
"survived"

Quantities that entered  
subsequent state  $q(i)$   
Quantities that are  
in subsequent state  
 $Q(i)$



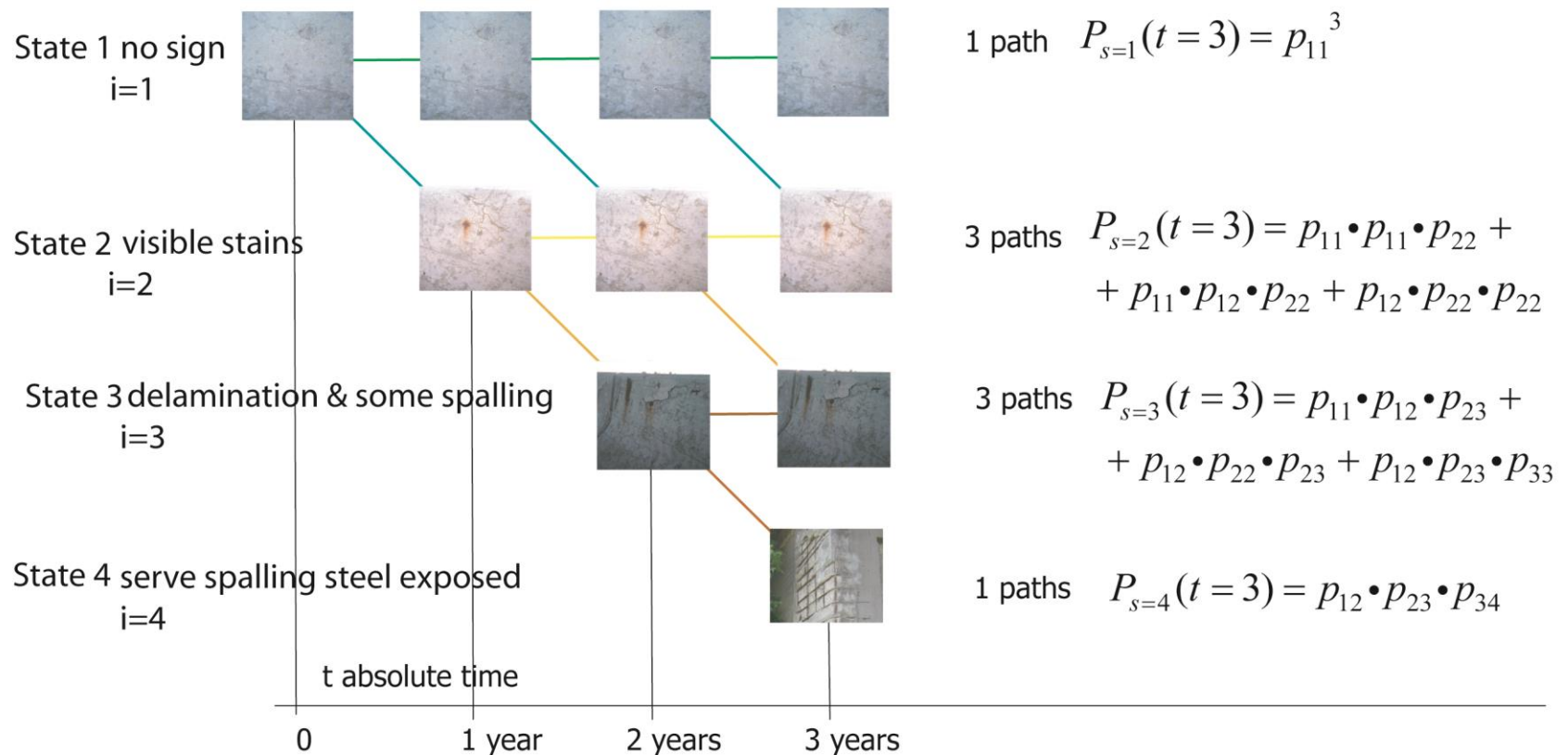
$$p_{11}(i) = p_{11}; \quad i = 1, 2, 3 \dots n; \quad S_1(i) = p_{11}^i$$

$$p_{1,2}(i) = 1 - p_{11} = q_2$$

$$Q_2(i) = \sum_{j=1}^i (1 - p_{11}) p_{22}^{i-j}; \quad S_2(k) = p_{22}^k$$

# EVENT TREE - CORROSION

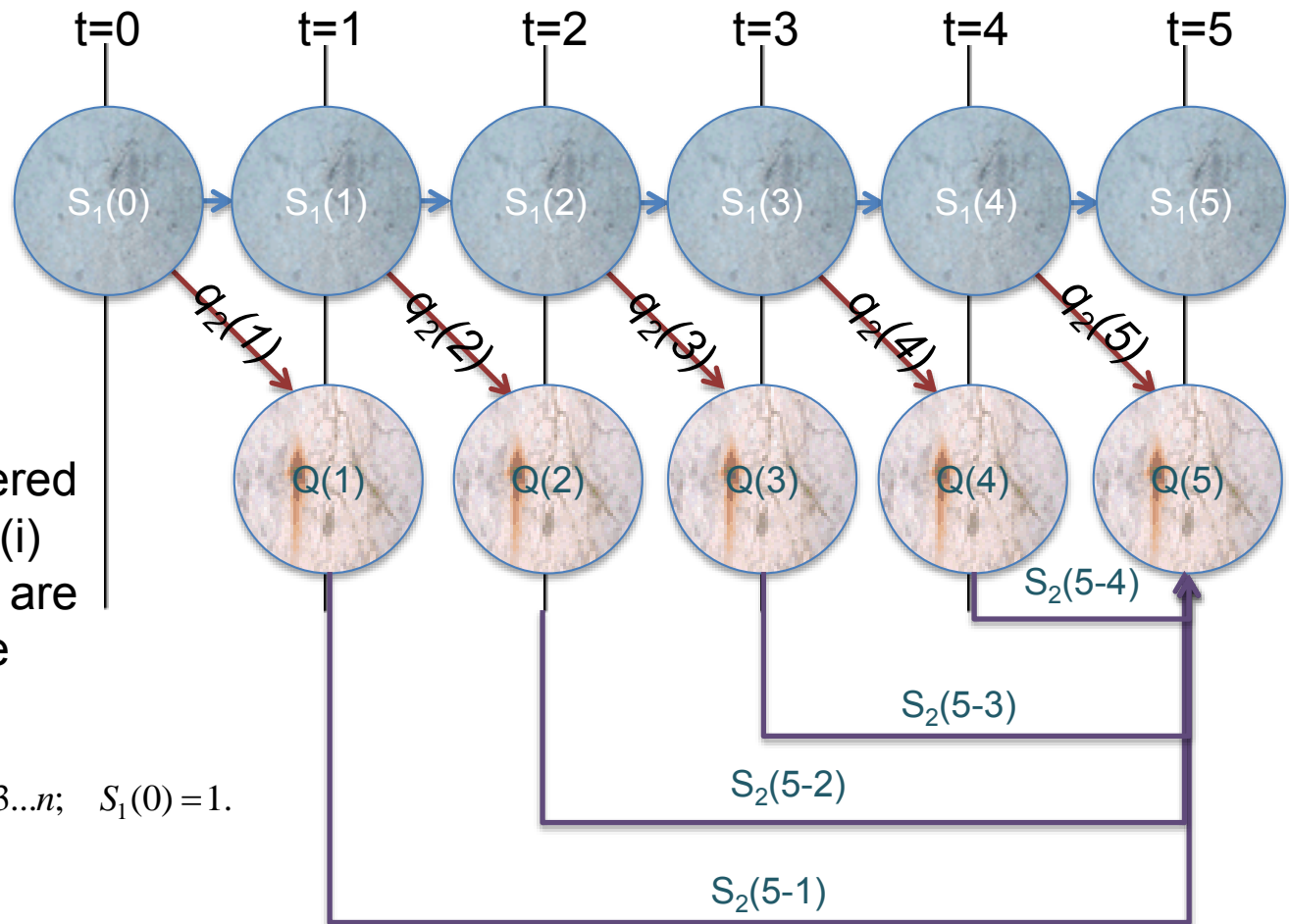
t=3 Years



# MODEL OF THE SEMI MARKOV PROCESS

Quantities that  
"survived"

Quantities that entered  
subsequent state  $q(i)$   
Quantities that are  
in subsequent state  
 $Q(i)$



$$p_{11}(i) = \frac{S_1(i)}{S_1(i-1)}; \quad i = 1, 2, 3, \dots, n; \quad S_1(0) = 1.$$

$$p_{1,2}(i) = 1 - p_{11}(i) = q_2(i)$$

$$Q_2(i) = \sum_{j=1}^i q_2(j) \cdot S_2(i-j); \quad S_2(0) = 1.$$

# Expected time to transition between the corrosion states



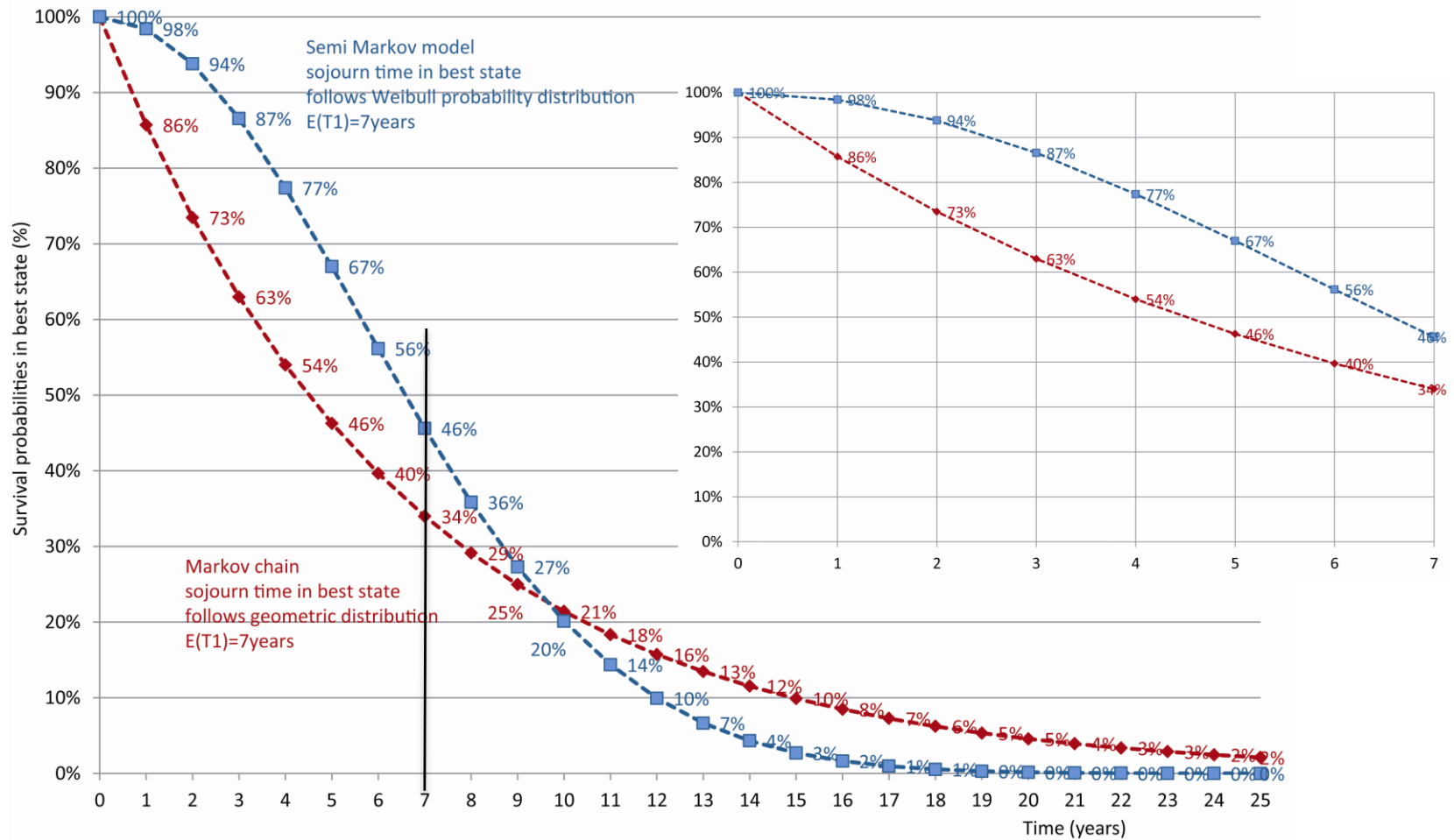
Panel of experts

$E_t(S_i)$	$S_i$
7 years	
6 years	
5 years	
2.5 years	



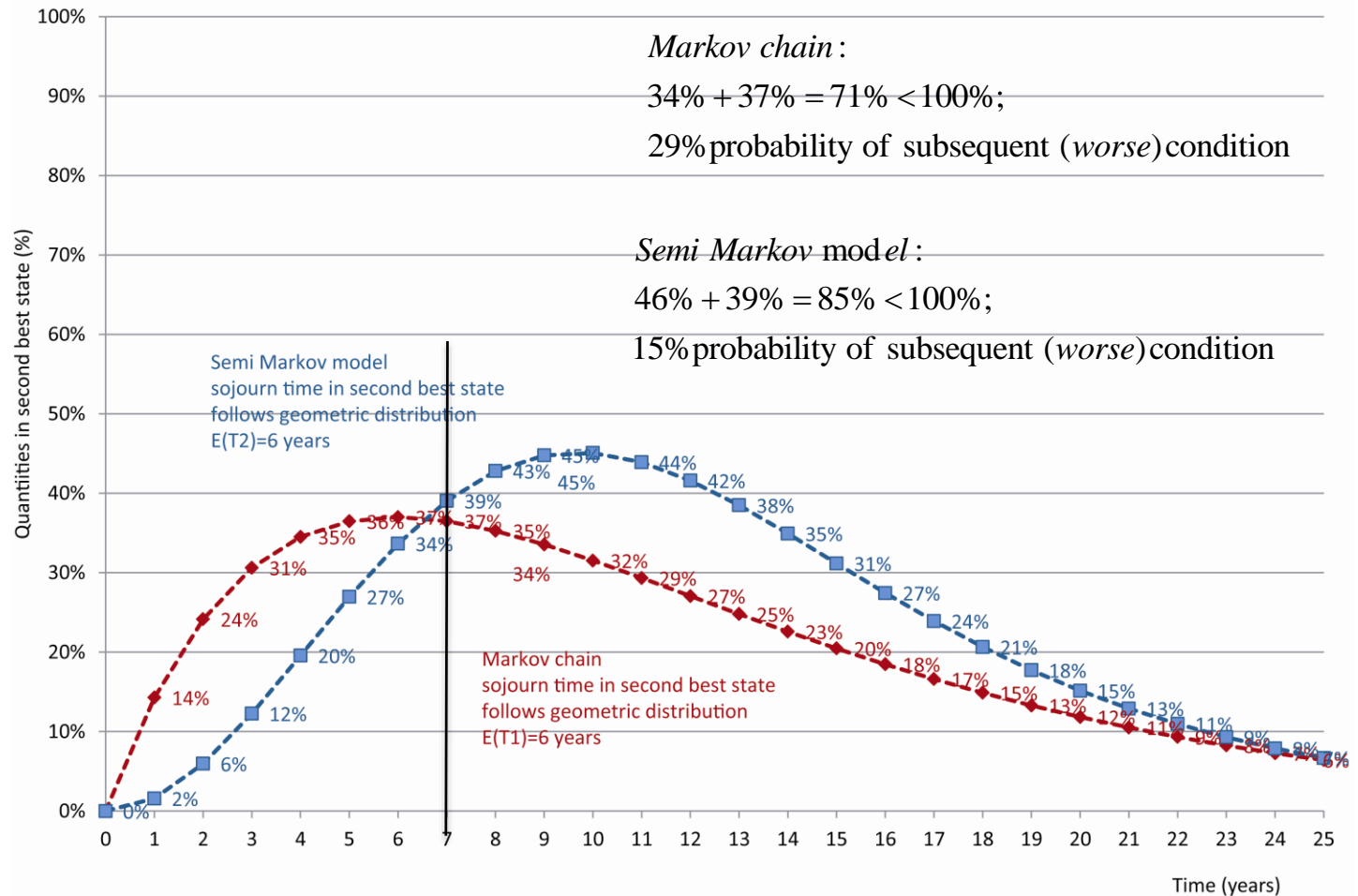
Expected time to reach  
failure state 20.5 years.

# COMPARISONS – NUMERICAL EXAMPLE



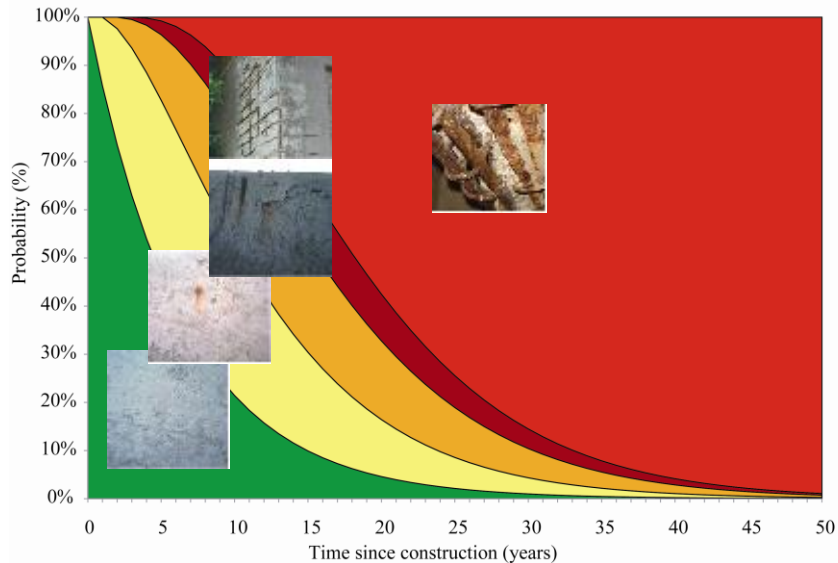


# QUANTITIES IN SECOND BEST STATE

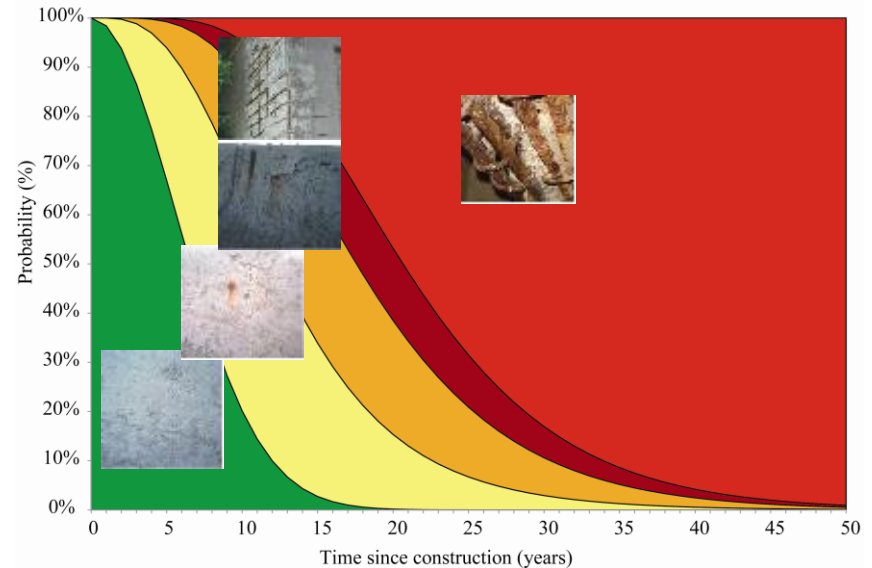


# FRACTIONAL DISTRIBUTION OF CONDITION

Markov chain

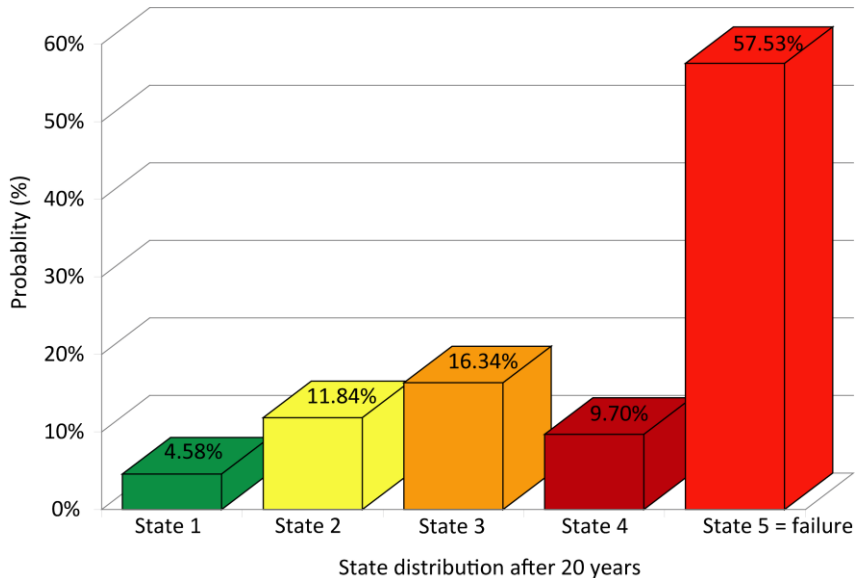


Semi Markov model

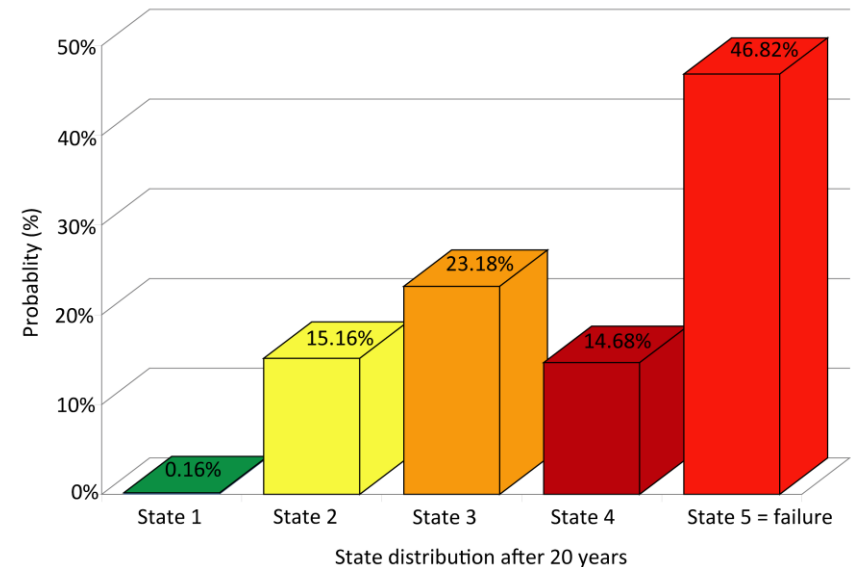


# CONDITION DISTRIBUTION AFTER 20 YEARS

Markov chain



Semi Markov model



# CONCLUSIONS

- Stochastic model is proposed for forecasting performance indicators.
- Two types of Markov processes can be employed:
  - Markov chain model;
  - Semi Markov model.
- Transition probabilities estimations:
  - Experts judgements,
  - Historical data,
  - Simulations of mechanical process of deterioration using developed analytical models.
- Semi Markov model seem more appropriate from a physical point of view, but:
  - hampered estimation of sojourn time distribution;
  - absence of the memoryless property poses severe mathematical complexity for short-time horizon optimization.



[link to paper](#)

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### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **Interface for collection of performance indicators for roadway bridges – STSM experiences**

**Ivan Zambon** - University of Natural Resources and Life Sciences, Vienna, Austria

**Tanasic Nikola** - Faculty of Civil Engineering, University of Belgrade, Serbia

[link to paper](#)



**30<sup>th</sup> March - 1<sup>st</sup> April 2016**

**Belgrade, Serbia**



# OUTLINE

- INTRODUCTION
- MAIN CONCEPT
- THE CREATION OF INTERFACES
- APPLIED PI DATABASE
- THE GLOSSARY
- THE TUTORIAL
- DISSEMINATION OF INTERFACES
- THE CREATION OF RESEARCH DATABASE
- FINDINGS OF BUDAPEST MEETING
- CONCLUSIONS

# INTRODUCTION – WG1

- **Main tasks** of the **WG1** is to carefully plan the procedure and conduct the process of both applied and research **indicators' collection and classification**



# MAIN CONCEPT

- **BASIC IDEA:**

- Collection of documents from different countries
- More than 100 documents was collected
- Screening to be performed by WG1 members

- **GENEVA:**

- Nomination of **Country responsible persons**
- Elaboration of simple, user friendly **Interface** to aid in the screening of the data from relevant national documents and
- Elaboration of a **Tutorial** for its application
- Elaboration of **Glossary** for
- Analyse/Control of the gathered data and consideration of the users feedback on the interface

Executed during 2  
STS Ms

# THE CREATION OF INTERFACES - 1<sup>st</sup> STSM

- **Main Challenges**
  - Structure/Architecture of the interfaces,
  - Systematic and comprehensive screening of any document type,
  - Connections between *key parameters*: Performance Indicators/Methods/Index/Thresholds/Goals/Criteria.
- **Main issues –solutions**
  - Heterogeneous data in documents – chapters are screened one by one
  - Data overlap/repetition – chapters are screened one by one,
  - Terminology – Glossary / Drop-down lists,
  - Some connections between key data is unavailable – additional documents need to be screened.
- **Main Conclusions**
  - Free input is enabled in MS Excel interface,
  - Access interface may be developed when connections between the *key parameters* are defined.

# APPLIED PI DATABASE

- **Structure:**
  - Blank sheet the code refers to this sheet
  - *Names\_Table* holds the information of the drop-down lists
  - *General\_data* comprises the basic information about the chosen documents for screening
  - *Cou\_Num* created by the user; contains the input of the data

SURVEY OF PERFORMANCE INDICATORS					
		Country			New Document
num	Responsible Person	Document	Doc. Type	Author	Year
1					
2					
3					
4					
5					

# THE GLOSSARY

- **Structure**

- Glossary presents definitions and keywords in relation to Performance indicators, thresholds, goals, criteria and methods
- Damages contains the list of damages affecting roadway bridges
- New terms for user to add additional definitions
- Country specific terms serves for translation of definitions to user's native language

Performance Indicator	Performance Threshold	Performance Goal	Performance Criteria	Performance Method
X				
	X			
	X	X		



# THE TUTORIAL

- Provides the **explanations of the data surveying** procedure and illustrates the process of filling up the database
- Explains how should one **use Database and Glossary** files
- Provides **examples** for screening
- Examples:
  - Inspection document from Austria
  - Evaluation document from United Kingdom.

# DISSEMINATION OF INTERFACES – 2<sup>nd</sup> STSM

- Naming:
  - One **Responsible person** per country
  - One responsible **Management Committee (MC) Member** per country
- Responsible person:
  - Screen the national documents for performance indicators by using the provided interfaces
- MC Member:
  - Contact roadway owners and operators and to purchase the documents used
- Main tasks of STSM:
  - Ensuring that the documents prepared for screening were examined and improved
  - Familiarizing responsible persons with philosophy of screening
  - To transfer the ideas from the leaders of the Action to the nominated persons
  - Working as a link between the designers of screening documents and nominated persons in several smaller errors in the database excel emerged and were pointed out, but were soon fixed

# CREATION OF RESEARCH DATABASE

- Performance indicators that are in the **stage of research** and are still not approved or applied.

SURVEY OF RESEARCH PERFORMANCE INDICATORS

Article	Performance assessment of concrete structures based on probabilistic prediction models and monitoring information
Author	Strauss, Zambon, Vidovic, Grossberger, Bergmeister
Year	2015
Abstract	An efficient evaluation and prediction of time variable mechanical and chemical degradation processes is fundamental requirement for life-cycle analysis as well as for the complete assessment of concrete structures... Important tools and
Journal	IABSE Conference – Structural Engineering: Providing Solutions to Global Challenges; September 23-25 2015, Geneva, Switzerland
Keywords	life-cycle analysis; performance indicators; probabilistic performance prediction; efficient maintenance

Performance Indicator	Young modulus
Type of Indicator	Material property
Mathematical Formulation	
Threshold	
Intentions (where to apply)	In order to evaluate the fatigue performance of the critical cross-sections
Level of maturity	Research stage
Case study	STRABAG test foundation in Cuxhaven
Performance Indicator	Reliability index
Type of Indicator	Reliability
Mathematical Formulation	
Threshold	
Intentions (where to apply)	In order to evaluate the fatigue performance of the critical cross-sections
Level of maturity	Research stage
Case study	STRABAG test foundation in Cuxhaven

# FINDINGS OF BUDAPEST MEETING

## Future obligations:

- Adjustment of database and glossary :
  - Separation between damages and damage processes / mechanisms in the database
  - Columns with condition rating (CR), frequency of assessment and a link to the page with applied formulae for CR computation will be included in the database
  - The country specific analyses will be performed with respect to components and the materials
- List of definitions
- Provide the table of terms to countries representatives
- Provide instructions for cross-checking the database

Ref	Ref	Ref	Ref
E) Condition Rating			
number based	probabilitty based	other	frequency

# CONCLUSIONS

- The main goal of WG1 was **screening of relevant national documents** in order to point out key performance indicators.
- First task included forming the concept of a **simple yet comprehensive user interface** to perform screening of various types of documents - evaluation, inspection and research documents.
- The second task comprised **testing of the interface** features, its **dissemination** and **analysis of the feedback** from COST countries.
- Feedback on the screening process was received from **27 out of 37** COST countries.



[link to paper](#)

**THANKS FOR YOUR ATTENTION!**

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### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **A new perspective for robustness assessment of framed structures**

**Hugo Guimarães** - University of Minho, Guimarães

**João Fernandes** - University of Minho, Guimarães

**José C. Matos** - University of Minho, Guimarães

**António A. Henriques** - University of Porto, Porto

[link to paper](#)

30<sup>th</sup> March - 1<sup>st</sup> April 2016

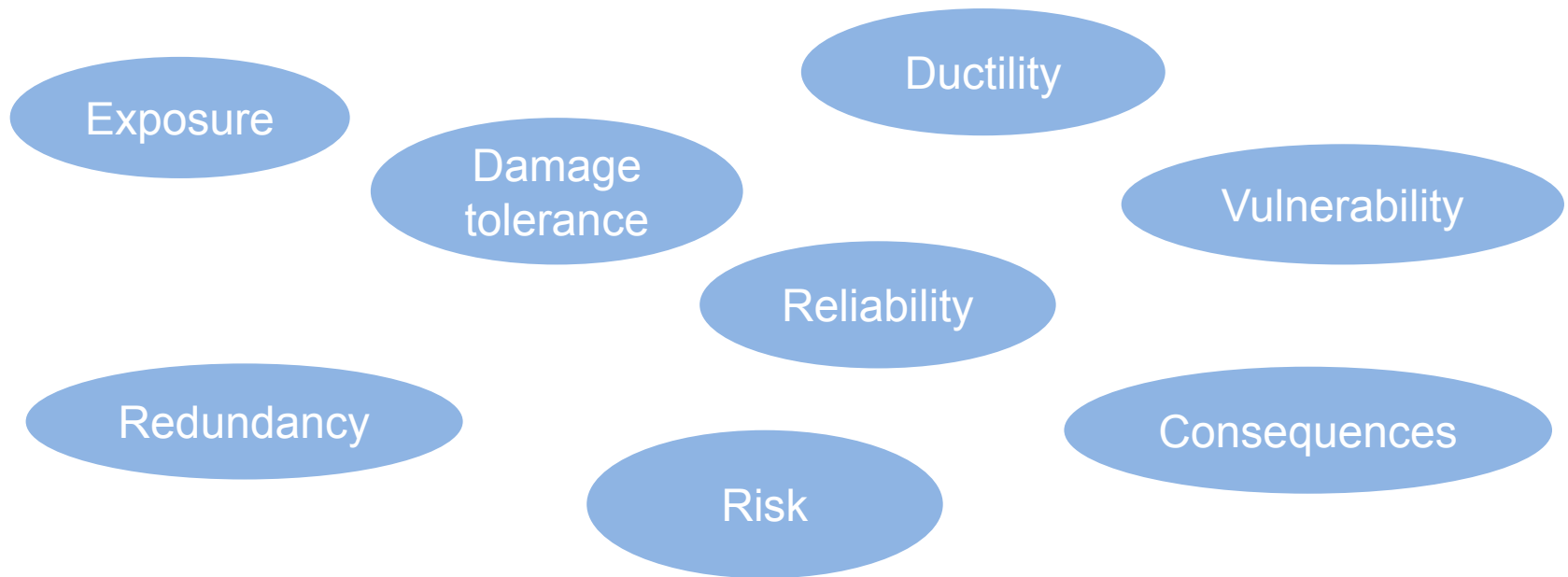
# OUTLINE

- Robustness – Brief Overview
- Proposed framework
- Numerical Applications
  - Example 1 – Clamped beam
  - Example 2 – Highway overpass
- Conclusions

# ROBUSTNESS

... from the structural perspective

*“The consequences of structural failure should not be disproportional to the effect causing the failure”*



*COST action TU06010*

# ROBUSTNESS ASSESSMENT

## *... Quantitative approaches*

- Deterministic index based on structural measures
- Probabilistic index based on probabilities of failure
- Risk-based index based on risk analysis

Complexity



## *... Exposure scenarios*

- Performance evaluation of a given scenario
- Reliability or risk under multi hazards

# ROBUSTNESS ASSESSMENT

	Frangopol and Curley (1987) Fu and Frangopol (1990)	Lind (1995)	Ghosn and Moses (1998)	ISO (2007)	Starossek (2008)	Baker et al. (2008)	Biondini and Restelli (2008)	Cavaco (2013)
<b>Nature</b>	Probabilistic	Probabilistic	Det. and Prob.	Deterministic	Deterministic	Risk-based	Deterministic	Det. or Prob.
<b>Attribute</b>	Redundancy Reliability	Vulnerability Damage Tolerance	Redundancy	Performance indicator	Stiffness-based Damage-based Energy released	Robustness index	Performance indicator	Performance indicator
<b>Range</b>	$[0, \infty]$ $\longleftrightarrow$ $[0, \infty]$ $\longrightarrow$	$[1, \alpha]$ $\longleftrightarrow$ $[\alpha^{-1}, 1]$ $\longrightarrow$	Target Reliabilities verification	$[0, 1]$ $\longrightarrow$	N.A $[0, 1]$ $\longrightarrow$ N.A	$[0, 1]$ $\longrightarrow$	$[0, 1]$ $\longrightarrow$	$[0, 1]$ $\longrightarrow$
<b>Scenario</b>	Damaged vs Intact	Damaged vs Intact	Limit states	Damaged vs Intact	Damaged vs Intact	Multi hazard	Damaged vs Intact	Spectrum of Damage States

$\longrightarrow$  Increasing robustness

# ROBUSTNESS ASSESSMENT

*... Existing approaches' cons*

- **Ghosn and Moses (1998, 2001, 2010)**
  - Deterministic reserve capacity factors
  - Redundancy factor to assess overall system safety
- **Baker et al. (2008)**
  - Quantification of consequences
- **Cavaco (2013)**
  - Deterministic approach when dealing with damage states' spectrum



# ROBUSTNESS ASSESSMENT

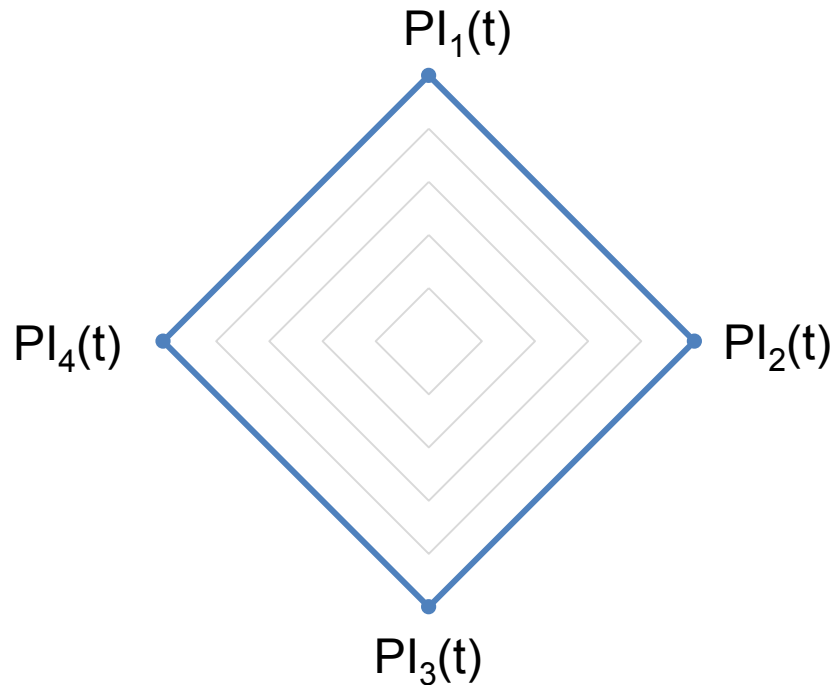
*... Proposed framework*

- **Main objective**
  - Facilitate application by practitioners
  - Normalization from 0 (null) to 1 (full robustness)
  - Combination of existing knowledge
  - Application at two performance levels: ultimate and service states
  - Extension to life-cycle performance

# ROBUSTNESS ASSESSMENT

... *Proposed framework*

- Robustness is computed as equal to the area of a quadrilateral, whose sides' lengths represent a performance indicator (PI).



# PROPOSED FRAMEWORK

... *Example of a selection of performance indicators*

Attribute	Performance Indicator	Reasoning
Reliability	$P_{\beta} = \frac{\beta_{dam}}{\beta_{int}}$	Reliability indexes
Damage tolerance	$P_{Dt} = \frac{LF_{dam}}{LF_{int}}$	Load factors
Redundancy	$P_R = \frac{\int M(\phi)_{dam}}{\int M(\phi)_{int}}$	Moment curvature areas
Ductility	$P_{\phi} = \frac{\phi_u / \phi_y _{dam}}{\phi_u / \phi_y _{int}}$	Flexural curvature ductility factor

*Each PI is computed through deterministic analysis based on design points' coordinates*

# PROPOSED FRAMEWORK

## *... Reliability Analysis*

- **For high dimension and complex systems, classical reliability methods do not yield a good efficiency evaluating small probabilities of failure.**
  - Existence of multiple design points
  - Non linearity of Limit State Surface
  - Non linearity of system performance
  - Presence of different failure modes
- **FE based structural reliability analysis faces several difficulties**
  - Closed-form state functions are not always easily obtained
  - Pointwise representation of simulations
  - Additional computational effort
  - Random field characterization
  - Huge number of random variables

# PROPOSED FRAMEWORK

... *Reliability Analysis – Adaptive Monte Carlo approach*

## 1. Stochastic simulation – random basic variables and dependent variables

- Literature probabilistic models for loads and resistance. **Probabilistic Model Code (JCSS,2001)**
- Random field characterization – spatial variability.

## 2. Structural analysis

- Nonlinear analysis of the structural performance.

## 3. Statistical analysis

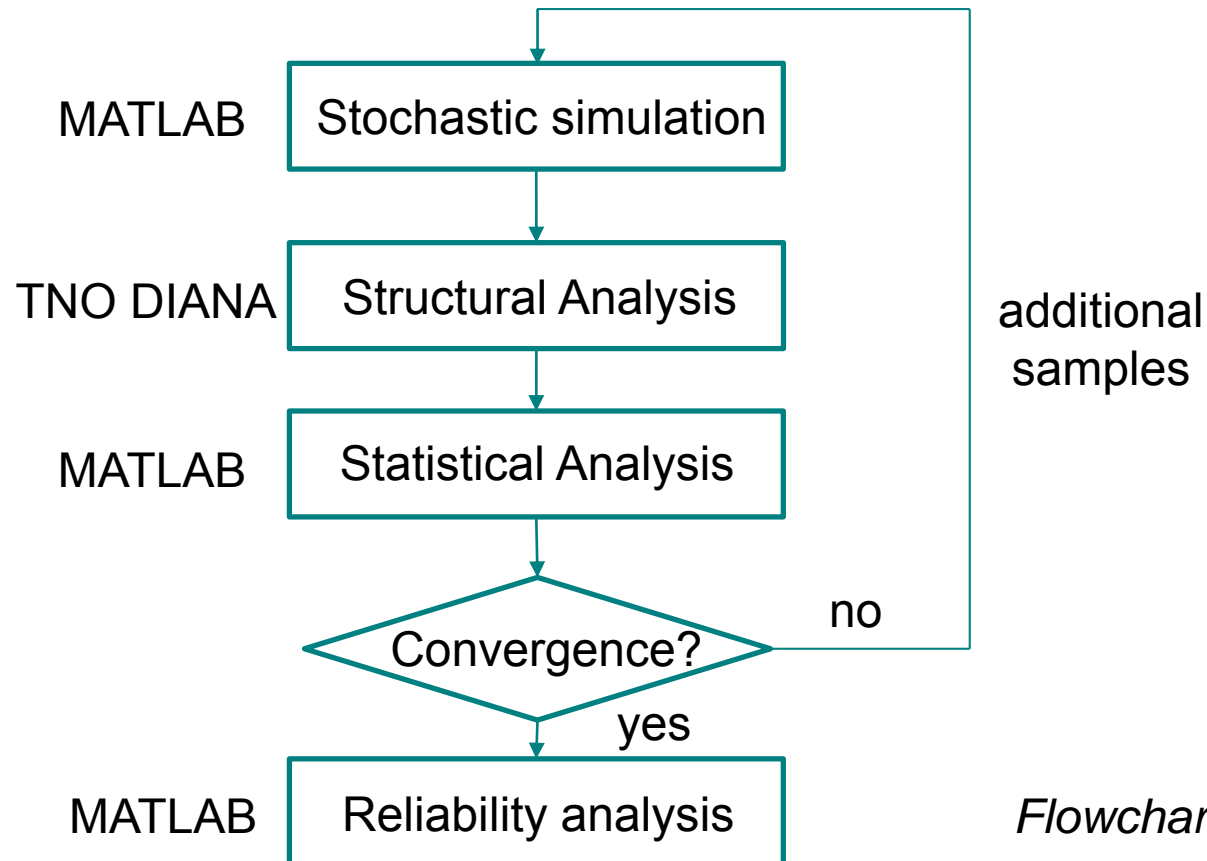
- *Distribution fitting analysis*
  - Expected value and variance
  - Quality examination – q-q plot, empirical versus theoretical CDF, ...
- *Linear regression model using stepwise regression*
  - Quality examination of the fitted model – residuals analysis, diagnostic plots, ...
  - Explicit limit state function

## 4. Structural reliability analysis

- Application of FORM for the obtained limit state function
- SORM, Importance Sampling and others approaches

# PROPOSED FRAMEWORK

... *Reliability Analysis – Adaptive Monte Carlo approach*

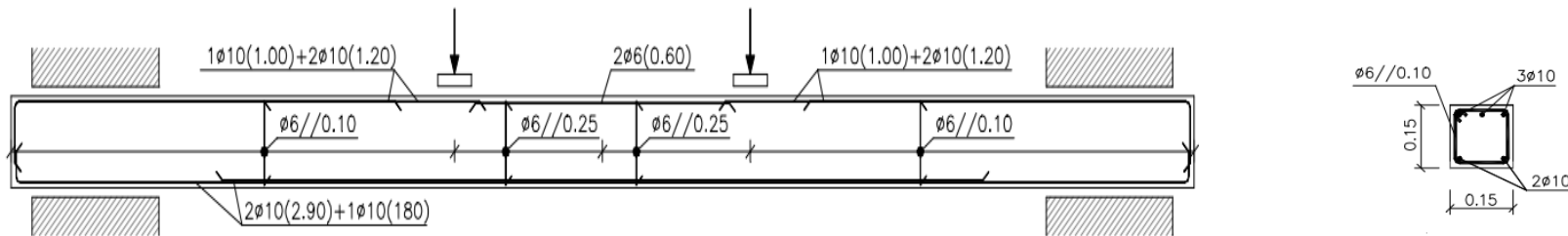


*Flowchart representation*



# NUMERICAL APPLICATION

... Example 1: Clamped beam



- 2D non-linear finite element analysis
  - Class III beam elements based on Mindlin-Reissner theory
  - Concrete behaviour - total strain fixed crack model
  - Steel tri-linear diagram

# CLAMPED BEAM

... *Probabilistic data*

Random Variable	Mean Value	CoV	Distribution Function	Reference
<b>Material Properties</b>				
Compressive strength ( $f_c$ )	30 MPa	12%	Normal	(Wiśniewski, 2007)
Tensile strength ( $f_{ct}$ )	2.9 MPa	20%	Log-Normal	(Wiśniewski, 2007, EN CEN 1992, 2010)
Young modulus ( $E_c$ )	32 GPa	8%	Normal	(Wiśniewski, 2007)
Steel yielding strength ( $f_{sy}$ )	460 MPa	6.5 %	Normal	(JCSS, 2001)
Steel ultimate strength ( $f_{su}$ )	530 MPa	7.5%	Normal	(JCSS, 2001)
<b>Applied Loads</b>				
Permanent load (G)	10 kN	9.5%	Normal	(Wiśniewski, 2007, JCSS, 2001)
Additional load (Q)	9 kN	15%	Gumbel	(JCSS, 2001)

# CLAMPED BEAM

## *... Damage Scenarios*

- Degradation of reinforcing steel cross-section area
  - *dam.1* : general degradation phenomena with a percentage of loss near 25%
  - *dam.2* : localized reduction of steel cross section area up to 40% regarding top layers at beams ends

# CLAMPED BEAM

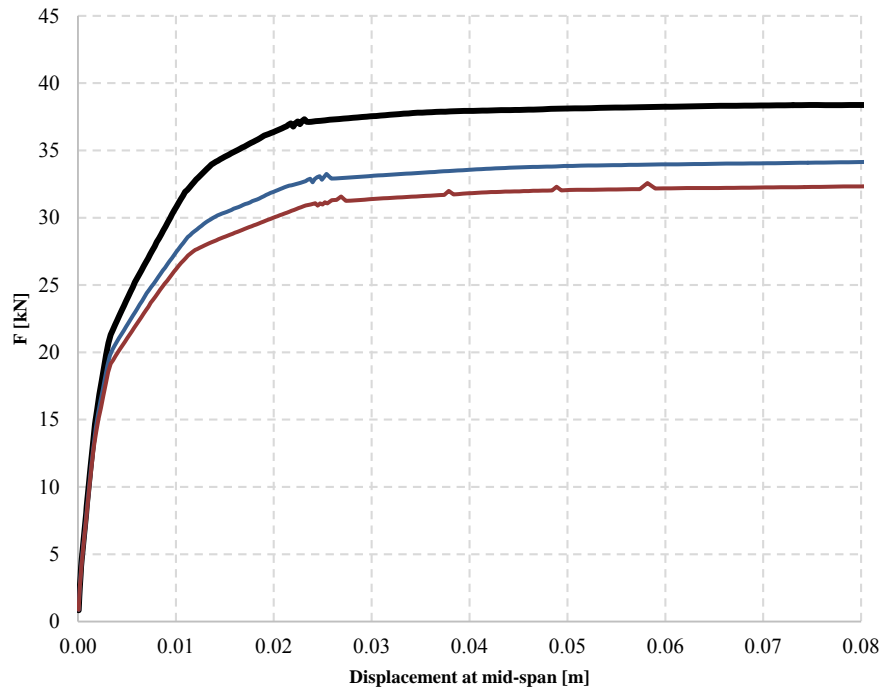
... Results

Design Points  
Coordinates

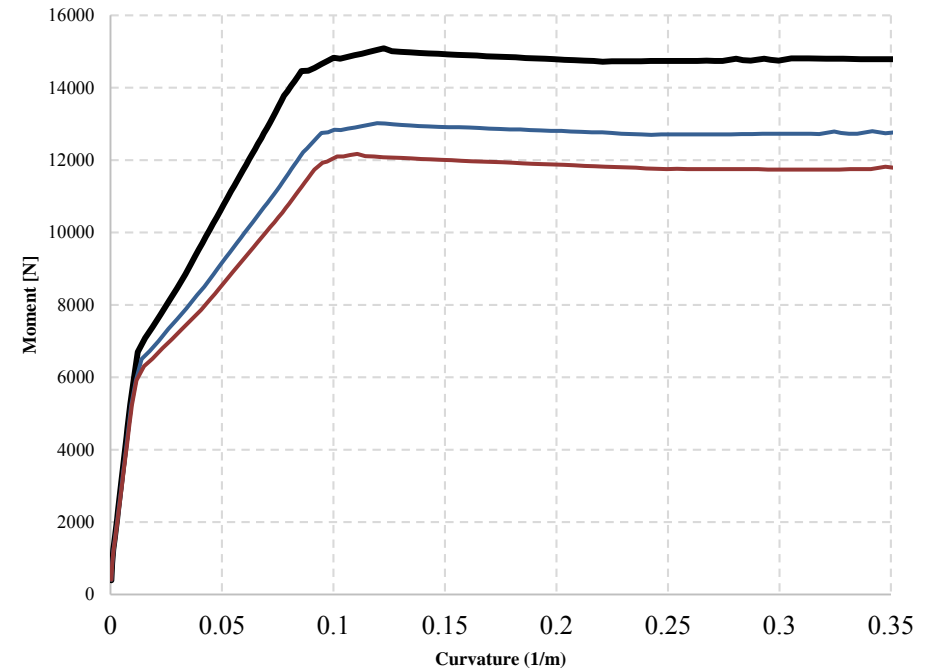
	int.	dam. 1	dam. 2
fc	16.3	16.2	15.6
fct	1.7	1.7	1.6
Ec	23.3	23.2	22.8
fsy	371.7	398.0	403.5
fsu	399.7	436.8	444.0
G	11.2	11.2	11.2
Q	27.3	23.2	21.5
$\beta$	8.78	7.83	7.58
$LF$	38.5	34.4	32.5
$\phi_y$	0.016	0.014	0.012

# CLAMPED BEAM

... Results



— Int. — dam. 1 — dam. 2

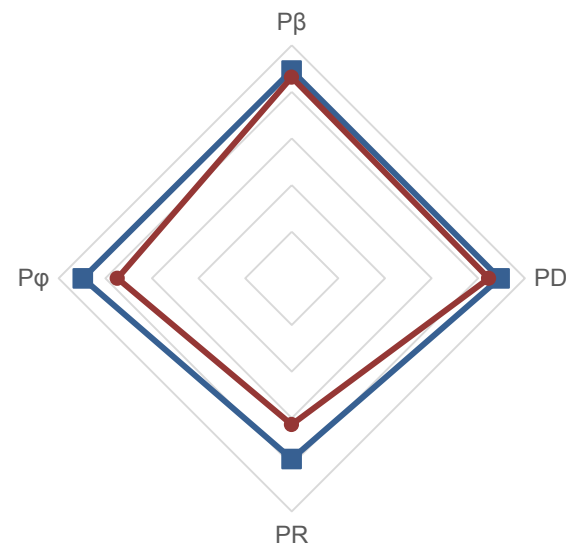


— int. — dam. 1 — dam. 2

# CLAMPED BEAM

... *Robustness assessment*

$P_{\beta}$	0.892	0.863
$P_{Dt}$	0.892	0.845
$P_R$	0.775	0.627
$P_{\phi}$	0.896	0.748
Robustness	0.74	0.58





# HIGHWAY OVERPASS

*... Robustness assessment based on different hazard*

*(Additional slides) – Multi hazard analysis*

# CONCLUSIONS

- A reliability-based robustness assessment framework to evaluate bridge's safety is introduced;
- The main goal is to facilitate the understanding of some attributes regarding robustness, aiming to propose a versatile framework to evaluate robustness according to a choice of key performance indicators;
- The methodology seeks not only to obtain a normalized robustness index but also to visualize the influence of different attributes/hazards;
- Qualitative risk measures can be implanted by weighting PI;
- Time-varying PIs can be considered to extend this methodology to life-cycle performance.

# FUTURE WORK

## ... Reliability analysis

- use of pseudo random-generators to populate region of failure;
- establishing cross-validation procedures;
- considering model error as random variable;
- bootstrap sampling to estimate boundaries of probability of failure.

## ... Robustness assesment

- application of time-varying degradation phenomena
- wise selection of non-redundant performance indicators
- extension of robustness assessment to both service and ultimate limit states.



[link to paper](#)

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### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **LIFECYCLE-BASED DISCRETIZATION OF BRIDGE PERFORMANCE INDICATORS**

**Dimosthenis Kifokeris** – Ph.D. candidate, Aristotle University of Thessaloniki,  
Faculty of Engineering, School of Civil Engineering, Greece

[link to paper](#)



30<sup>th</sup> March - 1<sup>st</sup> April 2016

# BRIDGE PERFORMANCE INDICATORS (BPIs)

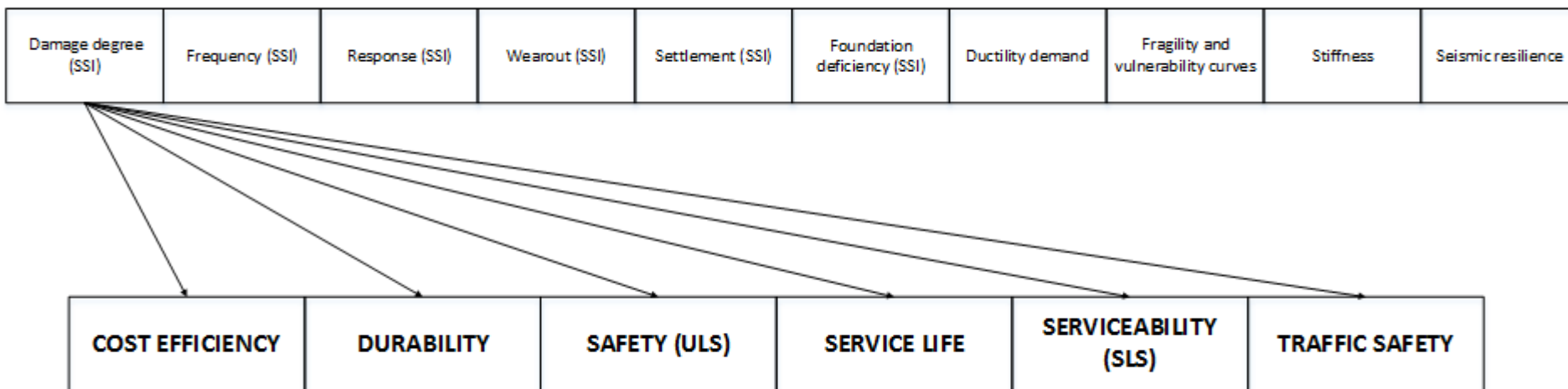
- Damage degree, frequency, response, wearout, settlement and foundation deficiency of the constituent bridge parts due to SSI (soil-structure interaction) during ground motions
- Ductility demand
- Fragility and vulnerability curves, most often interconnected
- Stiffness
- Seismic resilience

The above were the results of a targeted and filtered literature review of the recent (2006-2016) Greek research output



# BRIDGE PERFORMANCE INDICATORS (BPIs)

Performance indicators



Performance indices

All BPIs were aggregately researched under the light of the above performance indices categories. Hence, each one is simultaneously part of every indices group.

# LIFECYCLE MANAGEMENT DETERMINANTS

- Project performance: the level of the desirable success in meeting the stated technical performance specifications and the mission to be performed
- Success determinants of project performance:
  - (i) Cost of completion
  - (ii) Time of completion
  - (iii) Quality of deliverables
- Additional determinants (considered separately or as aspects of the quality of the deliverables): safety, client satisfaction etc.

# LIFECYCLE MANAGEMENT RELATED NOTIONS

- **Constructability:** the optimum use of construction knowledge and experience in planning, design, procurement and field operations to achieve overall project objectives
- **Sustainability:** the promotion of the development that meets the needs of the present without compromising the ability of future generations to achieve their own
- **Risk analysis:** the collective methodology of risk assessment, through a systematic process of decision-making in order to accept a known or assumed risk and/or reducing the harmful consequences or probability of occurrence of the risk

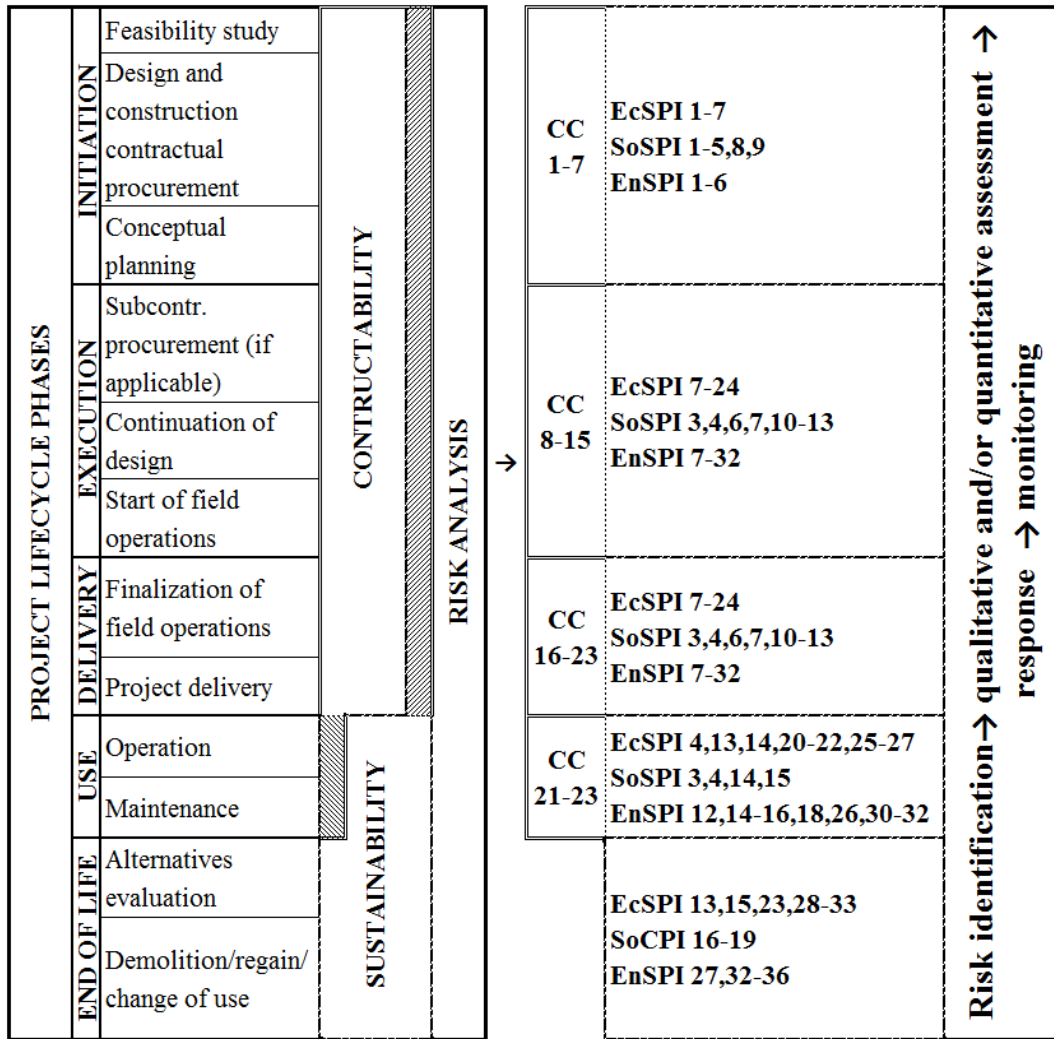
# RELATED NOTIONS AND LIFECYCLE MANAGEMENT

Constructability, sustainability and risk analysis, separately and in combination, aim for the achievement of the highest level of project performance by optimizing the success determinants.

Each utilizes distinct cognitive, methodological and mathematical tools and applications.

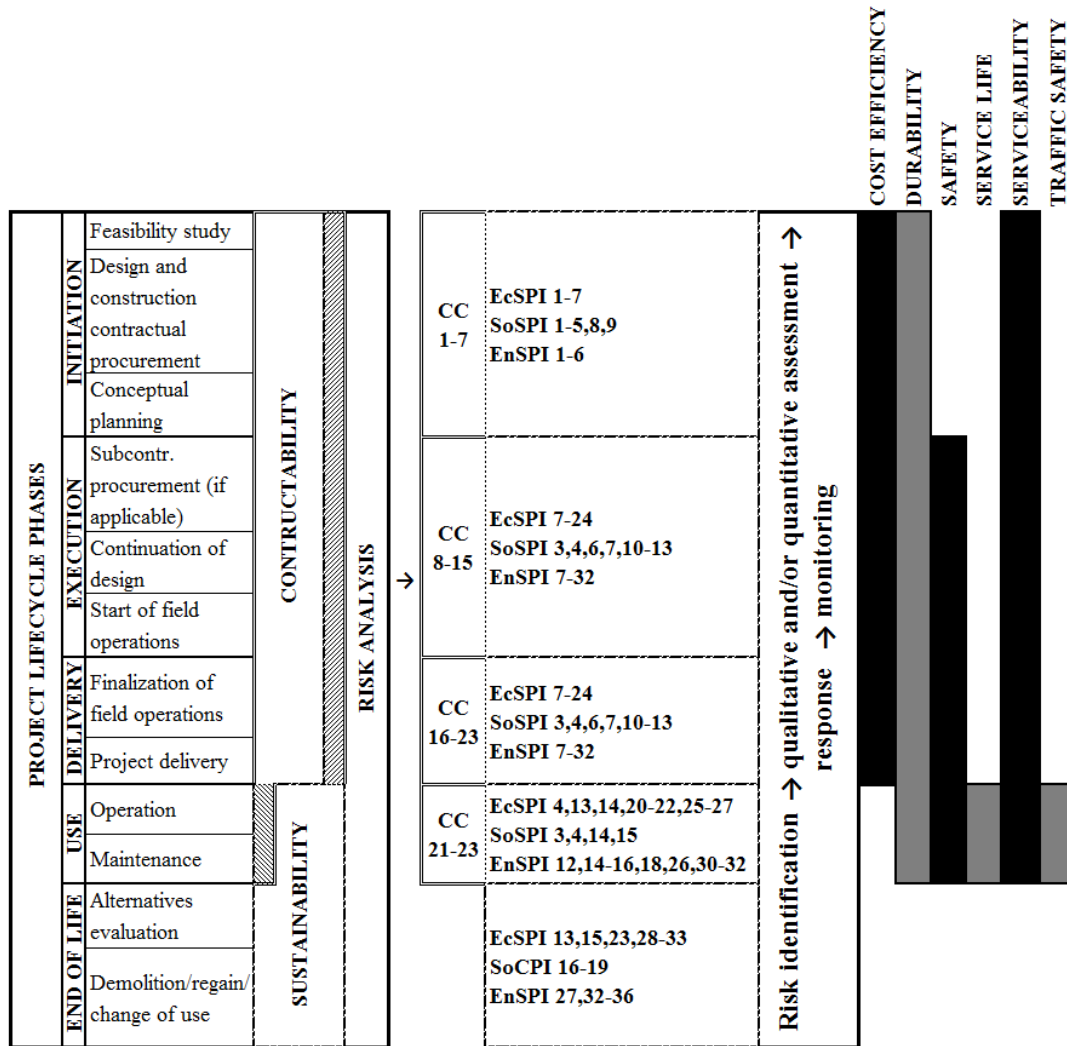
For a holistic lifecycle management, from the feasibility study of a project until its end of life, all three should be integrated, interconnected and facilitated.

# HOLISTIC LIFECYCLE MANAGEMENT



- **Constructability**
  - implemented through 23 Constructability Concepts (CCs)
  - pertains mainly the initiation, execution and delivery phases
  - extends in the use phase
- **Sustainability**
  - implemented through 32 economic (EcSPI), 19 social (SoSPI) and 36 environmental (EnSPI) sustainability performance indicators
  - pertains all of the project lifecycle, but more heavily the use and end-of-life phases
- **Risk analysis**
  - performed through risk identification, qualitative and/or quantitative assessment, response and monitoring
  - pertains all of the project lifecycle

# LIFECYCLE DISCRETIZATION OF BPis



- Each index encompasses all the noted BPis
- All BPis should be checked for the corresponding lifecycle phases pertained by the index and in conjunction with the CCs and SPIs
- Where the indices overlap, the corresponding BPis should be multiply checked under the light of every index



# CONCLUSIONS

- In the recent literature originating from Greek researchers, the most commonly researched BPIs account mainly for the cost efficiency, durability, safety, service life, serviceability and traffic safety of a bridge
- A true holistic lifecycle management plan for bridges should incorporate, interconnect and integrate the distinctive BPIs, grouped under the corresponding performance indices, along with the SPIs, CCs and risk analysis procedures
- The discretization and integration of BPIs, SPIs and CCs could expand to cover more data and also include several types of new indicators, towards the production of a general approach for enhanced lifecycle management for bridges and the standardization of bridge quality standards at the European level

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[link to paper](#)

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### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **The impact of the damage on the dynamic behavior of the composite bridge**

**Michal Polák, Tomáš Plachý, Tomáš Rotter, Pavel Ryjáček**

Faculty of Civil Engineering, CTU in Prague

[link to paper](#)



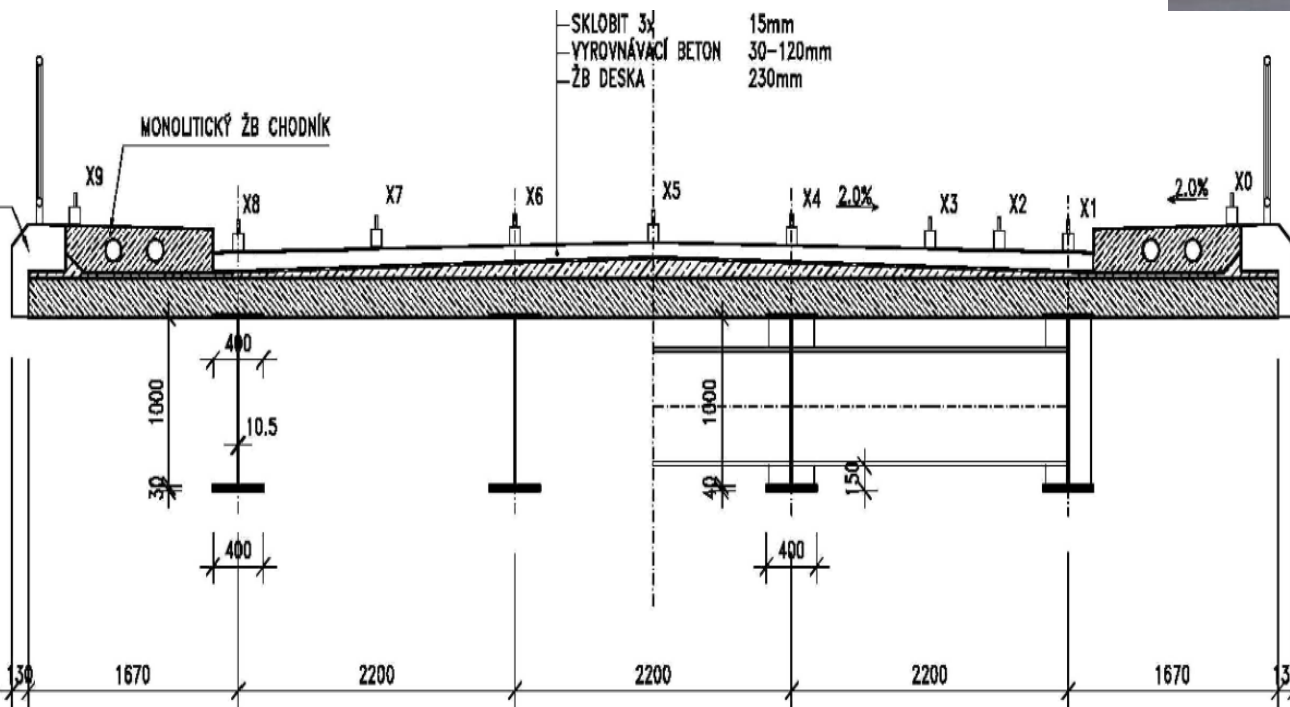
**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**

## Damage detection on the existing damaged bridge

- Bridge description
- Accident and damage description
- Bridge repaired after damage
- Modal analysis was performed on damaged and repaired bridge
- Damage identification by various methods
- Numerical model identification

## Bridge description

- Typical, composite bridge - concrete slab on four steel I-girders
- Three-spans of 11.7m + 35.1m + 11.0m





## Damage description

- Edge girder damaged, displacement app. 150mm
- Damage of the cross girder connection



**View on the damaged beam**



**Damaged web stiffener**

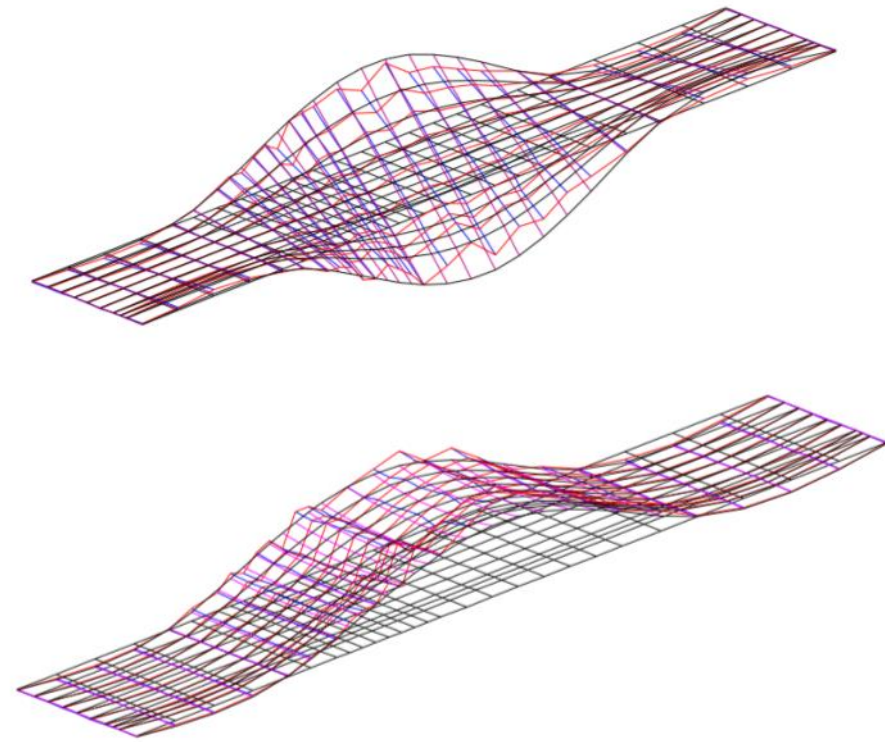
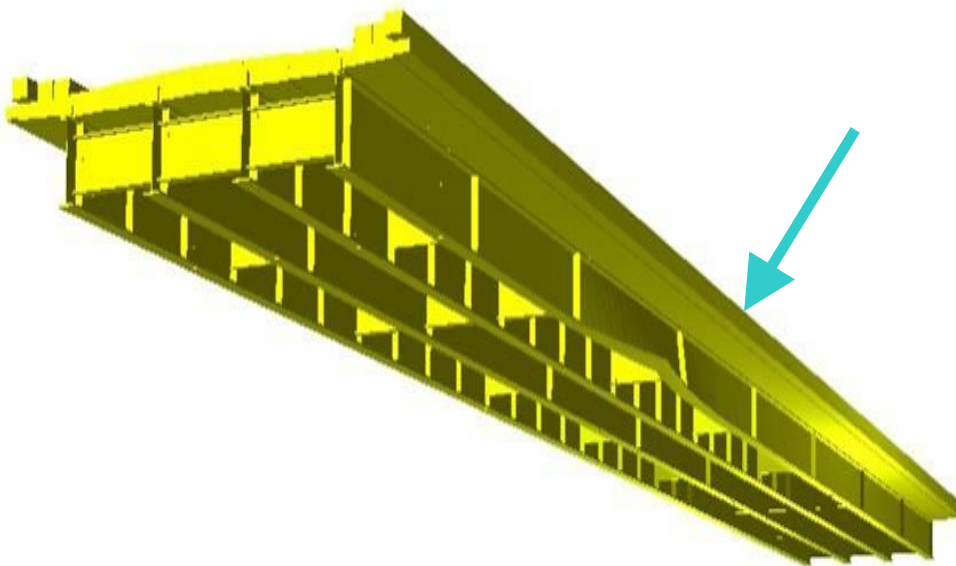
## Modal analysis on the damaged and repaired bridge

- The electrodynamic shaker TIRAVIB 5140
- 10 inductive accelerometers B12/200 HBM.
- Excitation by random driving force of white type noise 0 to 20 Hz
- The response of the bridge measured in the vertical direction in 280 points – 28 cross sections and 10 points in each one



## Model identification

- 2D elements for the concrete deck
- 2D elements used for the girders and cross beams
- Asphalt layers and parapets had to be included to the model, in order to get to the real behaviour



# Natural frequencies

- Model frequencies close to the measured
- Frequency change between damaged and repaired state
- First natural frequency change is 3,2%

The damaged state - June

Measurement		Model		
(j)	$f_{(j)}$ [Hz]	(j)	$f_{(j)}$ [Hz]	$\Delta f_{(j)}$ [%]
1	3,26	1	3,24	-0,62
2	3,41	2	3,60	5,28
3	8,16	3	7,88	-3,55
4	8,42	7	9,97	15,55
5	10,21	6	9,67	-5,58
6	12,01	10	12,02	0,08
7	13,74	11	13,33	-3,08
8	14,72	14	14,17	-3,88

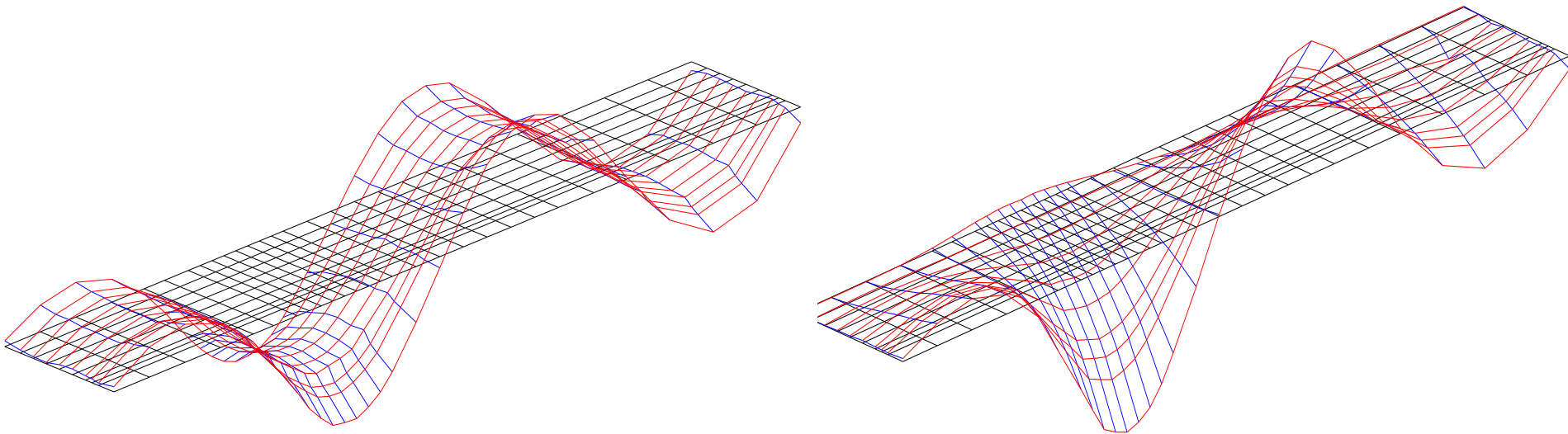
The state after reconstruction - October

Measurement		Model		
(j)	$f_{(j)}$ [Hz]	(j)	$f_{(j)}$ [Hz]	$\Delta f_{(j)}$ [%]
1	3,38	1	3,27	-3,36
2	3,65	2	3,66	0,27
3	8,54	3	8,08	-5,69
4	8,95	4	8,29	-7,96
5	10,86	5	9,74	-11,50
6	11,39	6	10,05	-13,33
7	14,18	10	13,39	-5,90
8	15,89	13	14,73	-7,88



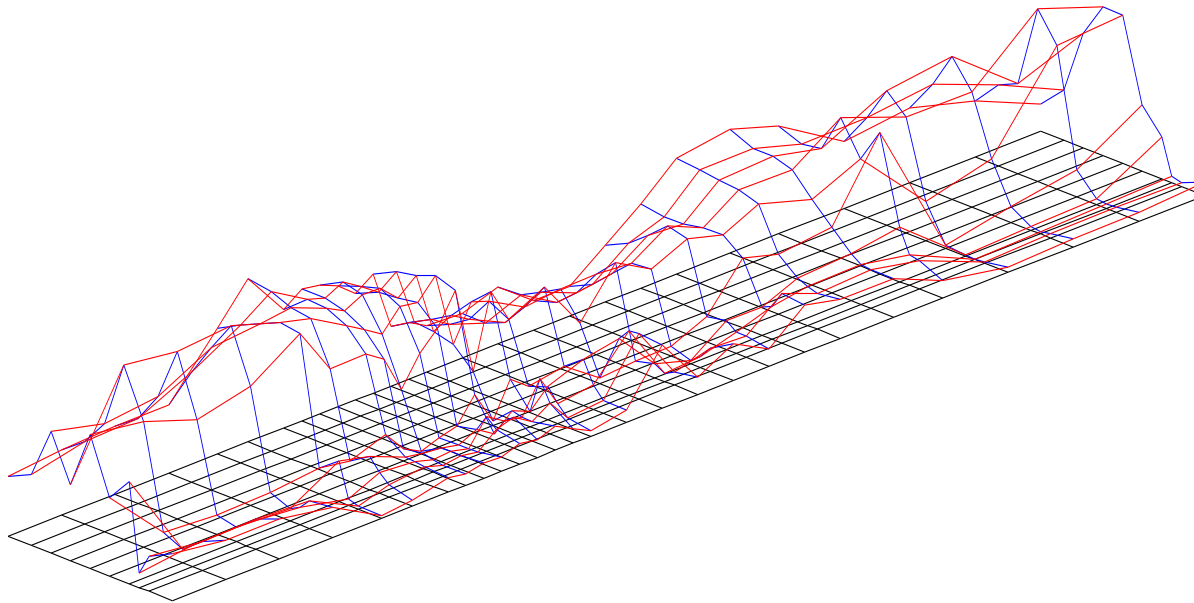
# Changes in the natural shapes

- Visual comparison of the third mode shapes for the damaged state (left) and for the state after reconstruction (right)
- $MAC(3,3)=0.618$ .
- Just the visual comparison of natural modes shows the change



# Changes in the COMAC

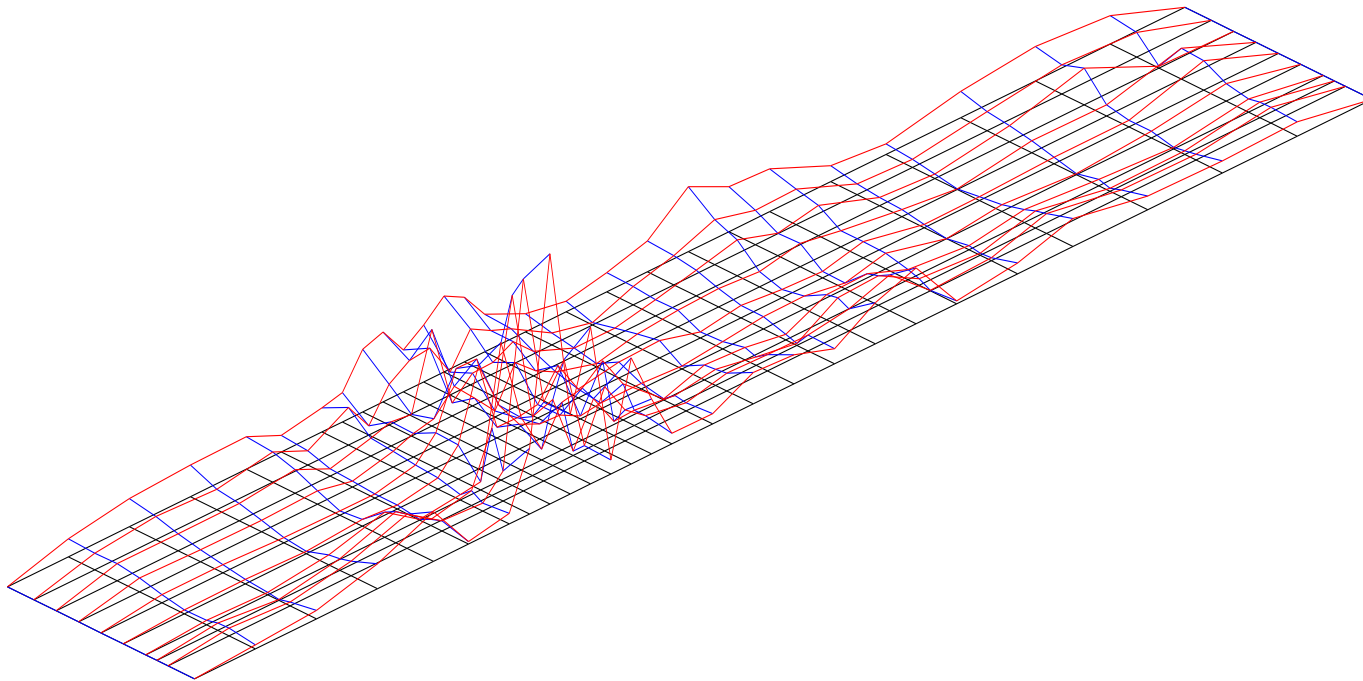
- Coordinate Modal Assurance Criterion  $\text{COMAC}_{(p)}$
- Minimal values on the right damaged state, function  $1-\text{COMAC}_{(p)}$  shown





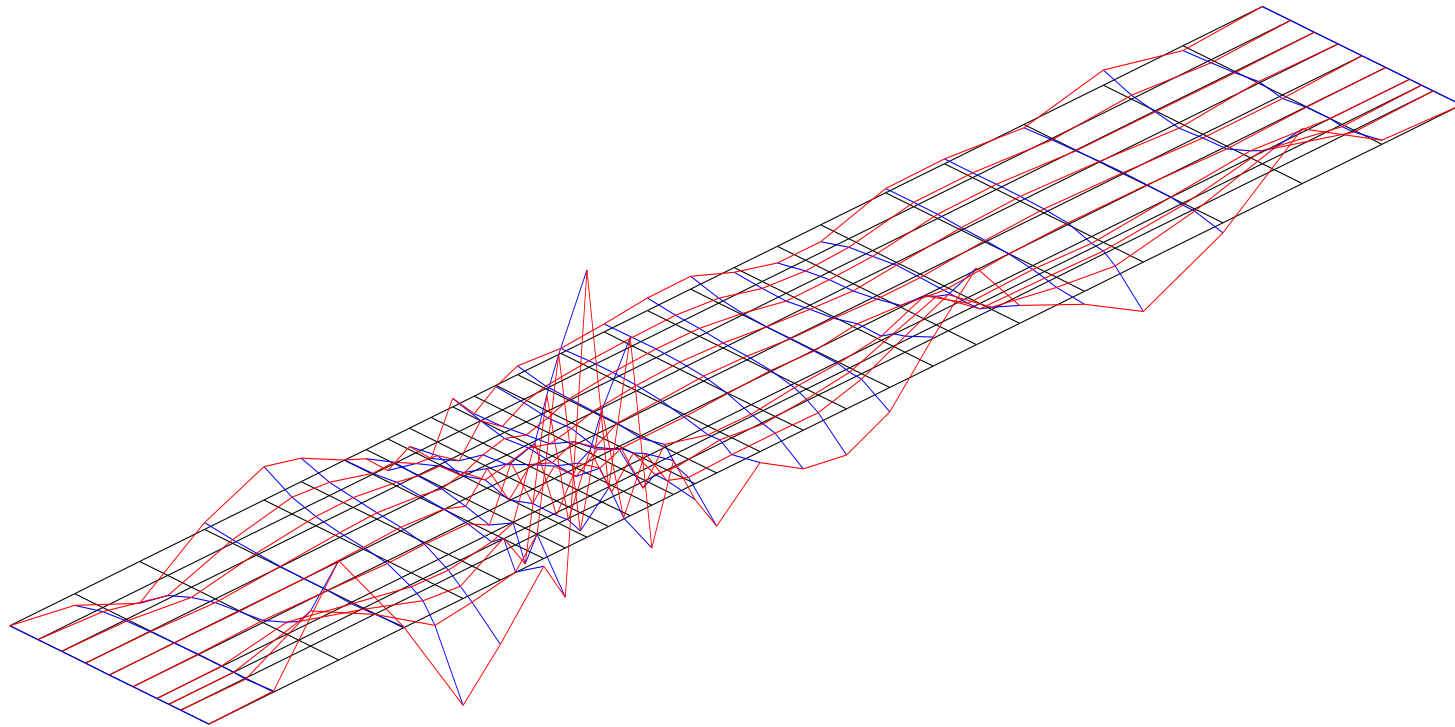
# Changes in the CAMOSUC<sub>(j),x</sub>

- The change of the curvature of natural mode shapes CAMOSUC<sub>(j),x</sub>
- The damaged state – state after reconstruction - the change of the curvature of the 3<sup>rd</sup> natural mode CAMOSUC<sub>(3)</sub> shown below



# Changes in the modal flexibility matrix $\Delta[\delta]$

- The 2<sup>nd</sup> derivative of changes of diagonal members of a modal flexibility matrix  $\Delta[\delta]''$
- The highest values shows the damage location



# Conclusion

- Damage of the main girder and its reconstruction significantly influence the dynamic behavior of the investigated bridge.
- Changes of modal characteristics are significant.
- For damage detection and localization, changes of a mode surface curvature **CAMOSUC(j),x**, changes of a **modal flexibility matrix**  $\Delta[\delta]$  and especially the **second derivative** of changes of diagonal members of a **modal flexibility matrix**  $\Delta[\delta]''$  proved to be appropriate.
- The FEM model verification show, that road layers, pavements and concrete leveling topping have to be included to the stiffness. The influence of these layers was important for the dynamic behavior of the structures



[link to paper](#)

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## WG MEETINGS & WORKSHOP

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# EFFECT OF VEHICLE TRAVELLING VELOCITY ON BRIDGE LATERAL DYNAMIC RESPONSE

**Luke J Prendergast** - University College Dublin, Republic of Ireland

**Kenneth Gavin** – Gavin and Doherty Geosolutions, Dublin, Republic of Ireland

**David Hester** – Queen's University Belfast, United Kingdom

[link to paper](#)



Queen's University  
Belfast



30<sup>th</sup> March - 1<sup>st</sup> April 2016

Belgrade, Serbia

# INTRODUCTION - SHM

- Vibration-based Structural Health Monitoring (SHM) is the art of monitoring the condition of a structure over its lifetime by monitoring dynamic properties with a view to preventing excessive damage from accumulating



ZAGREB RAILWAY BRIDGE



DUBLIN RAILWAY BRIDGE



# INTRODUCTION - SHM

- Local scour around bridge piers causes a rapid loss in foundation stiffness and can lead to collapse.
- This phenomenon can be monitored by analyzing the dynamic behavior of the bridge



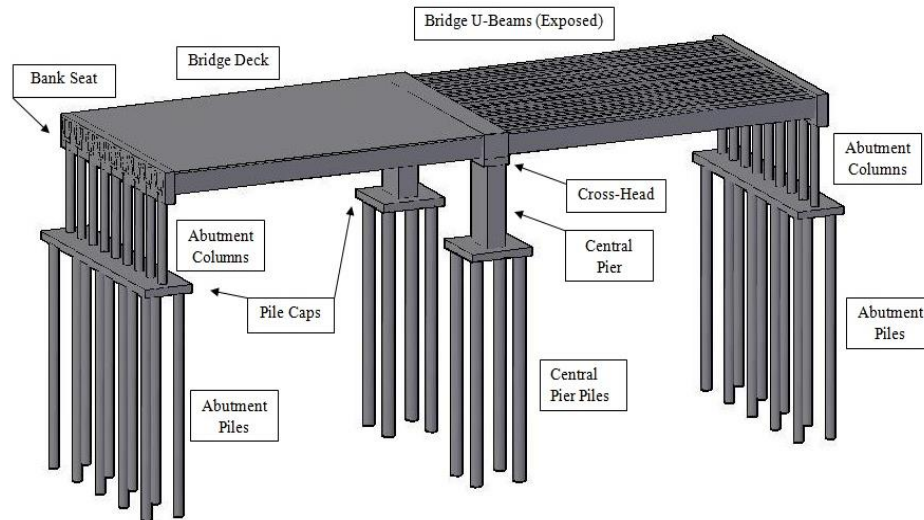
ZAGREB RAILWAY BRIDGE



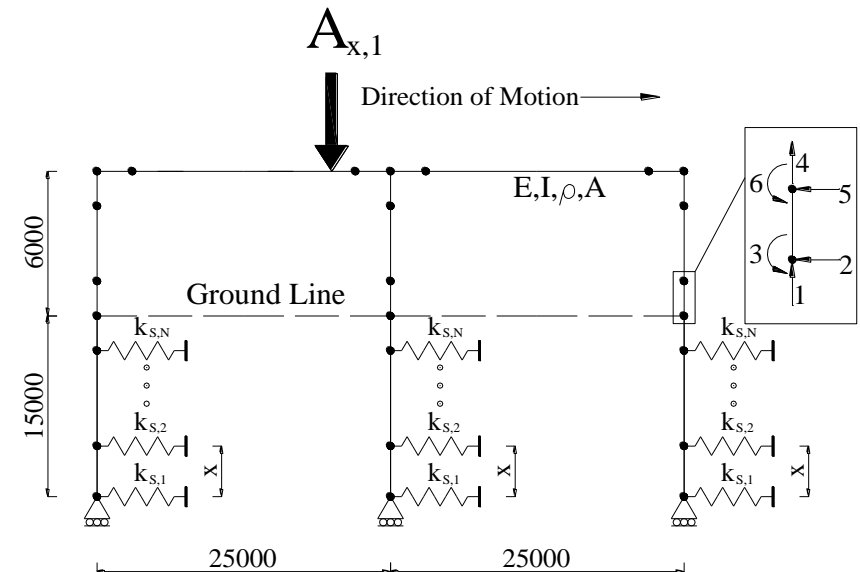
DUBLIN RAILWAY BRIDGE

# VEHICLE-BRIDGE-SOIL DYNAMIC INTERACTION MODEL

- A typical two-span concrete integral bridge is modelled and the dynamic response due to a traversing point load is calculated
- The first mode of this bridge (global sway –  $f_1 = 1.56$  Hz) is sensitive to scour



MODEL SCHEMATIC



NUMERICAL SCHEMATIC

# MODAL PROPERTIES – GLOBAL SWAY

$$f_1 = 1.56 \text{ Hz} \quad T_1 = 0.639 \text{ s}$$

MODAL SHAPE AT INTERVALS OF PERIOD

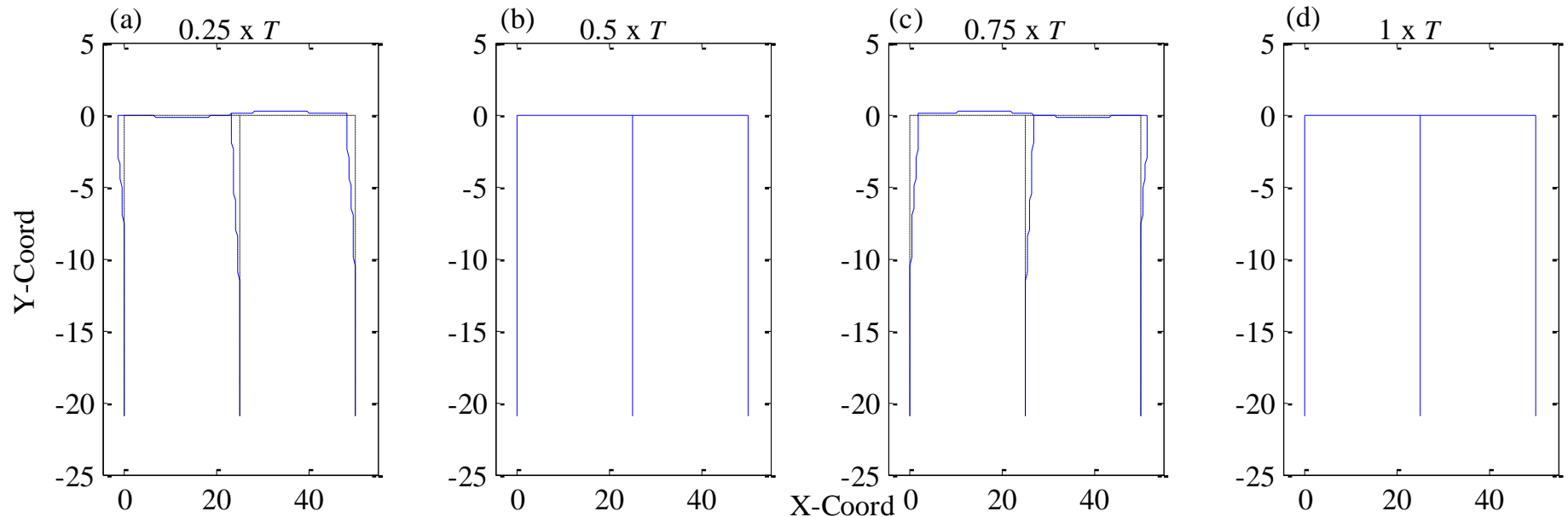
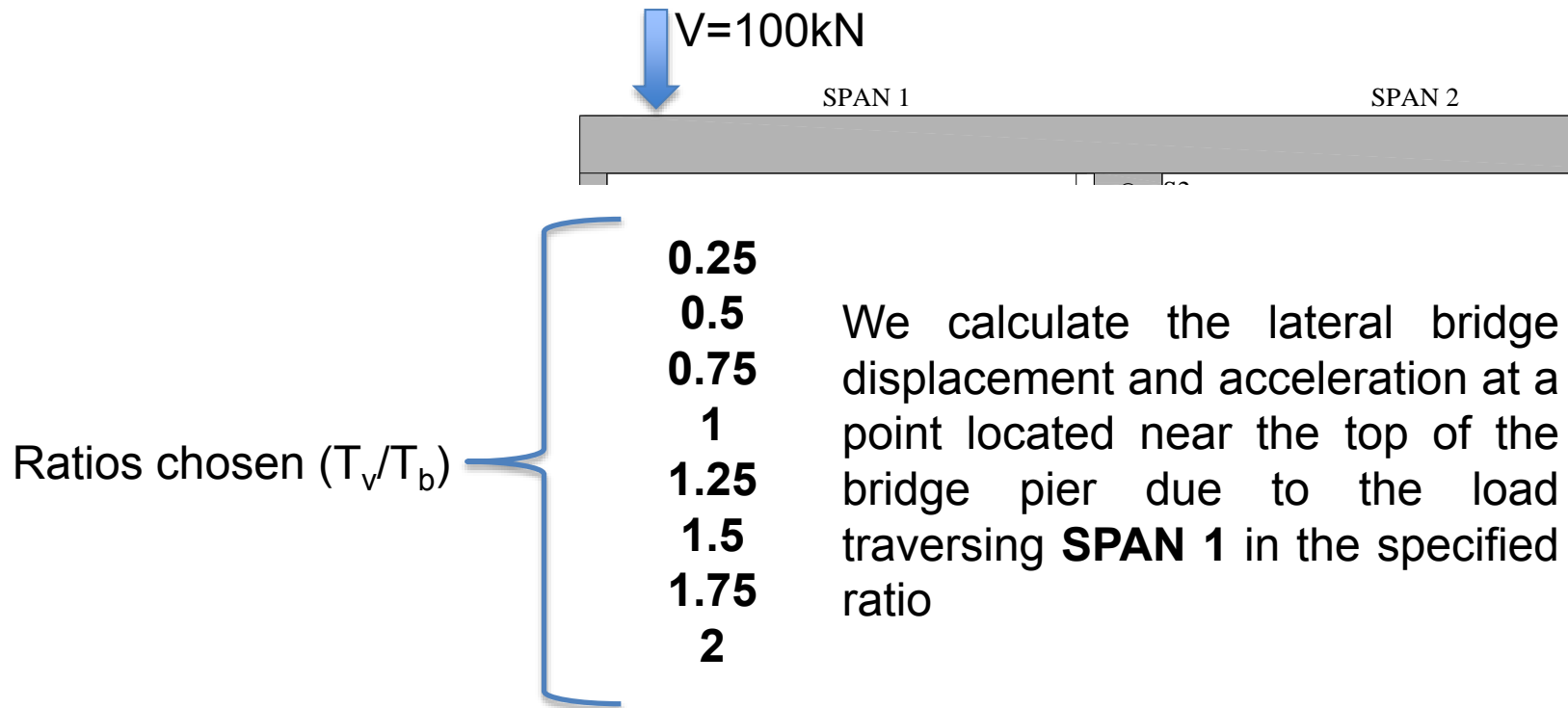


Image Ref	Arrival Time (s)	Motion Direction
(a)	$0.25 \times 0.639 = 0.16\text{s}$	Stationary (will move right)
(b)	$0.5 \times 0.639 = 0.32\text{s}$	Swaying to right
(c)	$0.75 \times 0.639 = 0.4795\text{s}$	Stationary (will move left)
(d)	$1 \times 0.639 = 0.639\text{s}$	Swaying to left

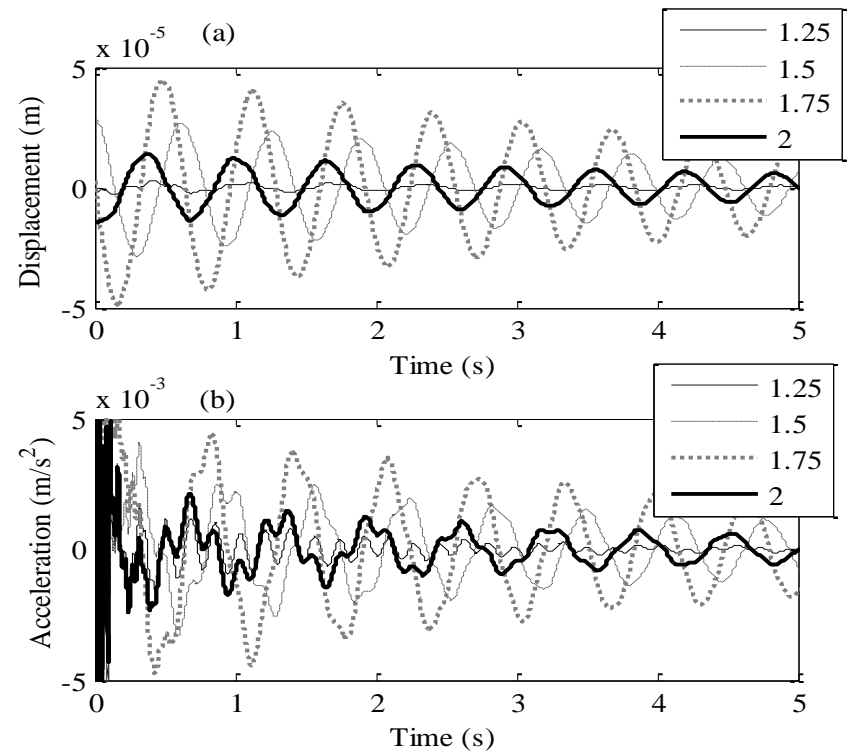
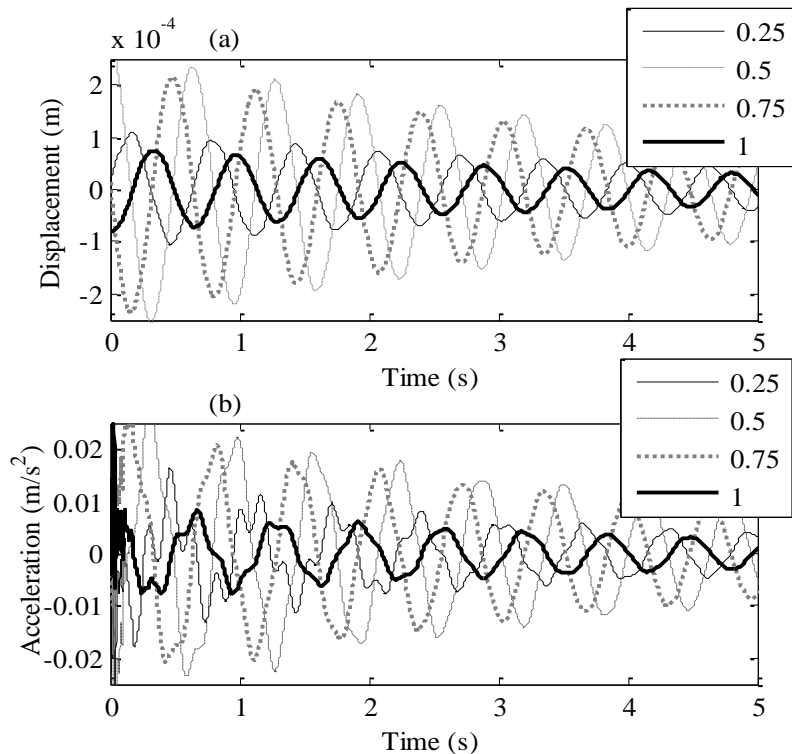
# EFFECT OF VEHICLE VELOCITY

- A single load is modelled as traversing the bridge such that it traverses **SPAN 1** in a time that is a specified ratio of the bridge's global sway period ( $T_v/T_b$ )



# EFFECT OF VEHICLE VELOCITY

- A single load is modelled as traversing the bridge such that it traverses **SPAN 1** in a time that is a specified ratio of the bridge's global sway period



# EFFECT OF VEHICLE VELOCITY

- For Speed Ratios  $< 1$

	Max Amplification	Min Amplification
Ratio	0.5	1

- For Speed Ratios  $> 1$

	Max Amplification	Min Amplification
Ratio	1.75	1.25



# SUMMARY / SIGNIFICANCE OF FINDINGS

- Vibration-based damage detection (VBDD) and SHM relies on good quality dynamic signals being detected to infer a damage state
- This study highlights that vehicle behaviour can affect the amplitude of the bridge free vibration response
- The results are not intuitive and the exact interaction is quite complex
- Since most VBDD rely on excitation by means of ambient traffic, the results are relevant to this field



[link to paper](#)

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### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **Damage detection for bridge structures based on dynamic and static measurements**

**Viet Ha Nguyen, Sebastian Schommer, Stefan Maas** - University of Luxembourg  
**Arno Zürbes** - Fachhochschule Bingen, Germany

[link to paper](#)

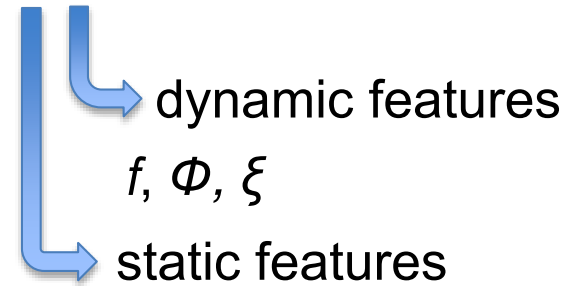


**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**

# INTRODUCTION



- structure of big size
- subjected to varying temperatures
- ▶ SHM is difficult

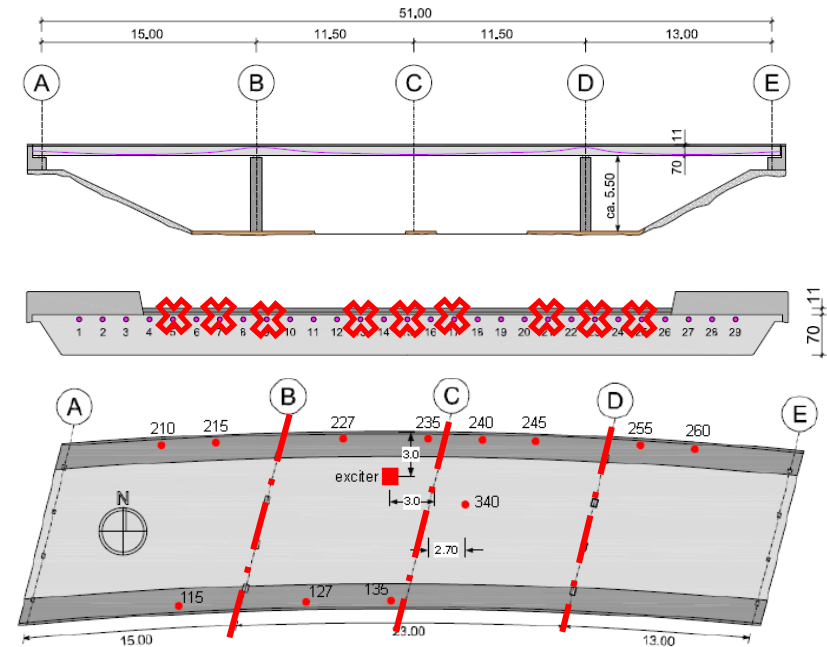


# Dynamic investigation

## "Deutsche Bank" Bridge



### 4 levels of damage



#1: cut 1 tendon

#2: cut 5 tendons

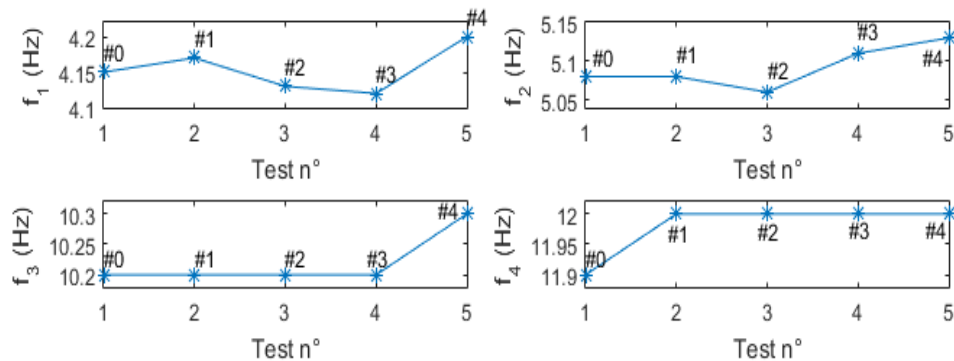
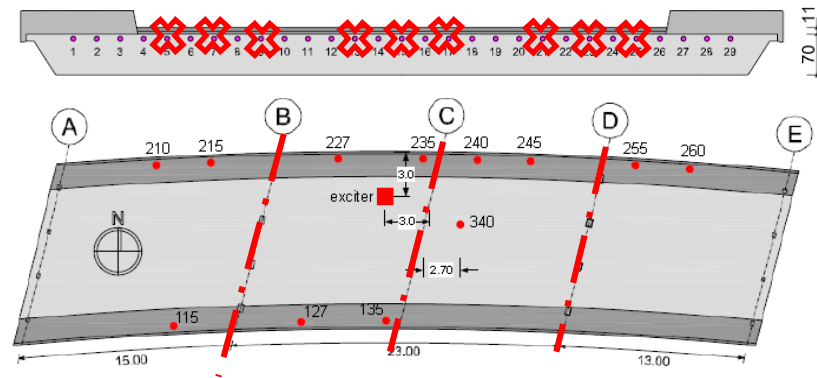
#3: cut 9 tendons

#4: cut 9x3 tendons

# Dynamic investigation

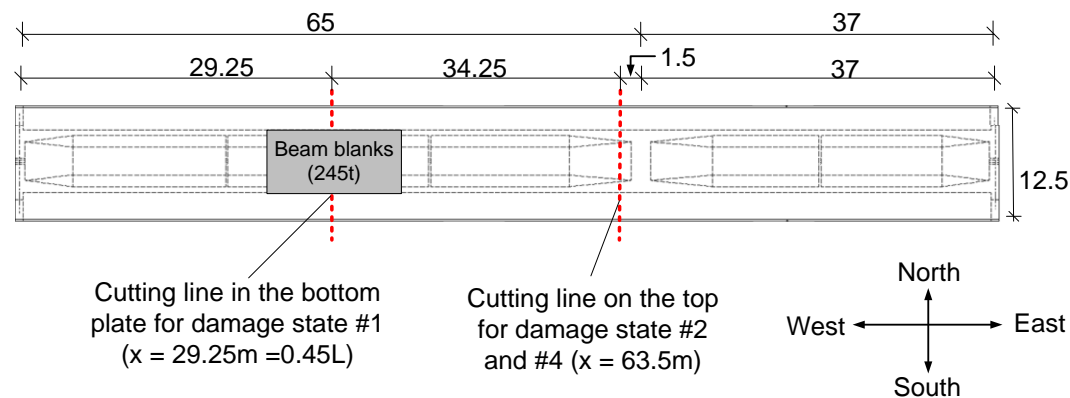
## "Deutsche Bank" Bridge

no visible cracking

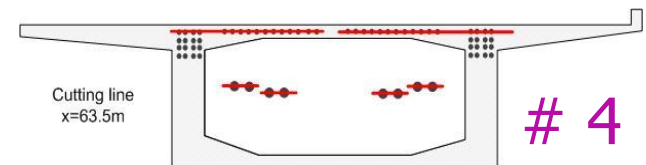
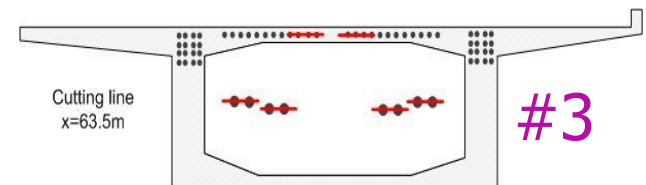
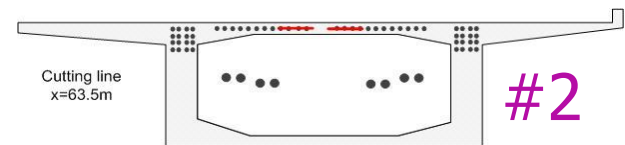
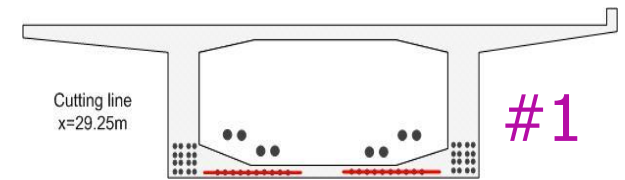
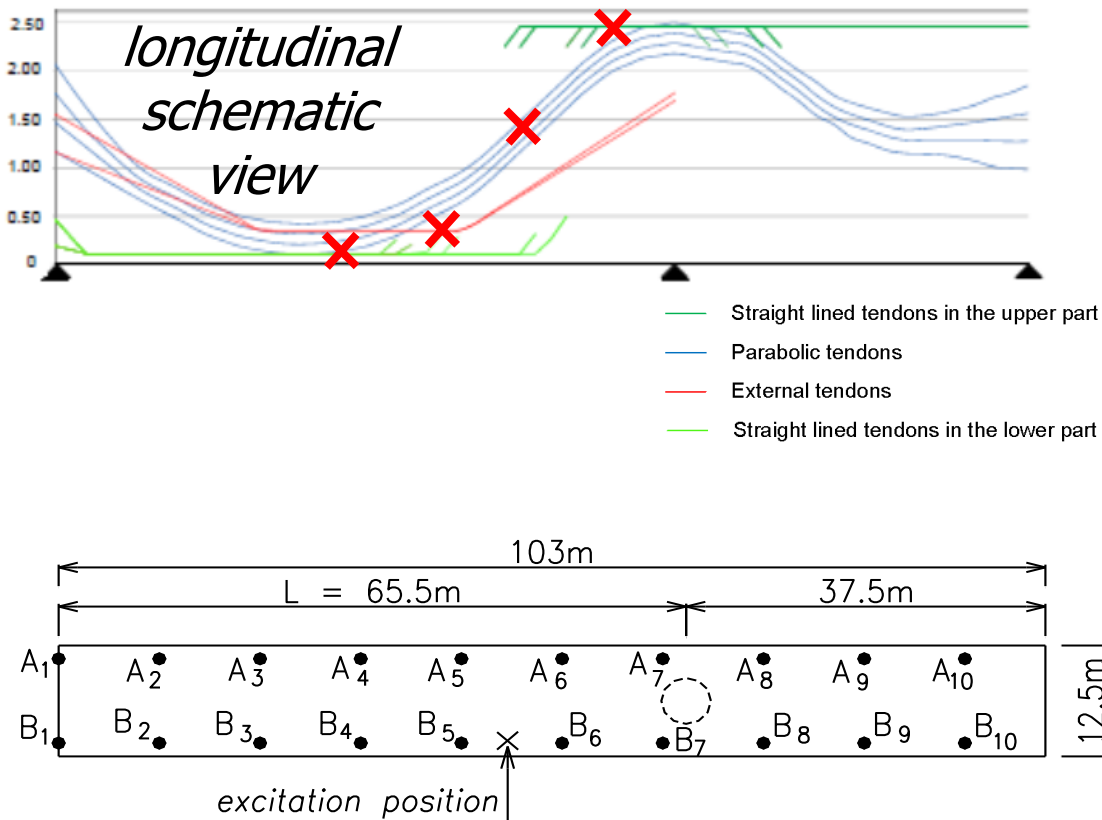




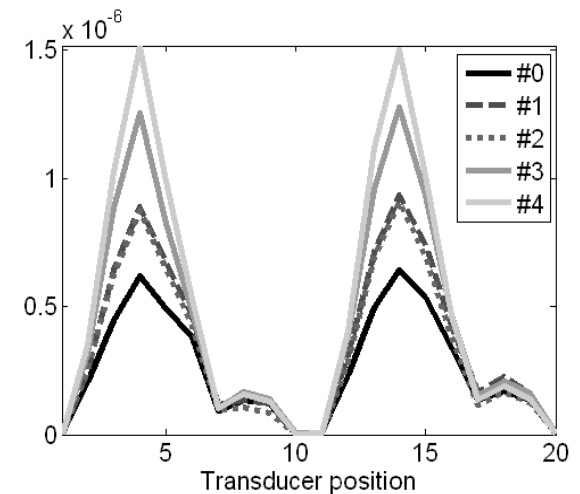
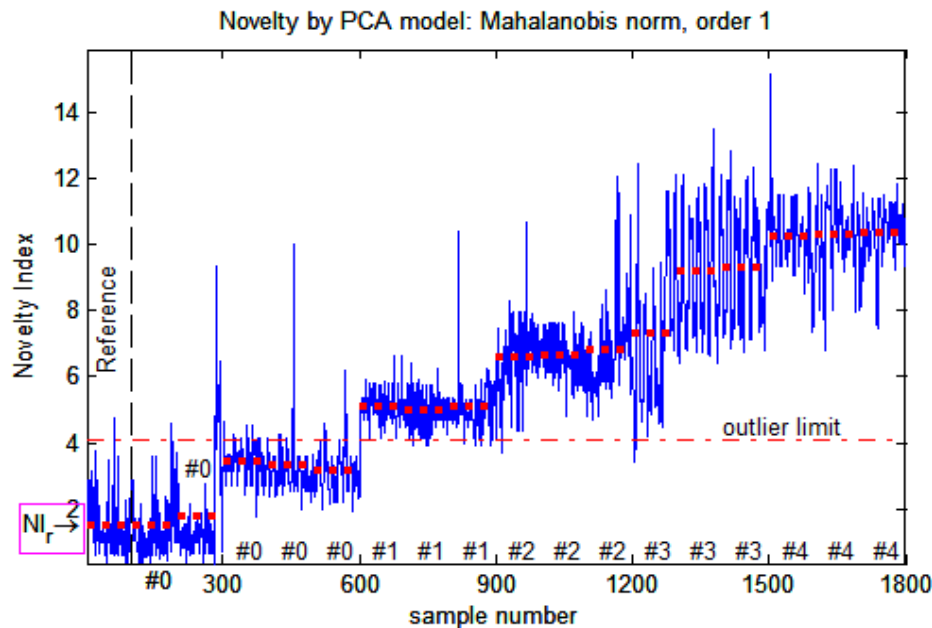
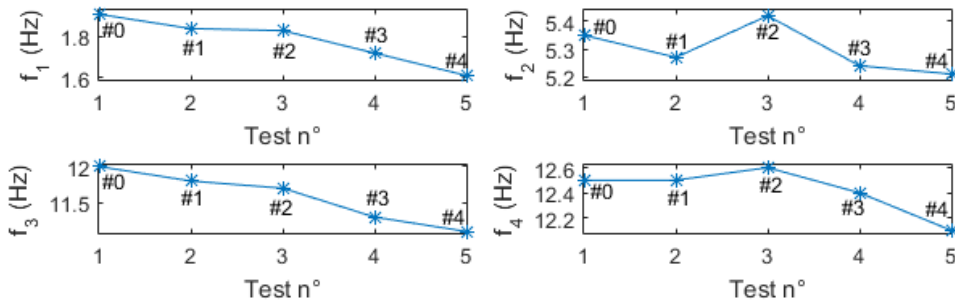
## Champangshiehl Bridge



# Champangshiehl Bridge



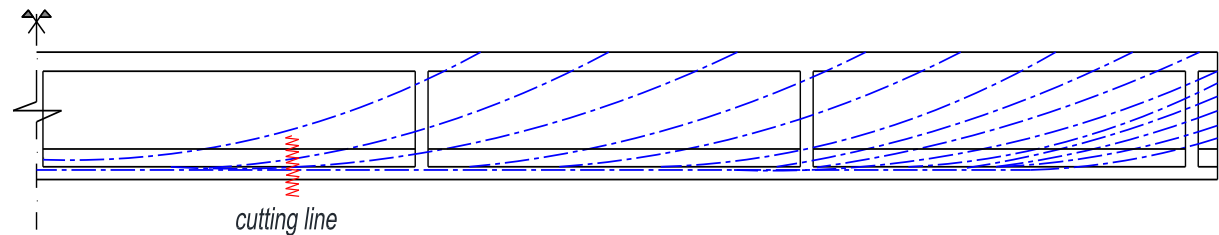
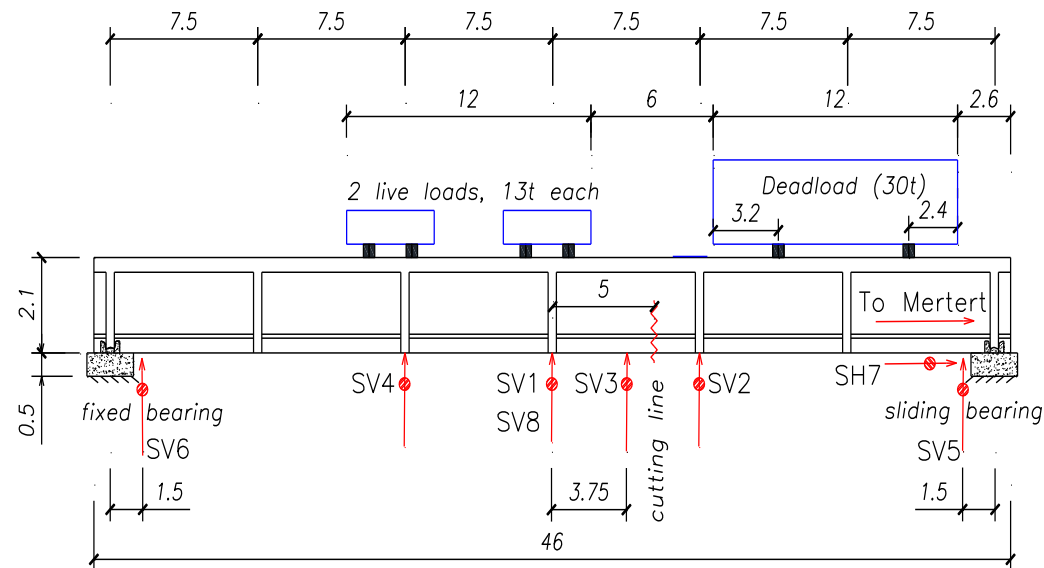
## Detection results



Diagonal elements of the flexibility

# Static investigation

part of Grevenmacher-Bridge



# Static investigation

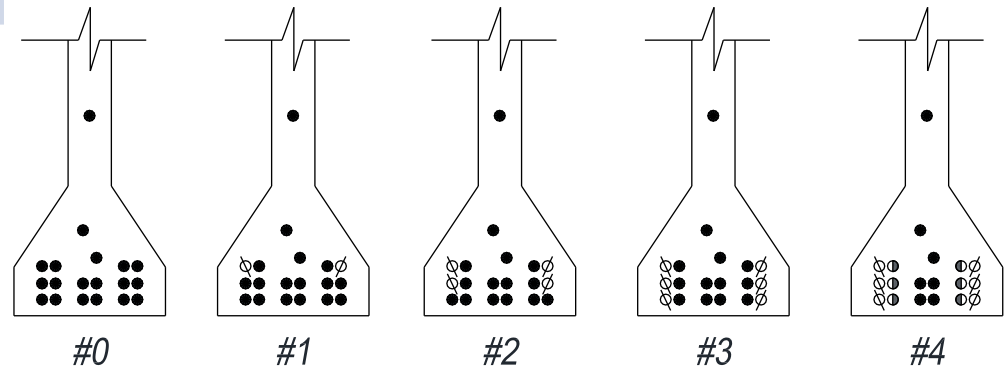
- ❖ shape deformation
- ❖ absolute values of deflection line

part of Grevenmacher-Bridge

State	Cutting of
#0	0 tendon
#1	2 tendons
#2	4 tendons
#3	6 tendons
#4	6 tendons+ half of 6 others tendons

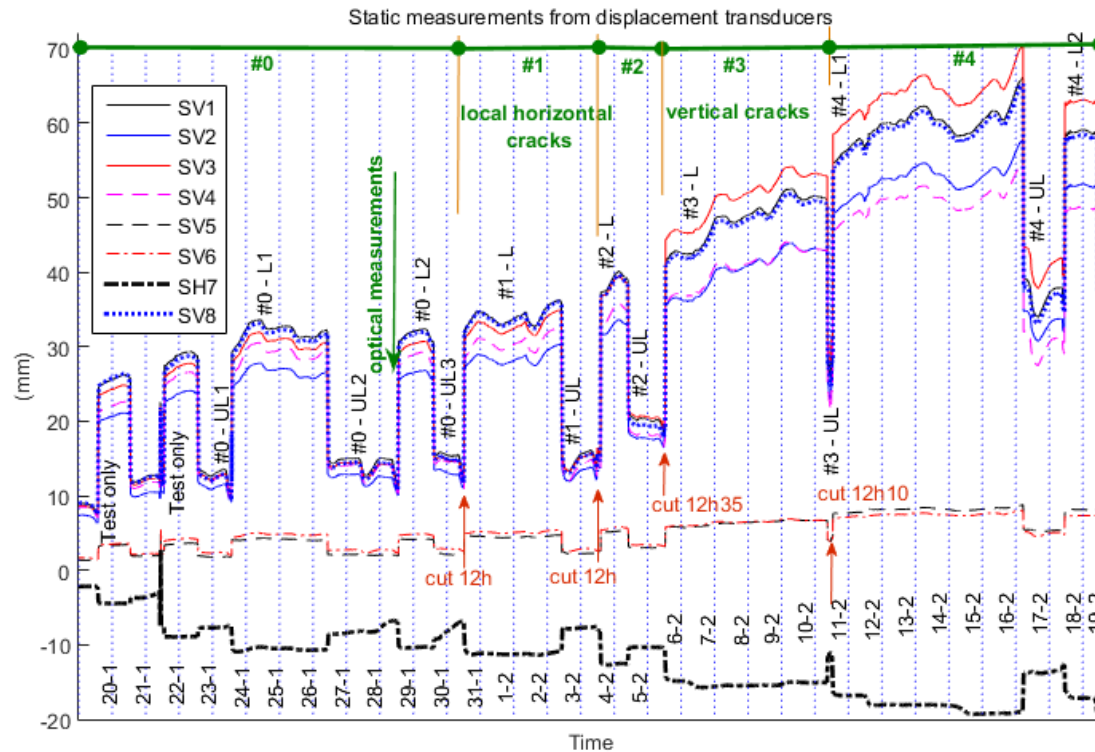


live loads: stayed at least 24h

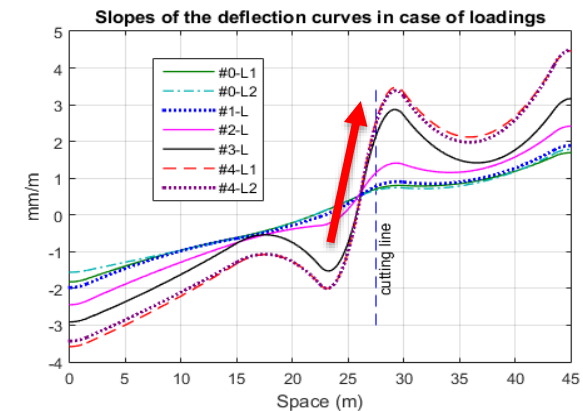
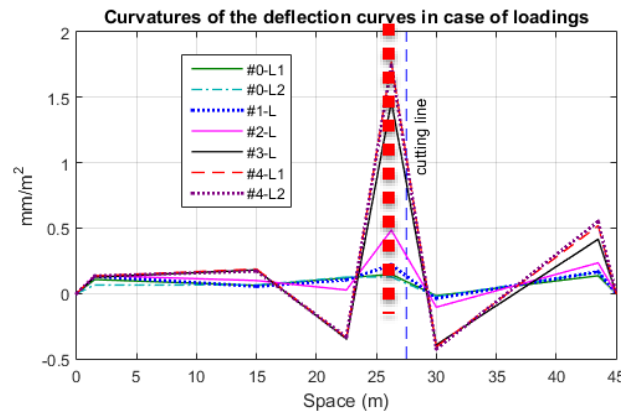
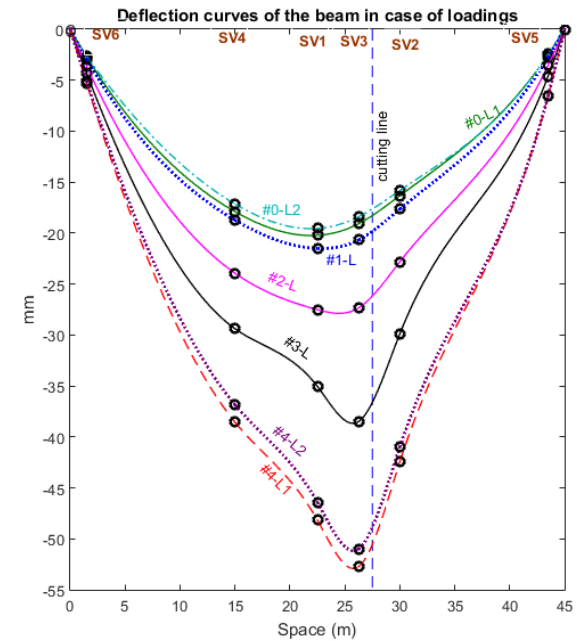
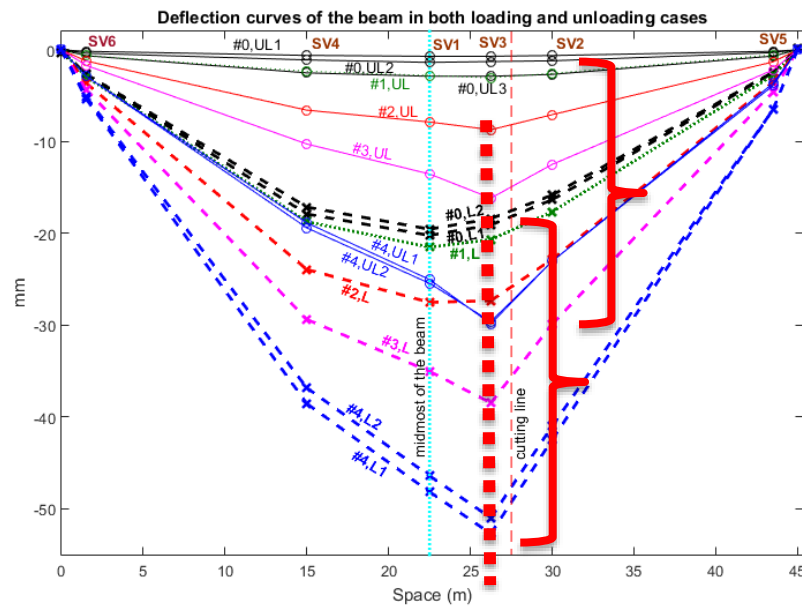




# Static investigation

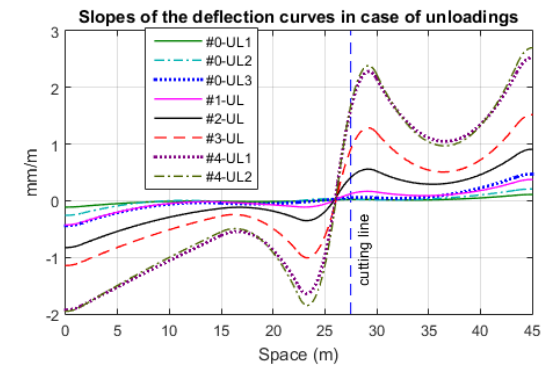
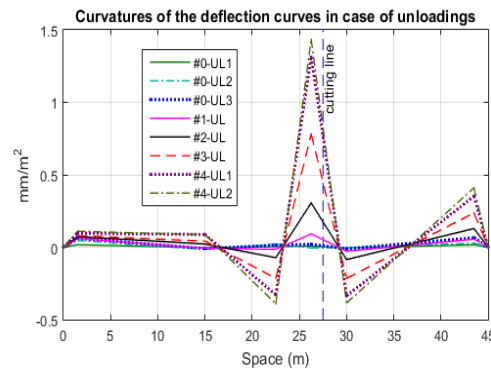
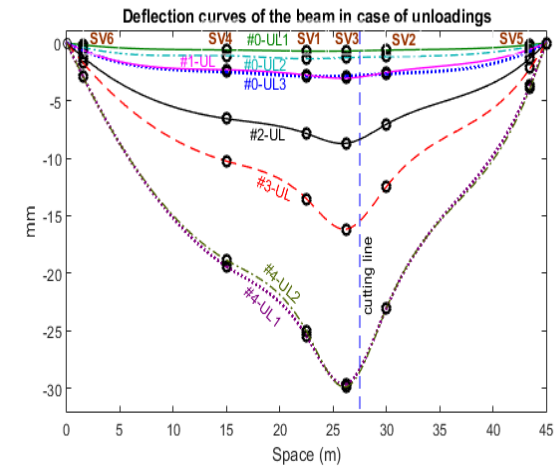
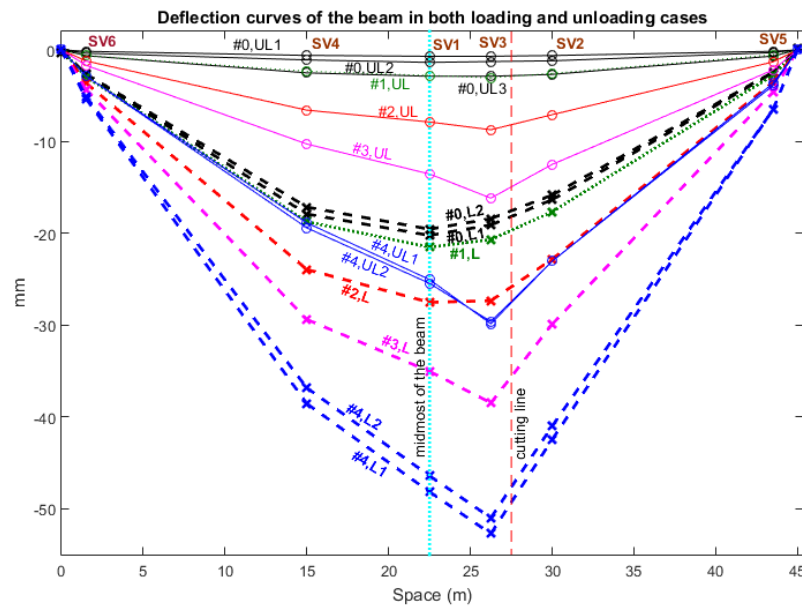






Results





Results

# CONCLUSION

- **Dynamic** methods:  $f$ ,  $\Phi$ ,  $\xi$ ,  $\mathbf{F}$ , *Novelty Index*



$t^\circ$ , excitation level

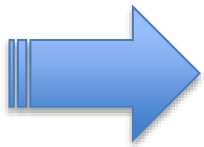
- **Static** deflection curves from load testing: sudden change to localize

- \* breaking point

- \* 1st derivative:



- \* 2<sup>nd</sup> derivative: peak



Model updating



[link to paper](#)

**THANKS FOR YOUR ATTENTION!**

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### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **QUALITATIVE PERFORMANCE INDICATORS FOR BRIDGE MANAGEMENT IN ITALY**

**Mariano Angelo Zanini** - University of Padova, Italy

**Flora Faleschini** - University of Padova, Italy

**Nicola Fabris** - University of Padova, Italy

**Carlo Pellegrino** - University of Padova, Italy

[link to paper](#)



**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**

# INTRODUCTION

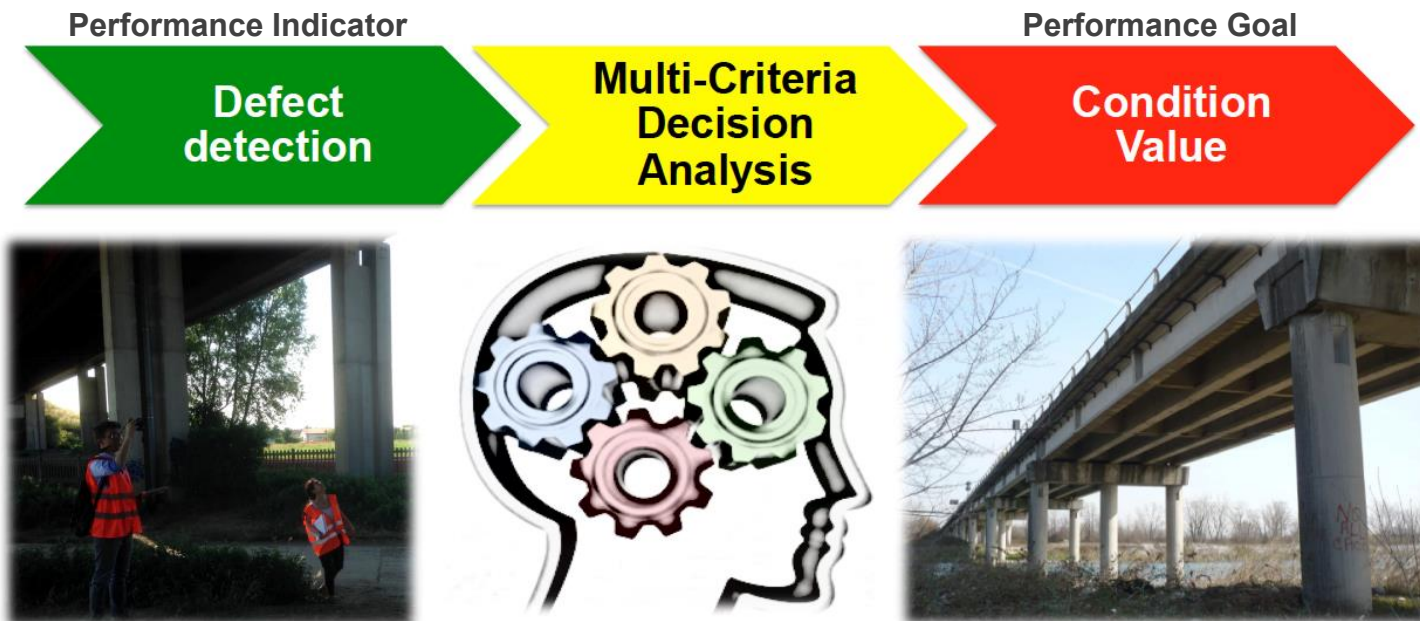
- In this contribution, the activities related to the definition of performance indicators for bridge management, carried out at the University of Padova, Italy, are shown.
- A procedure for the qualitative condition assessment aimed to define a Total Sufficiency Rating (*TSR*) is adopted.
- A time-dependent framework for the remaining service-life prediction is used for forecasting future deterioration states.
- A cost model for the quantification of maintenance and seismic retrofit costs was calibrated and can be adopted for economic analysis.
- Some procedures are currently applied on a real bridges' stock in the framework of an agreement between the University of Padova and an Authority managing highway networks and related infrastructures in the North-Eastern part of Italy.



# TOTAL SUFFICIENCY RATING ASSESSMENT

- When dealing with the management of medium-to-large size bridge portfolios, visual inspections – if properly performed - can be a cost-effective solution.
- How to rank bridges for maintenance planning purposes?

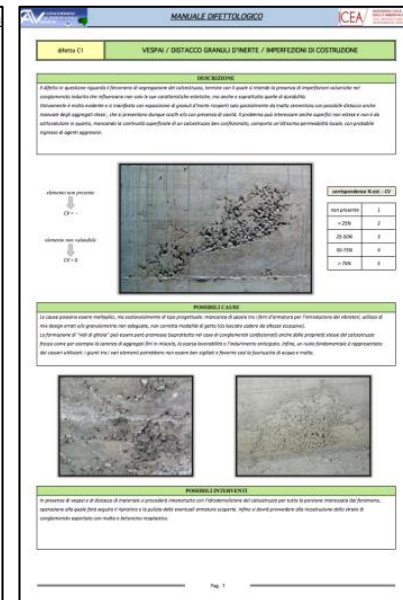
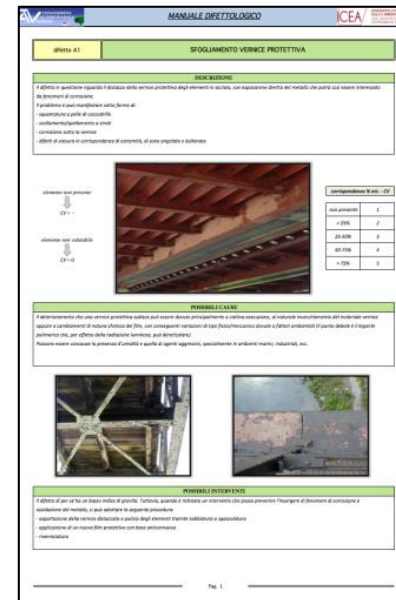
At component level



# TOTAL SUFFICIENCY RATING ASSESSMENT

- The first step is defect detection based on visual inspection survey.
- Defects are classified according to a specific defect database.
- Both structural and non-structural elements are evaluated.
- Technicians are trained with a theoretical and practical course aimed to reduce the subjectivity in their evaluation.

## At component level




# TOTAL SUFFICIENCY RATING ASSESSMENT

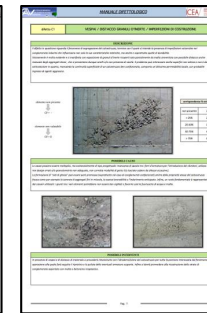
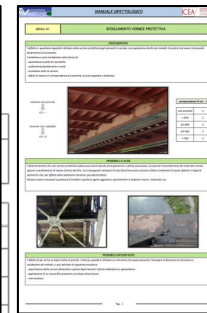
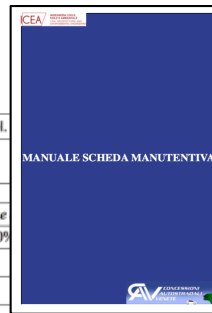
- For each structural/non-structural bridge element observed defects are converted into a specific *Condition Value (CV)* through the application of *Multi-Criteria Decision Analysis*.

## At component level Performance Indicator

SCHEDA 3.2		ELEMENTO		elemento presente		el.	
		SOLETTA IN C.A.		<input checked="" type="radio"/>			
descrizione difetti				estensione			
				non presente	< 25%	25-50%	
C1	vespai/distacco granuli d'inerte/imperfezioni di costruzione			<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	
C2	distacco copriferro/fenomeni di spalling			<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	
C3	ossidazione armature/staffe			<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	
C4	macchie di umidità/dilavamento/efflorescenze			<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	
C5	piccole lesioni a ragnatela o longitudinali			<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	
C6	fessure diagonali/trasversali			<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	
C9	lesioni localizzate attacco travi-soletta			<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>

MANUALE SCHEDA MANUTENTIVA





**Multi-Criteria  
Decision  
Analysis**

## Performance Goal

CV - Condition Value	
No judgement	0
No meaningful defects	1
Minor defects that do not cause damage	2
Moderate defects that could cause damage	3
Severe defects that cause damage	4
Non-functional element	5

# TOTAL SUFFICIENCY RATING ASSESSMENT

- CVs are condensed in a global qualitative indicator *TSR* as:

## At system level Performance Indicator

Element Weights  $W_i$

## Performance Goal

$$TSR = \frac{[TSR_{REALE} \sum_{i=1}^t W_i + TSR_{NV} (\sum_{i=1}^n W_i - \sum_{i=1}^t W_i)]}{\sum_{i=1}^n W_i}$$

$$TSR_{REALE} = \text{PF} \left( \frac{\sum_{i=1}^t CF_i W_i}{\sum_{i=1}^t W_i} \right)$$

Network level Performance Indicators

$$TSR_{NV} = \text{PF} \left( \frac{\sum_{i=1}^{n-t} CF_i W_i}{\sum_{i=1}^{n-t} W_i} \right)$$



### REGISTRO ISPEZIONI MANUTENTIVE



#### 5 - ISPEZIONI MANUTENTIVE

ID MANUFATTO 298

DENOMINAZIONE UFFICIALE Viadotto su Ferrovia VE-TS

DENOMINAZIONE CONVENZIONALE Viadotto su Ferrovia VE-TS



Esito ispezione (TSR)	Note
59	Affiancamento Ing. Zanini, Ing. Faleschini, All. Ing. Fabris

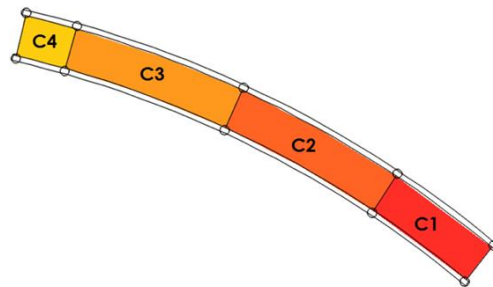
Campate	Travi	Traversi	Soletta	Pile	Appoggi	Spalle	Disp. antisismici	Muri andatori	Smalt. acque	Giunti	Pavimentazione	Guard-rail
1	2	1	2	1	0	4	-	2	5	1	1	1
2	2	2	2	1	0	-	-	-	3	-	1	1
3	2	1	3	1	0	-	-	-	4	-	1	1
4	1	1	1	-	0	4	-	2	1	1	1	1
5	2	1	1	1	0	4	-	3	4	1	1	1
6	2	2	1	1	0	-	-	-	1	-	1	1
7	2	1	1	1	0	-	-	-	1	-	1	1
8	3	1	1	1	0	-	-	-	1	-	1	1
9	2	1	1	-	0	4	-	3	1	1	1	1

Pellegrino C. et al. (2011). "A simplified management procedure for bridge network maintenance" *Structure and Infrastructure Engineering*, 7(5), 341-351.



# TOTAL SUFFICIENCY RATING ASSESSMENT

- At network level, performance goals are represented by intervention urgency (*TSR*) and restoration costs.



ISPEZIONE 11/08/2015												
Campate	Travi	Traversi	Soletta	Pile	Appoggi	Spalle	Disp. antisismici	Muri andatori	Smalt. acque	Giunti	Pavimentazione	Guard-rail
1	1	1	2	1	5	2	-	2	4	1	1	2
2	1	1	1	1	0	-	-	-	-	-	1	2
3	1	1	1	2	3	-	-	-	-	-	1	2
4	1	1	1	-	4	2	-	1	2	-	1	2

ISPEZIONE 11/08/2015												
Campate	Travi	Traversi	Soletta	Pile	Appoggi	Spalle	Disp. antisismici	Muri andatori	Smalt. acque	Giunti	Pavimentazione	Guard-rail
1	0	0	18.534	0	59.003	3.488	0	483	116	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	3.153	220	0	0	0	0	0	0	0
4	0	0	0	0	12.052	904	0	0	0	0	0	0

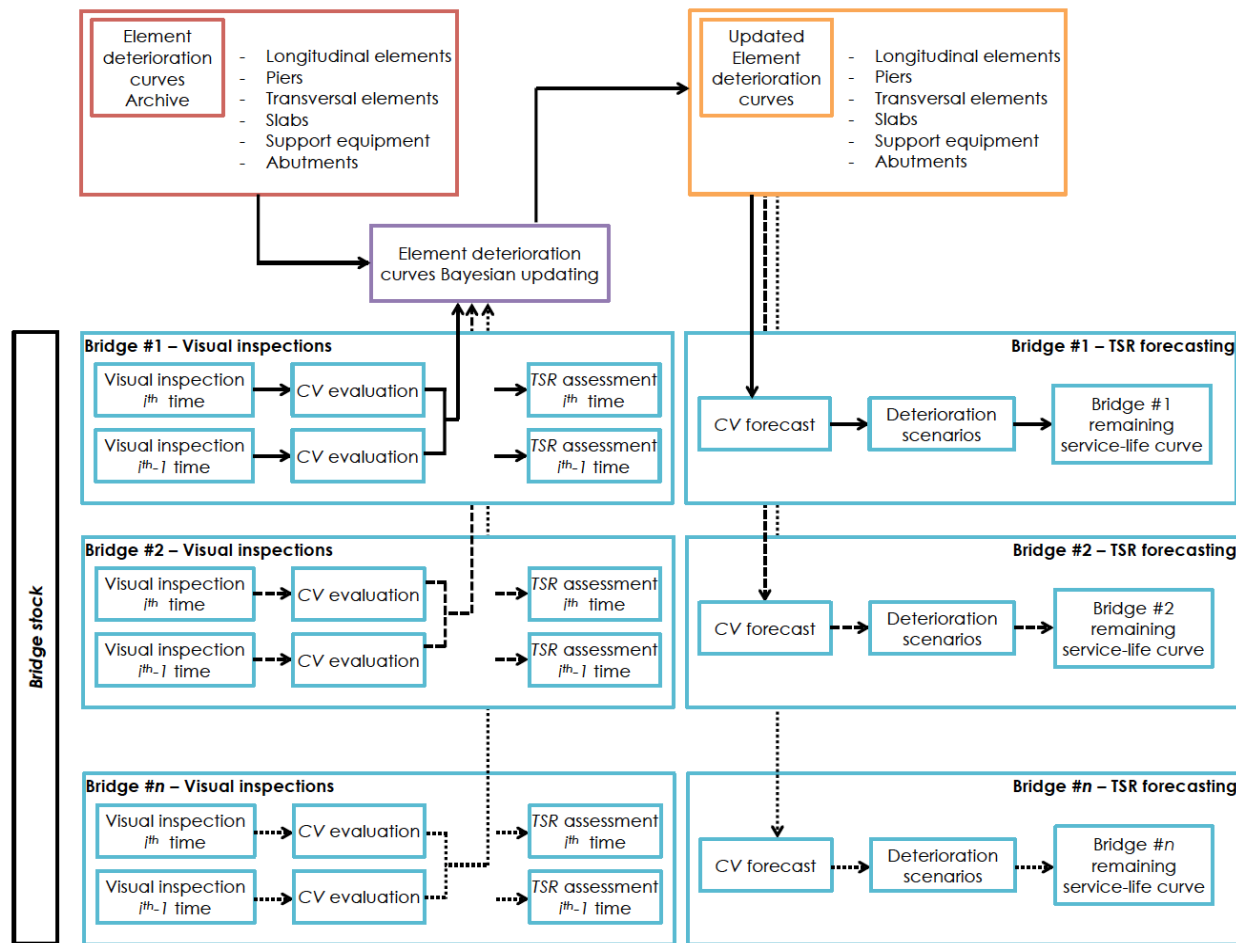
DATA ISP.	ISPETTORE	ESITO ISP. (TSR)	NOTE
11/08/2015	Ing. Sebastiano Nardin	58	Affiancamento Ing. Faleschini, All. Ing. Fabris

TOTALE SPESA PER RIPRISTINO MANUFATTO [€]	97.953	EURO / MQ DI MANUFATTO	61,76
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	Travi	Traversi	Soletta	Pile	Appoggi	Spalle	Disp. antisismici	Muri andatori	Smalt. acque	Giunti	Pavimentazione	Guard-rail
Tot. [€]	0	0	18.534	3.153	71.275	4.392	0	483	116	0	0	0

# REMAINING SERVICE LIFE FORECASTING

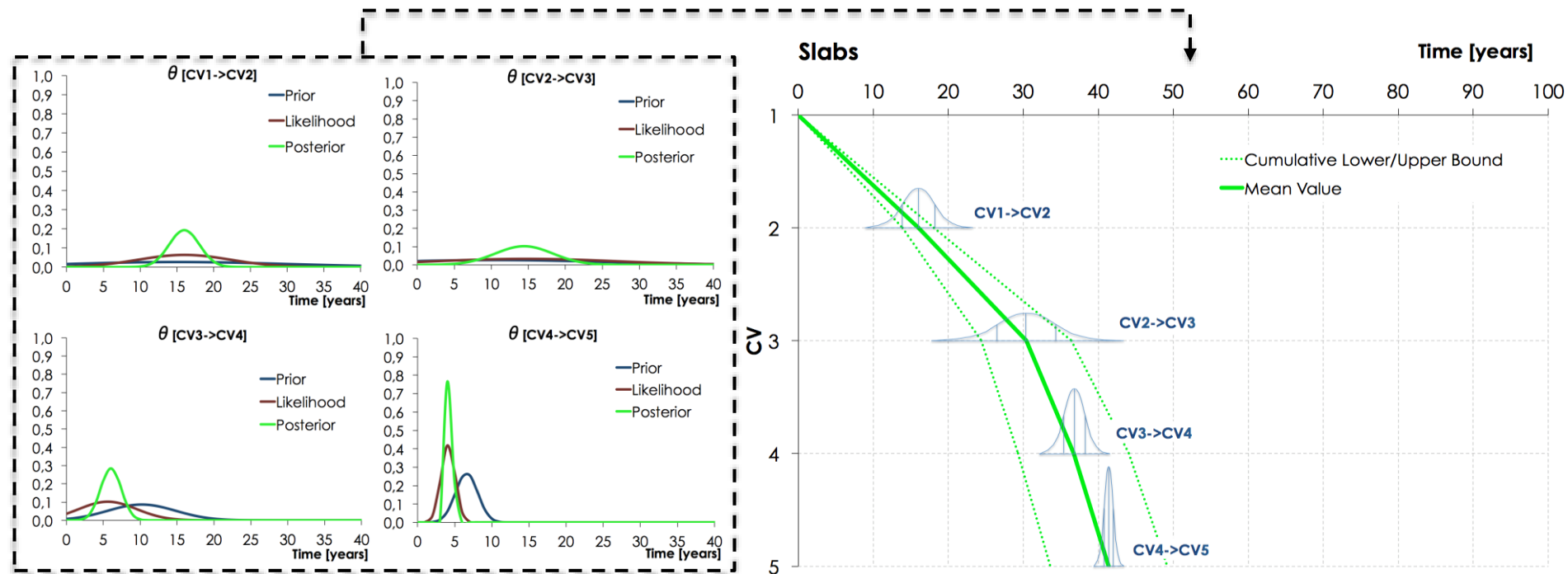
- Visual inspection data are useful also for deterioration forecasts.





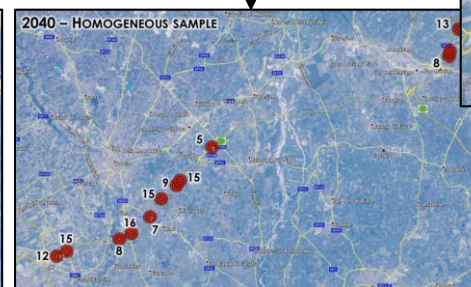
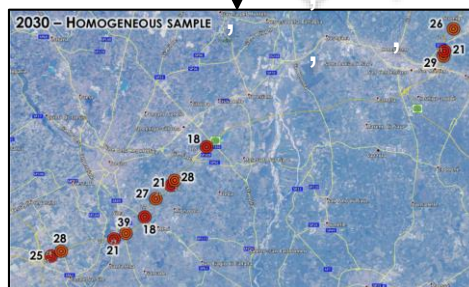
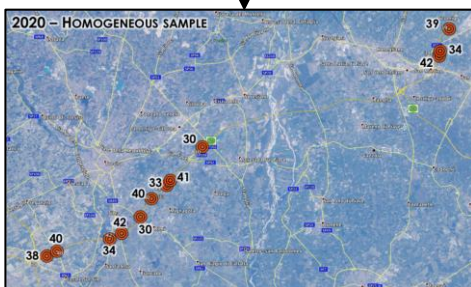
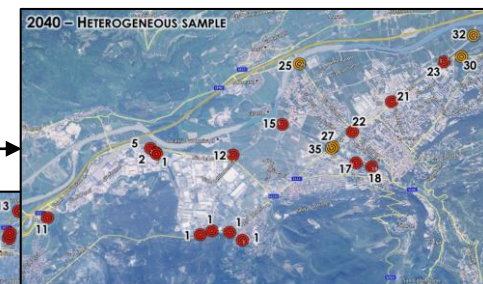
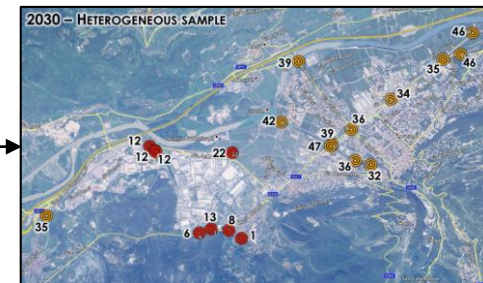
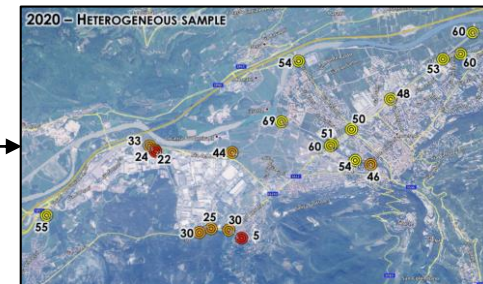
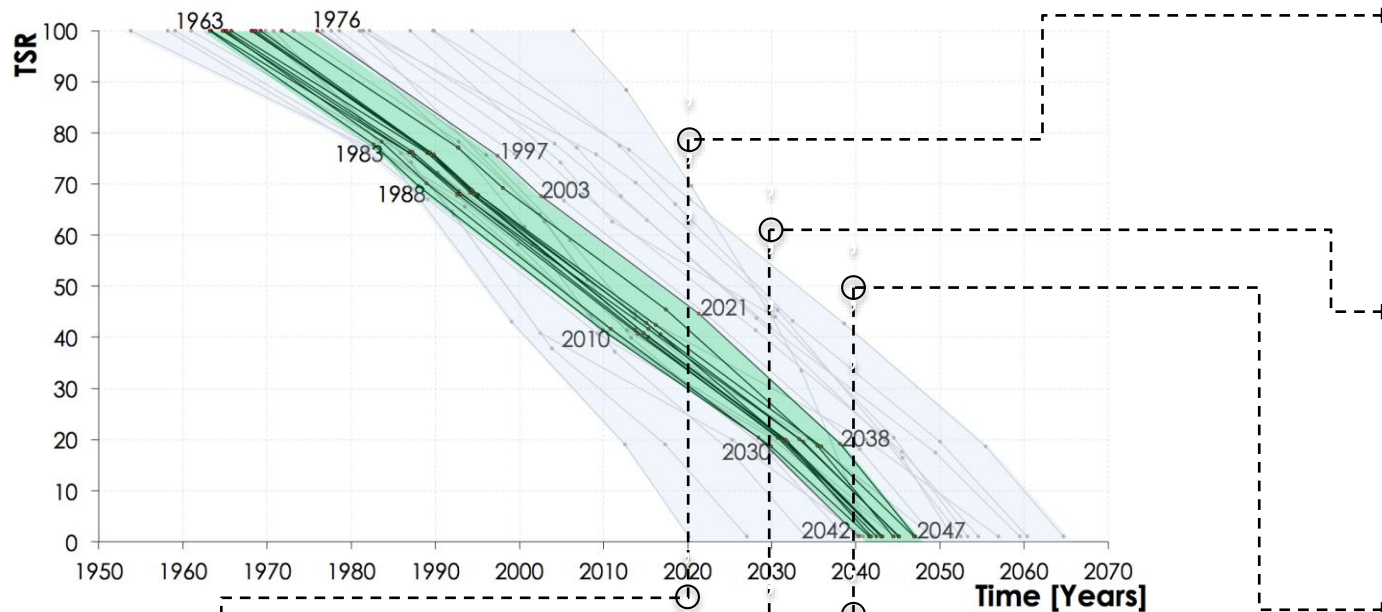
# REMAINING SERVICE LIFE FORECASTING

- Information on time intervals between consequent inspections and related CVs are stored in datasets.
- For each element it is possible to define deterioration curves updated when new data are available.



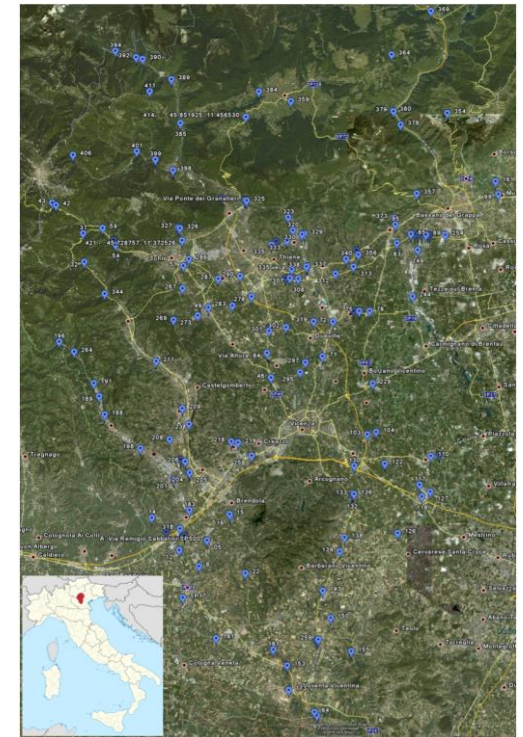
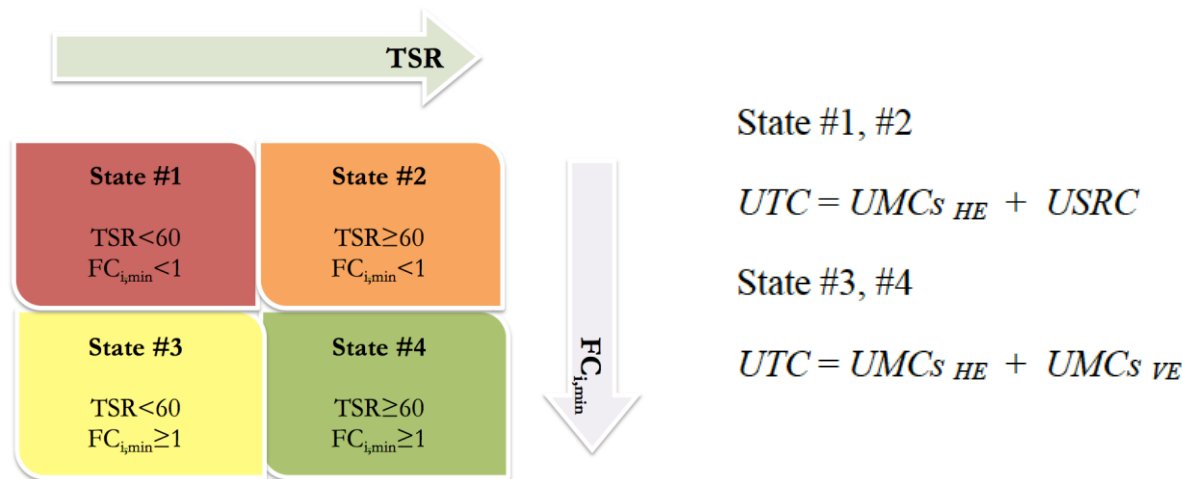
# REMAINING SERVICE LIFE FORECASTING

- *TSR* scenario forecasts for planning maintenance.



# COST MODEL FOR BRIDGE RESTORATION

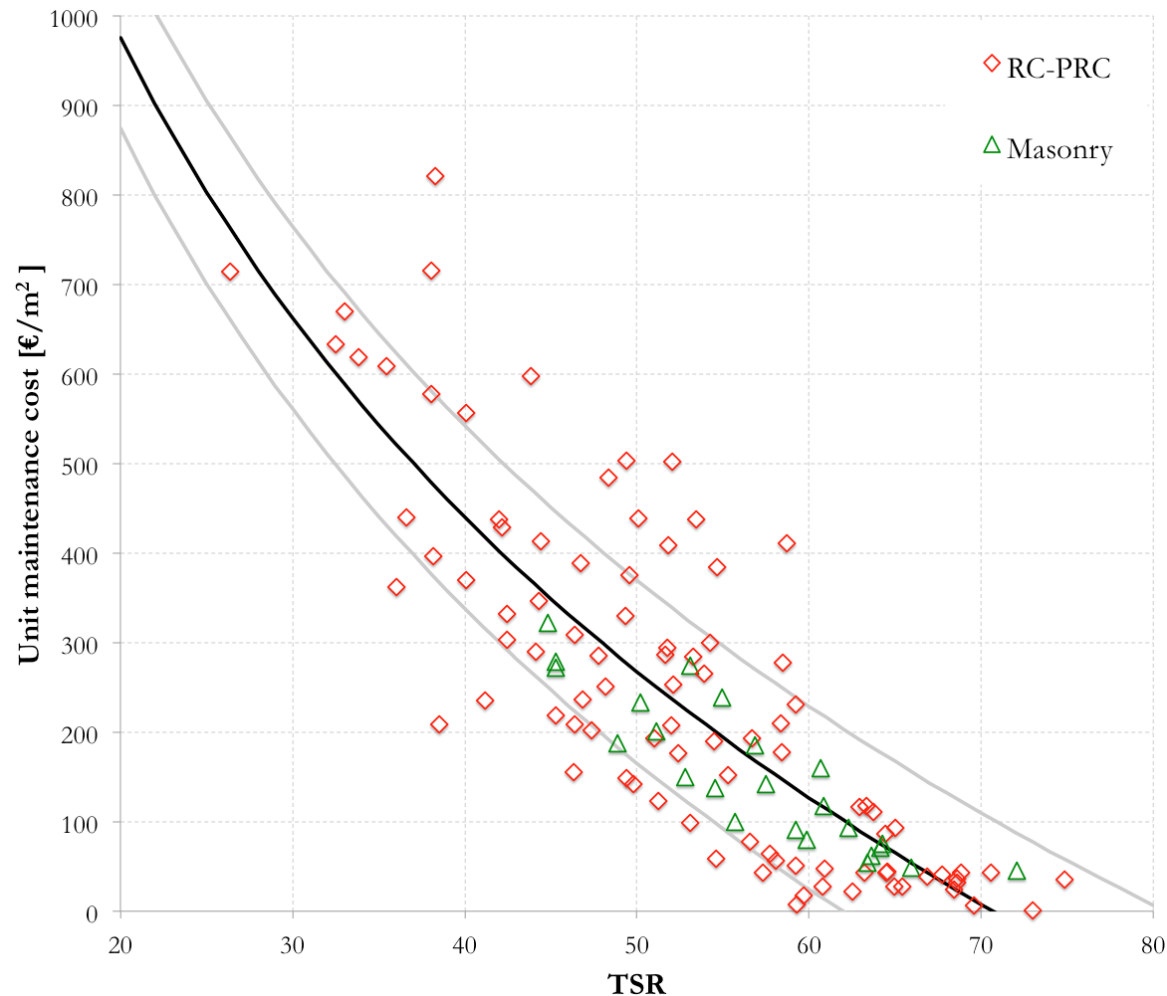
- A cost model was calibrated on the basis of *TSR* and simplified seismic vulnerability assessment of a stock of bridges in North-Eastern Italy.
- Restoration protocols have been defined for each *CV* and bridge element based on available data.



Pellegrino C. et al. (2014) "Contribution of in situ and laboratory investigations for assessing seismic vulnerability of existing bridges" *Structure and Infrastructure Engineering*, 11(9): 1147-1162.

Zanini M.A. et al. (2016). "Cost analysis for maintenance and seismic retrofit of existing bridges" *Structure and Infrastructure Engineering*, DOI 10.1080/15732479.2015.1133661.

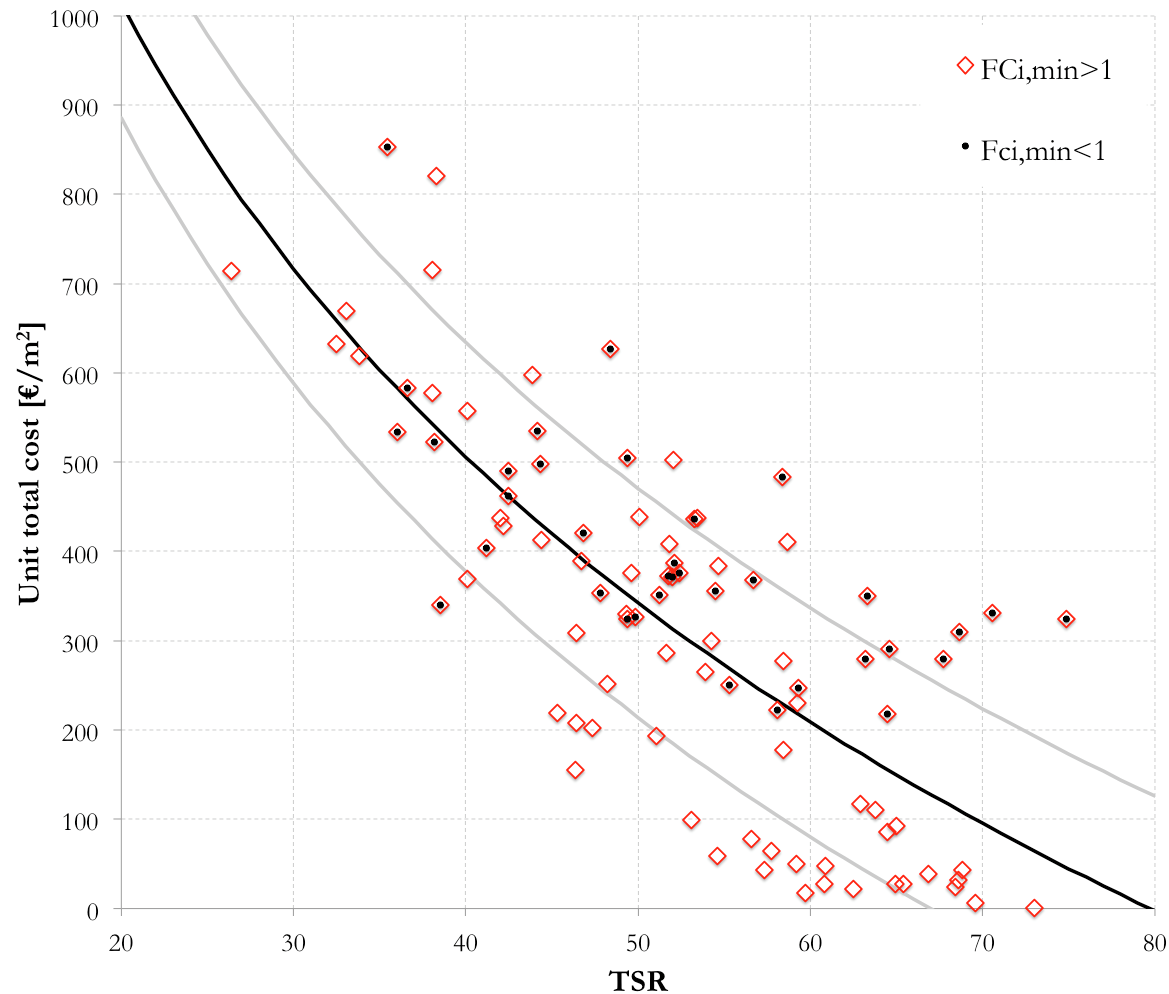
# COST MODEL FOR BRIDGE RESTORATION



Zanini M.A. et al. (2016). "Cost analysis for maintenance and seismic retrofit of existing bridges" Structure and Infrastructure Engineering, DOI 10.1080/15732479.2015.1133661.

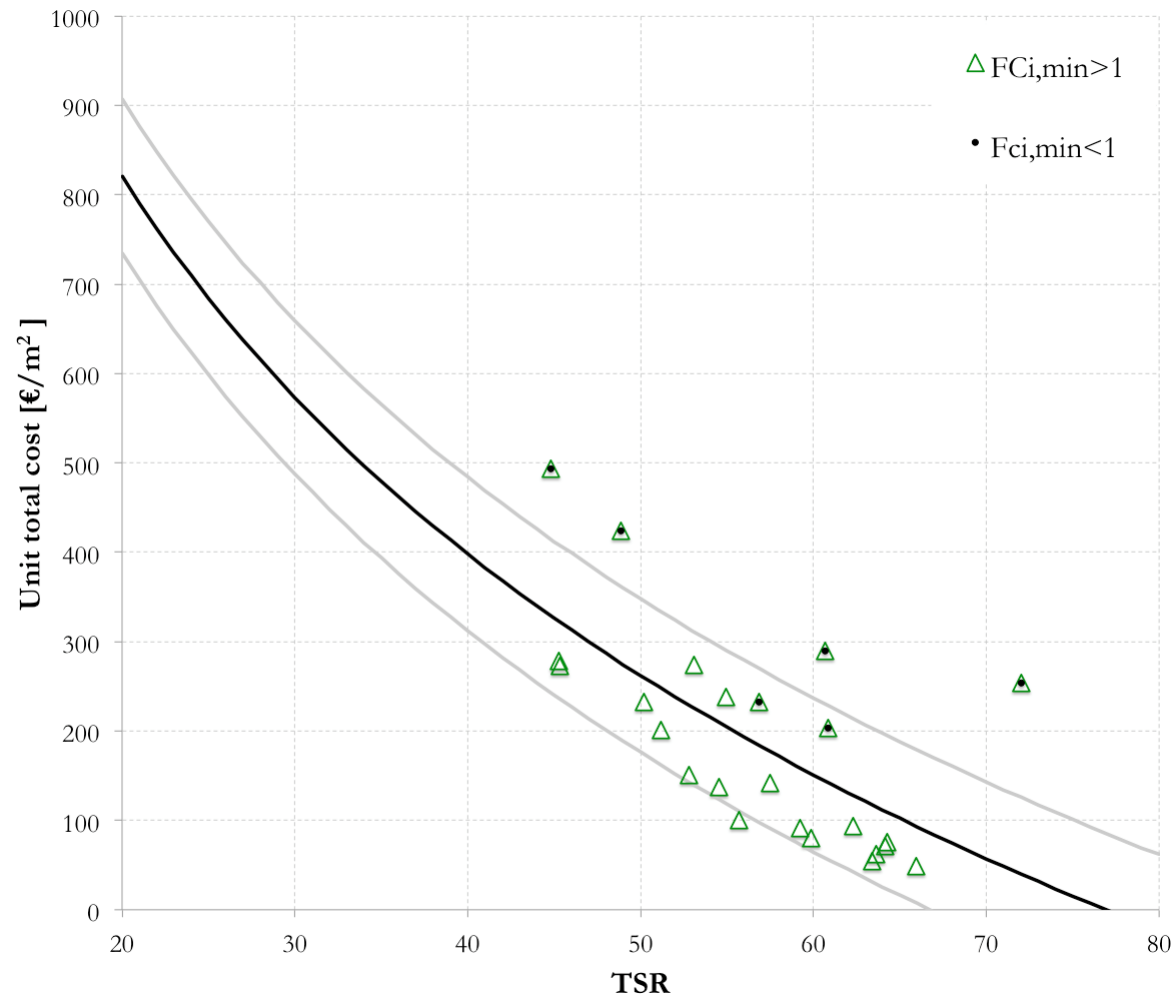


# COST MODEL FOR BRIDGE RESTORATION



Zanini M.A. et al. (2016). "Cost analysis for maintenance and seismic retrofit of existing bridges" Structure and Infrastructure Engineering, DOI 10.1080/15732479.2015.1133661.

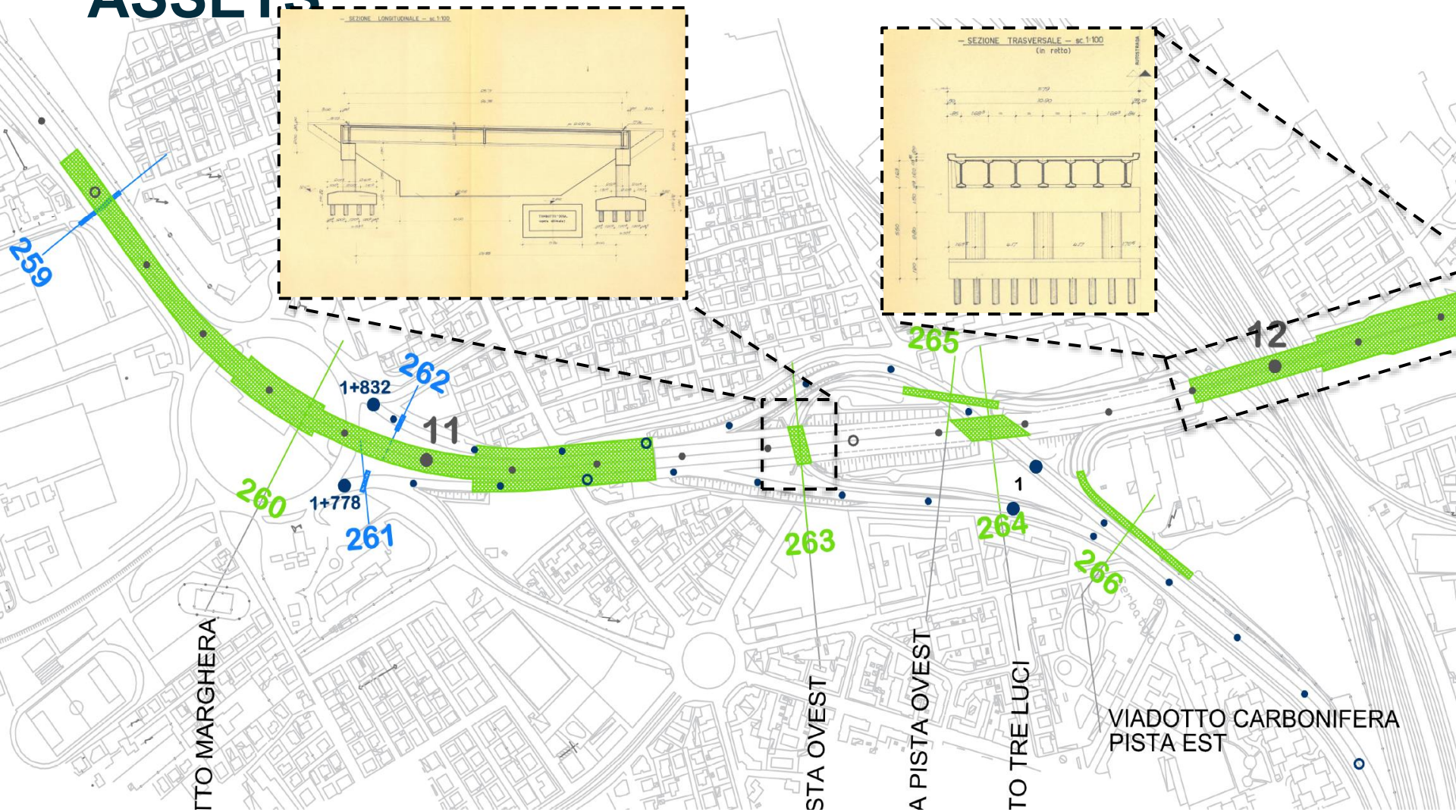
# COST MODEL FOR BRIDGE RESTORATION

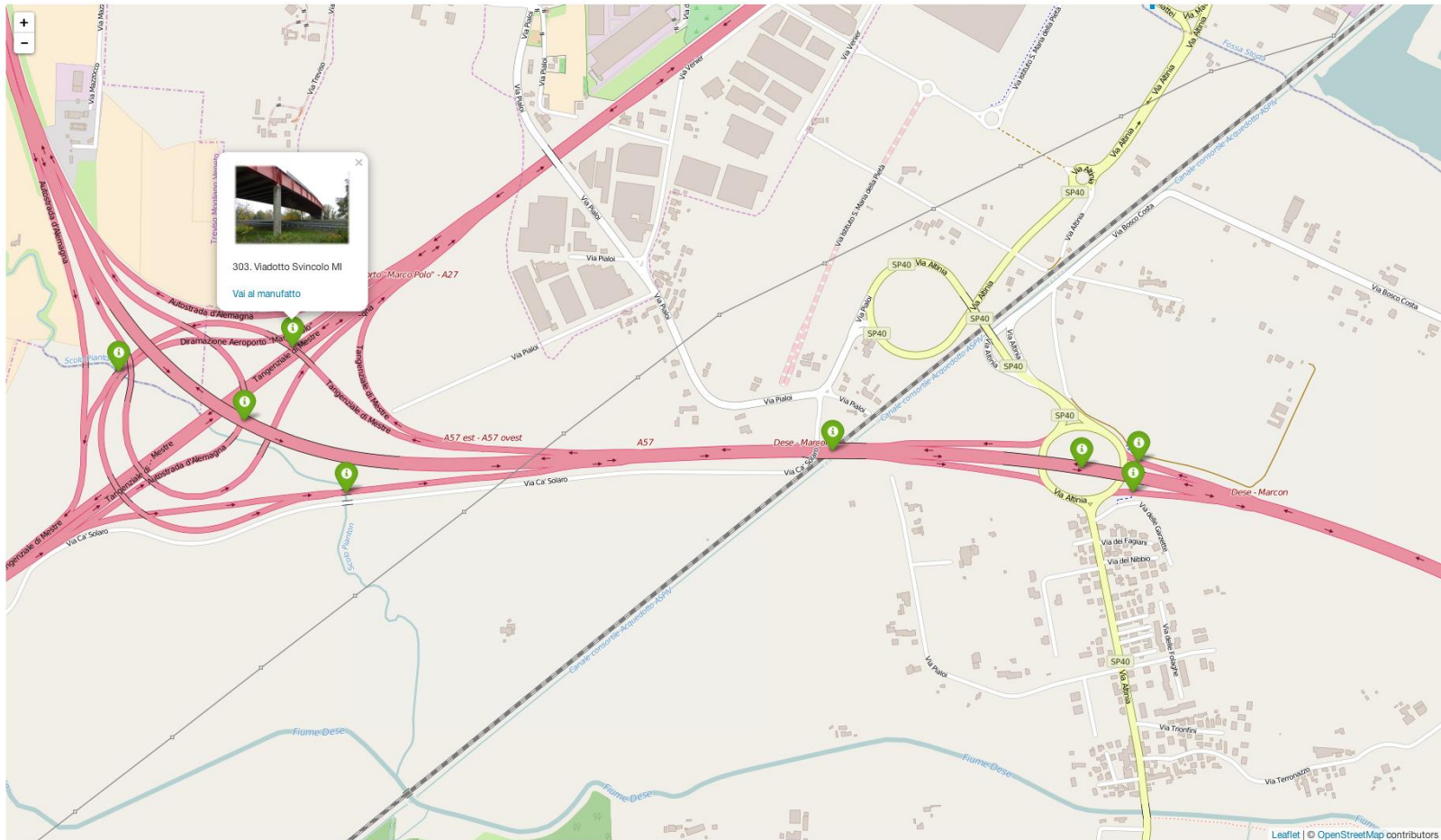


Zanini M.A. et al. (2016). "Cost analysis for maintenance and seismic retrofit of existing bridges" Structure and Infrastructure Engineering, DOI 10.1080/15732479.2015.1133661.



# APPLICATION ON EXISTING BRIDGE ASSETS







# APPLICATION ON EXISTING BRIDGE ASSETS

303. Viadotto Svincolo MI

Dati generali

Caratteristiche geometrico-strutturali

Caratteristiche elementi non strutturali

Documentazione di archivio

Ispezioni manutentive

ID MANUFATTO:	303
NOME UFFICIALE:	Viadotto Svincolo MI
NOME CONVENZIONALE:	Viadotto Svincolo MI

SCHEMA STRUTTURALE IMPALCATO:	Trave continua
MATERIALE IMPALCATO:	Travi in acciaio con soletta in c.a.
ANDAMENTO PLANIMETRICO:	Curvilineo (R=268 m)
LUNGHEZZA TOTALE [m]:	122
LARGHEZZA IMPALCATO [m]:	13

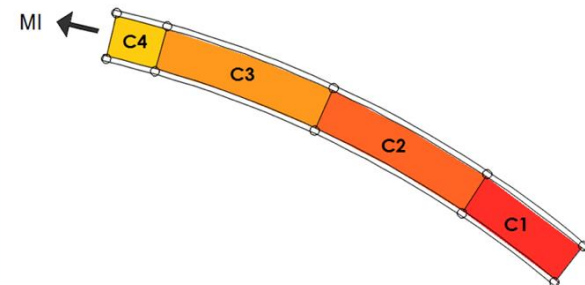
NUMERO CAMPATE:	4
LUCI CAMPATE [m]:	12 - 41 - 41 - 28
LARGHEZZA PIANO VIABILE [m]:	9.5
NUMERO CORSIE:	1
MARCIAPIEDE DI SERVIZIO SX [m]:	0.69
MARCIAPIEDE DI SERVIZIO DX [m]:	0.69
ALTEZZA UTILE MINIMA [m]:	-

SCHEMA STRUTTURALE PILE:	A telaio
MATERIALE PILE:	Calcestruzzo armato
SEZIONE PILE:	Circolare
NUMERO PILE:	3
ALTEZZA MAX PILE [m]:	8.22
TIPOLOGIA APPOGGI:	Mobili su spalla S1 e fissi su spalla S2
TIPOLOGIA GIUNTI:	-
TIPOLOGIA FONDAZIONI PILE:	Fondazioni su pali
TIPOLOGIA FONDAZIONI SPALLE:	Calcestruzzo armato

Foto generale

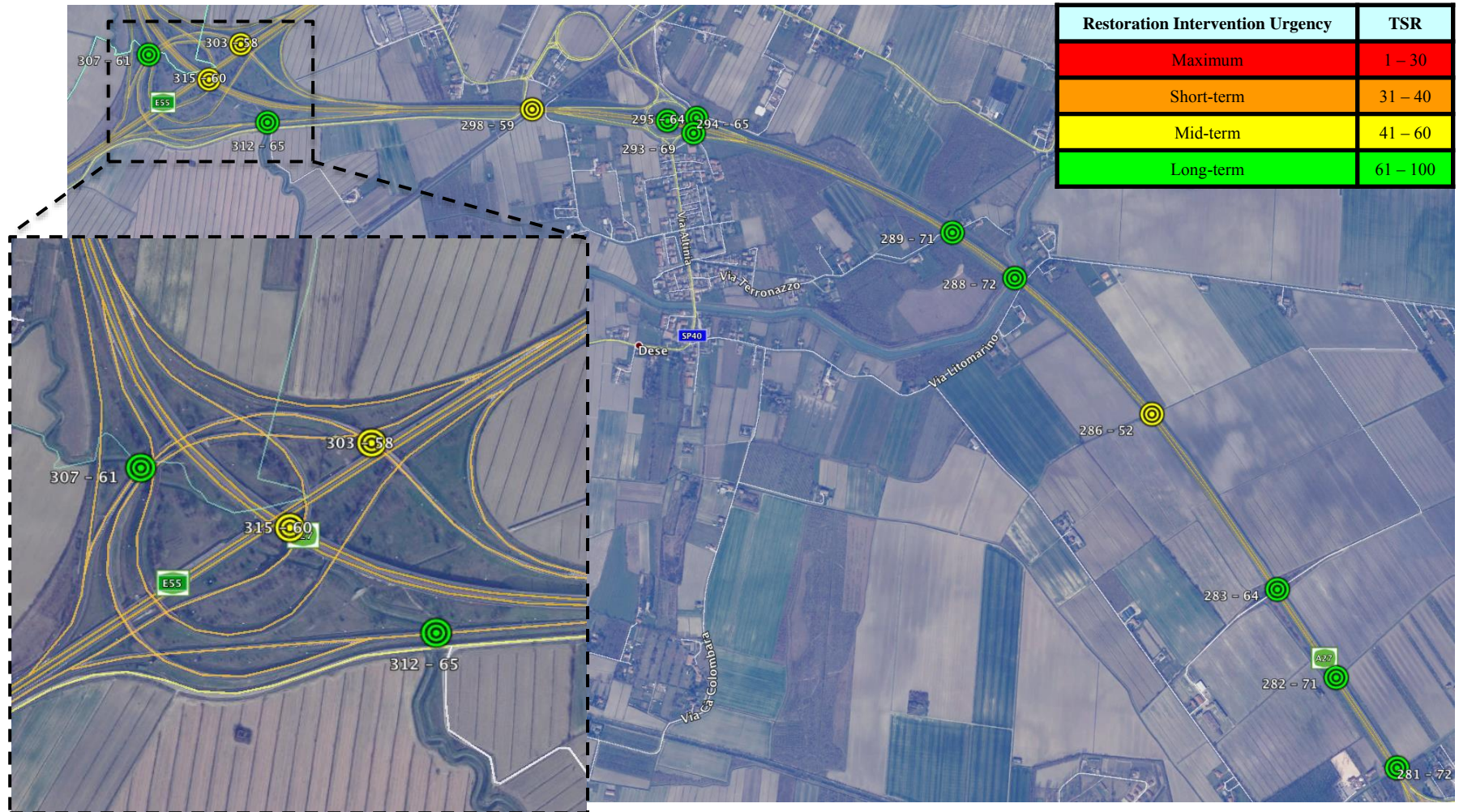


Schema campate



AGGIUNGI SCHEMA

# APPLICATION ON EXISTING BRIDGE ASSETS





[link to paper](#)

**THANKS FOR YOUR ATTENTION!**

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### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **USING AN AIR PERMEABILITY TEST TO ASSESS CURING INFLUENCE ON CONCRETE DURABILITY**

**Rui Neves** – ESTBarreiro/IPS, Portugal

**Roberto Torrent** - Quali-TI-Mat Sagl, Argentina/Switzerland

[link to paper](#)

**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**



# CONTENTS

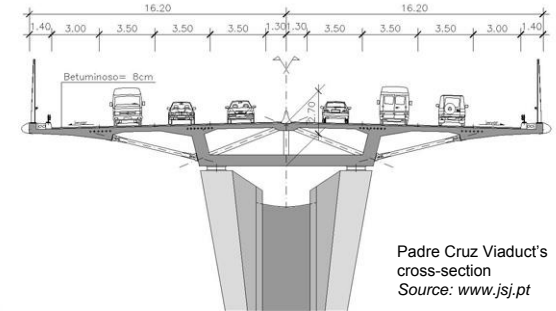
- Background and Objectives
- Experimental plan and Results
- Analysis and Conclusions

# BACKGROUND AND OBJECTIVES

- Huge amount of money is spent in the repair of bridges affected by deterioration mechanisms
- In concrete structures, the concrete itself acts as a barrier against the ingress of deleterious substances
- The concrete performance as a barrier is usually called permeability
- Traditionally, it has been intended to achieve a suitable permeability by specifying certain requirements for concrete mix, compressive strength and construction practices (prescriptive approach)
- Although simple, the prescriptive approach has several shortcomings

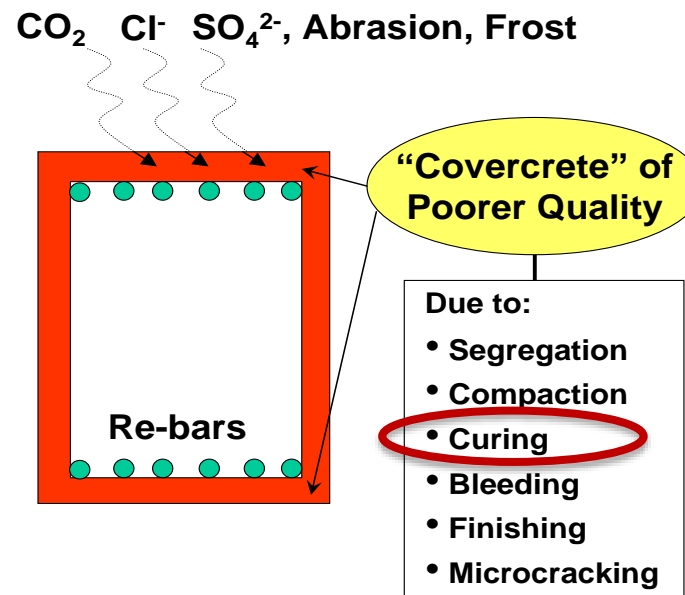
# BACKGROUND AND OBJECTIVES

- In the last decade, performance-based approaches became part of standards
- Recently, more attention has been paid to site testing in what concerns concrete durability
- In reinforced concrete structures, as bridges, the performance of cover concrete has a major relevance regarding reinforcement corrosion
- Air-permeability is acknowledged as suitable onsite performance indicator of that cover concrete

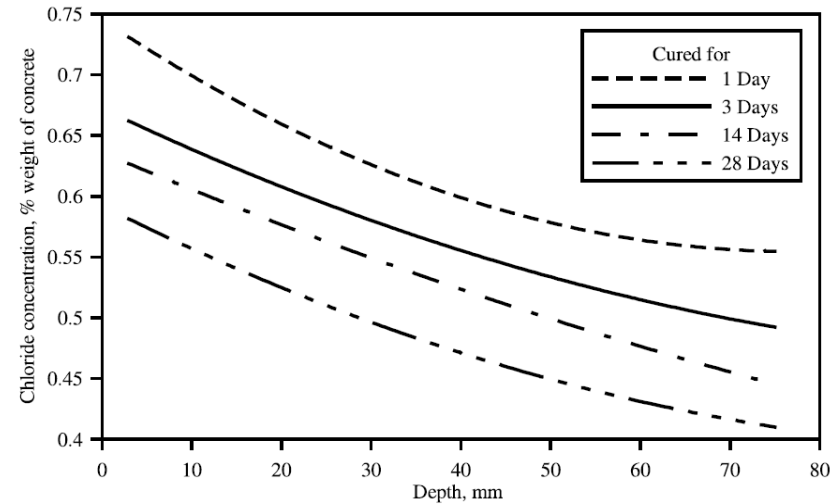
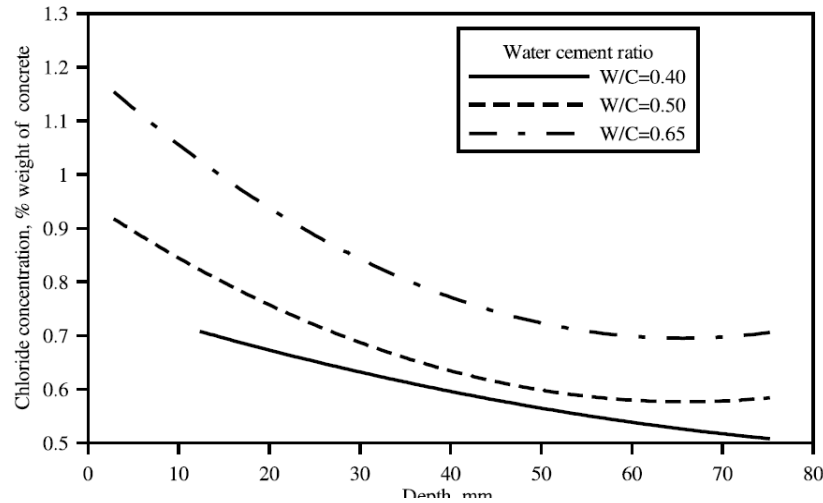


# BACKGROUND AND OBJECTIVES

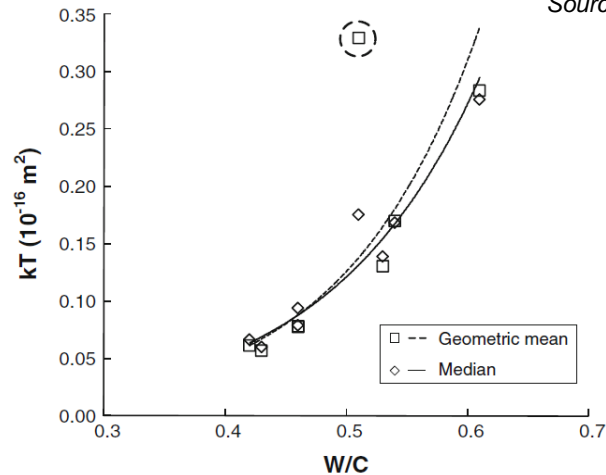
- “What is important is the recognition of test limitations so that valid interpretation of results can be made.” (Ho & Lewis. Cement and Concrete Research, 1987)
- Towards mastery of the (site) test methods



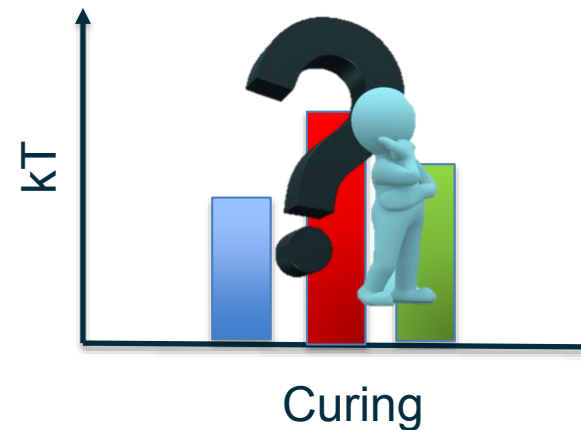
# BACKGROUND AND OBJECTIVES



Source: Bader. Cement and Concrete Composites, 2003



Source: Neves, Branco, de Brito. Materials and Structures, 2012



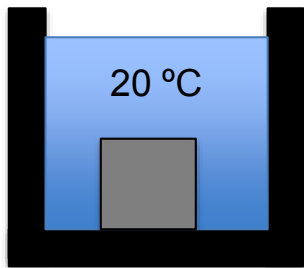
# EXPERIMENTAL PLAN AND RESULTS

- Different curing

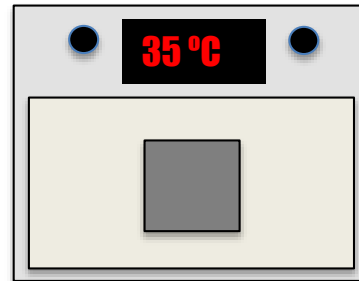
- Different binders

Blended cement (clinker + limestone powder)

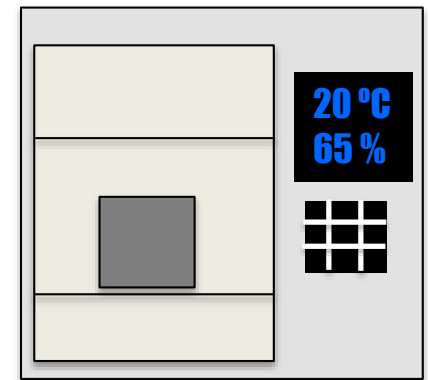
Pozzolanic cement (clinker + fly ash)



Until the age of :  
1, 3, 7, 14, 21 or 28 days



During 3 days

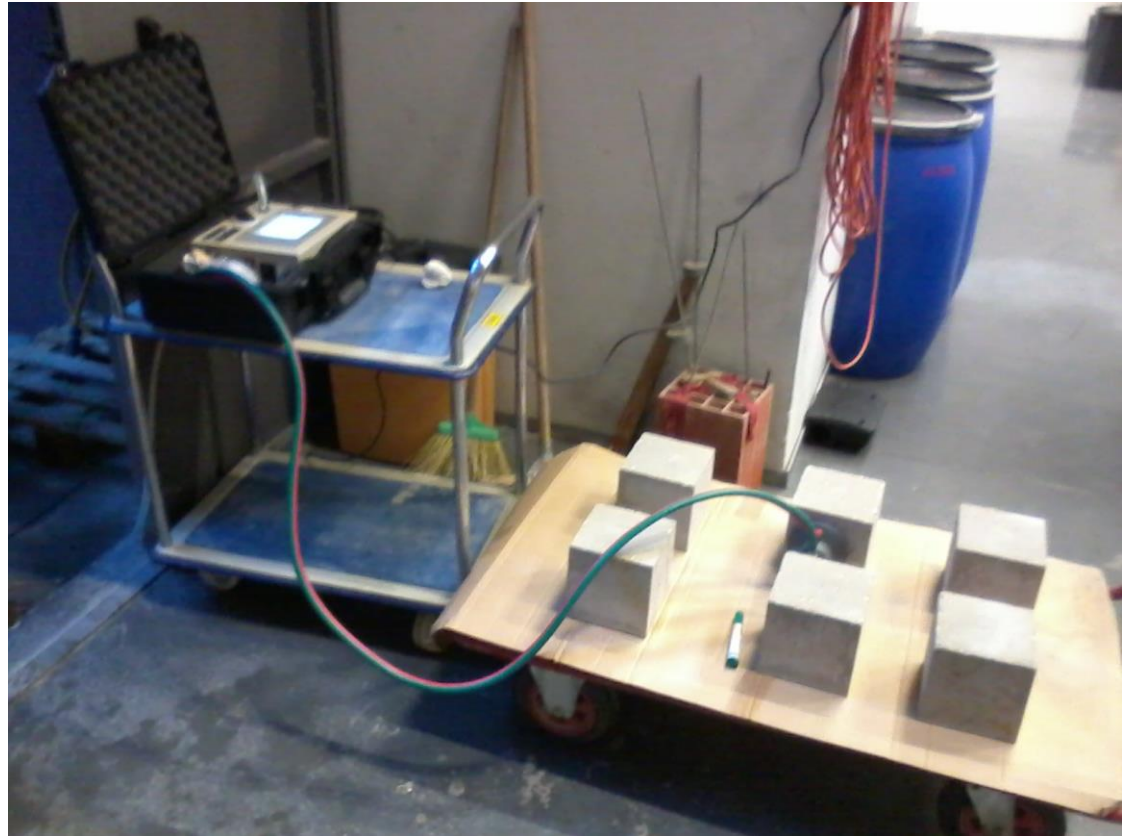


Until the age of 42 days



# EXPERIMENTAL PLAN AND RESULTS

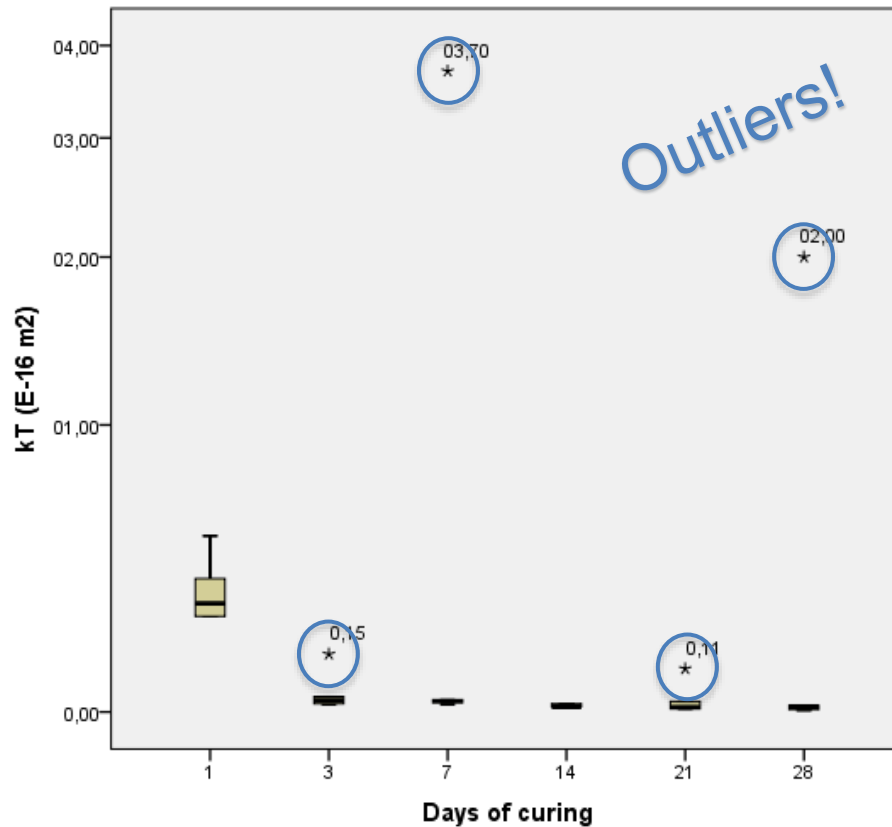
- Applied test:
  - Torrent's method
- For:
  - 2 mixes
  - 6 curing conditions
  - 1 specimen per curing condition
  - 5 tests/specimen
- Total of 60 results



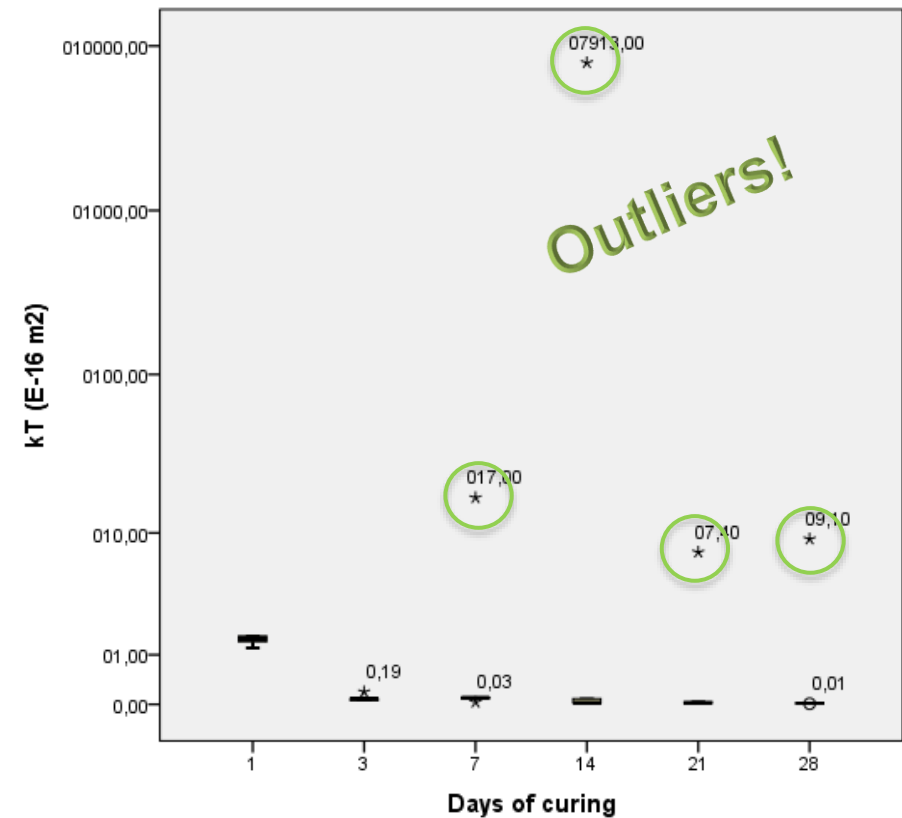
# EXPERIMENTAL PLAN AND RESULTS

- Summary of results

MIX PLC57

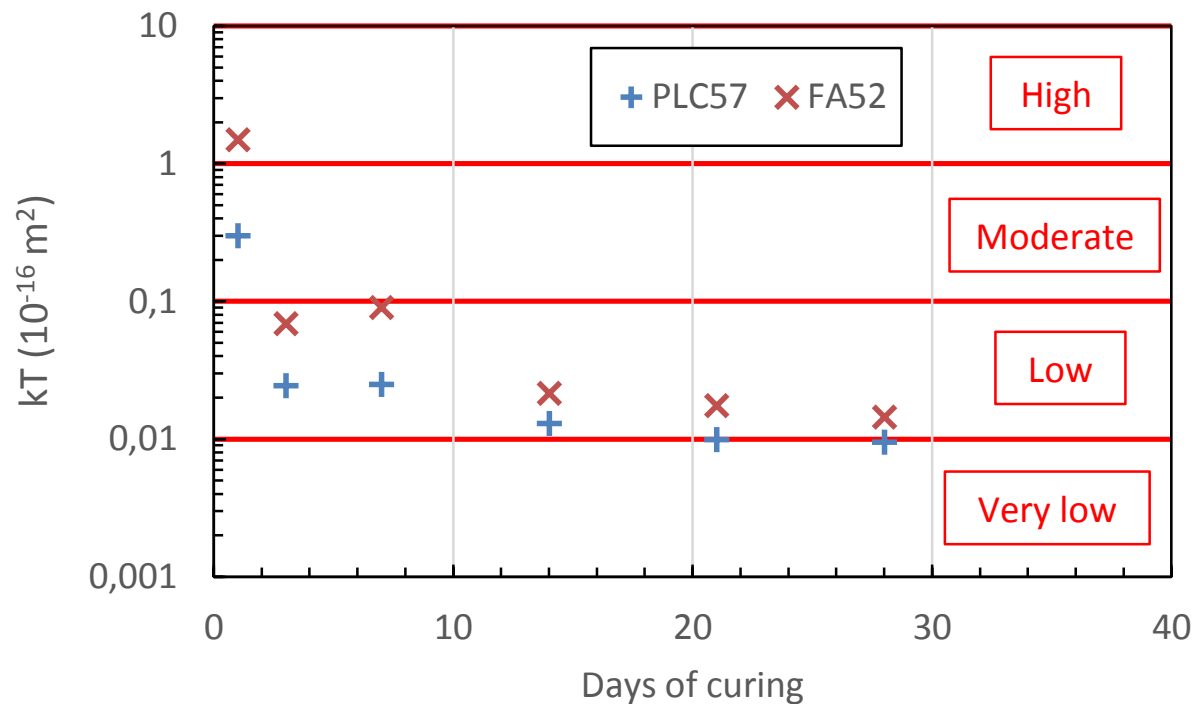


MIX FA52



# ANALYSIS AND CONCLUSIONS

- Variation of  $kT$  (median) with curing



# ANALYSIS AND CONCLUSIONS

- Differentiation capability for different curing conditions

Outlier detection according to Tukey's definition

Comparing results from different curing conditions: Mann-Whitney-Wilcoxon test at a significance level of 5%  Samples too small without outliers

Check sample normality: Shapiro-Wilk test at a significance level of 5% 

Comparing results from different curing conditions: Student test at a significance level of 5%

# ANALYSIS AND CONCLUSIONS

- Differentiation capability for different curing conditions
  - Student test p-values for mix PLC57 comparisons

Curing	1 day	3 days	7 days	14 days	21 days
3 days	4.5E-4	-	-	-	-
7 days	4.3E-4	0.37	-	-	-
14 days	1.0E-5	2.4E-2	1.1E-2	-	-
21 days	3.5E-4	4.0E-2	3.1E-2	0.32	-
28 days	3.3E-4	9.6E-3	3.5E-3	6.4E-2	0.25

# ANALYSIS AND CONCLUSIONS

- Differentiation capability for different curing conditions
  - Student test p-values for mix FAC52 comparisons

Curing	1 day	3 days	7 days	14 days	21 days
3 days	3.9E-7	-	-	-	-
7 days	4.4E-7	X	-	-	-
14 days	3.5E-7	4.6E-2	5.6E-2	-	-
21 days	3.1E-7	7.9E-4	7.9E-3	0.17	-
28 days	2.9E-7	1.3E-4	4.1E-3	9.3E-2	0.18



# ANALYSIS AND CONCLUSIONS

- For the different curing conditions considered, air-permeability varied up to two orders of magnitude
- The applied method was successful in distinguishing air-permeability in 70% of the tested situations
- Although some authors argue that wet curing beyond 7 days has a minor influence on concrete properties, the applied method was successful in distinguishing air-permeability in 42% of these situations
- However, it was not capable of distinguishing air-permeability between concretes with wet curing of 3 and 7 days

# ANALYSIS AND CONCLUSIONS

- It is believed that there was a problem with the specimens subjected to the 7-day wet curing, presumably leading to a higher permeability in these specimens
- Even if these cases are excluded from the analysis, the applied method is successful in distinguishing air-permeability in 70% of the remaining situations
- The 30% of failure situations corresponds to comparisons between concretes with wet curing of 14, 21 and 28 days

# ANALYSIS AND CONCLUSIONS

- The Torrent method is sensitive to the length of initial water curing period
- Another step towards the mastery in assessing meaningful concrete properties onsite was taken
- Nevertheless, there is still margin for improvement



[link to paper](#)

**THANKS FOR YOUR ATTENTION!**

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### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **Data-driven Decision Making on maintenance Activities in Serbia**

Momčilo Veljović - *Serbian Public Enterprise „Roads of Serbia“*

*E-Mail: momcilo.veljovic@putevi-srbije.rs*



30<sup>th</sup> March - 1<sup>st</sup> April 2016  
Belgrade, Serbia

# Introduction

„ Based on accurate data, a manager can make either correct or false decision, but the decision based on wrong data is always a wrong one “.

**Bridge Management System** – a tool which uses engineering & economic methods and collection of guidelines & standards to provide crucial information to responsible Road Authorities to make optimal decisions according to previously adopted strategy and budget.

## **Benefits of having a BMS:**

1. Overcome subjective assessment of bridge state based solely on visual inspections
2. Follow-up on effects of the applied maintenance activities
3. Optimal decision making / short term – long term



# Bridge Management System in Serbia - BPM

- System operational since 1990
- Developed by Serbian public enterprise „Roads of Serbia“ Sector for IT Management systems
- 3000 bridges on State roads
- Open, multi-segment system:
  - **Inventory data**
  - **Inspection data**
  - **Load carrying capacity**
  - Data on planned and executed maintenance activities
  - Records of exceptional traffic loadings



# Inventory data

- Location, geometry, structural system, equipment...
- Responsibilities (design, contractor, maintenance...)

BPM \ Ver 5.63.15.09.2015

Moma Pretraživanje Stanje Inventar Plan Metodologija Referentni sistem Šifarnici Izvestaji Opis Filter [isključuje selektovano] Type a question for help

### MOST - Unos i izmena inventarskih podataka

Prost Odaberi objekat ID: [ ] PDF

ID Objekta: **10409** Šifra objekta: R214-00-686-020-MPNN Stanje: **281.75**  
 Naziv Objekta: MOST PREKO REKE RAČE Rejting: **281.75**  
 Datum: 15.3.2005  
 Oцена: 2 PRIHVATLJIVO  
 Br. pr.: 2

Vrsta pripadnosti: 1 MOST U TRUPU PUTA Broj Konstrukcije: [ ]  
 Složeni obj. ID: [ ] Potrebna provera nosivosti: 0

Identifikacija Istorijat Elementi za OPIS Elementi za PREGLED Elementi za ODRŽAVANJE Slike Zapisnici Rejting

Oznaka puta: R-214 Naziv puta: MALA KRSNA-GRAN.SRBUE  
 ID deonice: 687 MARKOVAC (IZLAZ) - BATOČINA (MARKOVAC) (733-1621) Dužina: 9,882  
 ID čvora: [ ] Ime čvora: [ ] KrakČvora: [ ]

Stacionaža:

Na deonici	Početak	Sredina	Kraj
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Na kraku: [ ]  
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 Najbliže naselje: Markovac - Velika Plana Okrug: Podunavski okrug  
 Katastarski broj: [ ] Region: Centralna Srbija  
 Mogućnost obilaska: U NEPOSREDNOJ BLIZINI JE ŽELEZNIČKI MOST Država: SRBIJA  
 Naziv mikro lokacije: MARKOVAC Napomena / Predlog daljnjih aktivnosti:  
 Položaj X: 44,222447 Položaj Y: 21,094311 Uredba 2015 god. Put 158, deon. 15805.  
 Značaj Rang: [ ] MOST JE REKONSTRUISAN POSLE PRVOG PREGLEDA.  
 Stat. sistem konstr. Niz pr. greda

Record: 14 of 1778 of 3267 Filtered Search

### Inventarski podaci

INVENTARSKI LIST ZA: MOST

ID: 10409 Rejting: 281.75  
 Oцена: 2 PRIHVATLJIVO  
 Broj pregi: 2

Šifra objekta: R214-00-686-020-MPNN  
 Naziv objekta: MOST PREKO REKE RAČE  
 Vrsta pripadnosti: 1 MOST U TRUPU PUTA Broj Konstrukcije: [ ]  
 Složeni obj. ID: [ ]  
 Oznaka puta: R214 Naziv puta: MALA KRSNA-GRAN.SRBUE  
 ID deonice: 687 MARKOVAC (IZLAZ) - BATOČINA (MARKOVAC) (733-1621)

Stacionaža:

Na deonici	Početak	Sredina	Kraj
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 Najbliže naselje: Markovac  
 Katastarski broj: [ ]  
 Mogućnost obilaska: U NEPOSREDNOJ BLIZINI JE ŽELEZNIČKI MOST  
 Naziv mikro lokacije: MARKOVAC  
 Položaj X: 44,222447 Položaj Y: 21,094311  
 Značaj Rang: [ ]  
 Stat. sistem konstr. Niz pr. greda

Opština: Velika Plana  
 Okrug: Podunavski okrug  
 Region: Centralna Srbija  
 Država: SRBIJA

Napomena / Predlog daljnjih aktivnosti:  
 Uredba 2015 god. Put 158, deon. 15805.  
 MOST JE REKONSTRUISAN POSLE PRVOG PREGLEDA.

Potrebna provera nosivosti: [ ]  
 Izvedena provera nosivosti: [ ]

Elementi za Opis

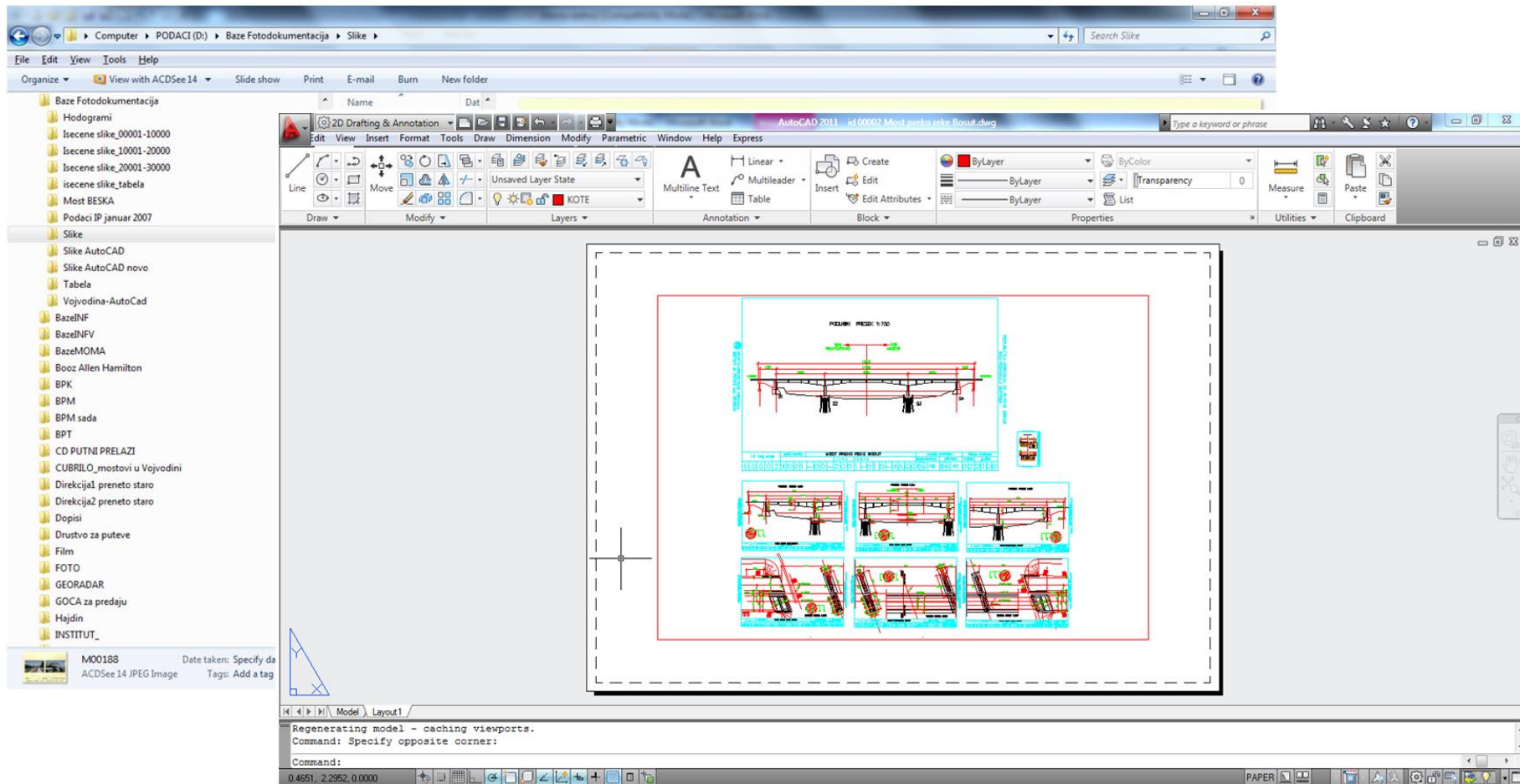
Red.	Naziv Elementa	Polovina	Vrednost	Jed.	Opis
130	VRSTA MOSTA				MOST.
140	RASPONI		28.7	m	
150	DUŽINA RASPONSKE KONSTRUKCIJE		29.3	m	
160	UKUPNA DUŽINA KONSTRUKCIJE		33.8	m	
170	ŠIRINA KOLOVOZA		7.65	m	
180	ŠIRINA LEVE PEŠAČKE STAZE		1.05	m	
190	ŠIRINA DESNE PEŠAČKE STAZE		1.05	m	
210	DILATACIONE SPRAVE VRSTA I TIP				NE POSTOJE.

15.03.2015 Strana 1 od 3

Page: 14 of 1 Filtered

# Inventory data

- Graphical documentation and pictures



# Inspection data – Bridge condition data

- Bridge Rating Score

BPM \ Ver 5.63.15.09.2015

Moma Pretraživanje Stanje Inventar Plan Metodologija Referentni sistem Šifarnici Izvestaji Opis Filter Isključuje selektovano Type a question for help

**MOST - Unos i izmena inventarskih podataka**

Prost Odbani objekat ID: [ ]

ID Objekta: 10409 Šifra objekta: R214-00-686-020-MPNN

Naziv Objekta: MOST PREKO REKE RAČE

Vrsta pripadnosti: 1 MOST U TRUPU PUTA Broj Konstrukcije: [ ]

Složeni obj. ID: [ ]

Stanje: Rejting: 281,75 Datum: 15.3.2005 Ocena: 2 PRIHVATLJIVO Br. pr.: 2

Potrebna provera nosivosti: 0

Identifikacija Istorijat Elementi za OPIS Elementi za PREGLED Elementi za ODRŽAVANJE Slike Zapisnici Rejting

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2	15.3.2005	200500100004326 / 15.3.2005 - SISTEMATSKI PRE	281,75	PRIHVATLJIVO	2

1 6.1 MOST - Stanje

ID stanje objekta: 2 Datum stanja: 15.3.2005 ID Objekta: 10409 Rejting: 281,75

Naziv objekta: MOST PREKO REKE RAČE Ocena stanja: P9 PRIHVATLJIVO (150-300)

Zapisnik o pregledu: 200500100004326 / 15.3.2005 - SISTEMATSKI PREGLED Tip održavanja: REDOVNO ODRŽAVANJE I KONTROLA

Napomena: [ ]

Stanje objekta po elementima Broj pregleda: 2

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3	TEMELJI SREDNJIH STUBOVA	NEMA ZNAKOVA NEPOVOLNIH POJAVA	1 DOBRO	Rejting elementa: 11,30 Fak.znač: 11,3
4	KRAJNJI STUBOVI SA KRILIMA U SASTAVU STUBOVA	NEMA OSTEĆENJA	1 DOBRO	Rejting elementa: 11,30 Fak.znač: 11,3
5	SLOBODNO STOJEĆA KRILA		0 NE POSTOJE	Rejting elementa: 0,00 Fak.znač: 8
6	SREDNJI STUBOVI	KRAJNJI STUBOVI POVEZANI TAKO DA CINE PO DVA PLATNA	5 PRIHVATLJIVO	Rejting elementa: 56,50 Fak.znač: 11,3
7	LEŽAJE	POSTAVLJENO NOVO	1 DOBRO	

Record: 1 of 1 Filtered Search

**Stanje objekta**

**STANJE OBJEKTA**

**VRSTA OBJEKTA: MOST**

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Broj zapisnika: 200500100004326  
Datum pregleda: 15.3.2005  
Vrsta pregleda: SISTEMATSKI PREGLED  
Učesnici u pregledu: N.VUKELJIC, R.LATINOVIC, Z.MILJIC  
Odgovorno lice: [ ]

ID Objekta: 10409  
Šifra objekta: R214-00-686-020-MPNN  
Naziv objekta: MOST PREKO REKE RAČE

Rejting: 281,75 Kategorija stanja: PRIHVATLJIVO

Ocena rejtinga: P9 PRIHVATLJIVO (150-300)

Tip održavanja: REDOVNO ODRŽAVANJE I KONTROLA

6.1 PREGLED KRAJNJIH STUBOVA

Factor a ređaja: 11,5  
Ocena stanja: 1  
Kategorija stanja: DOBRO  
Opis stanja elementa: NEMA ZNAKOVA NEPOVOLNIH POJAVA

6.2 PREGLED SREDNJIH STUBOVA

Factor a ređaja: 11,5  
Ocena stanja: 1  
Kategorija stanja: DOBRO  
Opis stanja elementa: NEMA ZNAKOVA NEPOVOLNIH POJAVA

7.0 KRAJNJI STUBOVI SA KRILIMA U SASTAVU STUBOVA

Factor a ređaja: 11,5  
Ocena stanja: 1  
Kategorija stanja: DOBRO  
Opis stanja elementa: NEMA OSTEĆENJA

8.0 SLOBODNO STOJEĆA KRILA

Factor a ređaja: 0  
Ocena stanja: 0  
Kategorija stanja: NE POSTOJE  
Opis stanja elementa:

9.0 SREDNJI STUBOVI

Factor a ređaja: 11,5  
Ocena stanja: 5  
Kategorija stanja: PRIHVATLJIVO  
Opis stanja elementa: KRAJNJI STUBOVI POVEZANI TAKO DA CINE PO DVA PLATNA

10.0 LEŽAJE

Factor a ređaja: 11,5  
Ocena stanja: 1  
Kategorija stanja: DOBRO  
Opis stanja elementa: POSTAVLJENO NOVO NEOPRANIKO LEŽAJE

15.03.2015 Strana 1 od 4

Page: 1 of 1 Filtered

# Inspection data – condition assessment of bridge

- Methodology for rating of bridges / Version SR-03 (1998)
  - Inspection data in 4 groups:
    - Safety items (load-carrying elements)
    - Expected further deterioration items (waterproofing, pavement ...)
    - Serviceability items (bridge equipment)
    - Additional prioritization items (ADT, location in network...)
  - 28 elements are rated

Partial Rating Scores

$$R = R1 + R2 + R3 + R4 = \sum_{i=1}^{28} a_i b_i$$

Condition state (inspection based) ↑

↓  
Impact factors (importance based)

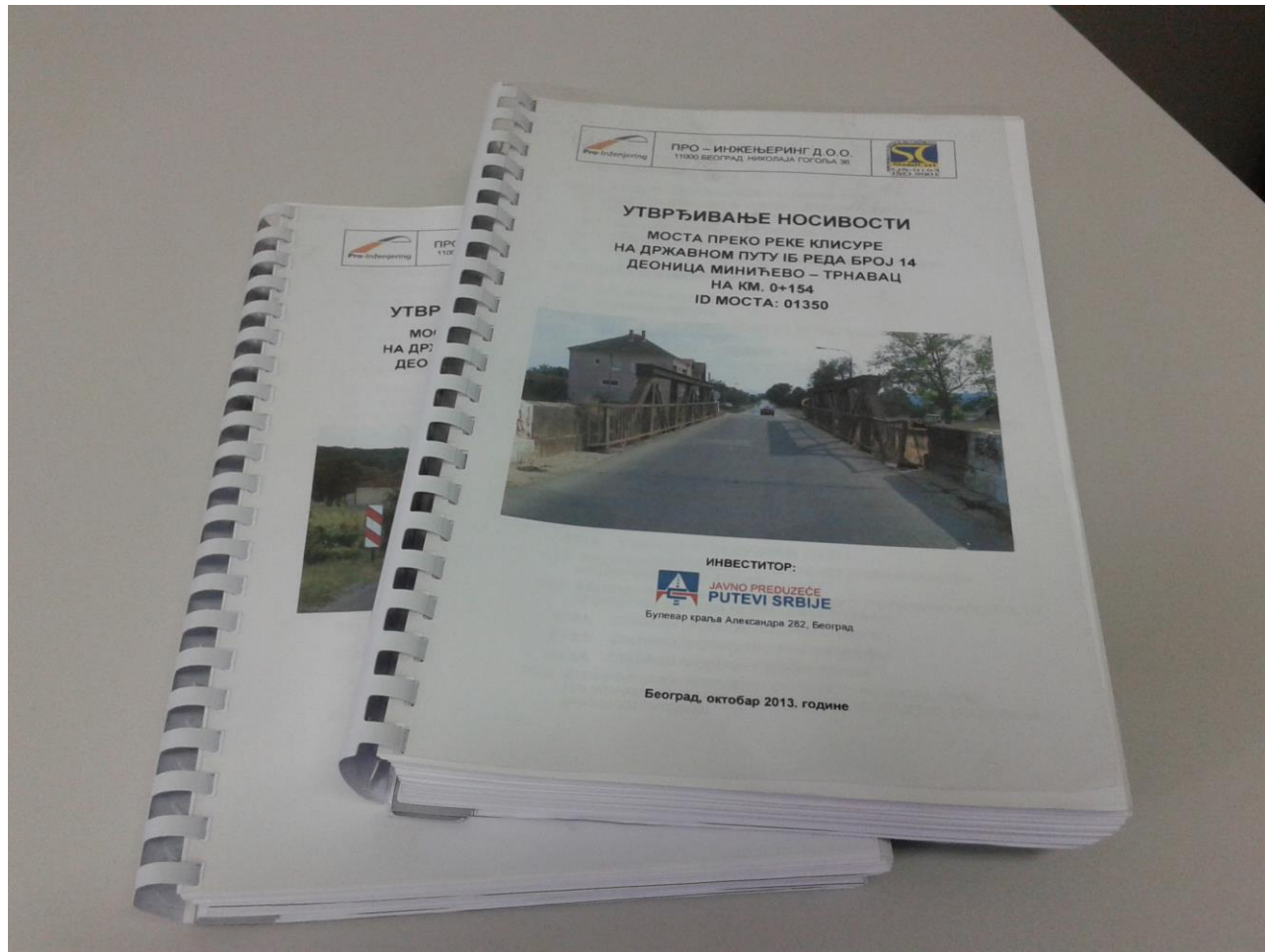


# Load carrying capacity (of a damaged bridge)

- **Guidelines for estimating load carrying capacity of existing bridges on state roads**
  - Special criteria used for bridges with high rating scores (Bridges in class 5 and 6 with uncertain repair schedule)
  - Evaluation of load carrying capacity for deteriorated elements & traffic loading update
- **Actions for bridges which do not meet certain requirements**
  - Traffic restriction / bridge closure
  - Minor repairs / urgent repair
- **Challenge**
  - No or insufficient project documentation
  - Special inspections with research works are necessary



# Load carrying capacity - technical documentation





# Application of the BMS data

- Rating list / total & partial rating scores

BPM \ Ver 5.63.15.09.2015

Moma Pretraživanje Stanje Inventar Plan Metodologija Referentni sistem Šifarnici Izvestaji Opis Filter [uključuje selektovano] Type a question for help

Rejting - MOST

Odaberi objekat ID:

Izbor: ☒ Aktivni ☐ Pasivni ☐ Svi Formiraj listu

Obrisi Uslov: ArhiviranDatum = 0  
Uslov prethodni: ArhiviranDatum = 0

ID	Naziv	Datum	Šif. st.	Oцена
10982	MOST PREKO REKE VETERNICE (1)	6.12.2004	O3	OPASNO
10983	MOST PREKO REKE VETERNICE (2)	5.1.1994	O3	OPASNO
15109	SRUŠENI MOST U JAMENI	1.5.2002	O3	OPASNO
10500	MOST PREKO REKE CRNICE U SELU SISEVAC	12.1.1992	O3	OPASNO
10714	MOST PREKO TIMOKA U ZAJEČARU	7.1.1993	O3	OPASNO
10496	MOST PREKO REKE RESAVE (1)	11.1.2005	O3	OPASNO
10901	MOST PREKO LOMNIČKE REKE	5.1.1993	O3	OPASNO
10728	MOST PREKO REKE PEK (5)	8.12.2004	O3	OPASNO
13759	MOST PREKO MIRIČKE REKE	23.8.2006	O3	OPASNO
10717	MOST PREKO KURVINOG POTOKA	6.9.2004	O3	OPASNO
10744	MOST PREKO SIKOLSKKE REKE	13.9.2004	O3	OPASNO
10503	MOST PREKO REKE RAVANICE U SELU SENJE	2.3.2005	O3	OPASNO
10835	MOST PREKO REKE KAMENICE	15.12.2004	O3	OPASNO
10523	MOST PREKO REKE KAMENICE U SELU TOPOLA	26.6.2006	O3	OPASNO

Record: 1 of 3176 Filtered Search

Rejting objekta

VRSTA OBJEKTA: MOST

ID	Naziv objekta	Datum	Šifra stanja	Oцена stanja	Oцена Rejting	R1	R2	R3	R4	M
10982	MOST PREKO REKE VETERNICE (1)	6.12.2004	O3	OPASNO	6	9752,4	9249,5	260,35	226,5	16
10983	MOST PREKO REKE VETERNICE (2)	6.12.2004	O3	OPASNO	6	7506,1	7169,8	237,75	162,5	16
15109	SRUŠENI MOST U JAMENI	1.5.2002	O3	OPASNO	6	6236,2	5923	148,2	141,1	23,9
10500	MOST PREKO REKE CRNICE U SELU SISEVAC	12.1.1992	O3	OPASNO	6	6225,7	5810	203,5	172,5	39,7
10714	MOST PREKO TIMOKA U ZAJEČARU	7.1.1993	O3	OPASNO	6	5752,1	5463,5	173,9	90,8	23,9
10496	MOST PREKO REKE RESAVE (1)	11.1.2005	O3	OPASNO	6	5355,9	5023,3	153	165,55	14
10728	MOST PREKO REKE PEK (5)	8.12.2004	O3	OPASNO	6	5197,3	4899	153	128,3	16
13759	MOST PREKO MIRIČKE REKE	23.8.2006	O3	OPASNO	6	5113,3	4754	187,35	157,9	14
10744	MOST PREKO SIKOLSKKE REKE	13.9.2004	O3	OPASNO	6	4434,2	4119,3	113,7	187,2	14
10717	MOST PREKO KURVINOG POTOKA	4.1.1993	O3	OPASNO	6	4353,2	4002	154,5	164,8	31,9
10503	MOST PREKO REKE RAVANICE U SELU SENJE	2.3.2005	O3	OPASNO	6	4327	4051	117	144,95	14
10523	MOST PREKO REKE KAMENICE U SELU TOPOLA	26.6.2006	O3	OPASNO	6	4263,5	3945,5	153	142,95	22
10835	MOST PREKO REKE KAMENICE	15.12.2004	O3	OPASNO	6	4296,9	3979	159,6	102,25	16
10502	MOST PREKO PRDANOVAČKOG POTOKA	12.1.1992	O3	OPASNO	6	4212,7	3832,5	154	186,5	39,7
14773	MOST PREKO REKE ŠTIRE 6	17.12.2004	O3	OPASNO	6	4143,4	3843,8	149	136,6	14
15106	MOST PREKO SUVOG POTOKA	1.5.2002	O3	OPASNO	6	3995,5	3695,6	111,2	170,8	27,9
1597	MOST PREKO SUVE PREPEKVE	20.4.2004	N9	NEPOVOLNO	3	3968,1	3685,6	191,25	95,2	6
10858	MOST PREKO REKE DAVIDOVCE	27.10.2005	O5	DOBRO	1	3955,1	3712,5	123,35	113,2	6
10146	MOST PREKO REKE MOŠTANICE U SELU KRUŠAR	11.1.1992	N9	NEPOVOLNO	3	3917,8	3531,2	222,4	124,5	39,7
10143	MOST PREKO GLADNANSKOG (Dubokog) POTOKA	11.1.1992	O3	OPASNO	6	3908,1	3511	136,9	220,5	39,7
10512	MOST PREKO REKE JASENICE	12.1.1992	O3	OPASNO	6	3639,2	3203,5	239,5	156,5	39,7

Uslov: ArhiviranDatum = 0  
18.03.2016

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# Application of the BMS data

- Sector for Road Maintenance
  - Regular maintenance (basic information)
  - **Prioritizing of interventions beyond regular maintenance for bridges are based on the rating score (score 5 & 6)**
- Insufficient funds

Q: Full repair on a few bridges or partial repairs on several bridges?  
Additional criteria are necessary

  - Available funds
  - **Partial rating scores for structural elements**
  - **Partial rating scores for traffic elements**
  - Road importance & traffic loading

# Application of the BMS data

- **Sector for for strategy, designing and development**
  - Scheduling of repairs
  - **Prioritizing of interventions is based on the rating score/insufficient load carrying capacity**
- **Sector for Investments**
  - Rehabilitation of entire roadway sections (bridge types & geometry)
- **Planning of special transport**
  - Load carrying capacity

# Challenges

- **State budget cuts**
  - Database information is obsolete or not up-to-date
  - Uncertain schedule for repairs & maintenance
  - Insufficient manpower
  - **Development of BMS segments is impeded !**
- **Four sectors in the Serbian public road enterprise**
  - Tasks overlapping
  - Communication between sectors is not optimal
  - Database is not multi-user oriented !



# Future steps in BMS development

- **Web oriented, multi-user BMS with a GIS platform is necessary**
- **Update of all BMS segments**
  - Inventory data as a basis for a definition of quantities of regular maintenance works
  - Inspection data should comprise assessments of necessary repair works
  - Carrying capacity and special transport data update
- **Additional segments development**
  - Modeling of deterioration
  - Natural hazards (flooding events)

# Conclusion

- The development of Information system for bridges must not be impeded by budget cuts
- The development should be carefully planned and carried out in stages taking into consideration technological & software aspects and human resources.



**THANKS FOR YOUR ATTENTION!**

[WWW.TU1406.EU](http://WWW.TU1406.EU)



### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

## **COST354**

# **The way forward for pavement performance indicators across Europe**

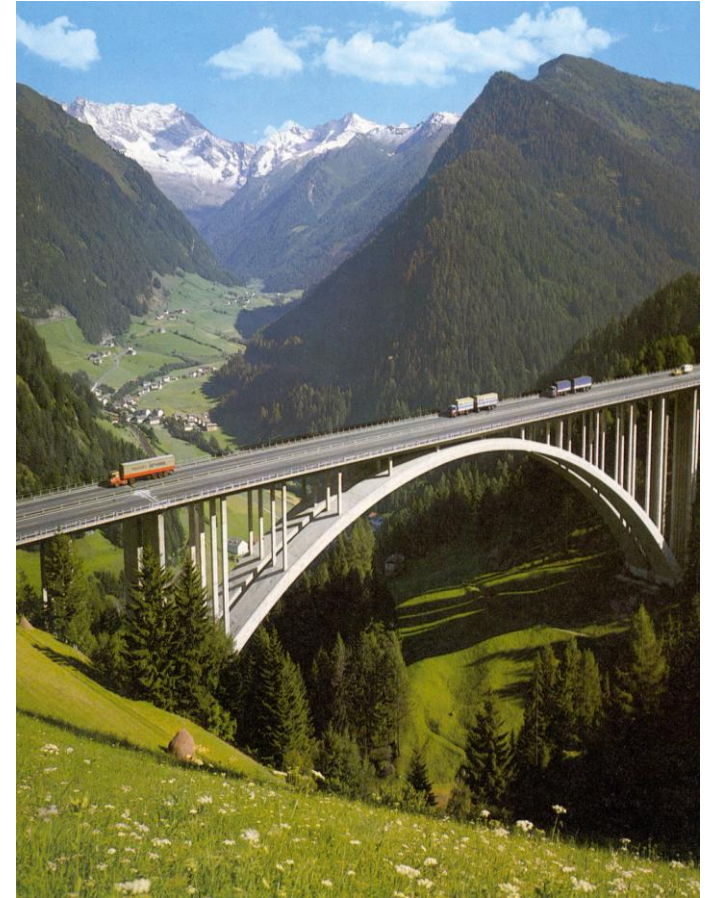
**Dr. Alfred Weninger-Vycudil – PMS-Consult Ltd., Austria**



**30<sup>th</sup> March - 1<sup>st</sup> April 2016  
Belgrade, Serbia**

# CONTENTS

- COST at a glance
- Introduction COST354
- Objectives and benefits
- Scientific program and organization
- Output and results of Work Packages
- Short term scientific missions
- Implementation and following up projects



# COST AT A GLANCE



**COST – European Cooperation in the field of Scientific and Technical Research** – is an European platform supporting cooperation among scientists and researchers across Europe. **COST** is an European intergovernmental network for coordination of nationally funded research activities.

**COST** mission is to strengthen Europe in scientific and technical research through the support of European cooperation and interaction between European Researchers.



COST is supported by  
the EU RTD Framework Programme

ESF provides the COST Office  
through an EC contract

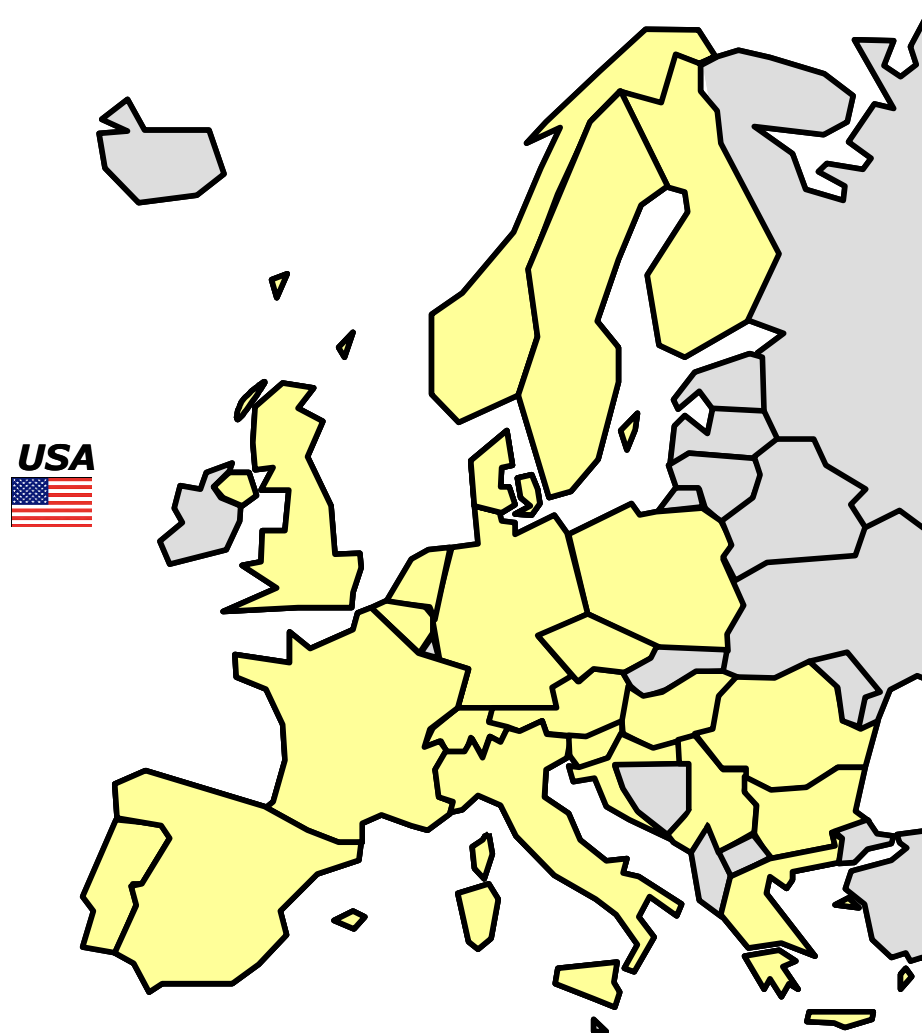




# **COST354 – PERFORMANCE INDICATORS FOR ROAD PAVEMENTS**

- **Initiated by FEHRL** (Forum of European National Highway Research Laboratories) and AT
- **Duration: 4 years** (+0.5 year extension)
- **Kick-Off-Meeting: March 2004**
- **COST-Domain: Transport and Urban Development**
- **24 participating countries:** 23 European countries and USA (FHWA)

# COST354 MEMBERS



**Austria**  
**Belgium**  
**Bulgaria**  
**Croatia**  
**Czech Republic**  
**Denmark**  
**Finland**  
**France**  
**Germany**  
**Greece**  
**Hungary**  
**Italy**  
**Netherlands**  
**Norway**  
**Poland**  
**Portugal**  
**Romania**  
**Serbia Montenegro**  
**Slovenia**  
**Spain**  
**Sweden**  
**Switzerland**  
**United Kingdom**  
**United States of America**

***Total: 24 Countries***

# OBJECTIVES

- **Definition of uniform European Performance Indicators for Road Pavements (PI)** taking the needs of road users and road operators into account
- **Definition of PI for different types of pavements and road categories**
- **Specification of limits and acceptance values for single (individual) PI** (for projected and existing roads)
- **Definition of single PI and grouping to combined PI**
  - Functional PI
  - Structural PI
  - Environmental PI
- **Definition of a general PI** (for describing overall pavement condition) -> **Basis for optimization procedures**

# BENEFITS

- Comparison of road networks and identification of investment requirements
- Basis for the development of international standards regarding to pavement condition
- PI for national and international road audits
- Widening the market for supervision and construction within Europe and thus strengthening the competition
- Use of PI as target criteria in life cycle analysis (pavement design, systematic road maintenance) at the national and the European levels
- Evaluation of effects of different design and maintenance strategies
- PI as objective assessment criteria in the context of privatization (PPP, BOT)



# COST354 WEBSITE



**COST 354** PERFORMANCE INDICATORS FOR ROAD PAVEMENTS

hosted by **ZAG**

Home Solutions Objectives Benefits Work programme Organisation Timetable Members Deliverables

## Home

### Welcome

The specification of performance criteria from the perspectives of both road users and road operators is a key prerequisite for the efficient design, construction and maintenance of road pavements. Particularly the increasing use of life-cycle analyses as a basis for the selection of road pavements and the decision of whether or not to implement a systematic road maintenance scheme calls for an exact definition of the goals to be achieved and/or the performance criteria to be satisfied. The extent to which goals are reached or performance criteria satisfied can be quantified by calculating special indexes characterizing the road pavement, which in turn permits an assessment of the efficiency of certain approaches from both a commercial and a macro-economic standpoint.

For a Europe-wide harmonization of standards to be met by road pavements it therefore appears useful and appropriate to specify pavement characteristics in terms of uniform "performance indicators" for different road categories.

[Download project overview \(PDF\)](#)

This COST Action was initiated by:



**<http://cost354.zag.si>**

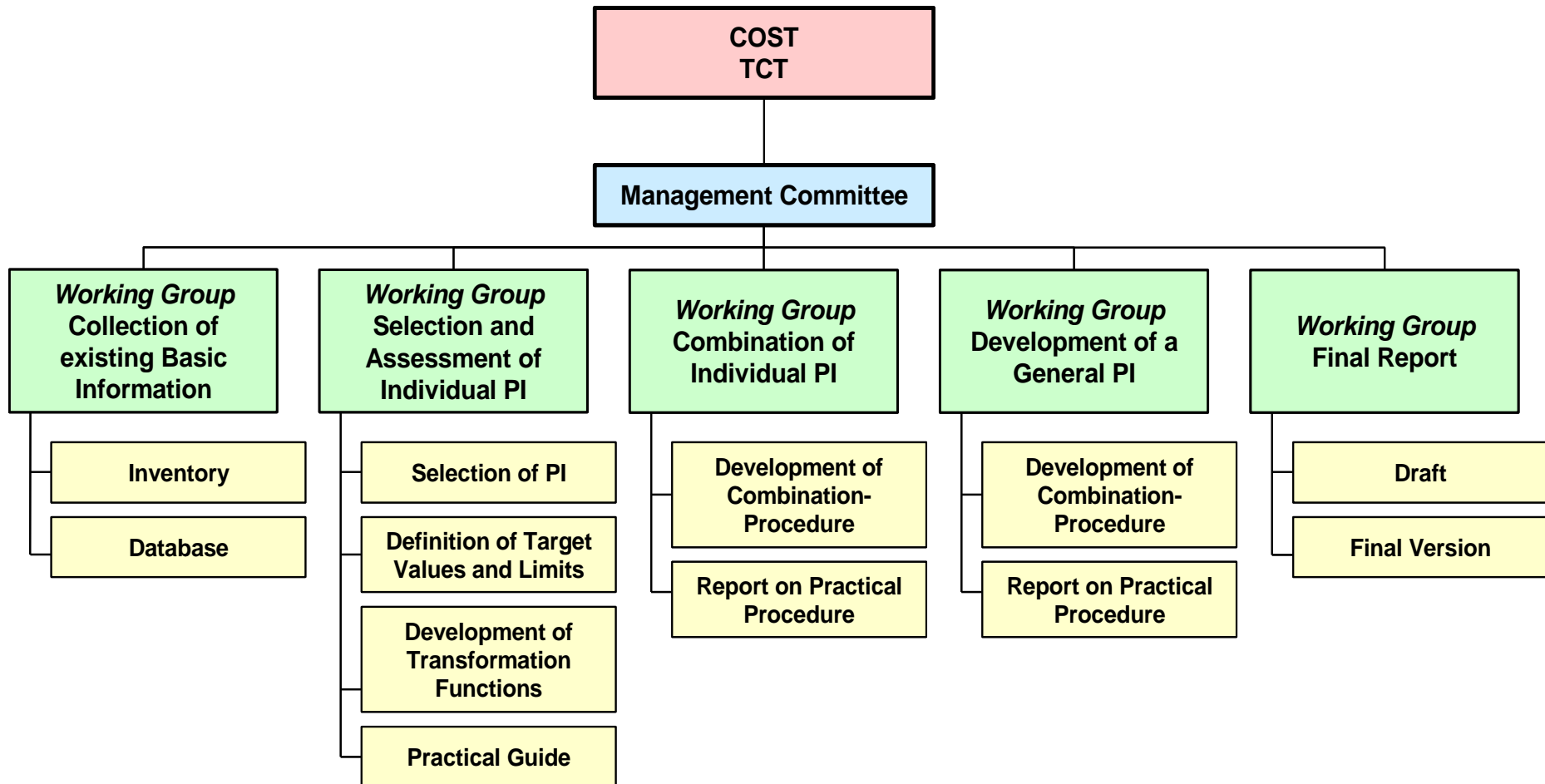
# SCIENTIFIC PROGRAMME

- **WP1:** Collection of existing basic information (SI)
- **WP2:** Selection and assessment of individual (single) PI (IT)
- **WP3:** Combination of individual PI (AT)
- **WP4:** Development of a general PI (PT)
- **WP5:** Final report (AT)





# ORGANISATION



# COLLECTION OF EXISTING INFORMATION

- Inventory of PIs in Europe and USA
- Basis for the following up work of WP2 to WP4
- Questionnaire for the collection of the information
- Implementation of the data into COST354 database

**Classification Single PI**

Performance Indicators for Road Pavements  
Classification Single PI

Scale Classification TP and/or Index

Definition "Very Poor" 5

Definition "Very Good" 1

Number Classes 5

Name TP

Friction coefficient

Unit TP: -

Criteria Classification (Transformation)

Criteria Number	Criteria Classification (Transformation)	I_SR	SR
1	1.49 <= I_SR <= 5.0	0.59	0.52
2			
3			
4			
5			
6			

Transformation Functions

Criteria Number	Transformation Function
1	I_SR = 9.9266-14.286 * SR
2	I_SR =
3	I_SR =
4	I_SR =
5	I_SR =
6	I_SR =

**COST 354 Database Open Form**

Performance Indicators for Road Pavements  
Welcome to the COST 354 Database

**General Information**

Information about the COST-Action [Open Information](#)

Contact Information (Questionnaires) [Open Contact List](#)

List of Tables and Data Fields [List of Data Fields](#)

**Information about Single Performance Indicators and Combined Performance Indicators**

Data Single Performance Indicators [Open Data Form](#)

Data Combined Performance Indicators [Open Data Form](#)

Traffic Data and Evaluation [Open Data Form](#)

Literature [Open Data Form](#)

**Queries and Reports**

Queries and Reports of Single and Combined Performance Indicators [Queries and Reports](#)

Report Literature [View Report](#)

**About Database**

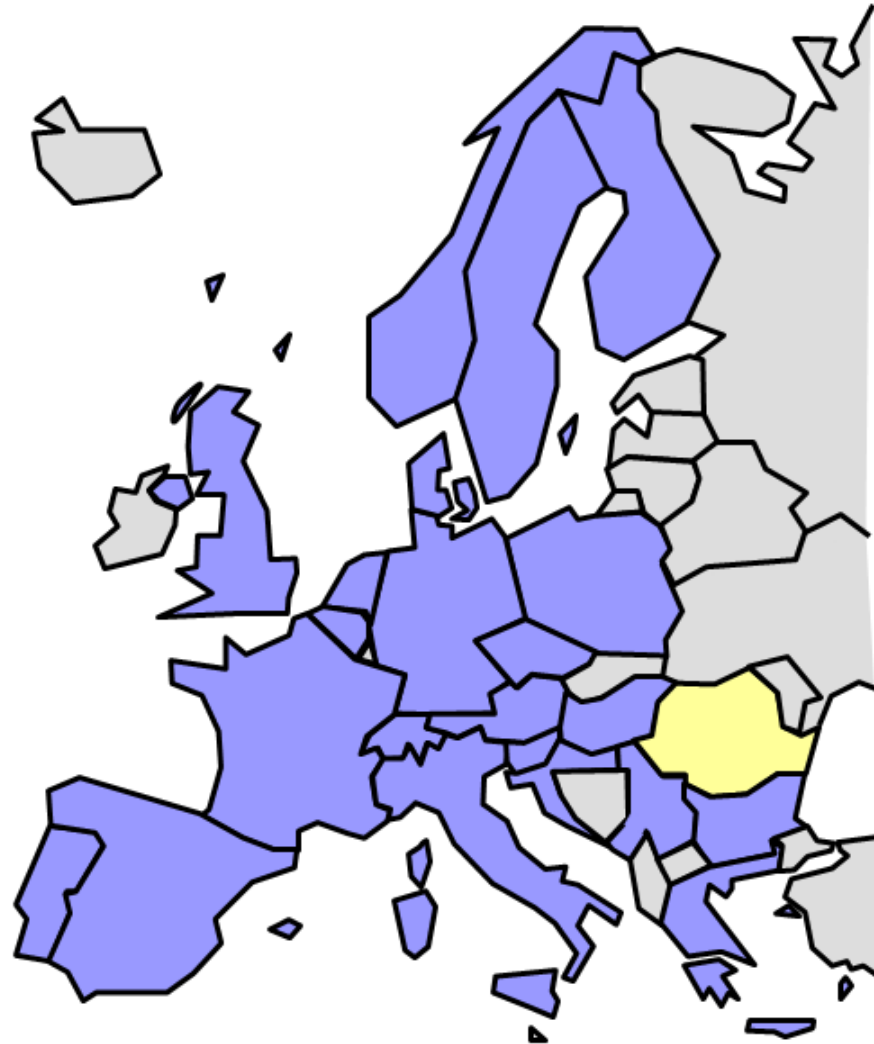
Version 2.0, 01/09/2005

Database designed by A. Weninger-Vycudil, Vienna, Austria

[Exit](#)

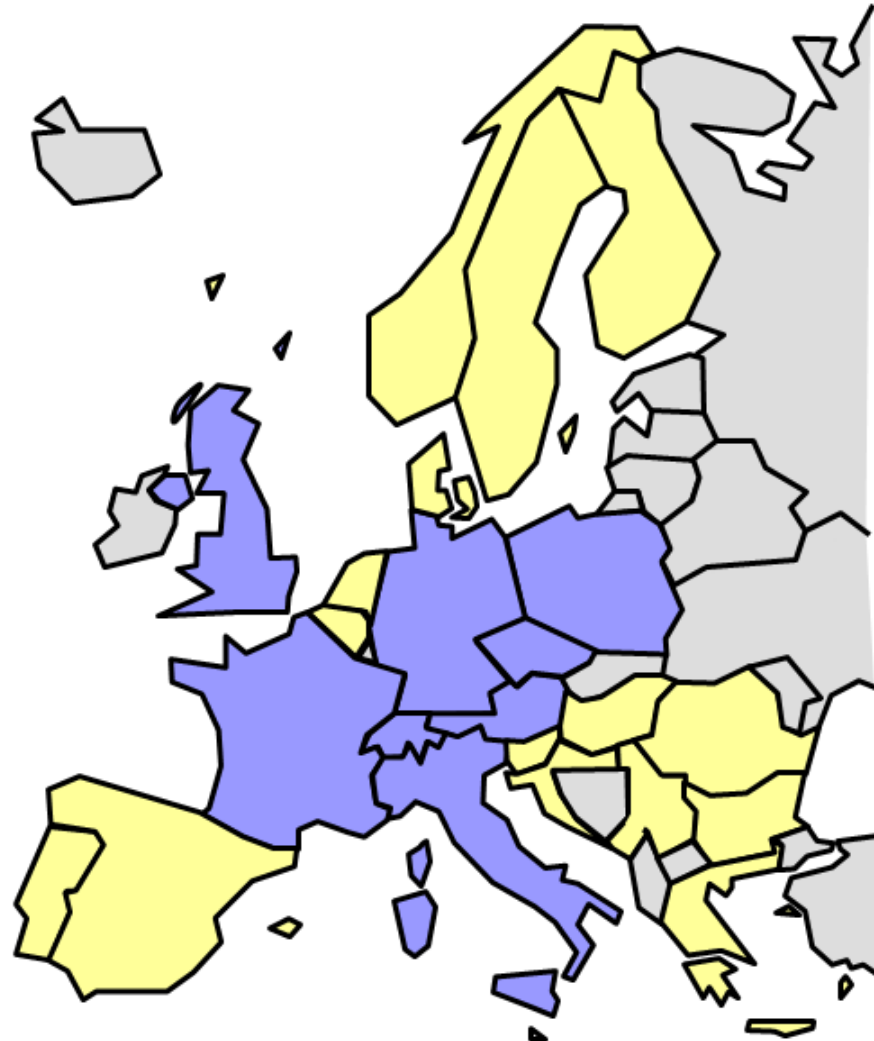
# COST354 DATABASE – SINGLE PI

Information of  
**209** Single PI  
were collected!



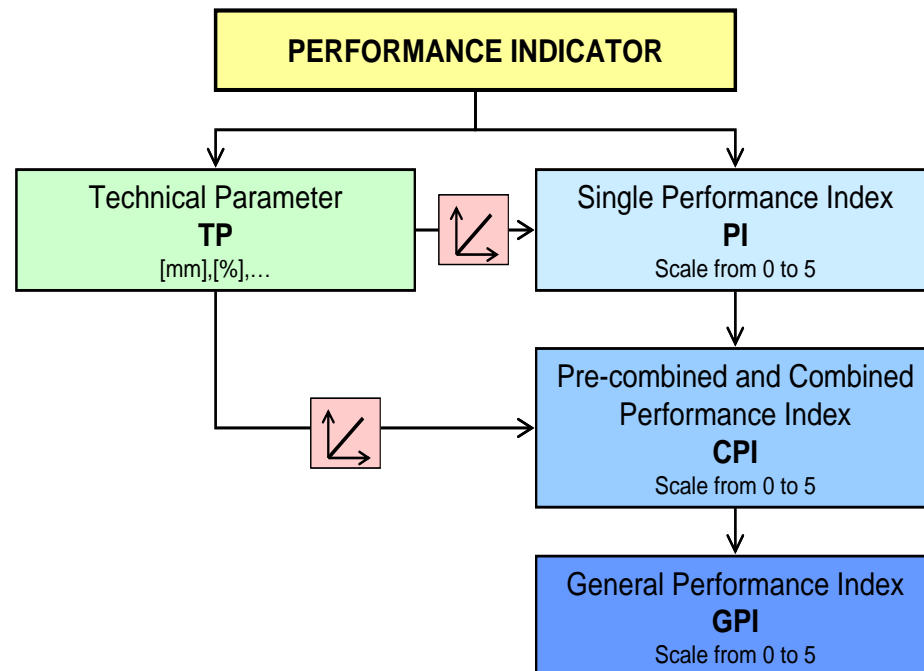
# COST354 DATABASE – COMBINED PI

Information of **46**  
Combined PI were  
collected!



# DEFINITION OF TERMS

<b>Performance Indicator</b>	A superior term of a technical road pavement characteristic (distress), that indicates the condition of it ( e.g. transverse evenness, skid resistance, etc). It can be expressed in the form of a <b>Technical Parameter</b> (dimensional) and/or in the form of an <b>Index</b> (dimensionless).
<b>Technical Parameter (TP)</b>	A physical characteristic of the road pavement condition, derived from various measurements, or collected by other forms of investigation (e.g. rut depth, friction value, etc.).
<b>Transfer Function</b>	A mathematical function used to transform a technical parameter into a dimensionless performance index.
<b>Performance Index (PI)</b>	An assessed Technical Parameter of the road pavement, <b>dimensionless</b> number or letter on a scale that evaluates the Technical Parameter involved (e.g. rutting index, skid resistance index, etc.) on a 0 to 5 scale, 0 being a very good condition and 5 a very poor one.
<b>Single Performance Indicator</b>	A dimensional or dimensionless number related to only one technical characteristic of the road pavement, indicating the condition of that characteristic (e.g. roughness) (also called Individual Performance Indicator).
<b>Pre-combined Performance Indicator</b>	A dimensional or dimensionless number related to two or more similar (related) characteristics of the road pavement, combined into one characteristic (e.g. linear cracking and alligator cracking combined into cracking) for further application or combination.
<b>Combined Performance Indicator</b>	A dimensional or dimensionless number related to two or more different characteristics of the road pavement, that indicates the condition of all the characteristics involved (e.g. PCI- Pavement Condition Index).
<b>General Performance Indicator (GPI)</b>	A mathematical combination of single and/or combined indicators which describe the pavement condition concerning different aspects like safety, structure, riding comfort and environment (also called Global Performance Indicator).

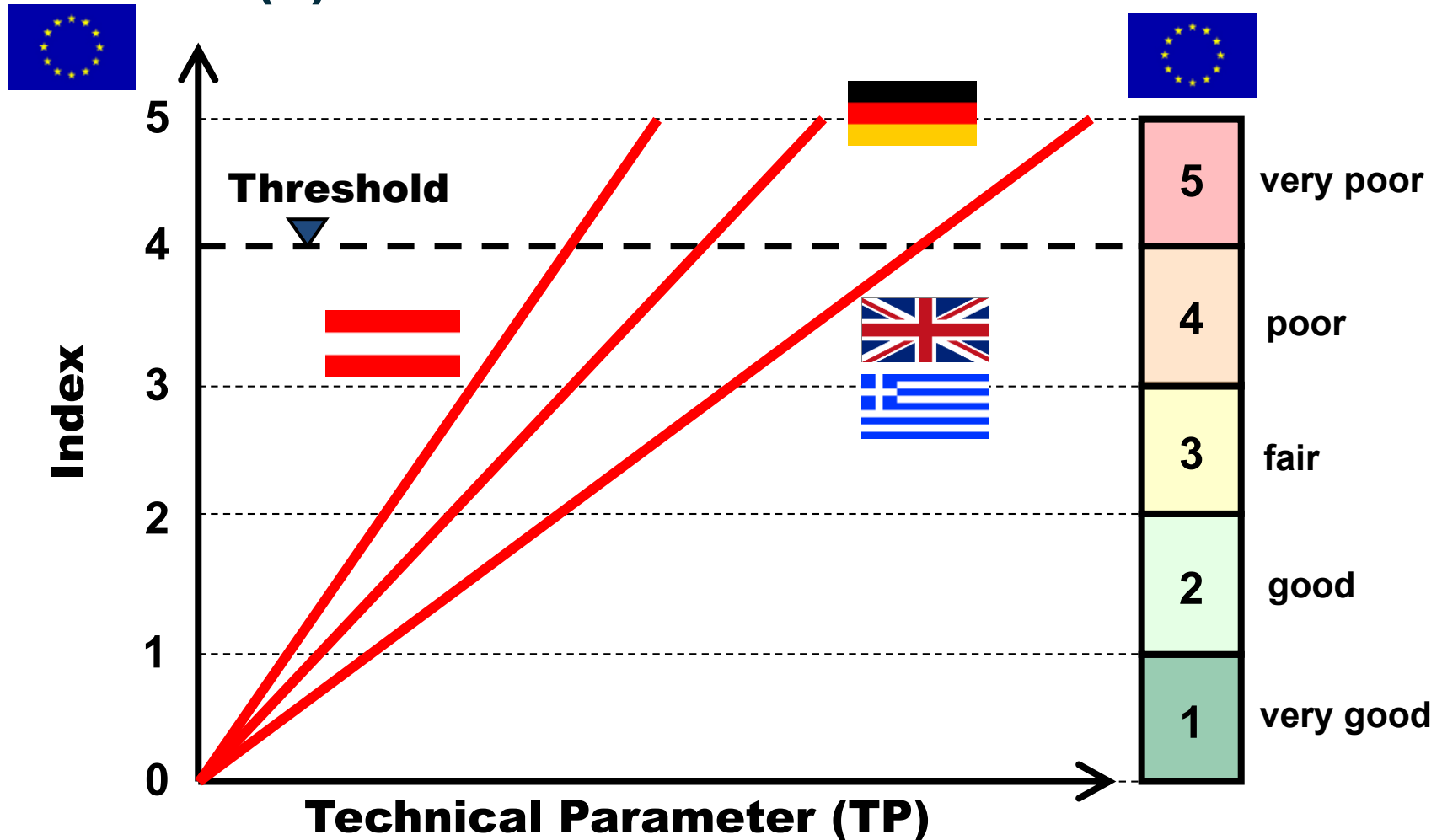


# SELECTION OF SINGLE PI

- **Longitudinal evenness:** IRI (international roughness index)
- **Transverse evenness:** rut depth
- **Skid resistance:** SFC (side force coefficient) and LFC (longitudinal force coefficient)
- **Macrotexture:** MPD (mean profile depth)
- **Bearing capacity:** R/D (residual life / design life) and SCI (surface curvature index)
- **Noise:** no PI at the moment
- **Air pollution:** no PI at the moment
- **Cracking:** cracking rate (pre-combined PI defined by WG3)
- **Surface defects:** surface defect rate (pre-combined PI defined by WG3)



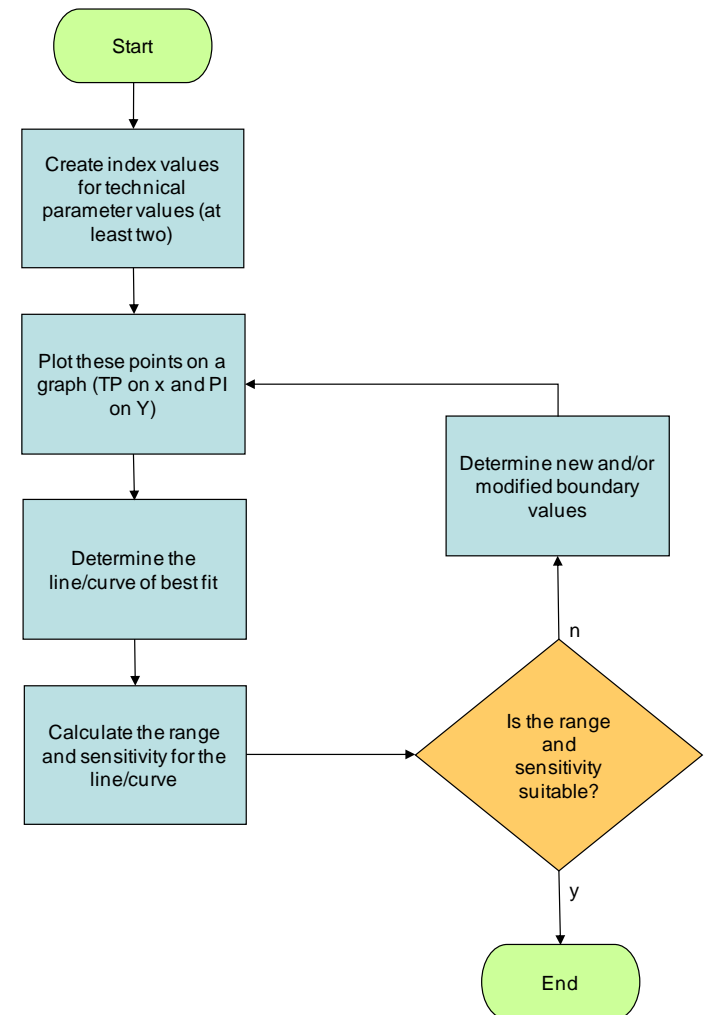
# SINGLE PI - TRANSFORMATION TP INTO INDEX (2)



# SINGLE PI - TRANSFORMATION TP INTO INDEX (2)

## Recommendation for the definition of transfer function

- Proposed TP with proposed transfer function
- Proposed TP with a custom transformation
- Existing TP with a custom transformation
- Supplying the Index directly



# DEVELOPMENT OF COMBINED PI

- Selection of adequate single PIs for the definition of combined PIs (CPI) to represent
  - Road safety
  - Riding comfort
  - Structural assessment
  - Environment
- Development of pre-combined PIs for cracking and surface defects
- Development of combination procedures based on advanced maximum criteria and weighting factors of the input values

$$CPI_i = \min \left[ 5; I_1 + \frac{p}{100} \cdot \overline{(I_2, I_3, \dots, I_n)} \right]$$

$$I_1 = W_1 \cdot PI_1, I_2 = W_2 \cdot PI_2, \dots, I_n = W_n \cdot PI_n$$

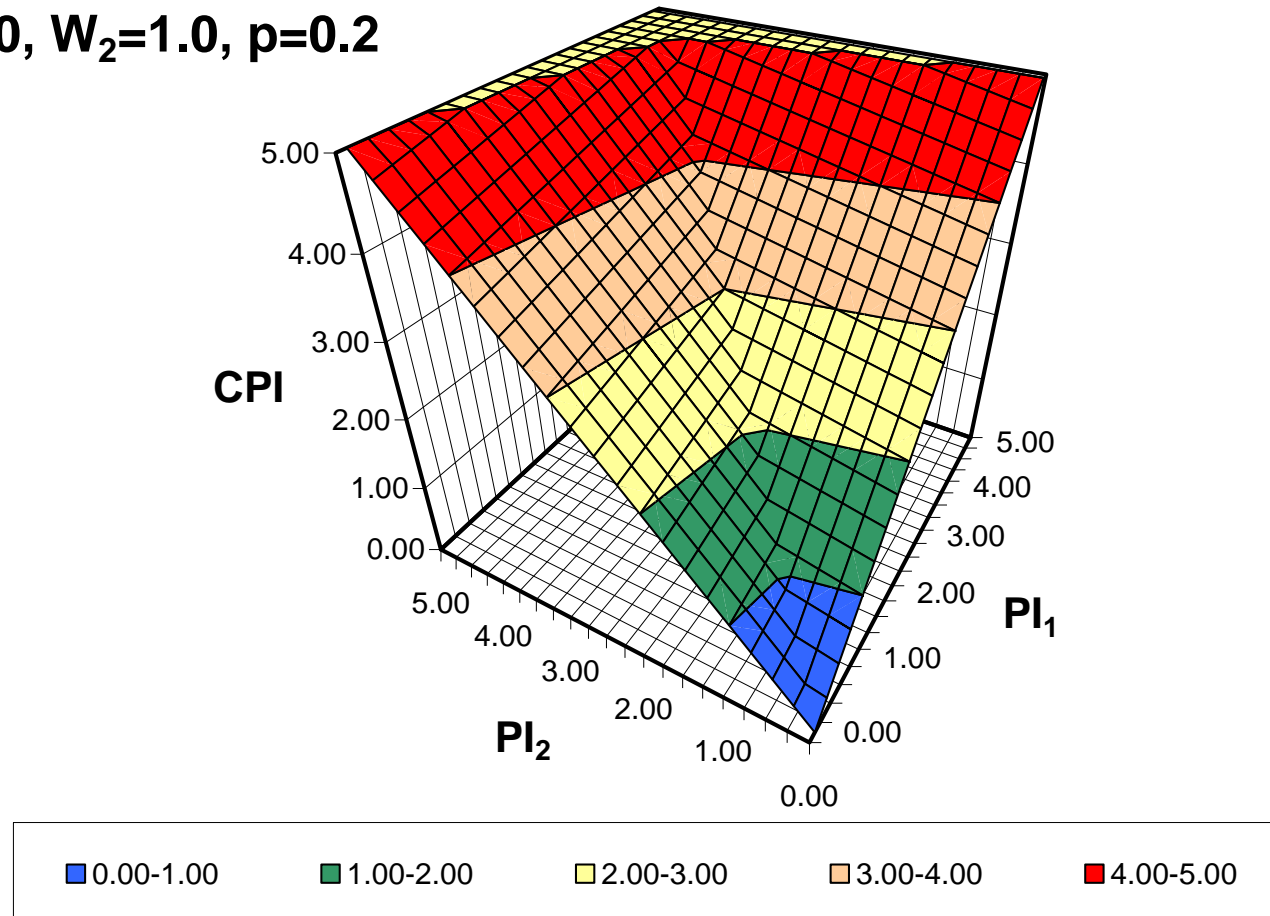
$$I_1 \geq I_2 \geq \dots \geq I_n$$

# INPUT PARAMETERS COMBINED PI

Level	Comfort Index	Safety Index
Minimum	PI_E	PI_F
Standard	PI_E, PI_SD, PI_R	PI_F, PI_R, PI_T
Optimum	PI_E, PI_SD, PI_R, PI_T, PI_CR	PI_F, PI_R, PI_T, PI_SD <sub>cat1</sub> <sup>*)</sup> , PI_SD <sub>cat2</sub>
Level	Structural Index	Environmental Index
Minimum	PI_B	-
Standard	PI_B, PI_CR	-
Optimum	PI_B, PI_CR, PI_R, PI_E	PI_E or air pollution, PI_T or noise labelling; PI_SD <sub>cat2</sub>
PI_E...PI evenness PI_F...PI friction PI_CR...PI cracking PI_SD...PI surface defects (all categories) PI_SD <sub>cat2</sub> ...PI surface defects category 2		
PI_R...PI rutting PI_T...PI macro-texture PI_B...PI bearing capacity PI_SD <sub>cat1</sub> ...PI surface defects category 1		

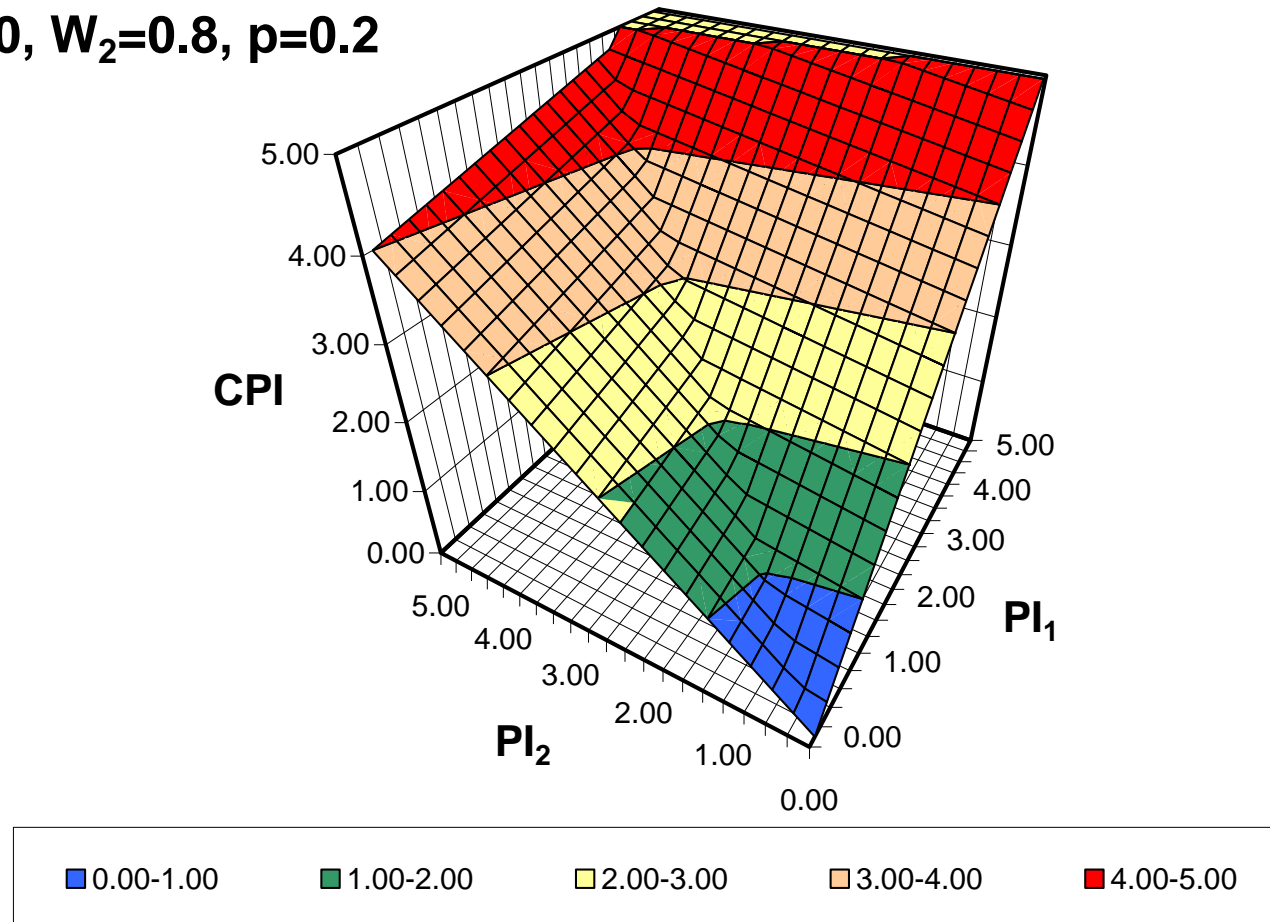
# EXAMPLE COMBINATION PROCEDURE

$$W_1=1.0, W_2=1.0, p=0.2$$



# EXAMPLE COMBINATION PROCEDURE

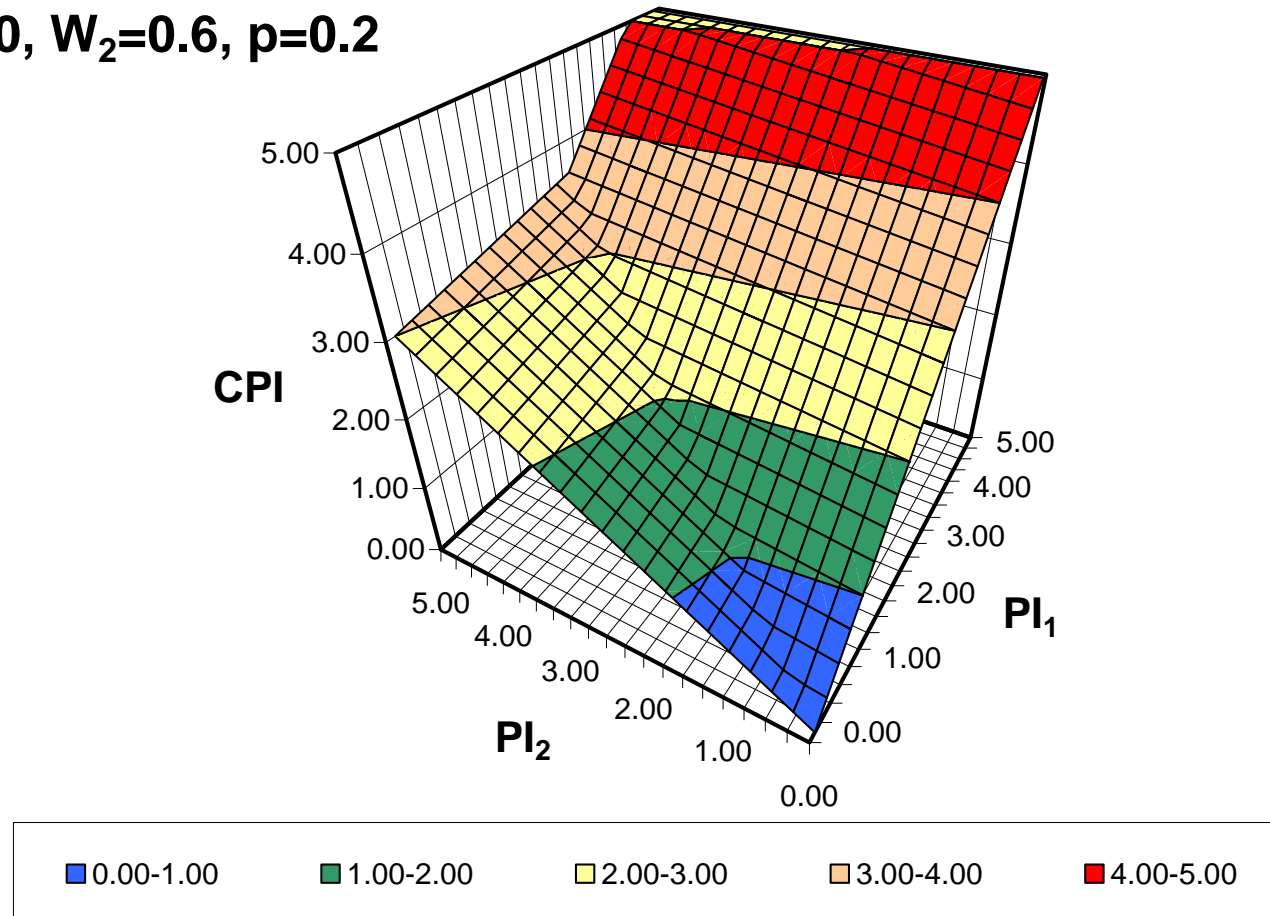
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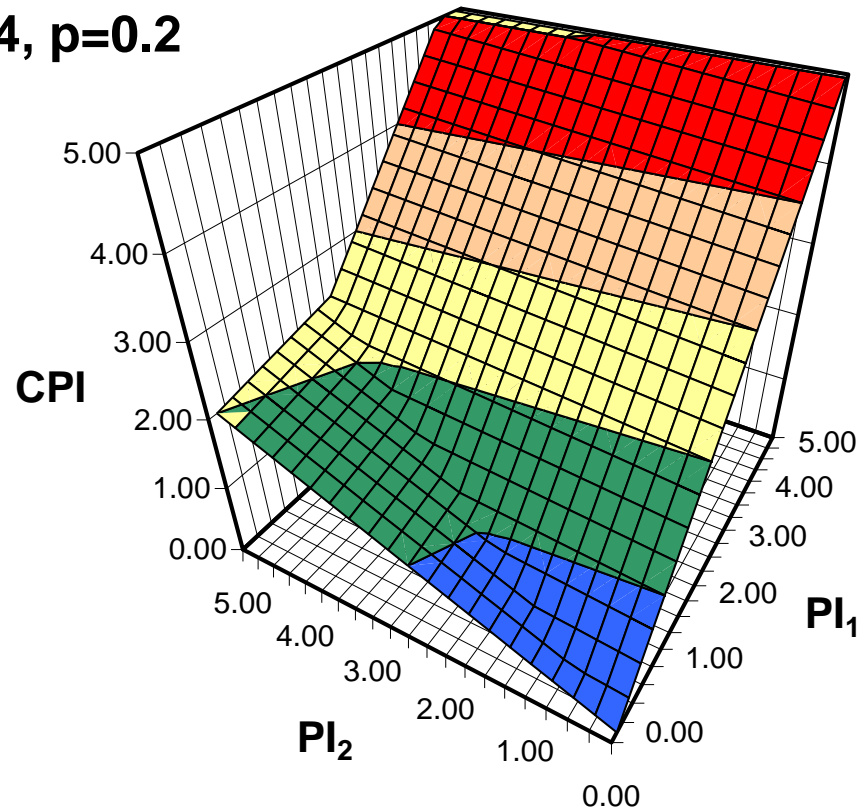
# EXAMPLE COMBINATION PROCEDURE

$$W_1=1.0, W_2=0.6, p=0.2$$



# EXAMPLE COMBINATION PROCEDURE

$$W_1=1.0, W_2=0.4, p=0.2$$



■ 0.00-1.00

■ 1.00-2.00

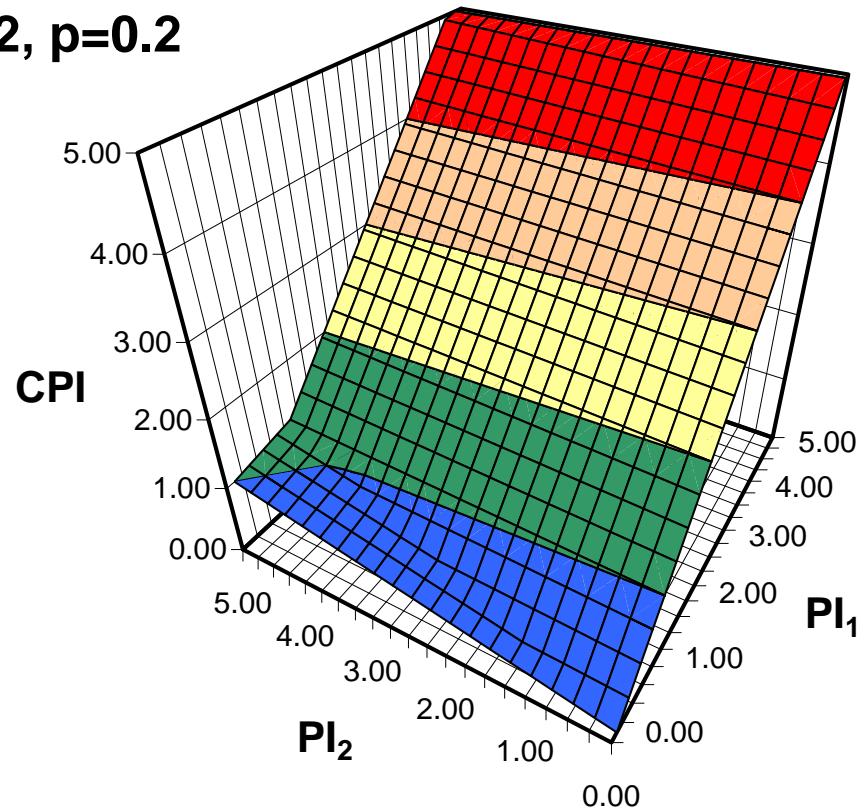
■ 2.00-3.00

■ 3.00-4.00

■ 4.00-5.00

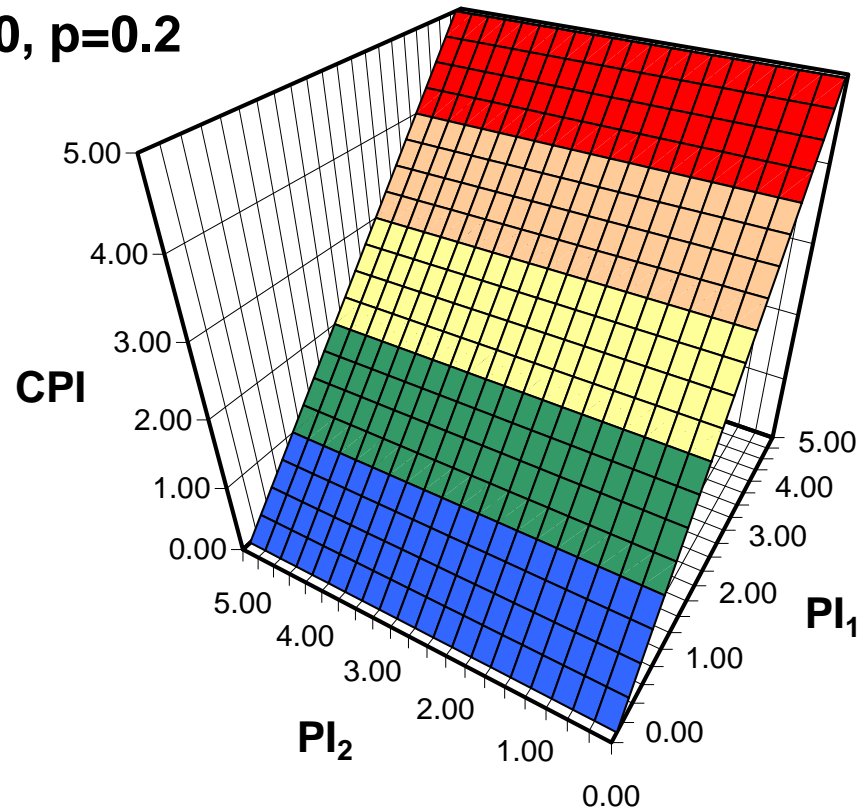
# EXAMPLE COMBINATION PROCEDURE

$$W_1=1.0, W_2=0.2, p=0.2$$



# EXAMPLE COMBINATION PROCEDURE

$$W_1=1.0, W_2=0.0, p=0.2$$



■ 0.00-1.00    
 ■ 1.00-2.00    
 ■ 2.00-3.00    
 ■ 3.00-4.00    
 ■ 4.00-5.00

# DEVELOPMENT OF GENERAL PI

- Definition of a general PI (GPI) based on combined PIs
- Investigation of weighting factors for the definition of the influence of the combined PIs
  - Road administrators
  - Road operators
  - Users
  - Researchers
- Development of combination procedures based on advanced maximum criteria and weighting factors of the input values

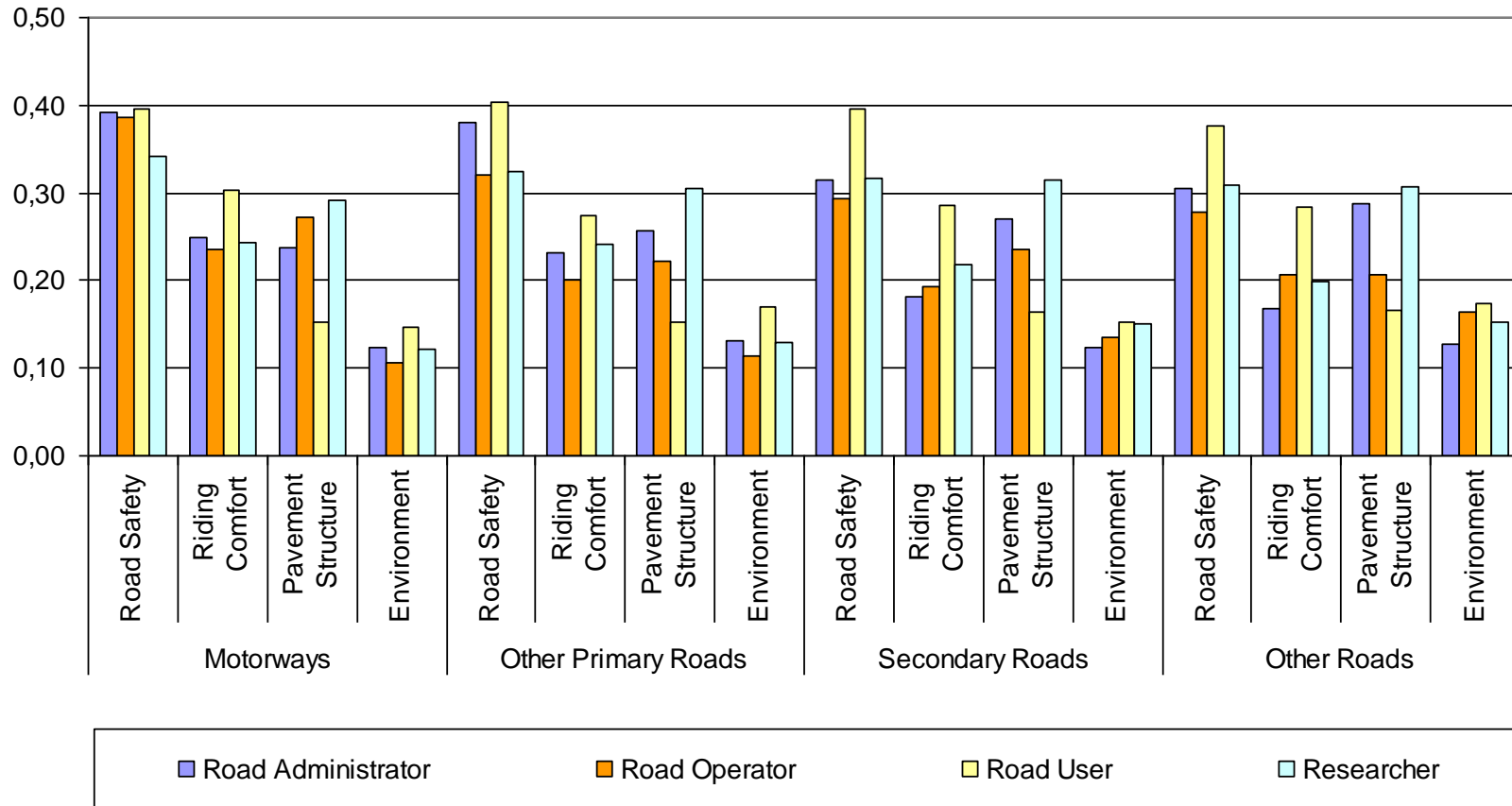
$$GPI = \min \left[ 5; I_1 + \frac{p}{100} \cdot \overline{(I_2, \dots, I_n)} \right]$$

$$I_1 = W_1 \cdot CPI_1, I_2 = W_2 \cdot CPI_2, \dots, I_n = W_n \cdot CPI_n$$

$$I_1 \geq I_2 \geq \dots \geq I_n$$

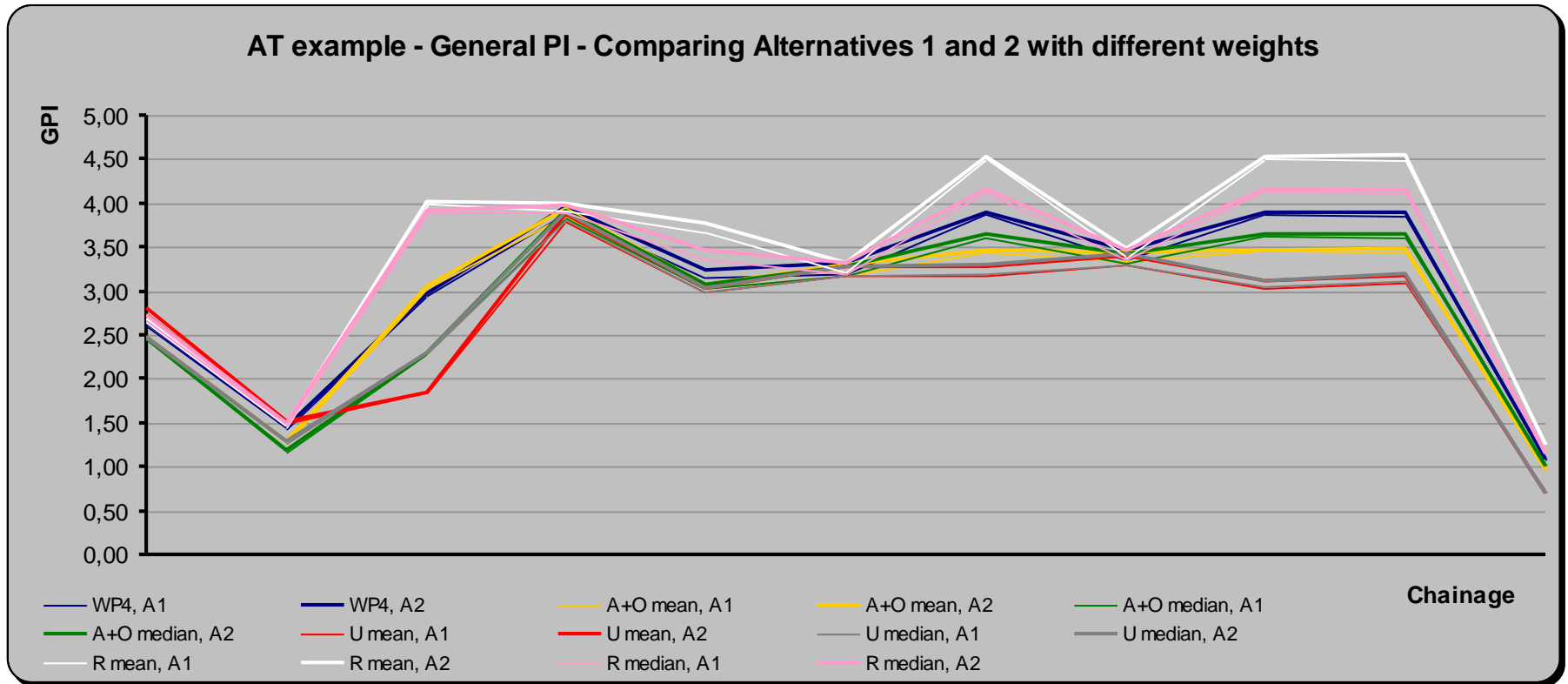
# GENERAL PI – WEIGHTING FACTORS

Relative importance factors - Average values





# SPREADSHEET TOOL SENSITIVITY ANALYSIS



# SPREADSHEET TOOL

## PRACTICAL APPLICATION

Road Section		Homogeneous section				
Road Category	ID Nr.	Description	From (km)	To (km)	Length (km)	Width (m)
Primary	1181		0,000	0,550	0,550	7,0
Choose Category	1181		0,550	1,200	0,650	7,0
Motorway	1181		1,200	3,950	2,750	7,0
Primary	1181					
Secondary	1181					
Primary	1181					
Primary	1181					
Primary	1181					
Primary	1181					
Primary	1181					
Primary	1181					
Motorway	0010					
Motorway	0010					
Motorway	0010					
Motorway	0010					

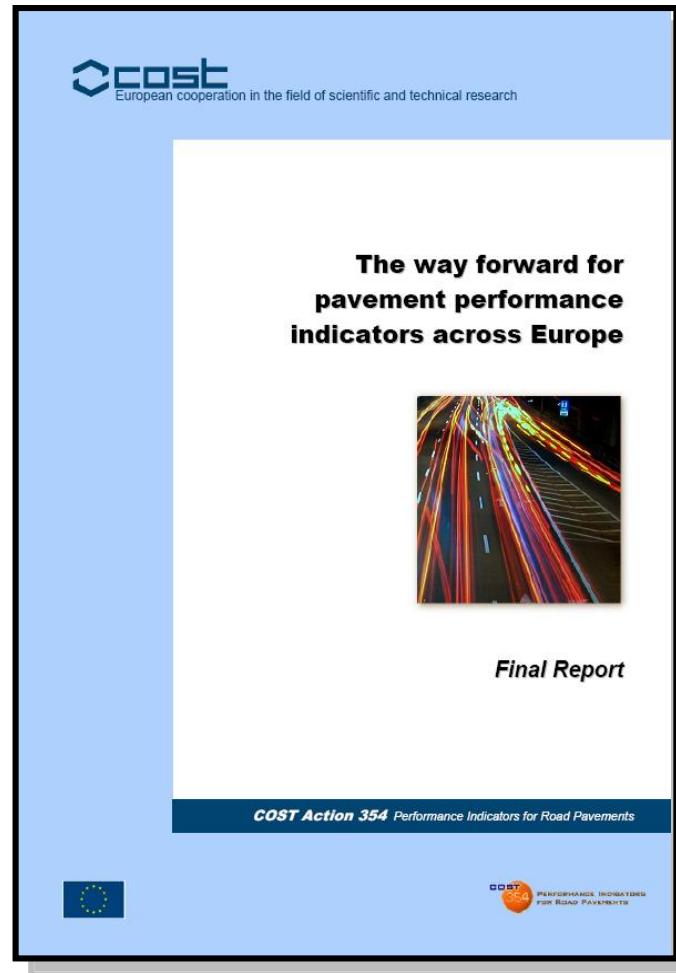
Proposed CPI Weights			
Choose CPI weights combination →		Proposed	
Riding Comfort	Road Safety		
0,70	1,00		
0,70	1,00		
0,70	1,00		
0,70	1,00		
0,70	1,00		
0,70	1,00	0,80	0,30
0,70	1,00	0,80	0,30
0,70	1,00	0,80	0,30
0,70	1,00	0,80	0,30
0,70	1,00	0,80	0,30
0,70	1,00	0,80	0,30
0,70	1,00	0,80	0,30
0,70	1,00	0,80	0,30
0,70	1,00	0,65	0,25
0,70	1,00	0,65	0,25
0,70	1,00	0,65	0,25
0,70	1,00	0,65	0,25

# SHORT TERM SCIENTIFIC MISSIONS

- Structural performance indicator based on GPR and bearing capacity measurements (BE, PT)
- Detection of structural damages based on GPR measurements for PMS purposes (FI, DE)
- Bearing capacity data evaluation for PMS purposes based on comparative measurements (DE, BE, DK)
- Practical guide for the application of single PIs (UK, IT)
- Practical guide for the application of combined PIs and general PI (SI, AT)



# DISSEMINATION



# FOLLOWING-UPS AND IMPLEMENTATION

- Following-up projects (based on findings of COST354)
  - ENR-project EVITA (environmental performance indicators) – finished 2013
  - CEDR-project ISABELA (socio-economic performance indicators) – in progress
- Implementation of results (partially) from COST354:
  - Austria
  - Germany
  - Slovenia
  - Croatia
  - Ireland
  - Portugal
  - ?





**THANKS FOR YOUR ATTENTION!**

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### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **Sustainable Construction of Bridges in Kanton Zürich**

**Dr. Martin Käser** - TBA / Abt. Ingenieurstab / Sektion Tragkonstruktionen



**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**



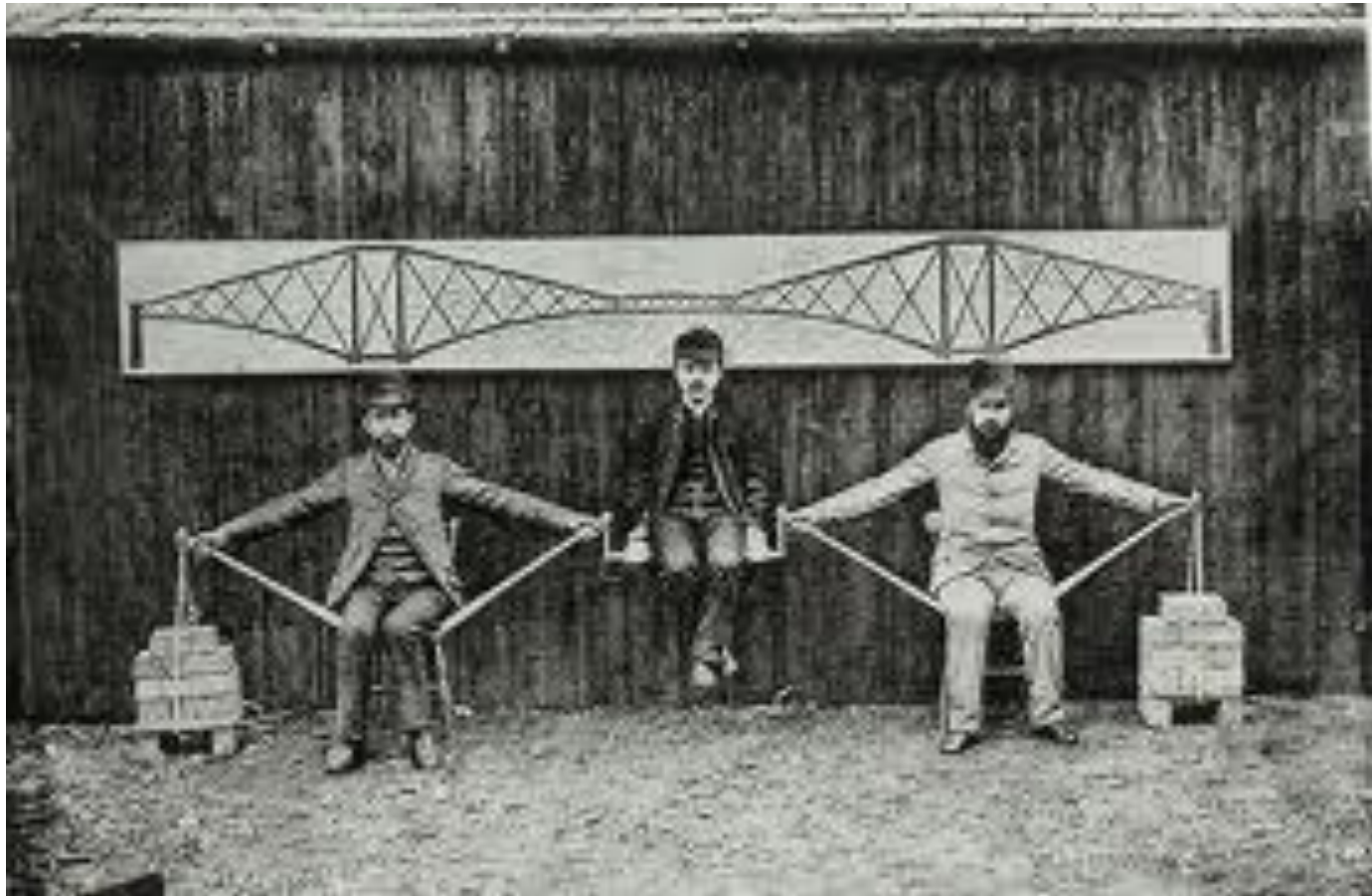
## ■ Statics

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## ■ Statics

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- Sustainability

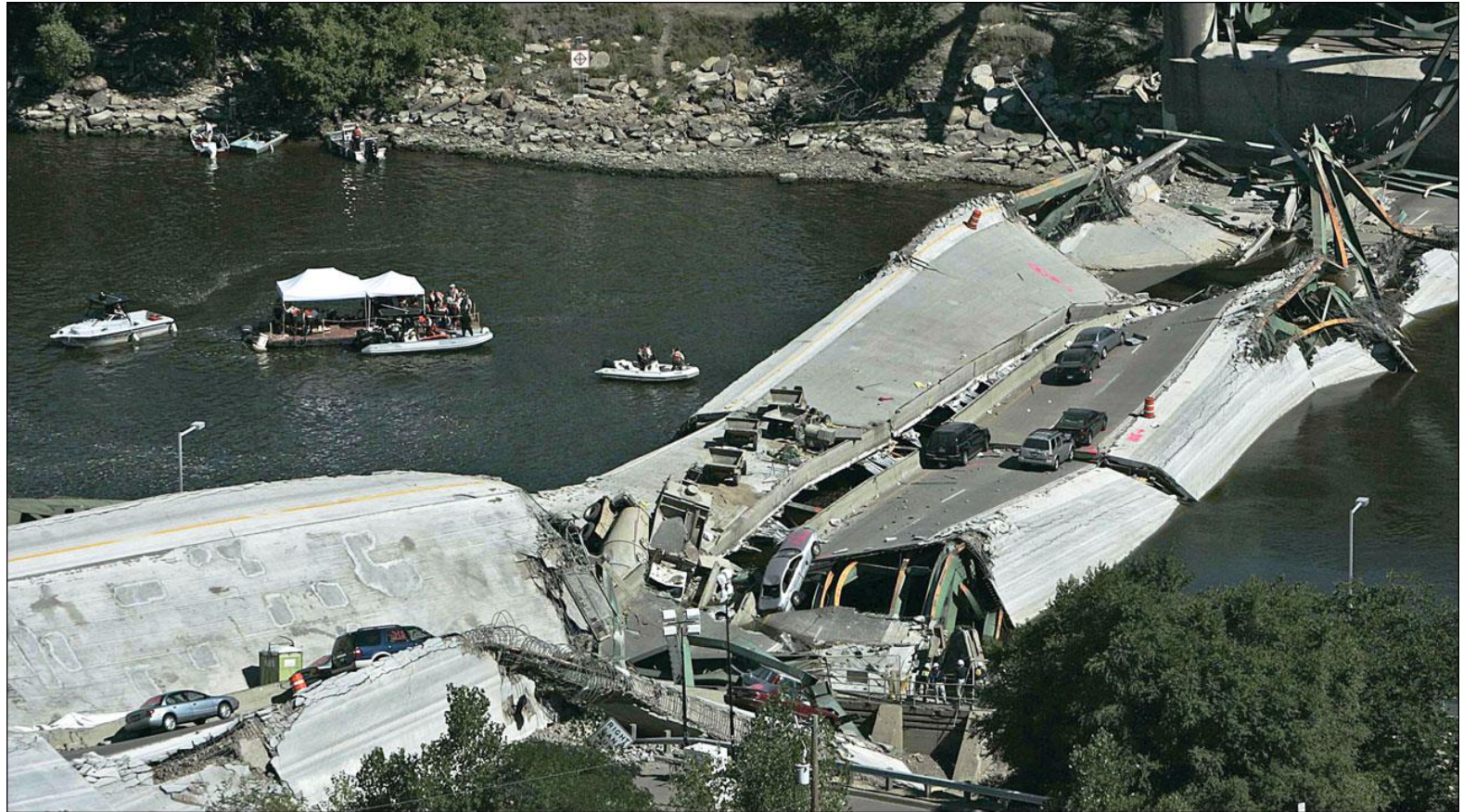
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I-35W Bridge Mississippi River Crossing, Minneapolis, Minnesota 1967 (8 lanes)



## ■ Sustainability



Collapse of the I-35W Bridge 2007



- Sustainability



individual parts of the steel beam post-collapse

- 
- 1713 Forestry  
"...**sustainable** use of forests..." (Hans C. von Carlowitz)
- 1972 The Limits to Growth (Club of Rome)  
"...searching for a model output.. that is **sustainable**..."
- 1987 UN World Commission on Environment and Development (H. Brundtland)  
Def. **sustainable** development: "...rendering development **sustainable**, implies that the present generation satisfies its needs without compromising the ability of future generations to meet their own needs..."
- 1999 CH state target / rooting in the Federal Constitution (Federal Constitution)  
"...The Swiss Confederation promotes the general welfare, **sustainable** development, internal cohesion..."
- 2013 **Actual Mission Statement of the Baudirektion Kt. Zürich (BD Kt. Zürich)**  
**Vision: "...The Canton of Zurich ensures a **sustainable** and attractive environment for the population and economy ..."**

- Impact of rediscovery of the term
  - ▶ Roads are today built differently to the practice of 30 years ago
  - ▶ Example: reconnection of residential areas

▼ before                      during construction ▶



550 m long Coverage in Entlisberg



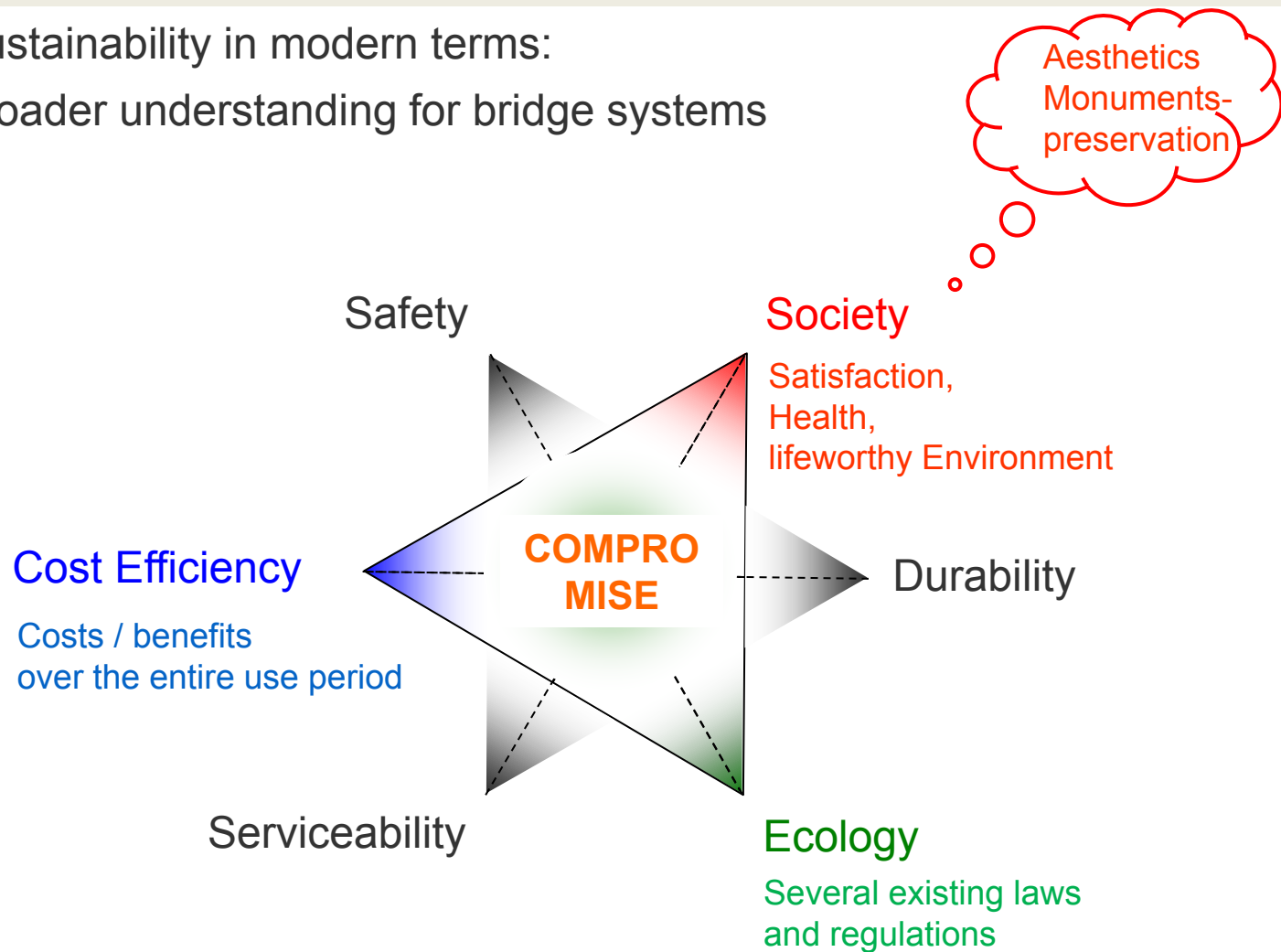
- Impact of rediscovery of the term

▶ today



550 m lange Überdeckung Entlisberg

- Sustainability in modern terms:
- Broader understanding for bridge systems



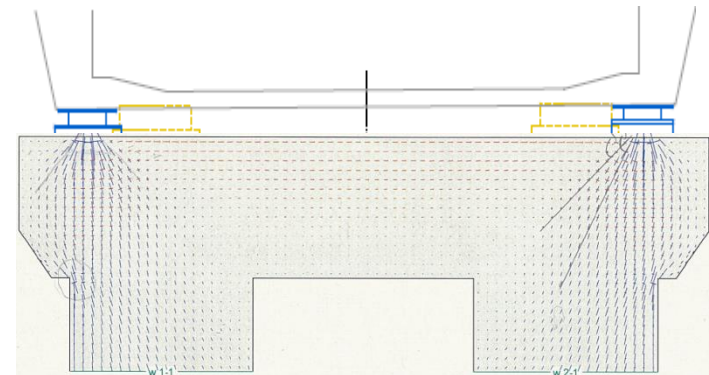
- Conversion from indirect to direct support of the main girder on the piers



Verkehrsdreieck ZH Süd  
Entlastung Querträger Obj. Nr. 261-037



SBB ÜF Bülach Nord  
Entlastung Querträger Obj. Nr. 261-037





## Sustainable Construction: Structural Safety



SBB ÜF Bülach Nord

## Sustainable Construction: Structural Safety

- Repair and Strengthening



Lättenbrücke Glattfelden



## Sustainable Construction: Structural Safety

- Repair and Strengthening



Lättenbrücke Glattfelden  
Web Reinforcement 2013

## Sustainable Construction: Structural Safety

- ▶ long-term deformations



Pfeilerersatz Rampenbrücke  
A3 Zürich - Chur



## Sustainable Construction: Serviceability

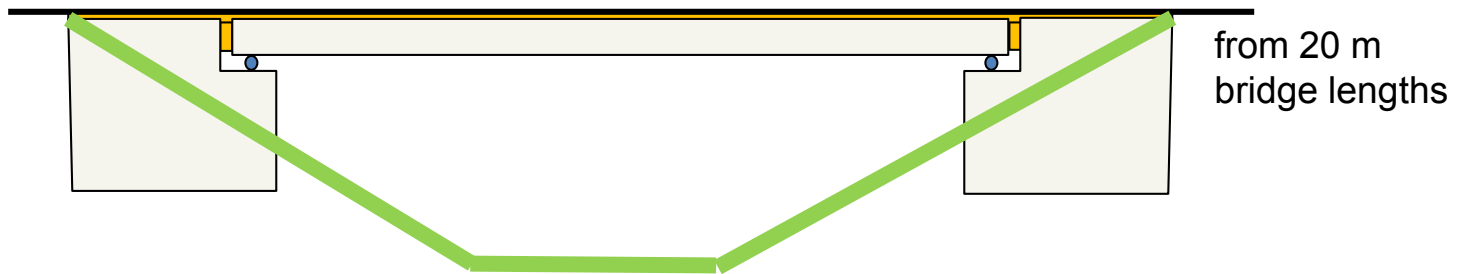
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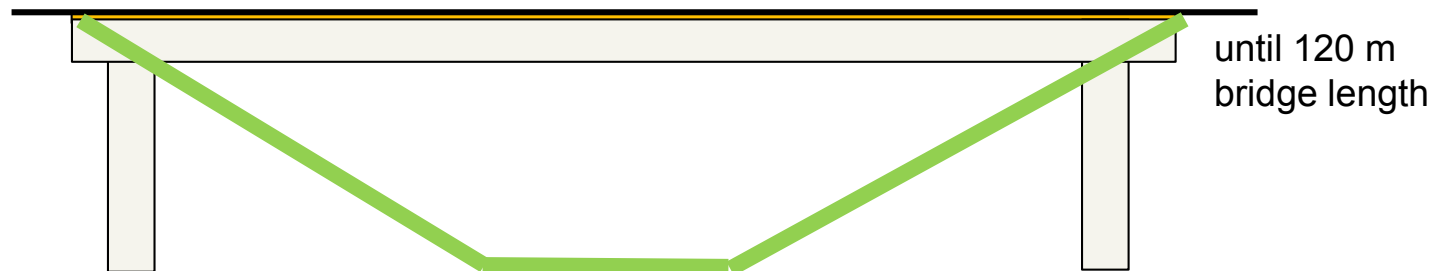
Steg im Schiffli, Obj. Nr. 132-303 / © Synaxis AG

## Sustainable Construction: Durability

- earlier : several leaking joints / bearing / no sealing



- today: no joints / no bearing = **integral Bridge System**



## Sustainable Construction: Durability

- Integral Bridge: Ramp bridge Zürich West Interchange
  - ▶ no joints
  - ▶ No bearings
  - ▶ No expansion joints



Verkehrsdreieck Fildern Rampenbrücke N4 / N20

## Sustainable Construction: Durability

- Integral Bridge: Ramp bridge Zürich West Interchange

- ▶ 1000 m<sup>3</sup>  
Beton in  
single pouring





## Sustainable Construction: Durability

- Waterproofing / Seal

- ▶ Epoxy Isolation
- ▶ Bitumine Isolation



Jonentobelbrücke  
der A4 bei Hedingen

- (Semi-) integral Structure



Wildbachbrücke bei Fehraltdorf



- Brush finish in freshly poured Beton





- Completed Wildbach bridge, Fehralt Dorf

---



- Prefabrication of entire Structure



Pedestrian Bridge over  
the SBB at Bonstetten



- Placement of the assembled structure



Pedestrian Bridge over  
the SBB at Bonstetten

- Prefabrication of entire Structure



Thurbrücke der Kantonsstrasse  
bei Andelfingen



## Nachhaltiger Brückenbau: Denkmalschutz

- Handling of objects worthy of preservation



Pedestrian Bridge über  
die Töss in Zell



## Sustainable Construction: Preservation

- Handling of objects worthy of preservation



Bridge over the Inn in Zuoz  
/ GR (Robert Maillart)

## Nachhaltiger Brückenbau: Denkmalschutz

- Handling of objects worthy of preservation

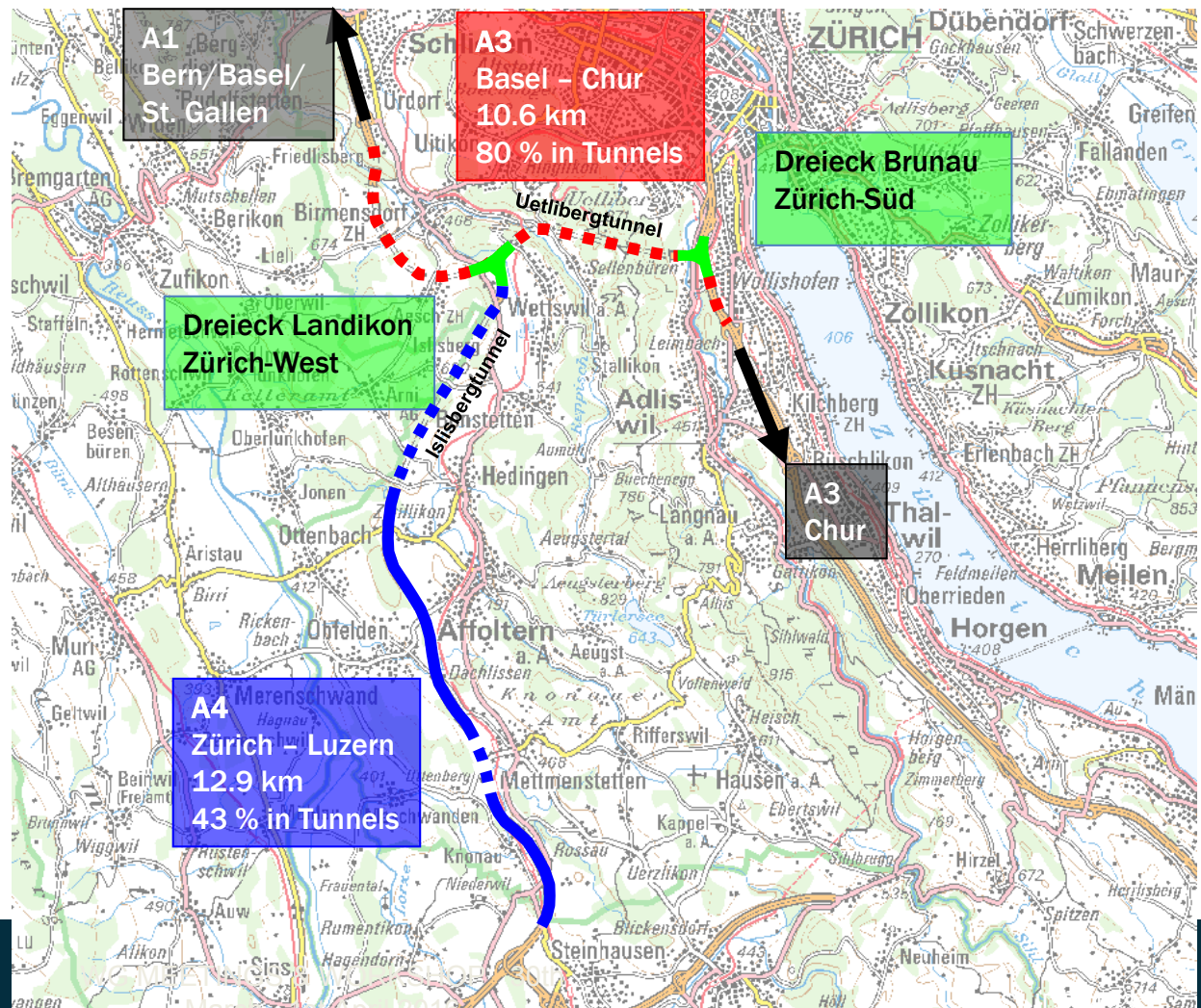


Pedestrian Bridge  
über die Töss in Zell



## Sustainable Construction: Adaptation in the landscape

- A3 Bypass and A4 in Knonaueramt



## Sustainable Construction: Adaptation in the landscape

- Requirements

Tieflage?



Interchange Zürich Süd (Brunau)



## Sustainable Construction: Adaptation in the landscape

- Ecologic rehabilitation measures

- ▶ reshaped  
riverbed of Sihl  
river

Renaturation of Sihl /  
Interchange Brunau



## Sustainable Construction: Adaptation in the landscape

- Aesthetics / Flora und Fauna consideration



Interchange Zürich Süd (Brunau)



## Sustainable Construction: Adaptation in the landscape

- Noise protection



Galerie with noise protection –  
earthwall / Interchange Brunau

## Sustainable Construction: Adaptation in the landscape

- Noise protection / Wild life crossings



Cover-up A4 Rüteli (foreground)  
and Eigi (Background)

" In former times the construction of a road required overpowering of the nature; modern road construction, to the contrary, is indicated less by the extent to which it overpowers Nature, but rather by respecting and preserving it."

*M. Kägi, Baudirektor Kt. ZH*



**THANKS FOR YOUR ATTENTION!**

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## **WG MEETINGS & WORKSHOP**

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# **CONSEQUENCE MODELLING FOR BRIDGE FAILURES**

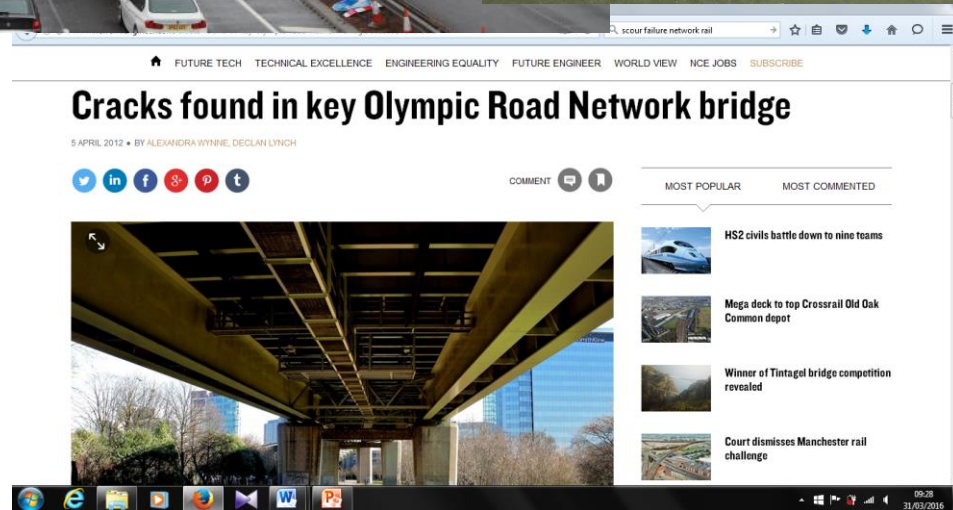
**Dr Boulent Imam** - University of Surrey, United Kingdom

[link to paper](#)



**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**

# Bridge Failures



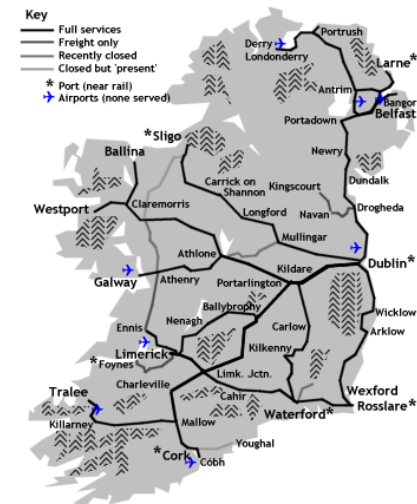


# Influencing factors

- Source and nature of hazard (*magnitude & duration*)
- Bridge type (*structural form, material used, age, condition, quality of construction*)
- Bridge location (*type of road or rail route, traffic intensity, rural vs. urban, availability of emergency services, labour & material transportation*)
- Time of failure (*day vs. night, peak vs. off-peak*)

# Influencing factors

- Consequence modelling depends on:
  - System boundaries
  - Time frame considered
- System boundaries
  - Structural domain
  - Spatial domain
- Time frame
  - Short term post-event
  - Longer term, equilibria



# Consequences of failure - Categorization

Type	Direct	Indirect
<b>Human</b>	Injuries Fatalities	Injuries Fatalities Psychological damage
<b>Economic</b>	Repair of initial damage Replacement/repair of contents Rescue costs Clean up costs	Replacement/repair of structure/contents Rescue costs Clean up costs Collateral damage to surroundings Loss of functionality/production/business Temporary relocation Traffic delay (detour)/management costs Regional economic effects Investigations/compensations Infrastructure inter-dependency costs
<b>Environmental</b>	CO <sub>2</sub> Emissions Energy use Pollutant releases Noise disruption	CO <sub>2</sub> emissions Energy use Pollutant releases Noise disruption Environmental clean-up/reversibility
<b>Social</b>		Loss of reputation Erosion of public confidence Undue changes in professional practice

*Often  
practical to  
express all  
consequences  
in terms  
of monetary  
units*

# Human consequences

- ***Fatalities*** and / or ***injuries***
- Highly variable in terms of predicting & valuing
- Valuation of human life
  - UK DfT: £1.43 million for road fatalities (2005 prices)
  - EU: €1.5 million for road fatalities
  - RSSB: £3.46 million for rail fatalities (2003 prices)
  - HSE: £1 million for fatality (2001 prices)
- Encompass direct human and economic loss i.e. loss of output, medical costs, amount to reflect pain & grief
- Injury costs – fraction of fatality costs

# Human consequences

- Estimation of number of casualties / injuries
- Regional loss estimation framework HAZUS
- Number of people on or under bridges:

$$K_S = 0.07 \times F \times N$$

where  $F$  is a usage factor

$F = 0.01$  during day and night

$F = 0.02$  during commute time

$N$  = commuter population

- Assuming one bridge every two miles of major urban road!

# Economic consequences

- Reconstruction time:
  - highway bridges: mean=230 days, st.dev.=110 days
  - railway bridges: mean=110 days, st.dev.=73 days
- These can be used to estimate traffic delay costs
- Debris clean up costs:
  - transportation of failed material
  - number of trucks, capacities, distance to disposal site, fuel consumption



# Economic consequences

	Passenger Transport	Freight Transport
Car	Business: €21.00/person-hour Commuting/Private: €6.00/person-hour Leisure/Holiday: €4.00/person-hour	Light Goods Vehicle: €40.0/vehicle-hour Light Goods Vehicle: €43.0/vehicle-hour
Interurban Rail	Business: €21.00/person-hour Commuting/Private: €6.40/person-hour Leisure/Holiday: €3.20/person-hour	Full train load (950 tonnes): €725.0/tonne-hour Wagon load (40 tonnes): €30.0/tonne-hour Average per tonne: €0.76/tonne-hour

# Economic consequences

Traffic management (TM) costs in case of bridge closure:

- over or under the bridge
- selection of scheme depends on traffic volume and road type

	Carriageway closure / full contraflow	One-lane closure	Two-lane closure
Motorway	£850 (1 km TM scheme)	£350	£450
	£1,250 (3 km TM scheme)		
Dual carriageway	£500	£350	£450
Single carriageway	£800 (traffic signal control management)	£300	

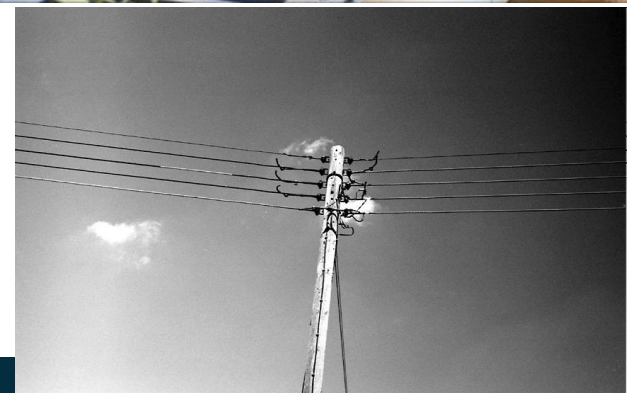
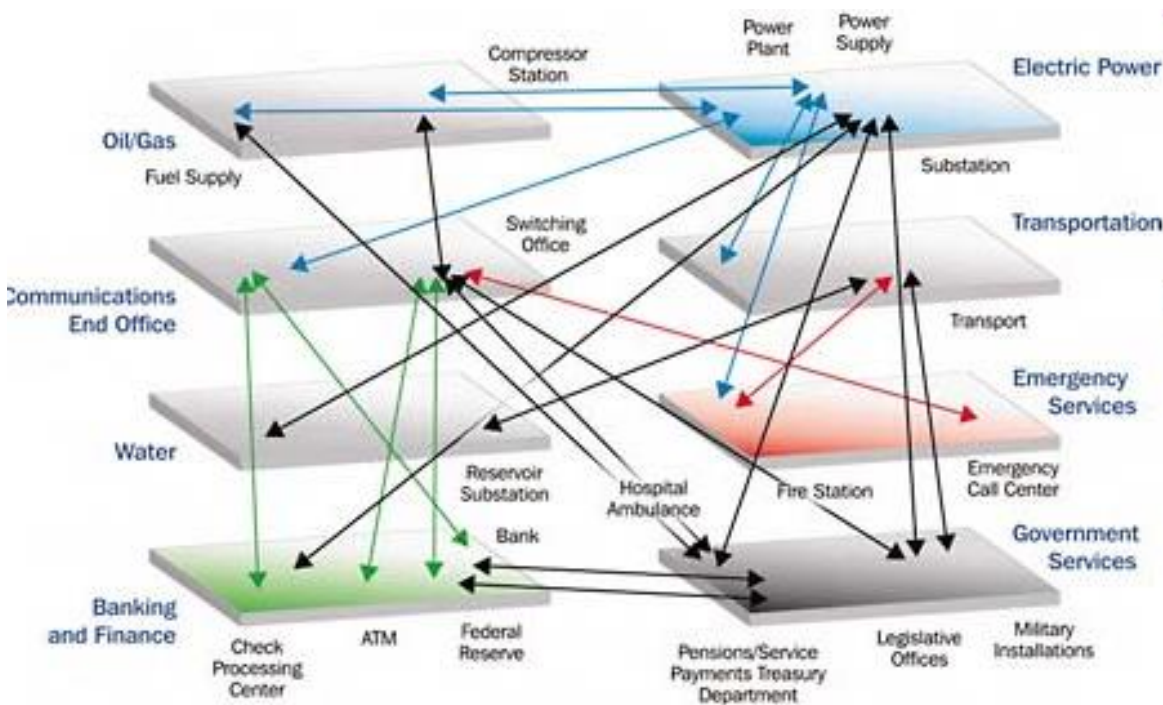
# Economic consequences

- Consequences on business
- Disruption of normal business activities
- Delays on customers, deliveries, suppliers
- Loss of business, increased production costs etc.
- Economic expertise is required



# Economic consequences

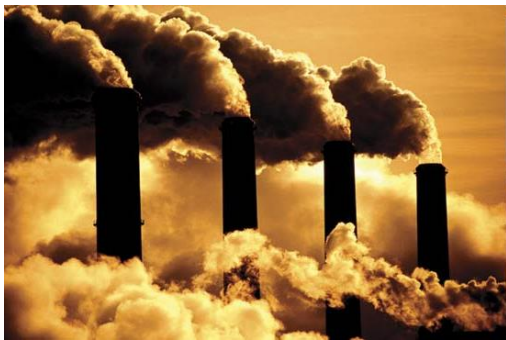
- Infrastructure interdependencies
  - bridges can be part of electricity, telephone, water, gas networks



# Environmental consequences

- Carbon emissions from production of bridge materials

Material	Carbon emitted
Steel	1,820 Kg CO <sub>2</sub> /tonne
Cement	800 Kg CO <sub>2</sub> /tonne
Reinforced Concrete	260-450 Kg CO <sub>2</sub> /tonne
Asphalt	46 Kg CO <sub>2</sub> /tonne



# Environmental consequences

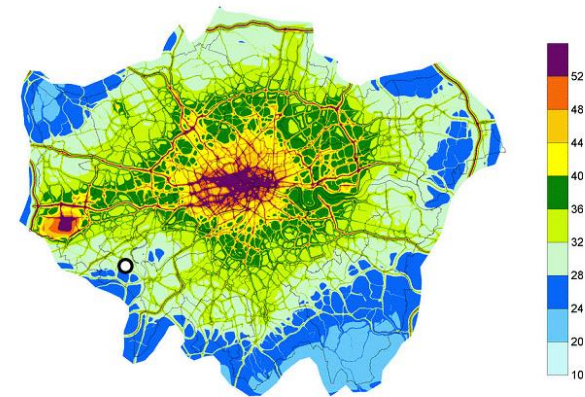
- Emissions from traffic related sources

Vehicle type	CO <sub>2</sub> emissions
Petrol car	0.1730-0.2994 kg CO <sub>2</sub> / passenger km
Diesel car	0.1452-0.2455 kg CO <sub>2</sub> / passenger km
Hybrid car	0.1191-0.2173 kg CO <sub>2</sub> / passenger km
Light commercial van (petrol)	0.1941-0.2558 kg CO <sub>2</sub> / vehicle km
Light commercial van (diesel)	0.1571-0.2691 kg CO <sub>2</sub> / vehicle km
Heavy goods vehicle (diesel)	0.5276-1.163 kg CO <sub>2</sub> / vehicle km
Rail (passenger)	0.05340 kg CO <sub>2</sub> / vehicle km
Rail (freight)	0.02850 kg CO <sub>2</sub> / tonne km

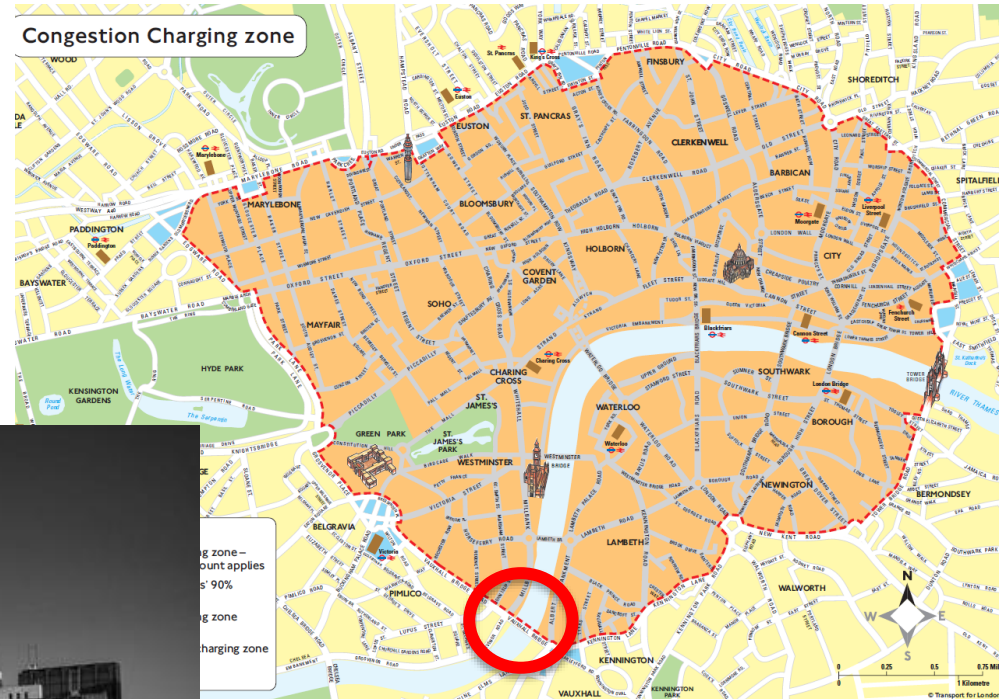


# Environmental consequences

- Air / Noise pollution
- Number of affected households
- PM<sub>10</sub> pollution; NO<sub>x</sub> pollution
- ~ €135/household/1µg/m<sup>3</sup> for PM<sub>10</sub>
- ~ €1,300/tonne for NO<sub>x</sub>
- Different noise severity levels
- €40/household for 50 decibels
- €165/household for 75 decibels.



# Case Study



Vauxhall bridge - London

# Case Study – Human consequences

$$K_S = 0.07 \times F \times N$$

$F = 0.02$  during commute time

$N = \text{commuter population} = 124,864$

$$K_S = 175 = \textit{number of casualties}$$

Casualty cost is assumed equal to €2.25 million

# Case Study – Economic consequences



Route Type	North - South			South - North		
	Distance (Miles)	Time (Minutes)	Cost	Distance (Miles)	Time (Minutes)	Cost
Black (CG)	1.2	5	1.46	1.2	5	1.46
Purple	2.9	12	3.16	2.9	12	3.16
Green	7.2	43	7.46	7.2	43	7.46

Traffic split



# Case Study – Economic consequences

- Bridge reconstruction cost = original construction cost, translated in today's figure = €62 million
- 2 years reconstruction time



# Case Study – Environmental consequences





# Case Study – Environmental consequences

London Borough	Total Population (2011 census)	2014 (Population predication increase by 0.9%)	Assumed Percentage of disrupted households	Total number of disrupted (1 year)	Total number disrupted households (2 years)
Southwark	120,400	121,573	70%	85,101	170,202
Lambeth	130,000	130,000	55%	71,500	143,000
Wandsworth	130,500	130,500	10%	13,050	26,100
Kensington & Chelsea	78,500	78,500	10%	7,850	15,700
City of Westminster	105,800	105,800	25%	26,450	52,900
Hammersmith & Fulham	303,100	303,100	5%	15,155	30,310
		Total number of households		219,106	438,212

# Case Study - Summary

Consequence type	Costs (€ millions)	Percentage (%)
Fatality/Casualty costs	€393.8	28.7
Traffic delay/ Detour costs	€844.3	61.5
CO <sub>2</sub> emission costs	€7.2	0.52
Noise pollution costs	€5.4	0.39
Air quality costs	€59.8	4.36
Traffic management costs	€0.32	0.02
Reconstruction costs	€62.0	4.52
Total Costs	€1,372.8	100.0

# Concluding remarks

- Categorisation of bridge failure consequences
- System boundaries – spatial & temporal
- Detailed investigation of past failures instructive & valuable
- Use of common framework for meaningful comparisons is challenging
- Commonly acceptable models
- Understanding uncertainties & variabilities



[link to paper](#)

**THANKS FOR YOUR ATTENTION!**

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### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **Data collection on Bridge Management Systems**

Nikola Tanasic - *Faculty of Civil Engineering, University of Belgrade, Bul. kralja Aleksandra 73, 11000, Serbia*  
E-Mail: [nikola@imk.grf.bg.ac.rs](mailto:nikola@imk.grf.bg.ac.rs)

[link to paper](#)



**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**

# OUTLINE

- INTRODUCTION
- IABMAS QUESTIONNAIRE
- UPDATE OF THE QUESTIONNAIRE
- SYNERGY OF THE IABMAS AND COST



# Introduction

- Two main **THREATS** to bridges:
  - *Deterioration processes* / **SLOW** (corrosion, alkali-aggregate....)
  - *Natural hazards* / **SUDDEN** (flood, earthquake, avalanche...)



- Principal task in management of transportation infrastructure  
Maintenance of aging bridges !

# Introduction

- **Management of threatened bridges**
  - Methodology ?
  - Assessments / Criteria ?
  - Adequate quality control plans ?
- **Bridge Management Systems (BMS)**
  - Databanks (Inventory & Inspection data)
  - Methodology – (rating systems / criteria) \*
  - Expert tools – analysis of engineering and economic factors \*
- **Gathering knowledge on bridge management practices is necessary !**

} **BMS**

**\* currently being developed**

# Data collection on bridge management practices

- **Two main aspects to look for in bridge management practices**
  - 1) Methodologies in decision making processes
  - 2) Data applied in the methodologies
- **IABMAS** (International Association for Bridge Management and Safety) **Questionnaire** – gathering data on **BMS**
- **COST TU1406 Survey**  
Database for **Performance Indicators**  
(**National documents + Research documents**)

# The IABMAS questionnaire

- Structured in MS Word
- **18** countries responded / data on **25 BMS** collected
- One million objects of transportation infrastructure  
(**65% bridges**, 32% culverts, 3% tunnels and retaining structures)

## Data gathered in the Questionnaire:

- General system and IT information
- Inventory, Inspection and Intervention information
- Prediction information
- Use Information, and
- Operation information - data collection and quality assurance.

# Questionnaire example

## General BMS Data

Name (version)		KUBA 5.1.2 (2014)
Basic information	Aspect	description
	Owner (webpage)	Swiss Federal Road Office
	Date implemented (current / first version)	26.02.2014 / 1989
	Developer(s) (webpage)	Concept and functional design: Swiss Federal Roads Office / Infrastructure Management Consultants LLC, Zurich <a href="http://www.imc-ch.com">www.imc-ch.com</a> Coding: CAD Rechenzentrum AG, Allschwil <a href="http://www.cadrz.ch">www.cadrz.ch</a>
	References, Manuals & Catalogues	User Manual (German, French, Italian), Administration and deployment manual (German only), Operation manual, Data Collection Guidelines (German, French, Italian), Inspection Manual (German, French), Technical catalogues (German, French, Italian) Available at <a href="http://www.mobilityplatform.ch">www.mobilityplatform.ch</a>
	Users (Principal / Other)	Swiss Federal Road Office / 18 cantons and various cities and communities
IT information	Aspect	description
	Platform	Web client (not browser, self-installing Windows 7 client; port 8000), .NET IIS Application server, Oracle or SQL Server Web Browser (IE, Firefox, Opera) for read-only Mobile Client: Window 7, SQL Server and iPad
	Architecture	Three Tier Architecture: Smart Client, Application Server, Database
	Data collection capabilities	Manually on desktop, inspection data with iPad Mass Collection: XML and INTERLIS 2 interface
	Reporting capabilities	Ad-hoc reporting aided by data universe (similar to Data Objects) Combined GIS and alphanumeric ad hoc reporting Pre-prepared reports: Inventory, Inspection and performed interventions
	Web access	√ (read only)

# Questionnaire – Inspection information

- Data Collection level
- Assessment on element/structure level

Inspection information	<b>Data collection level</b>	<b>C</b>	<b>description</b>
	Element level (type of inspection method possible, e.g., visual, non-destructive, destructive)	√	Visual inspections with quantification of damage extent and damage description (based on catalogue), photos, damage plans etc. Some data from non-destructive methods (potential measurements) can be stored as well.
	Quantification of defects	√	Extent of defect groups related to same deterioration process.
	Structure level (type of inspection method possible, e.g., visual, non-destructive, destructive)	√	Generally there is no difference between element level and structure level.
	Quantification of defects	√	See above
	<b>Assessment on element level</b>	<b>C</b>	<b>description</b>
	Condition (physical)	√	The condition rating (1-5) refers to physical condition.
	Load carrying capacity	√	A special mode allows the quick assessment of load carrying capacity for a given loading
	Safety (probability of crash)	X	The concept is prepared at will be implemented in KUBA 5.2
	Risk (probability and consequences of failure)	X	See line above.
	<b>Assessment on structure level</b>	<b>C</b>	<b>description</b>
	Condition (physical)	√	Manual input
	Load carrying capacity	√	Automatic assessment
	Safety (probability of crash)	X	The concept is prepared at will be implemented in KUBA 5.2
	Risk (probability and consequences of failure)	X	See line above.
	Additional	√	Individual damages are grouped in groups if affected by the same deterioration process



# Questionnaire - Prediction information

- Deterioration modeling
- Intervention strategies
- Work programs

Prediction information	Aspect	C	description
	Deterioration, i.e. change in <ul style="list-style-type: none"> <li>- Physical condition</li> <li>- Performance indicators</li> </ul>	√	Physical deterioration is modeled by Markov chains. No change in performance indicators is modeled.
	Effects of intervention/Improvement, i.e. change following an intervention in <ul style="list-style-type: none"> <li>- Physical condition</li> <li>- Performance indicators</li> </ul>	√	Change in physical condition due to standard interventions is modeled. No change in performance indicators is modeled.
	Optimal intervention strategies <ul style="list-style-type: none"> <li>- Period of time analyzed</li> <li>- Cost estimation<sup>vi</sup></li> <li>- Life cycle cost</li> <li>- Risk analysis</li> <li>- Optimization method<sup>vii</sup></li> </ul>	√	Optimal and minimal (only in condition state 5) intervention strategies are estimated by the system both for elements and structures. <ul style="list-style-type: none"> <li>- Analysis period of time for network level is infinite and for structural level is up to 25 years.</li> <li>- The construction costs are considered on element level based on unit costs. On structure level user costs, setup costs, traffic control costs, design costs and assessment costs are considered.</li> <li>- The optimum strategy is estimated based on minimum life cycle cost</li> <li>- Risk analysis is not currently implemented</li> <li>- Linear program on structural level incremental cost/benefit ratio</li> </ul>
	Work programs <ul style="list-style-type: none"> <li>- Period of time analyzed</li> <li>- Project packaging</li> <li>- Cost estimation</li> </ul>	√	Based on optimal element strategies application establishes a work program. <ul style="list-style-type: none"> <li>- Up to 25 years</li> <li>- Project are generating by combining optimum intervention on element level</li> </ul>

# Update of the IABMAS questionnaire

- **Old questionnaire (two feedbacks 2009 and 2013) – solid databank !**
- **New questionnaire key aspects**
  1. Google Forms – interactivity enhanced!
    - i. Predefined answers – multiple choice, dropdown lists...
    - ii. Easier data post-processing
  2. Questions based on affiliation of a respondent – more precise data
    - i. Owners of the transportation infrastructure
    - ii. Consultant companies
    - iii. Universities/Institutes

# Updated questionnaire

**BMS Survey**

START

\* Required

Your name: \*

Your answer

Your e-mail: \*

Your answer

You represent: \*

- ☐ Owner of transportation infrastructure
- ☐ Consultant company
- ☐ University/Institute

NEXT

Never submit passwords through Google Forms.

---

**BMS Survey**

\* Required

For owners of transportation infrastructure

General Information

Name of the owner: \*

Your answer

web: \*

Your answer

What are your principal duties in management of transportation infrastructure?

- ☐ Budget planning
- ☐ Setting performance levels
- ☐ Maintenance and Repairs
- ☐ Life lines (emergency, hazards...)
- ☐ Special / overweight transport
- ☐ Other:

BACK NEXT

Never submit passwords through Google Forms.

---

**BMS Survey**

\* Required

Software information

In decision making you rely on: \*

- ☐ Solutions obtained from a consultant
- ☐ Solutions developed in own assessment

Decision making is supported by: \*

- ☐ Spreadsheets (e.g. databank and MS Excel)
- ☐ Database management system - DBM data structured in MS Access, MySQL
- ☐ DBMS with Spreadsheets and/or standalone which includes expert modules/functions
- ☐ Expert system (e.g. software with DBM implemented expert engineering/man tools/modules/functions)

This software/platform is: \*

- ☐ Proprietary - developed/updated for own use
- ☐ Proprietary - development and maintenance by consultant company/institution
- ☐ Proprietary - updates (e.g. of methods) by consultant company/institution
- ☐ Commercial but tailored specifically for use by a consultant company/institution
- ☐ Commercial

---

**BMS Survey**

\* Required

Data Access/Handling and Analyses Output

Access to infrastructure data \*

	Unrestricted	Limited	Subject to departments	None
Inventory data	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Inspection data	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Analyses Output	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Data access over a network/web

- ☐ One user have WRITE access to specific data while multiple users have READ access, at the same time
- ☐ Multiple users have WRITE access at the same time to data on different levels. READ access is allowed at all times
- ☐ Periodical network/internet connection necessary for update/upload of the data
- ☐ N/A.

Besides regular inspection data, the information which is necessary for the decision making is obtained in: \*

- ☐ in-situ tests (e.g. concrete cover depth, deflection, soil properties, etc.)
- ☐ laboratory tests (e.g. material properties, soil properties, etc.)

# Key questions are put forward

## 1. The decision making process

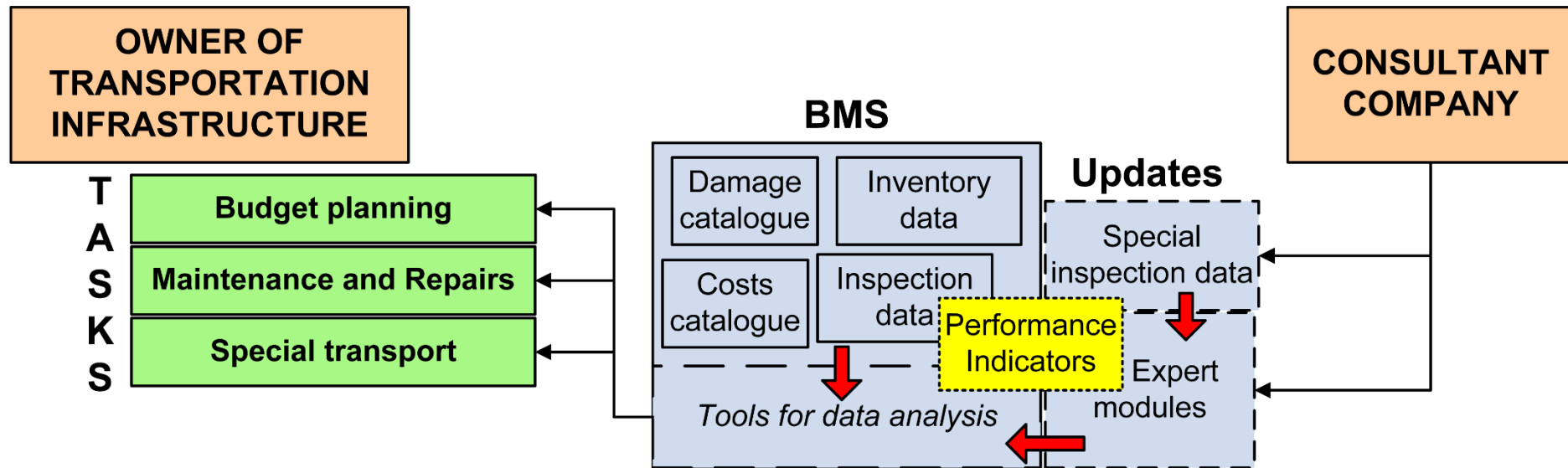
- a) The primary concerns & duties of owners of the infrastructure (maintenance/repairs scheduling, performance goals etc.)
- b) The participants in the process and their relationships & duties

## 2. The features of an BMS

- a) Stage of development of a BMS (i.e. structure, IT platform)
- b) Ownership/use of a BMS and its development strategy
- c) Bridge database information, input of surveying/monitoring data and use other databases
- d) Type, extent and mode of assessment of the infrastructure
- e) Specific Analysis and Expert tools/modules
- f) Future development/update (functionality& methodology)

# Synergy of the IABMAS and COST Surveys

- General (IABMAS) and detailed (COST) approach
- Up-to-date review of the capabilities of the most advanced BMS
- Merging of the initiatives of IABMAS and COST



# Conclusion

- Review of a country's readiness to cope up with future threats to transportation infrastructure
- Knowledge on various practices = improvement of current methodologies - benefits to all participants in the decision making process
- Identification of technical and social performance indicators is necessary for establishment of adequate quality control plans







[link to paper](#)

**THANKS FOR YOUR ATTENTION!**

WWW.TU1406.EU



### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **Scheduling bridge rehabilitations based on probabilistic life cycle condition information**

**Dimos C. Charmpis** - University of Cyprus, Nicosia, Cyprus

**Filippos Alogdianakis** - University of Cyprus, Nicosia, Cyprus

**Ioannis Balafas** - University of Cyprus, Nicosia, Cyprus

[link to paper](#)



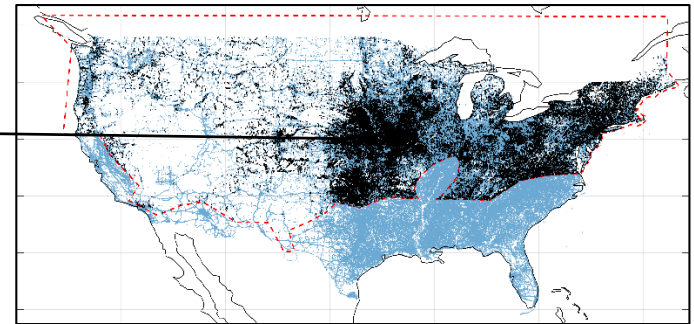
**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**

# Aim

- Quantitatively explore the effect of risk attitude when deciding for the rehabilitation schedule of an aging bridge
- Consider various influencing aspects:
  - probabilistic life cycle condition information for bridge
  - expected life cycle costs for scheduled rehabilitations, possible replacement, users

# Probabilistic life cycle condition information

- Exploitation of data for from the National Bridge Inventory (NBI) of the US Federal Highway Administration (FHWA)
- 57,056 steel bridges of various ages exposed to deicing salts and humidity (*black dots*)



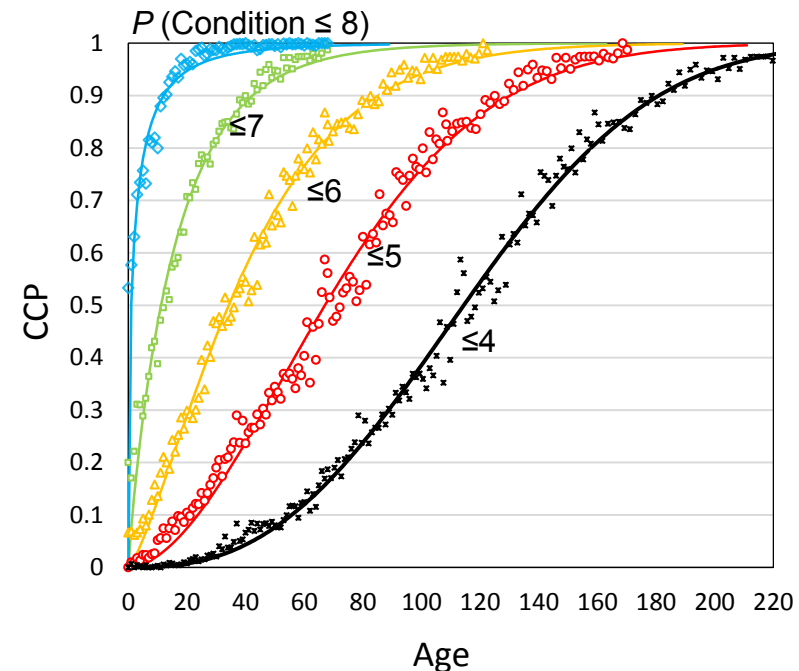
- Bridge condition ratings recorded on a scale of 0-9

Rating	9	8	7	6	5
Condition	Excellent	Very good	Good	Satisfactory	Fair

Rating	4	3	2	1	0
Condition	Poor	Serious	Critical	'Imminent' failure	Failed

# Probabilistic life cycle condition information

- Data used to calculate cumulative probabilities for each structural condition
- CCP = Cumulative Condition Probability =  $P(\text{Condition} \leq i)$   
(probability of a bridge of a certain age to be equal or below a certain structural condition  $i$ )
- Time-shifts and scalings are applied and Weibull distribution functions are fitted to the available data



# Risk attitude spectrum

The decision maker's response to uncertainty and the resulting attitude toward risk

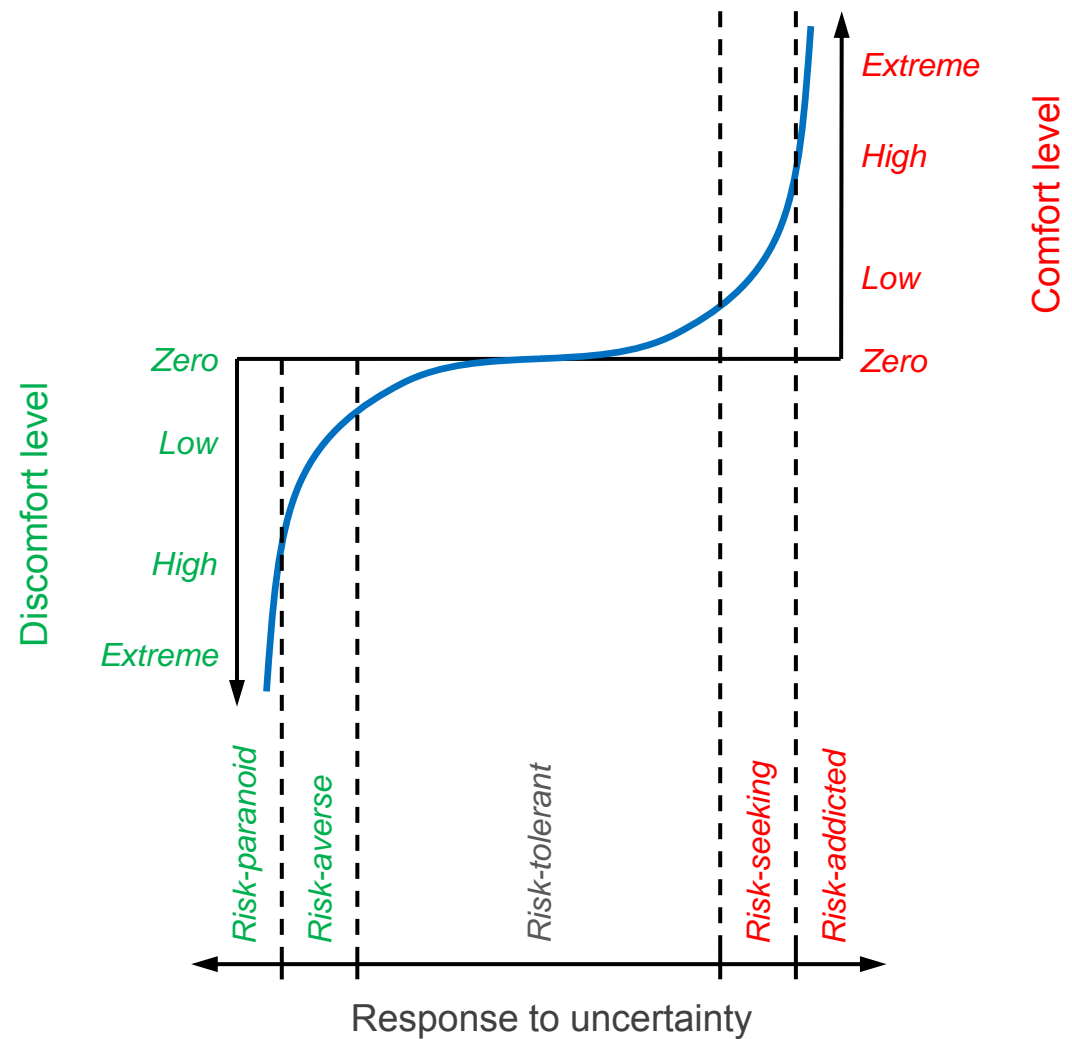
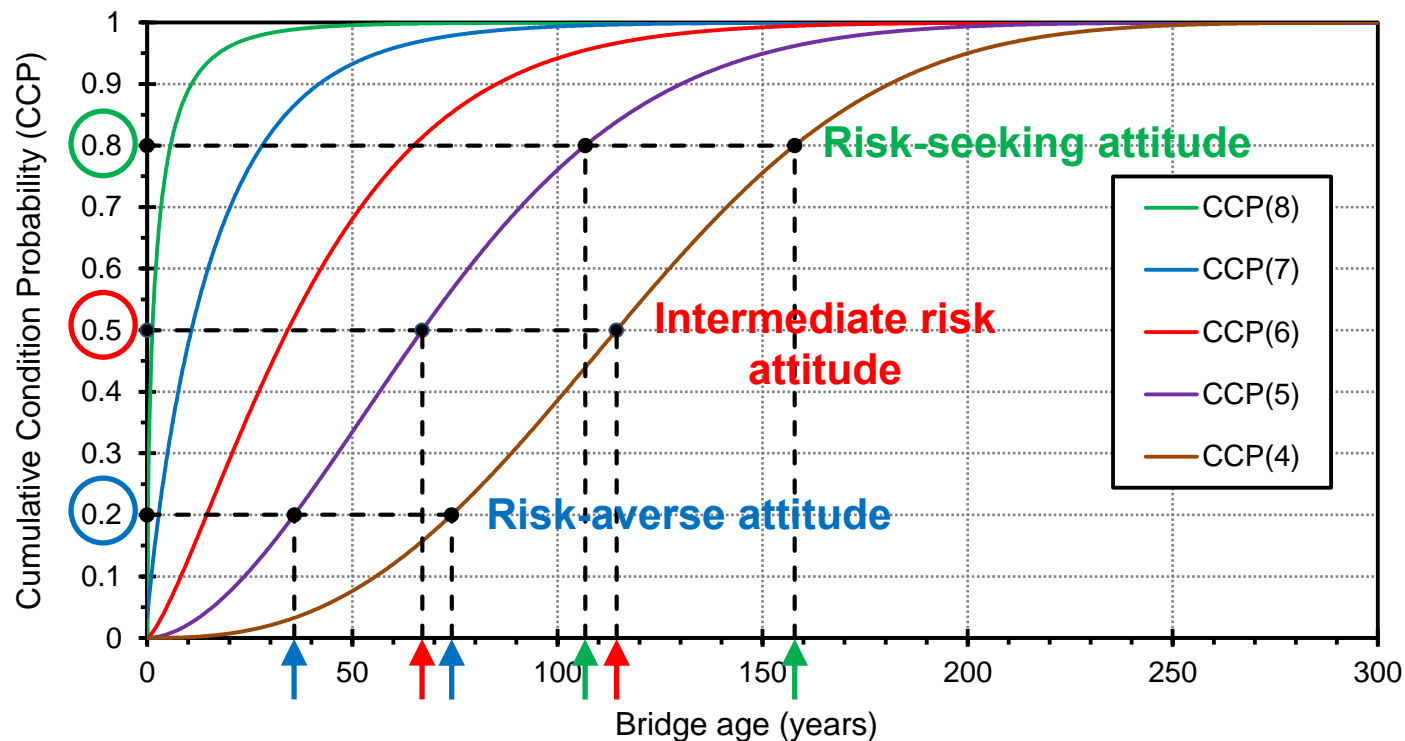


Figure adjusted from:  
D. Hillson, R. Murray-Webster,  
*Understanding and managing risk attitude*,  
Gower, England, 2005.



# Scheduling bridge rehabilitations based on the decision maker's risk attitude

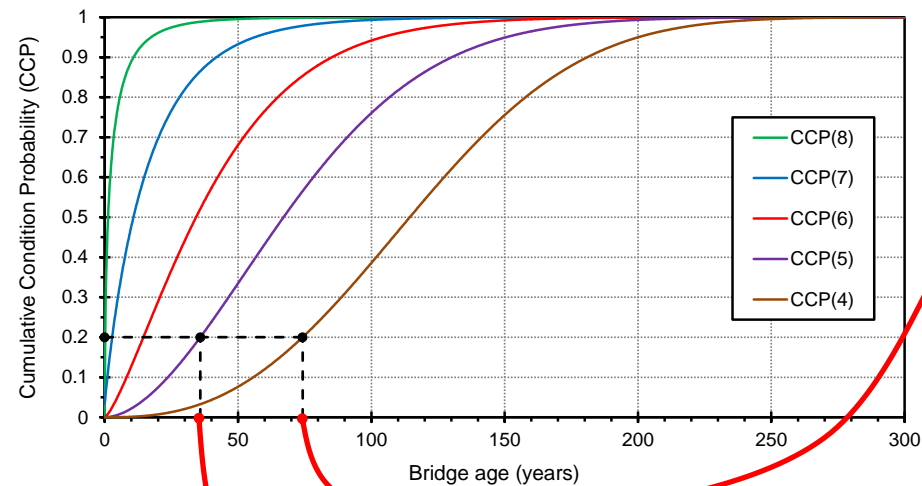
Scheduling bridge rehabilitations when:  $P(\text{Condition} \leq 4 \text{ or } 5) = 0.2, 0.5 \text{ or } 0.8$



# Risk-averse attitude of decision maker

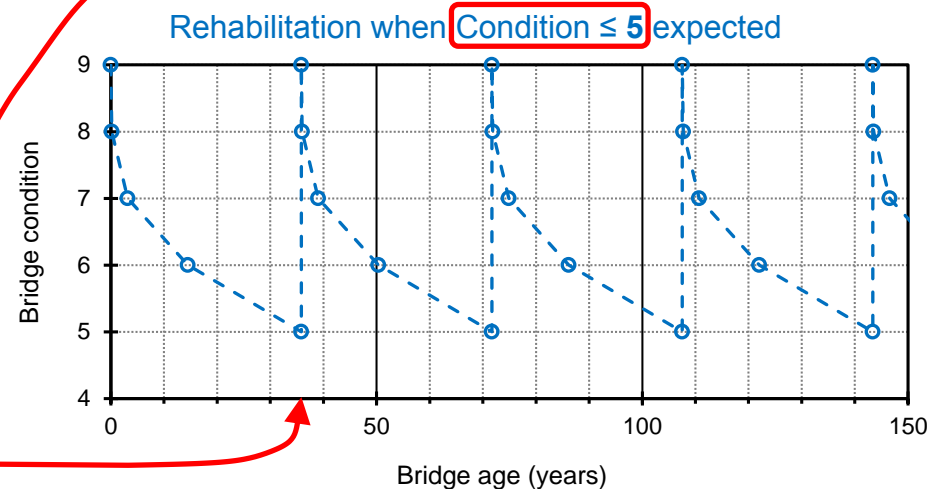
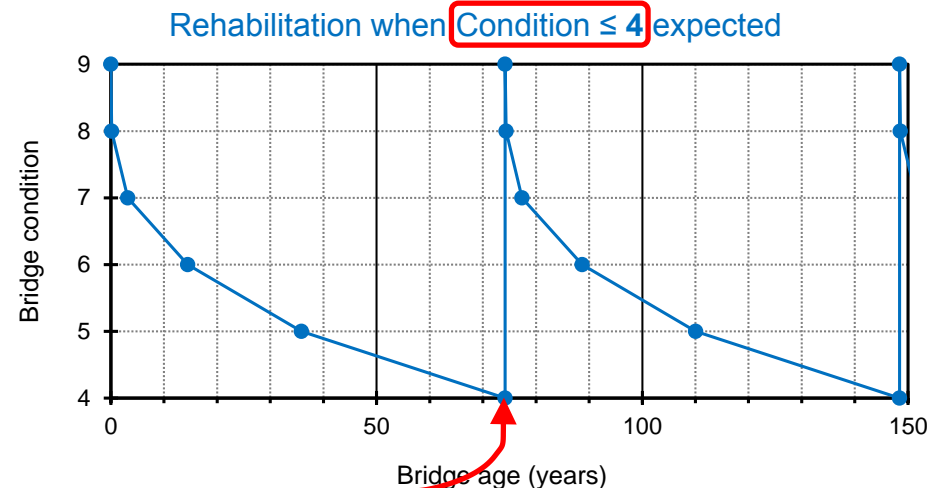
Scheduling  
bridge rehabilitations  
when:

$$P(\text{Condition} \leq 4 \text{ or } 5) = 0.2$$



Rehabilitation every ~36 years

Rehabilitation every ~74 years

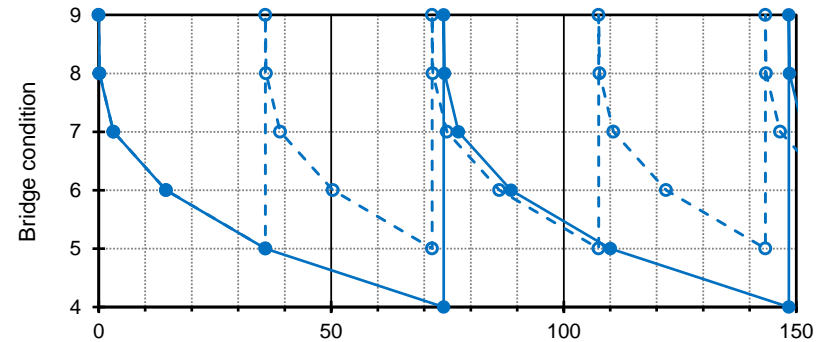


# Scheduling bridge rehabilitations

## Risk-averse attitude

$P(\text{Condition} \leq 4 \text{ or } 5) = 0.2$

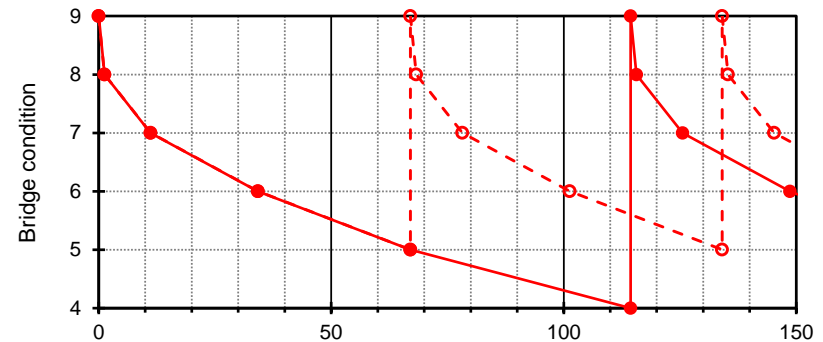
Total: 2-4 rehabilitations



## Intermediate risk attitude

$P(\text{Condition} \leq 4 \text{ or } 5) = 0.5$

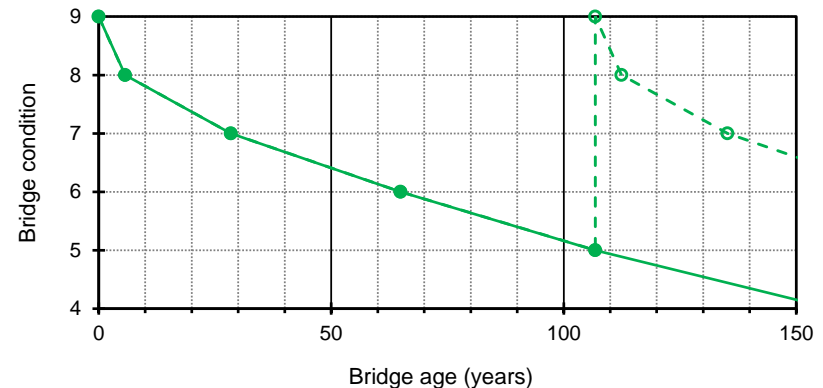
Total: 1-2 rehabilitations



## Risk-seeking attitude

$P(\text{Condition} \leq 4 \text{ or } 5) = 0.8$

Total: 0-1 rehabilitations



# Expected life cycle cost estimation of rehabilitation schedules

- Initial construction cost ( $t=0$ ):  $C_0$
- Rehabilitation costs  
 Cost to restore condition 9 from condition
 

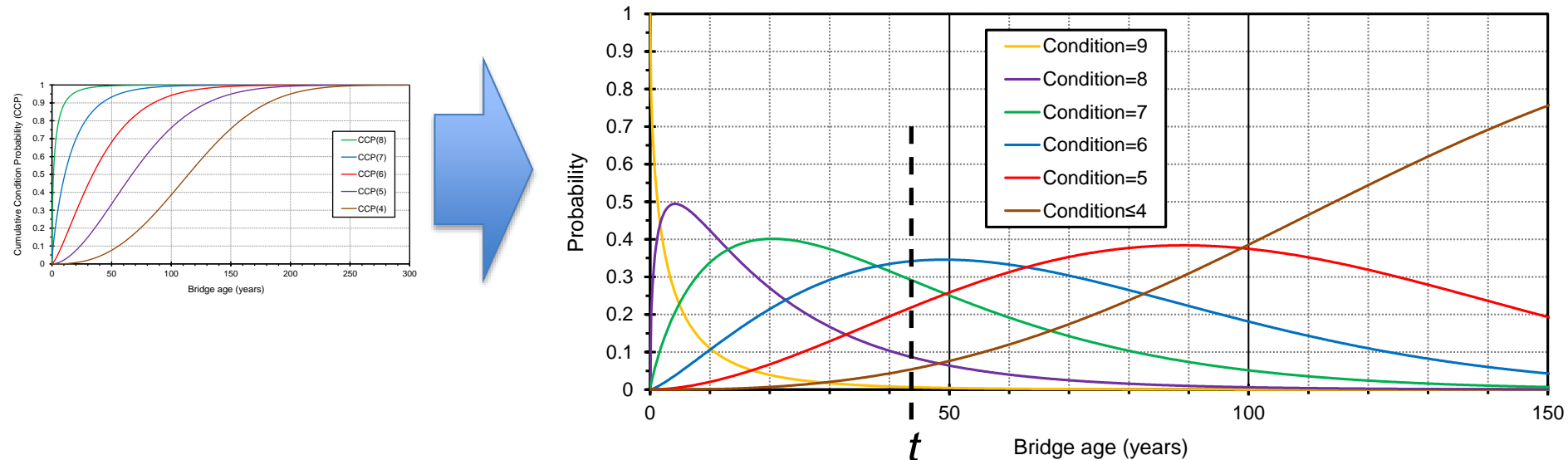
8:	$C_{R8}=0.005C_0$
7:	$C_{R7}=0.01C_0$
6:	$C_{R6}=0.03C_0$
5:	$C_{R5}=0.1C_0$
$\leq 4$ :	$C_{R4}=0.4C_0$
- User costs during rehabilitation:  $3C_0$  / month of bridge closure  
 (due to delays, increased travel expenses, increased accident rates, inconvenience, ...)  
 Rehabilitation from condition
 

5:	bridge closed for 0.1 months
$\leq 4$ :	bridge closed for 0.5 months

 Total cost to restore condition 9 from condition
 

5:	$C_{R5}=0.4C_0$
$\leq 4$ :	$C_{R4}=1.9C_0$

# Expected life cycle cost estimation of rehabilitation schedules



Expected rehabilitation cost of the bridge at any time  $t$ :

$$C_{\text{Reh}}(t) = \sum_i [P(\text{Condition}=i) \times C_{Ri}] + P(\text{Condition} \leq 4) \times C_{R4} \quad (i=8,7,6,5)$$

# Expected life cycle cost estimation of rehabilitation schedules

Risk of the bridge dropping to such a condition that rehabilitation is not a suitable choice anymore

**Bridge replacement** may be dictated by extensive failure that renders uneconomical the repairs required, partial/full collapse, dropping of the safety level provided below an acceptable/tolerable threshold, etc.

- Bridge replacement cost at any time  $t$ :  $1.2C_0$   
( $0.2C_0$  for removal of old bridge +  $C_0$  for construction of new bridge)
- User costs during replacement:  $5C_0$  / month of bridge closure  
Bridge closed for 12 months for removal of old bridge, establishment of detour, design/bidding/construction of new bridge, etc.
- Total replacement cost at any time  $t$ :  $61.2C_0$ .
- Replacement probability at any time  $t$ :  $P_{\text{rep}} = 0.2 \times P(\text{Condition} \leq 4)$   
Expected replacement cost at any time  $t$ :  $C_{\text{Rep}}(t) = P_{\text{rep}} \times 61.2C_0$



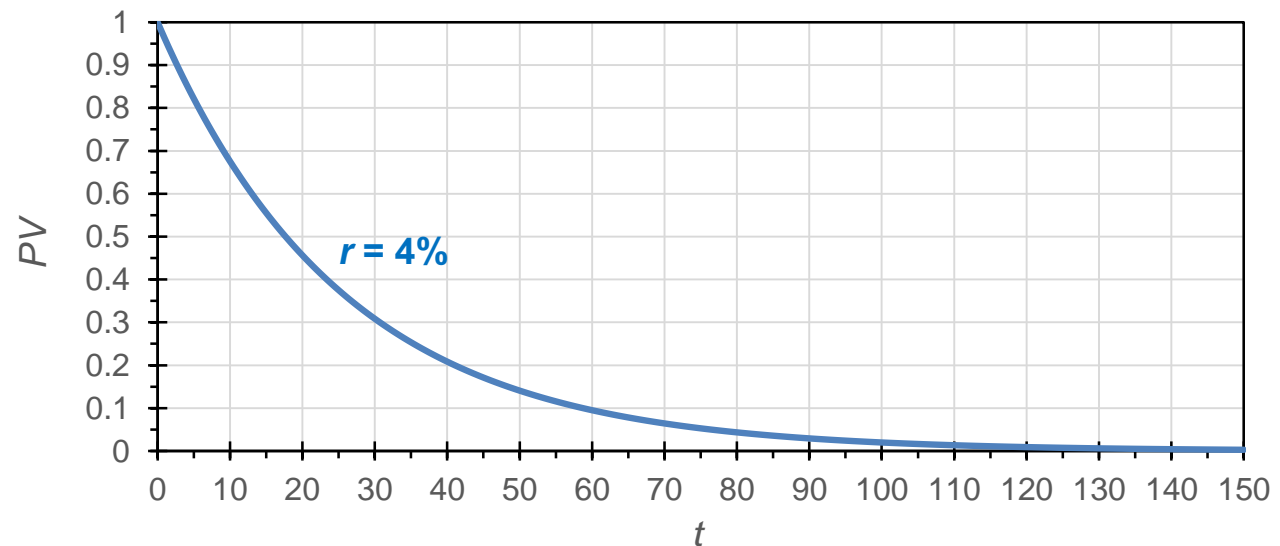
# Expected life cycle cost estimation of rehabilitation schedules

The expected rehabilitation cost  $C_{\text{Reh}}(t)$  and replacement cost  $C_{\text{Rep}}(t)$  are **Future Values (FV)** (paid at various instances  $t$ )

Any FV at time  $t$  is transferred to time  $t=0$  by discounting it to the corresponding **Present Value (PV)**:

$$PV = \frac{FV}{(1+r)^t}$$

$r$  = discount rate



# Expected life cycle cost estimation of rehabilitation schedules

Total expected rehabilitation cost:

$$C_{\text{Reh,tot}} = PV[C_{\text{Reh}}(t_1)] + PV[C_{\text{Reh}}(t_2)] + \dots$$

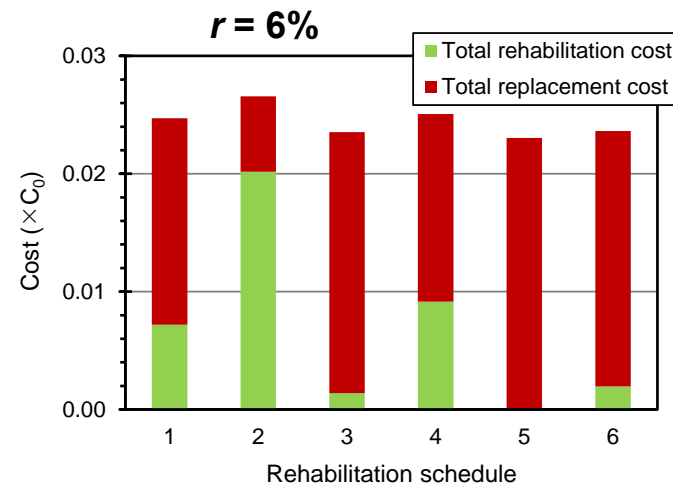
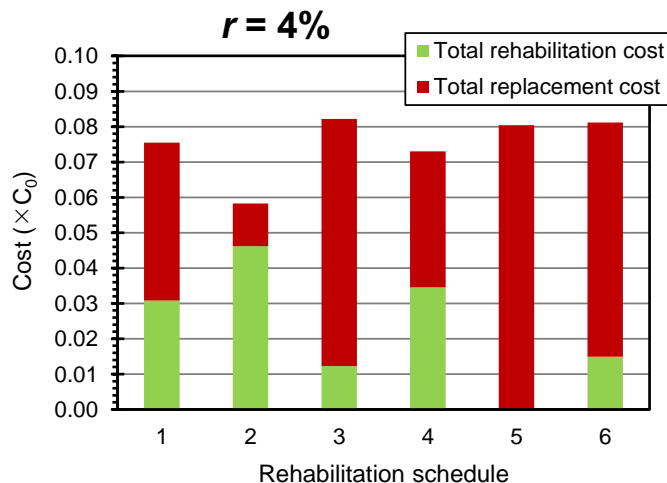
for planned rehabilitations at bridge ages  $t_1, t_2, \dots$

Total expected replacement cost:

$$C_{\text{Rep,tot}} = \text{average of } PV[C_{\text{Rep}}(t)] \text{ over all years } 0 \leq t \leq 150$$

# Expected life cycle cost estimation of rehabilitation schedules

Rehabilitation schedule	Probability-level	Time-to-rehabilitation (years)	Required rehabilitations	
1	$P(\text{Condition} \leq 4) = 0.2$	74.2	2	} Risk-averse attitude
2	$P(\text{Condition} \leq 5) = 0.2$	35.8	4	
3	$P(\text{Condition} \leq 4) = 0.5$	114.4	1	} Intermediate risk attitude
4	$P(\text{Condition} \leq 5) = 0.5$	67.1	2	
5	$P(\text{Condition} \leq 4) = 0.8$	157.8	0	} Risk-seeking attitude
6	$P(\text{Condition} \leq 5) = 0.8$	106.8	1	



# Conclusions

- Establishing cost-effective bridge rehabilitation schedules is a great challenge
- Data required that are hard to find:
  - probabilistic information regarding the bridge deterioration rate
  - rehabilitation, replacement, user costs
  - etc.
- The risk attitude of the decision maker is a crucial aspect in the life cycle cost assessment and management of a deteriorating bridge
- Interplay between the contributions of the rehabilitation and replacement costs in the total life cycle cost
- The discount rate  $r$  plays a decisive role in the cost comparison of alternative rehabilitation schedules
  - low  $r$ : favors risk-averse attitude
  - high  $r$ : favors risk-seeking attitude



[link to paper](#)



### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **ENVIRONMENTAL EFFECTS ON BRIDGE DURABILITY BASED ON EXISTING INSPECTION DATA**

**Filippos Alogdianakis** - Department of Civil and Environmental Engineering, University of Cyprus

**Ioannis Balafas** - Department of Civil and Environmental Engineering, University of Cyprus

**Dimos C. Charnpis** - Department of Civil and Environmental Engineering, University of Cyprus

[link to paper](#)



Πανεπιστήμιο Κύπρου  
University of Cyprus

30<sup>th</sup> March - 1<sup>st</sup> April 2016

Belgrade, Serbia



# Overview

- This study:
  1. identifies the conditions under which bridges deteriorate rapidly
  2. studies the durability performance of materials used in bridges
- The NBI database Published by the USA Federal Highway Administration is used
- Contains information in coded form (116 items) concerning location, structural condition, age, materials, traffic etc. (FHWA, 1995)
- Number of bridges in the database:
  - 118,961 reinforced (RC) concrete
  - 124,317 prestressed (PSC) concrete
  - 135,454 steel
  - 20,934 timber



## Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges

Report No. FHWA-PD-96-001

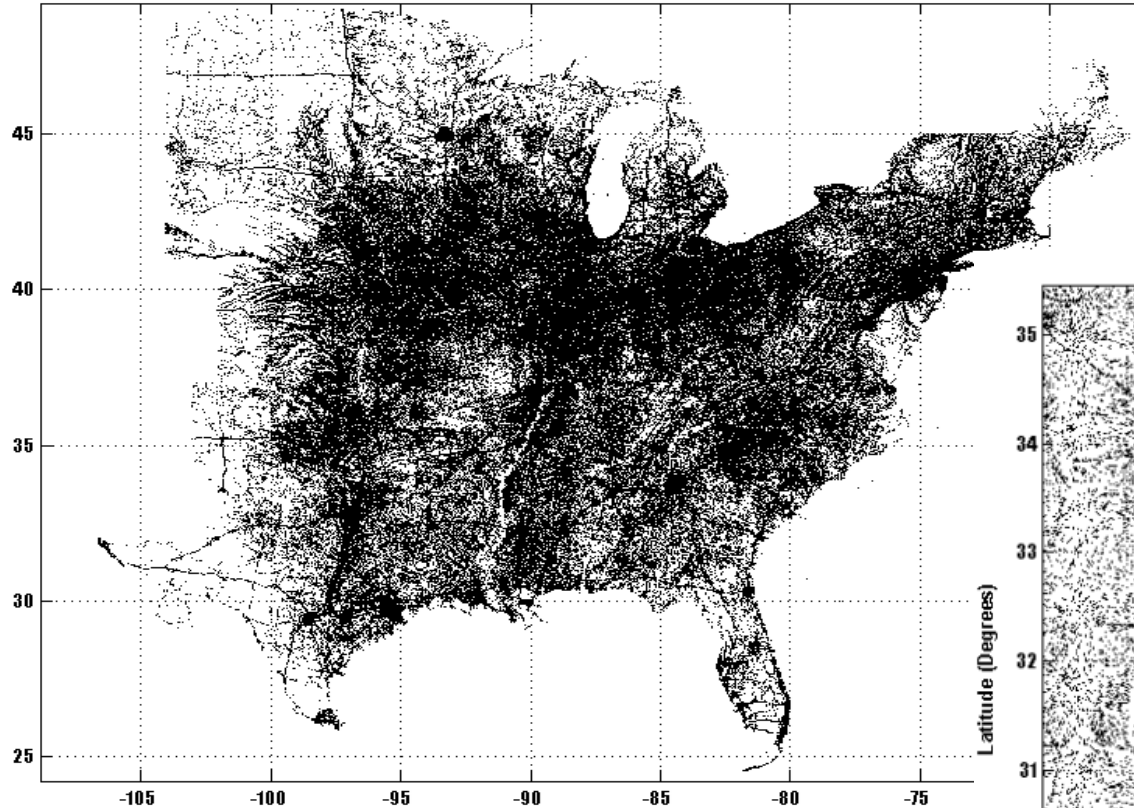


Office of Engineering  
Bridge Division

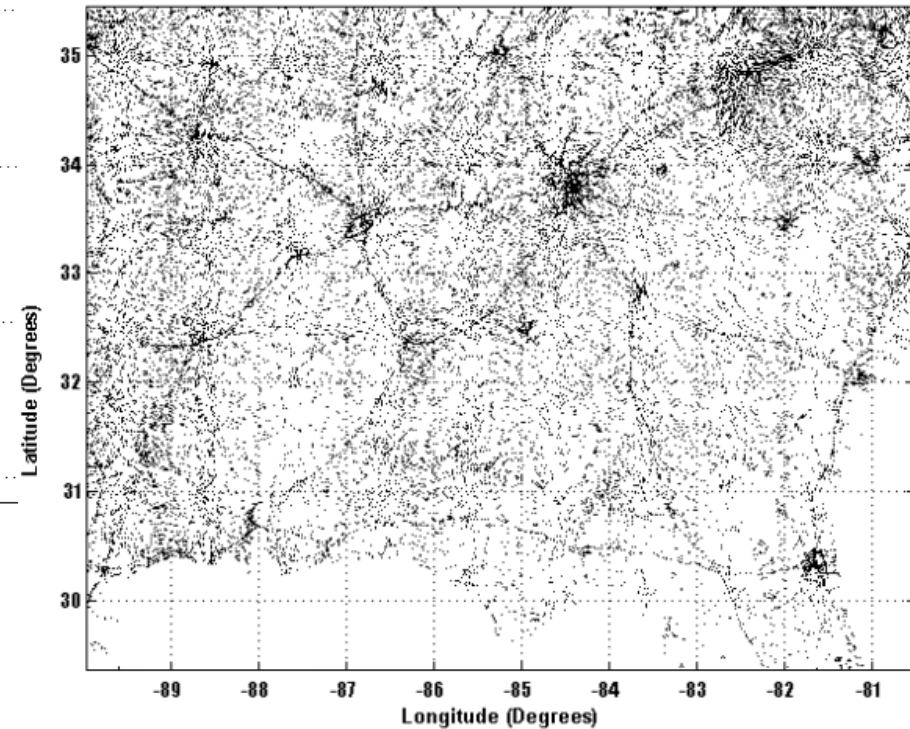
December 1995

# Bridge Topology

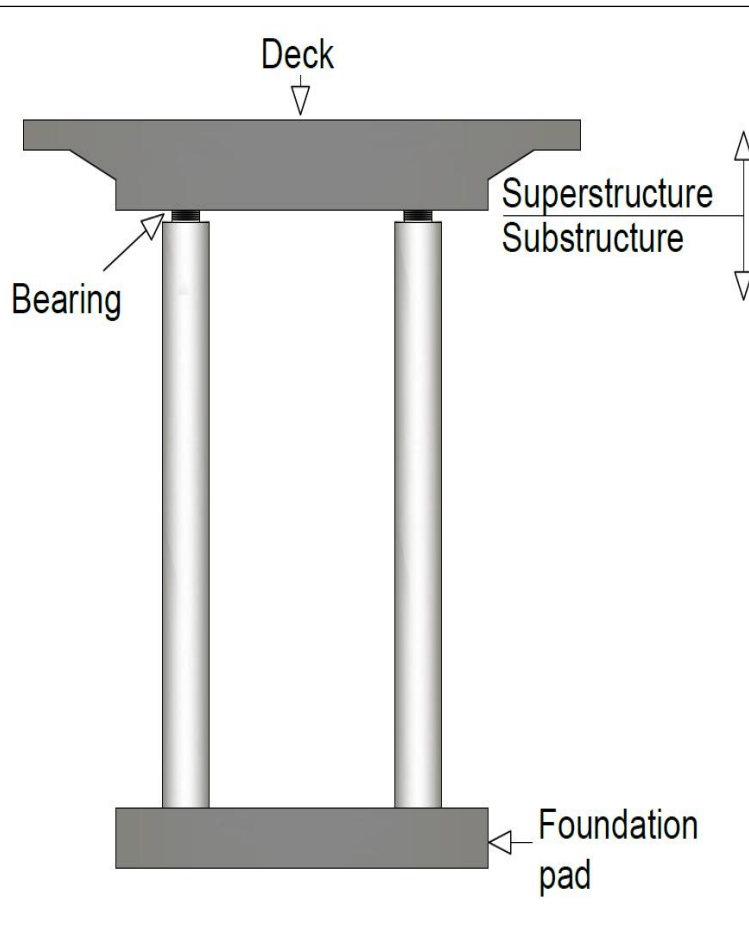
Sample of bridges



Zoom In



# Bridge Rating



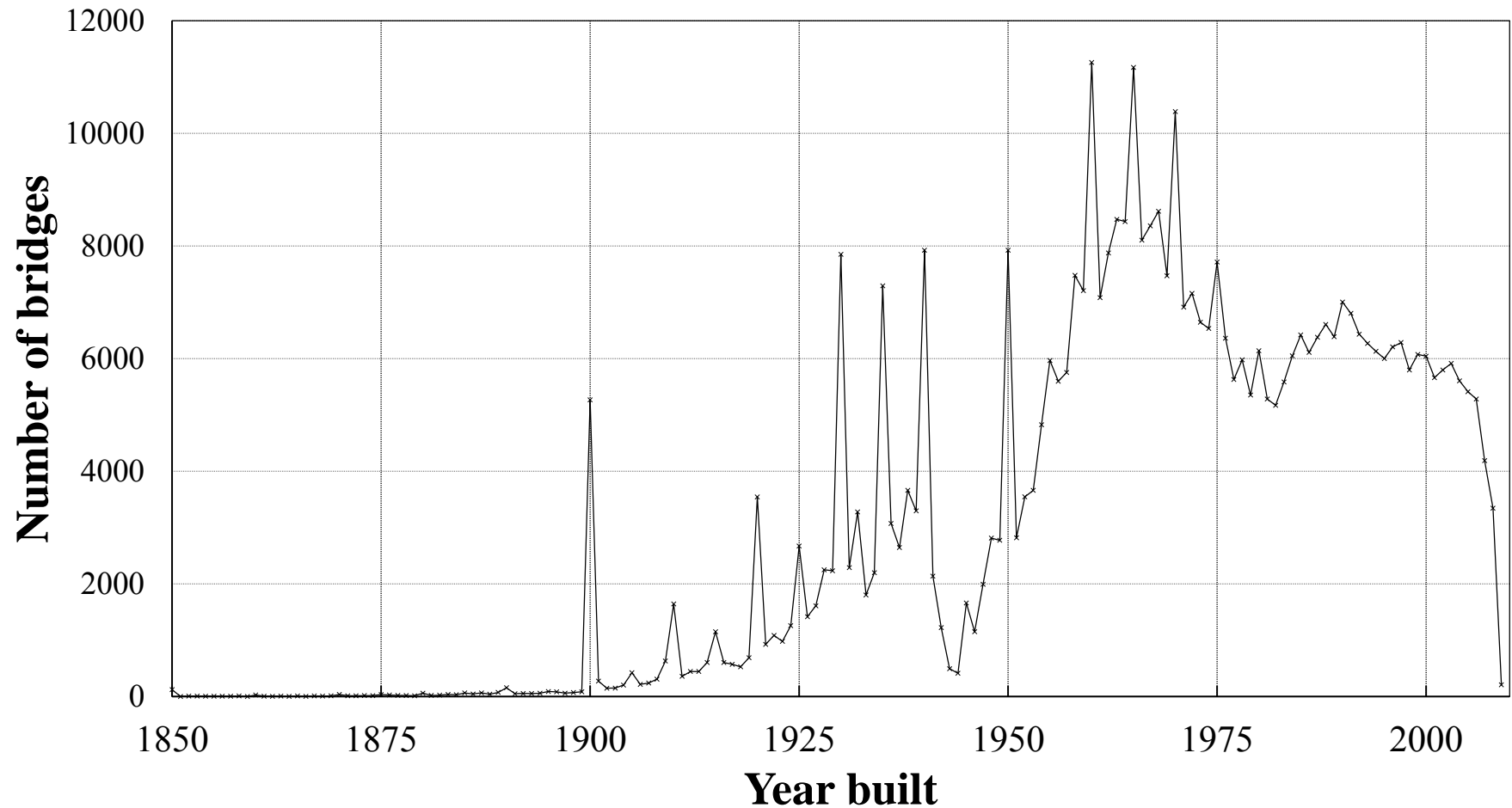
Rating	Description
9	EXCELLENT CONDITION
8	VERY GOOD CONDITION - no problems noted.
7	GOOD CONDITION - some minor problems.
6	SATISFACTORY CONDITION - structural elements show some minor deterioration.
5	FAIR CONDITION - all primary structural elements are sound but may have minor section loss, cracking, spalling or scour.
4	POOR CONDITION - advanced section loss, deterioration, spalling or scour.
3	SERIOUS CONDITION - loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	CRITICAL CONDITION - advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored, it may be necessary to close the bridge until corrective action is taken.
1	'IMMINENT' FAILURE CONDITION - major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.
0	FAILED CONDITION - out of service - beyond corrective action.

# Sample Preparation

- From 608,533 bridges 470,417 of these were included in the analysis
- Bridges excluded:
  - 131,980 non-bridge elements (e.g. culverts)
  - 545 bridges built before 1900
  - 2685 bridges last inspected before 2000
  - The database includes data from prestressed concrete bridges built before 1950 (332 bridges) - when prestressing was not well understood and most of which are rebuilt

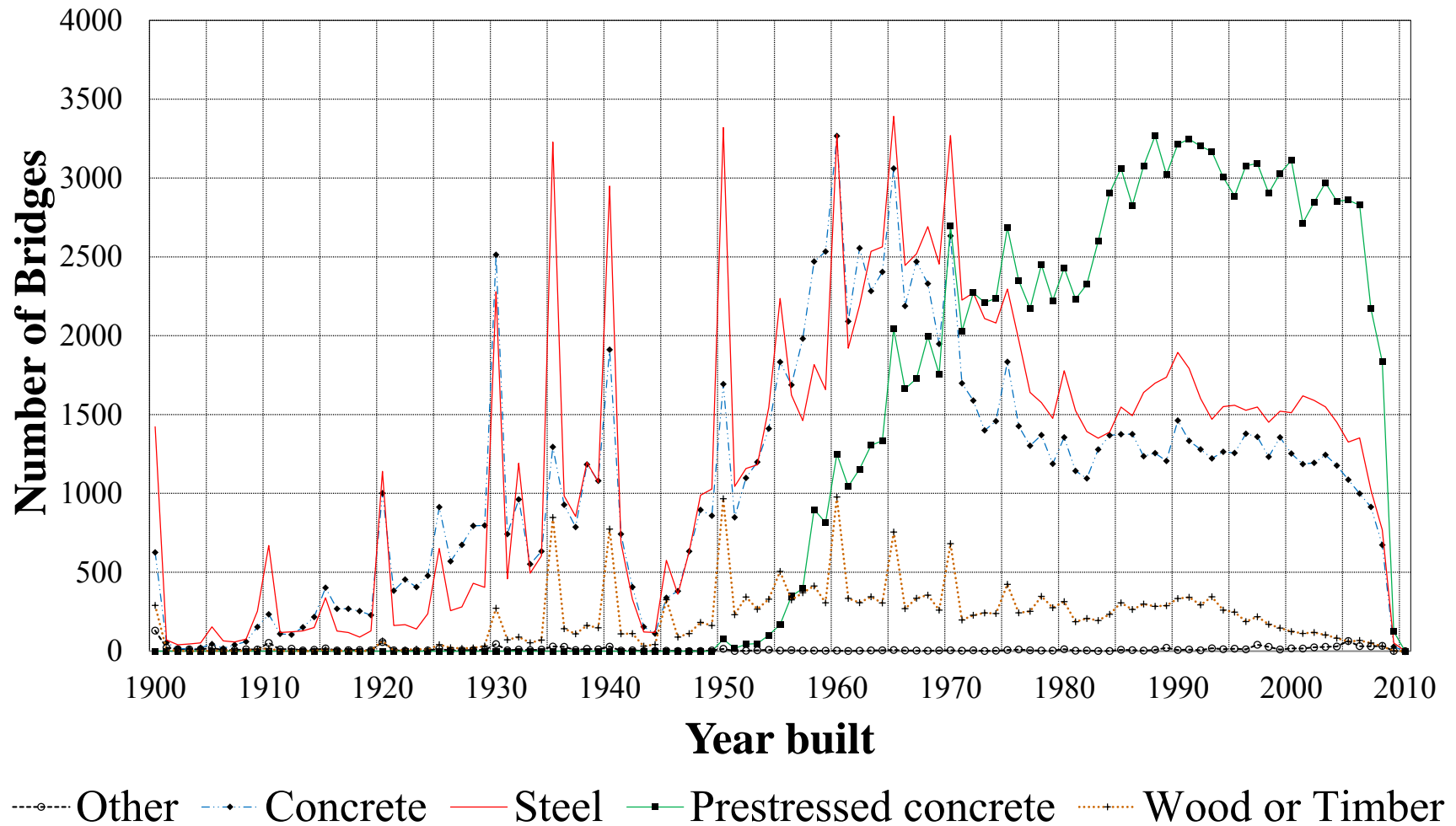


# Bridges Built per Year



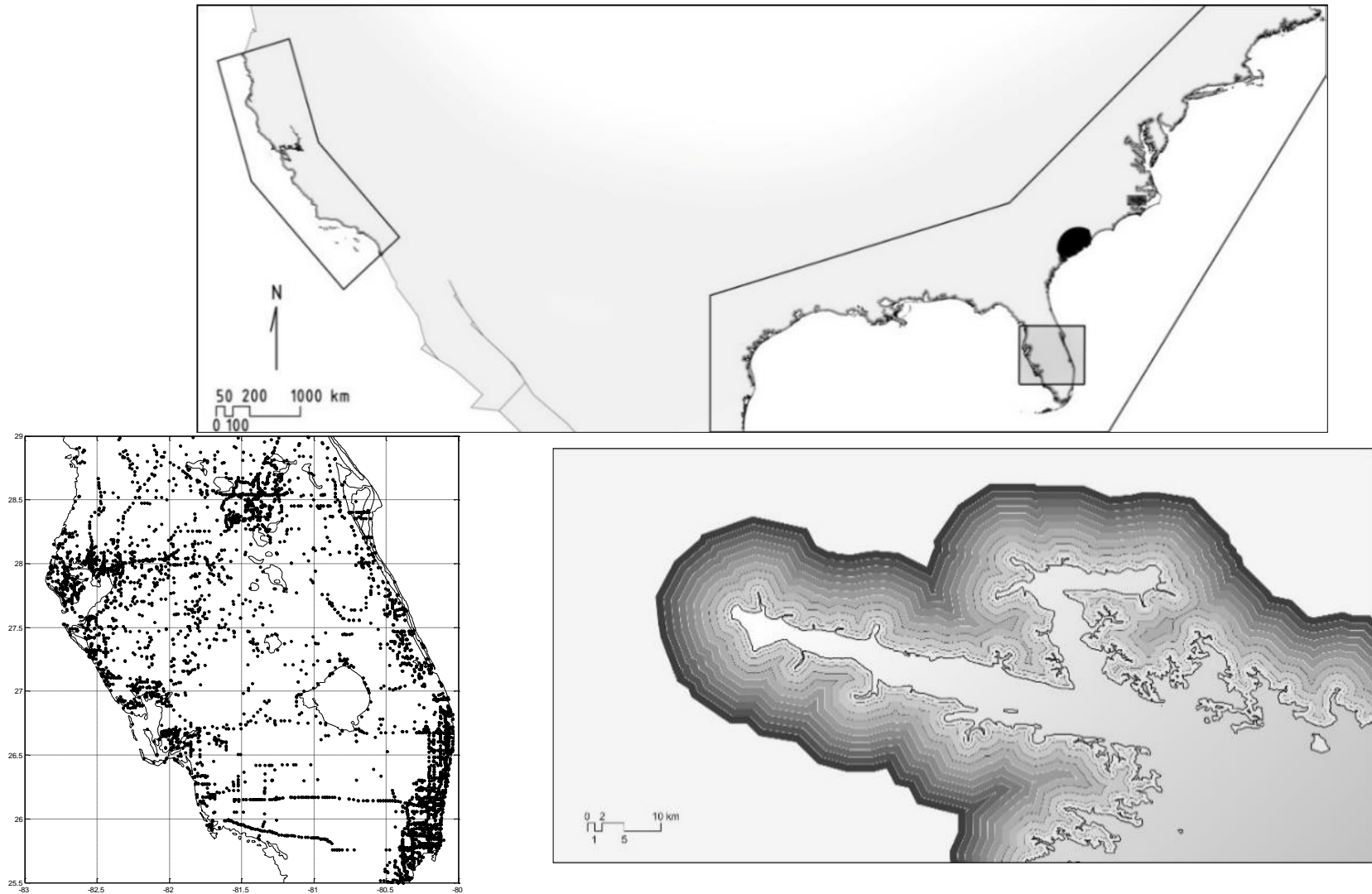


# Material Type



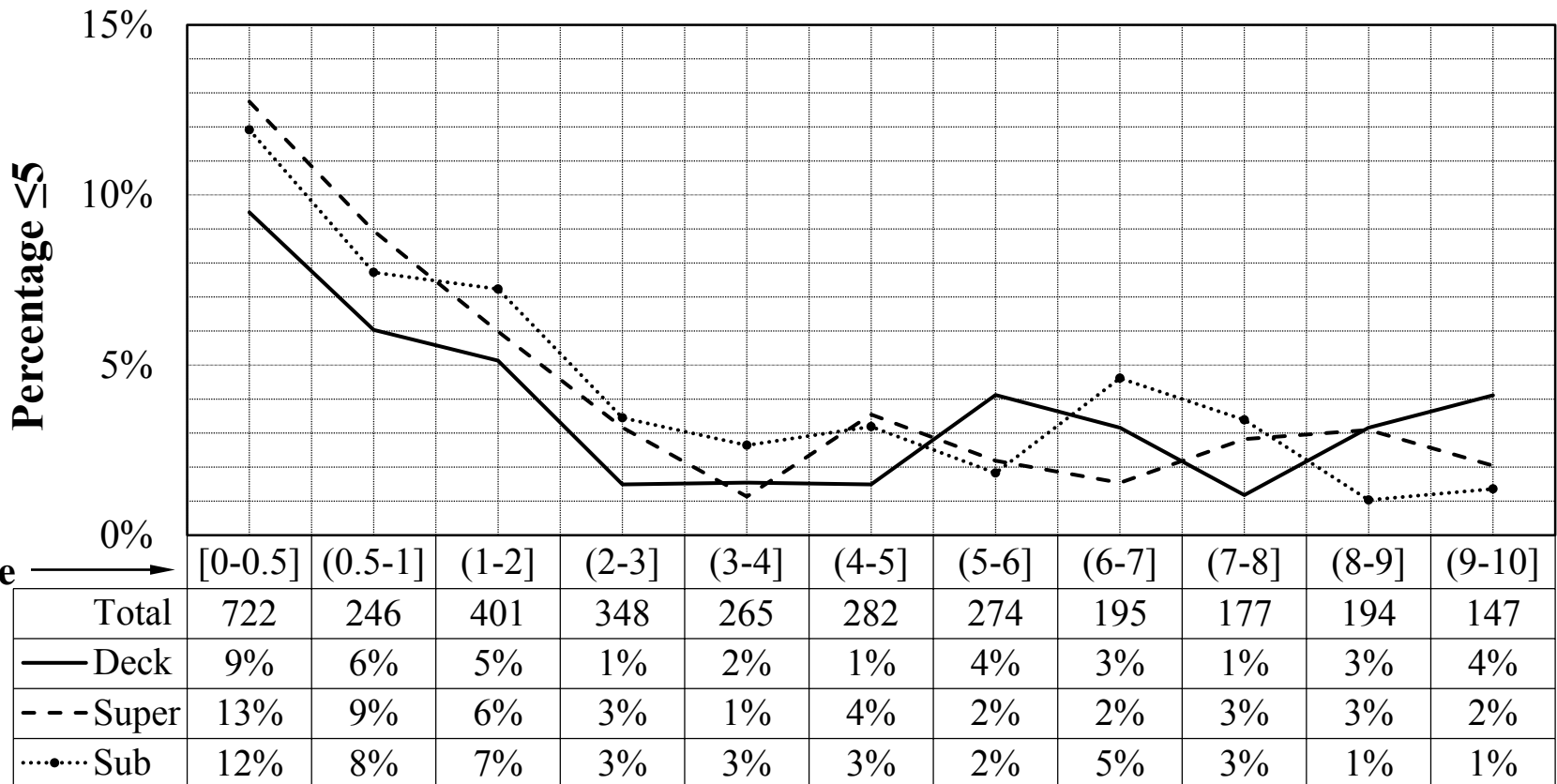


# Effect of Coastline on Corrosion



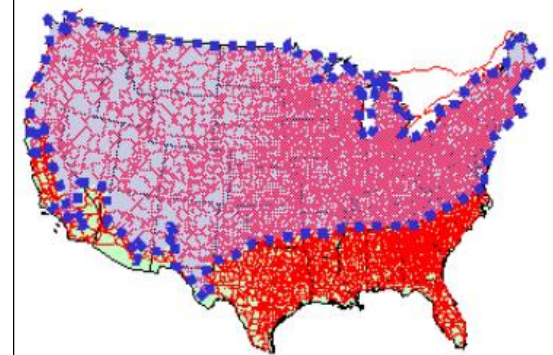
# Effect of Coastline on Corrosion

Condition Ratings  $\leq 5$  (Structural Defficiency), Built-only Bridges

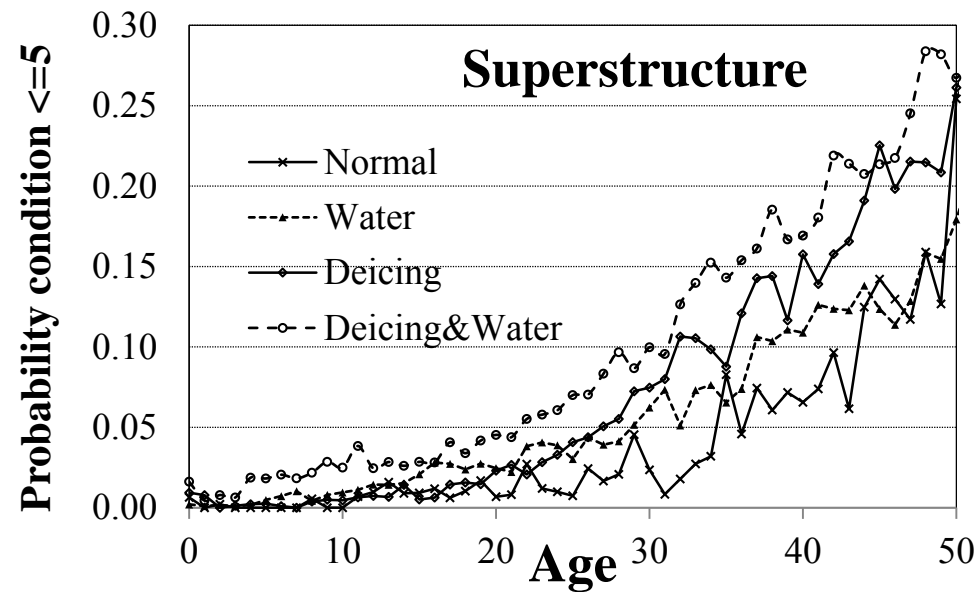
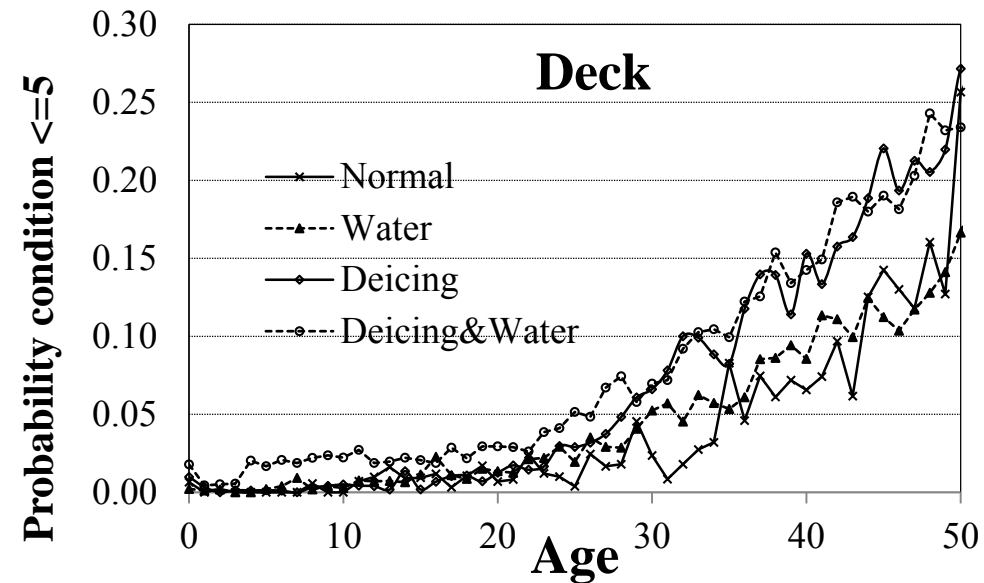
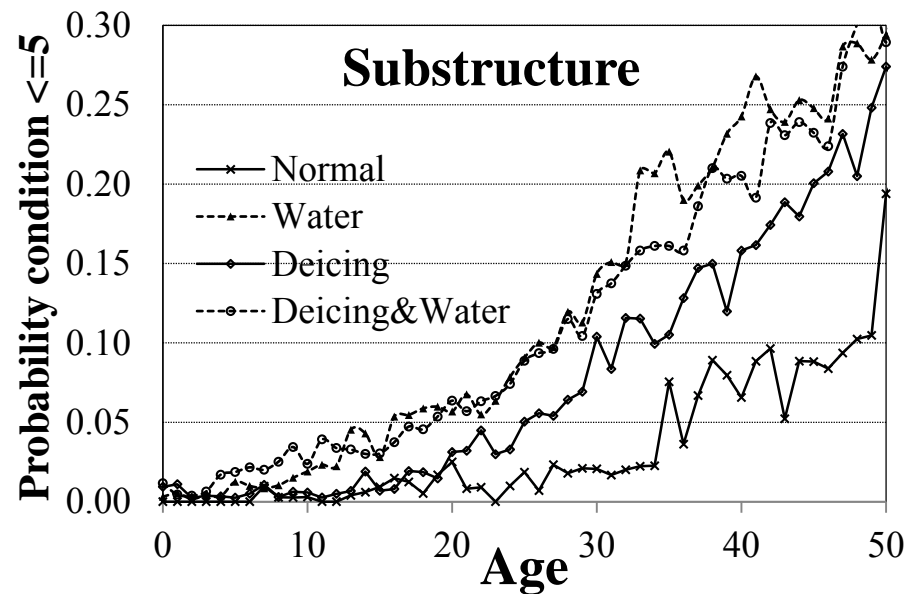


# Effect of Water and Chlorides on Durability

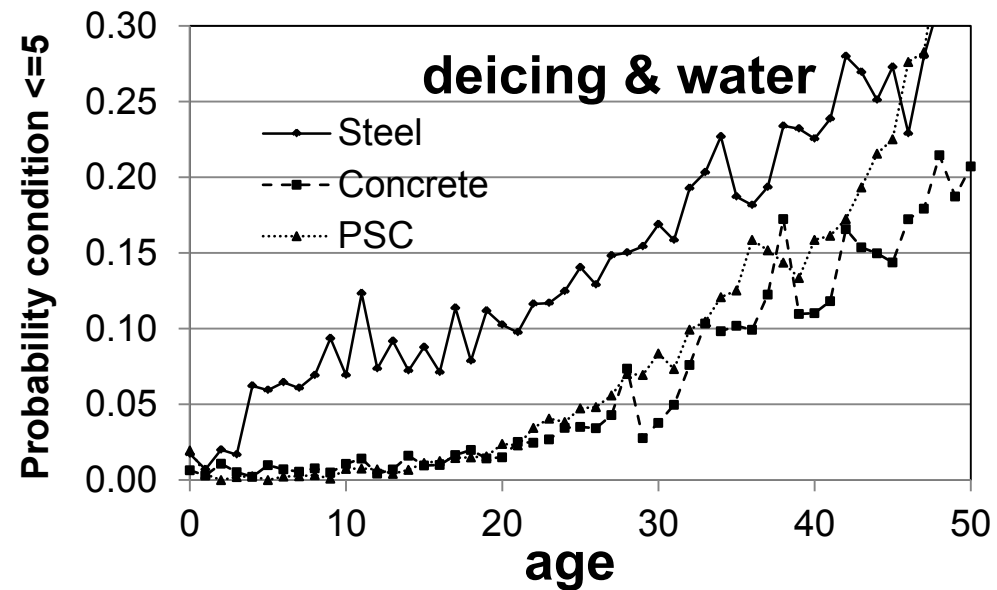
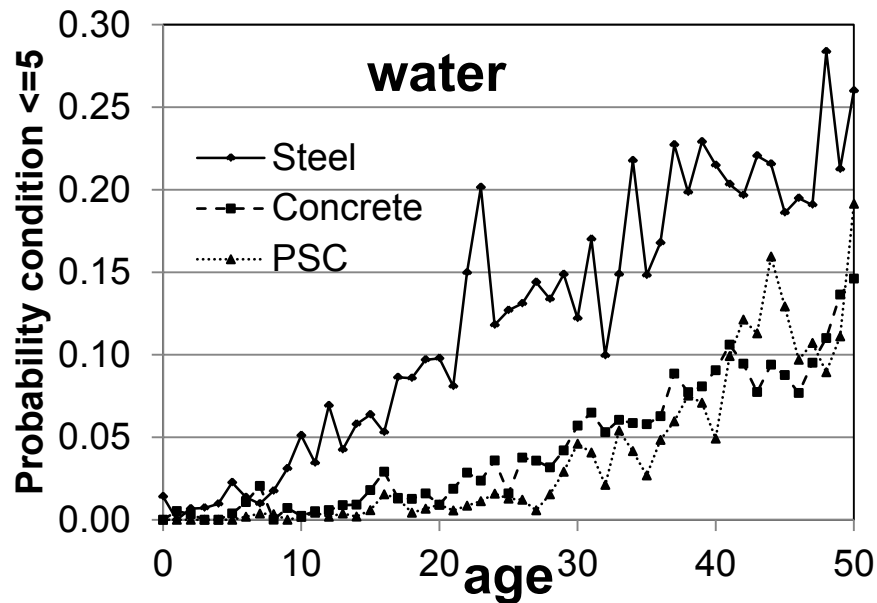
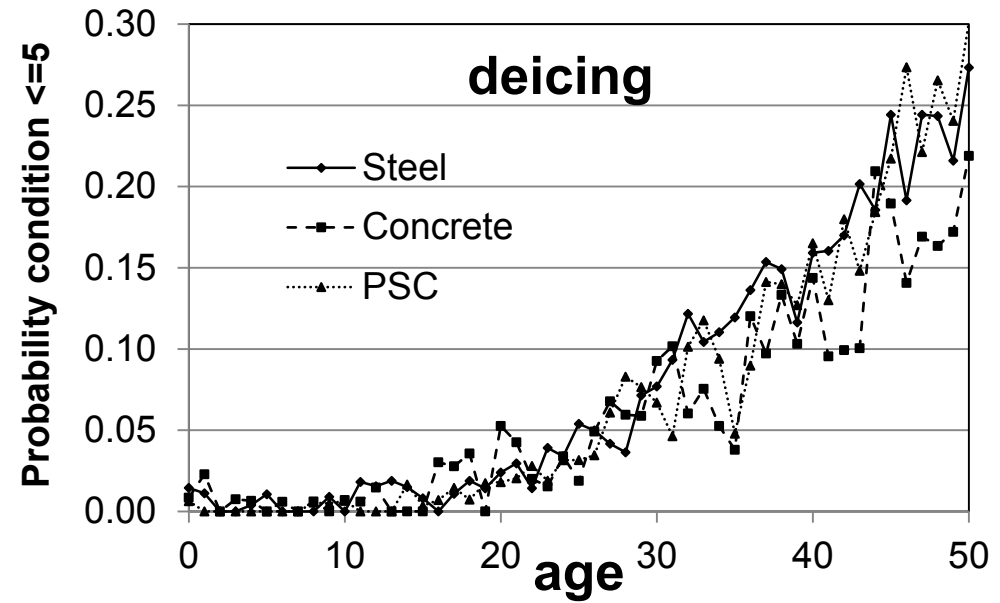
- To evaluate bridge durability under other environmental conditions four different environments are examined:
  - 'water': bridges with water underneath;
  - 'deicing': bridges exposed to deicing salts;
  - 'deicing & water': bridges with water underneath and exposed to deicing salts;
  - 'normal': bridges without water underneath and deicing salts.
- Bridges located near the sea coastline are excluded from this analysis



# Effect of Water and Chlorides on Durability



# Effect of Material Type



# Conclusions

- The results show that durability is threatened for:
  - bridges located within the first 3km from the sea coastline
  - substructures at humid locations (they are often in direct contact with water)
  - decks and superstructures exposed to deicing salts
  - steel structures at humid locations - especially when exposed to chlorides
- Reinforced and prestressed bridges gave similar corrosion probabilities at all environmental exposures.





Πανεπιστήμιο Κύπρου  
University of Cyprus

[link to paper](#)



### WG MEETINGS & WORKSHOP

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# DEVELOPMENT OF THE BRIDGE MANAGEMENT SYSTEM UNDER THE PROJECT BRIDGE<sup>SMS</sup>

<http://www.bridgesms.eu/>

**Vikram Pakrashi** - University College Cork, MaREI, Ireland

**Eamon McKeogh** - University College Cork, MaREI, Ireland

**Igor Kerin** - University College Cork, MaREI, Ireland [igor.kerin@ucc.ie](mailto:igor.kerin@ucc.ie)

**Sean McAuliffe** - University College Cork, MaREI, Ireland

**Damir Bekić** - University of Zagreb, Faculty of Civil Engineering, Croatia

[link to paper](#)



30<sup>th</sup> March - 1<sup>st</sup> April 2016  
Belgrade, Serbia

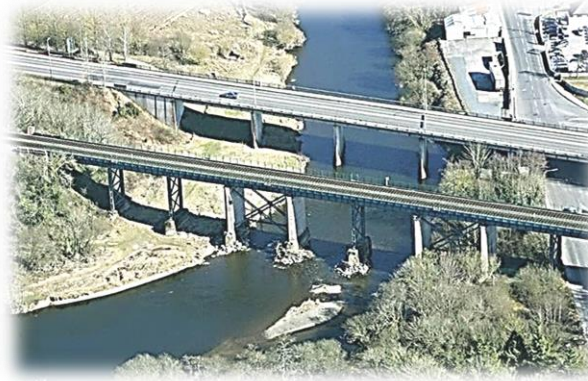
# OVERVIEW

- Background
- Introduction
- Summary of Bridge SMS
- Methodology and Approach
- Innovative features
- Dissemination of the Bridge SMS

# BACKGROUND

Collaboration between UCC and UNIZAG evolved as a result of a major railway bridge collapse at Malahide on the main Dublin to Belfast line in August 2009 as a passenger service passed over the Malahide Viaduct.

UCC carried out inspections and assessments of more than 100 railway bridges in Ireland (Bekic et al., 2012) and have carried out inspection, testing and assessments for around 250 road bridges in Ireland working closely with the National Roads Authority and the County Councils



# BACKGROUND



- BridgeSMS Project partners

## *Project partners*

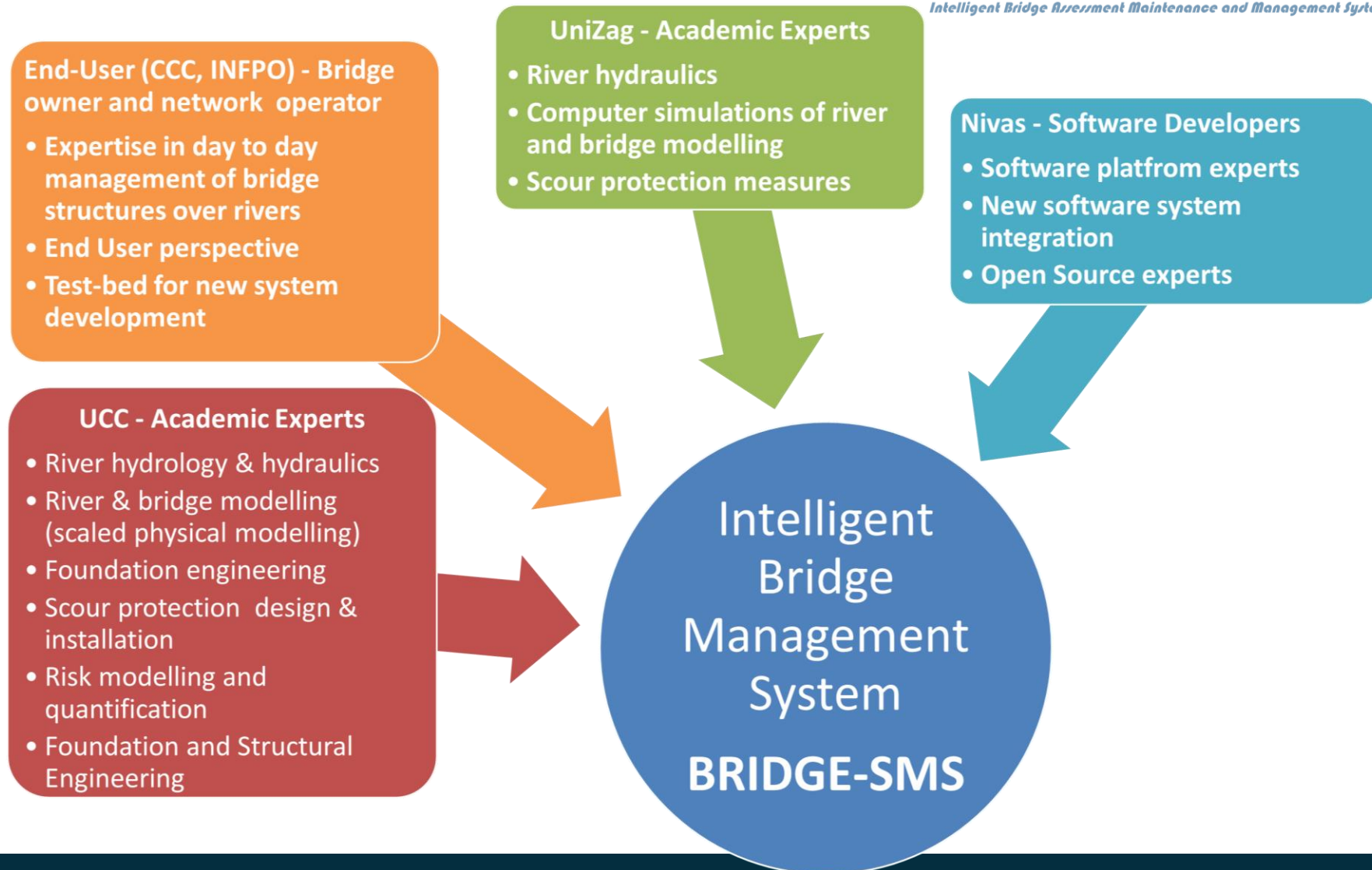


## *Supporting institutions*





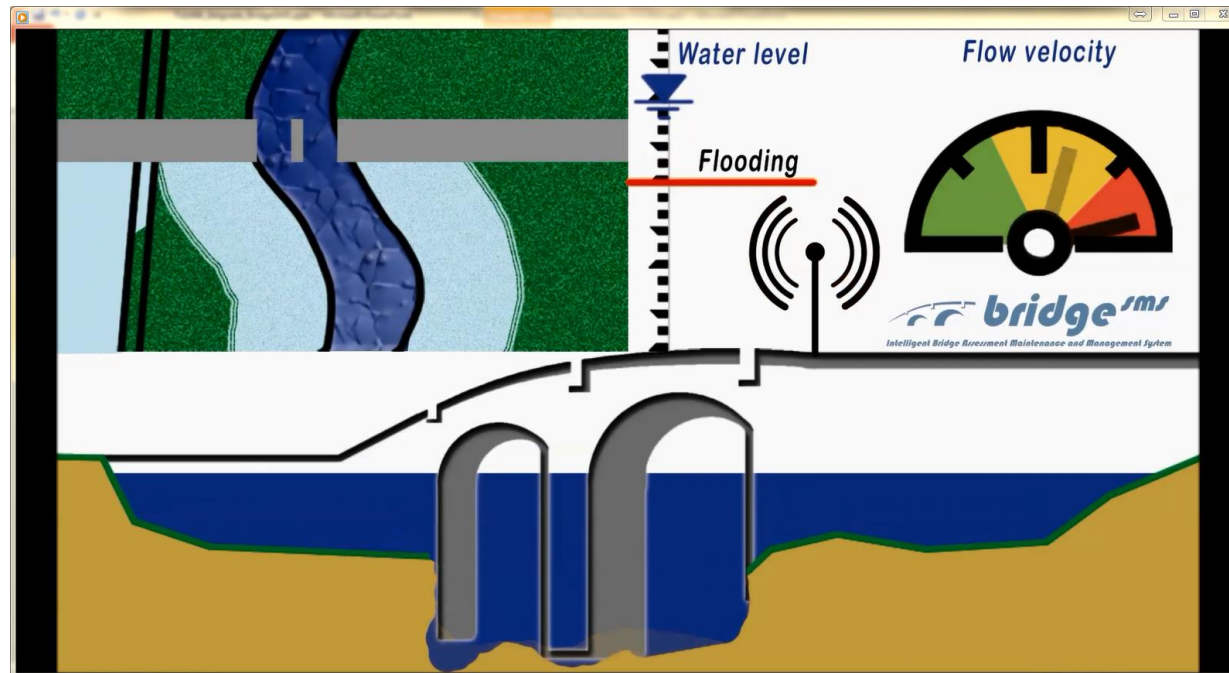
# BACKGROUND





# INTRODUCTION

- Bridge scour



[Bridge SMS youtube channel](#)

<https://www.youtube.com/watch?v=6GrFwF1rXEU>

# SUMMARY OF *bridge<sup>sms</sup>*

- What is Bridge<sup>SMS</sup>?



- “Intelligent Bridge Assessment Maintenance and Management System” (Bridge SMS) (Grant no: 612517) is a European Commission, Marie Curie 7th Framework Programme funded Project, under the Industry Academia Partnerships and Pathways (IAPP) call: FP7-People-2013-IAPP.
- Bridge SMS is a software application that empowers engineers and key personnel to predict, identify and prepare for potentially destructive flood events. It is robust and efficient tool designed to lower maintenance/planning costs and to provide more secured bridge management/operation.
- Project length: 4 years
- Project start: January 2015

WP	Work package title
WP 1	WP 1 Management
WP 2	WP 2 Technical Research
WP 3	WP 3 Development of Bridge Scour Management System
WP 4	WP 4 Knowledge Transfer and Training
WP 5	WP 5 Dissemination and Commercialisation

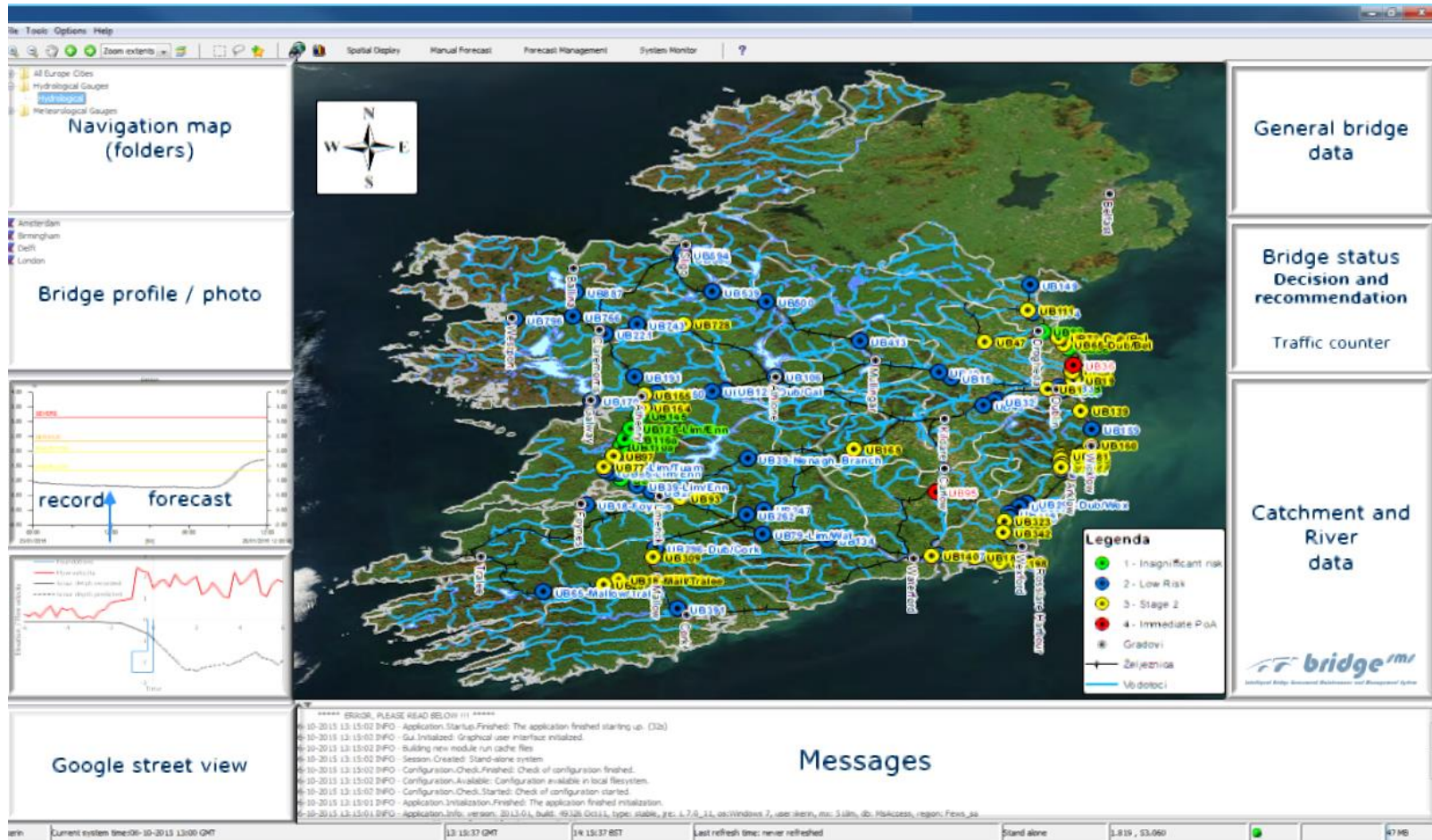
# SUMMARY OF *bridge<sup>sms</sup>*

Bridge SMS uses structural engineering, geotechnics, hydraulics, hydrology, materials and transport management. Bridge SMS key goals:

1. To develop standardised methods for bridge scour inspection.
2. To develop standards for bridge assessment and management.
3. To calculate the risk of and manages the potential effects of flood events.
4. To develop a database framework which is designed for intuitive use, encouraging participation by personnel at all levels within management authorities.
5. To develop a system that
  - collects integrates and processes real-time data at regular intervals from weather and hydrologic sources, meters and gauges, and other sensing devices.
  - will rapidly notify based on in-built intelligence and decision-making processes, relevant personnel of possible maintenance and failure issues.
  - will advise in relation to current Scour Risk at bridge structures and prompt an appropriate Plan of Action (POA) which may involve various levels of maintenance and repair.
  - which will prioritize and optimize the operational and maintenance budget spend for infrastructure companies.
6. Maximum use of new Information and Communications Technology (ICT) hardware such as tablets and cloud-based systems for on-site rapid communications, etc.

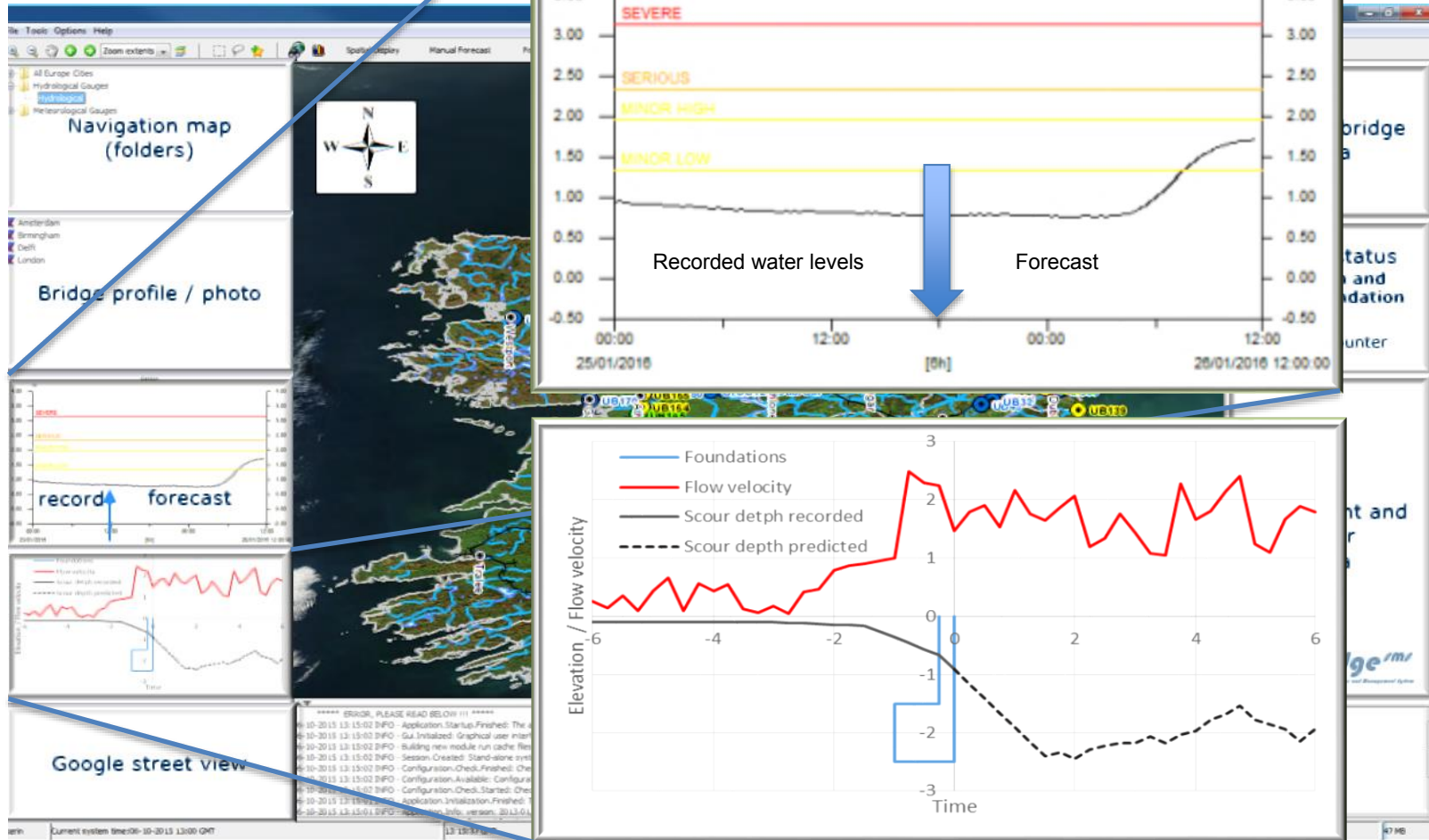
# SUMMARY OF *bridge<sup>SMS</sup>*

- User interface



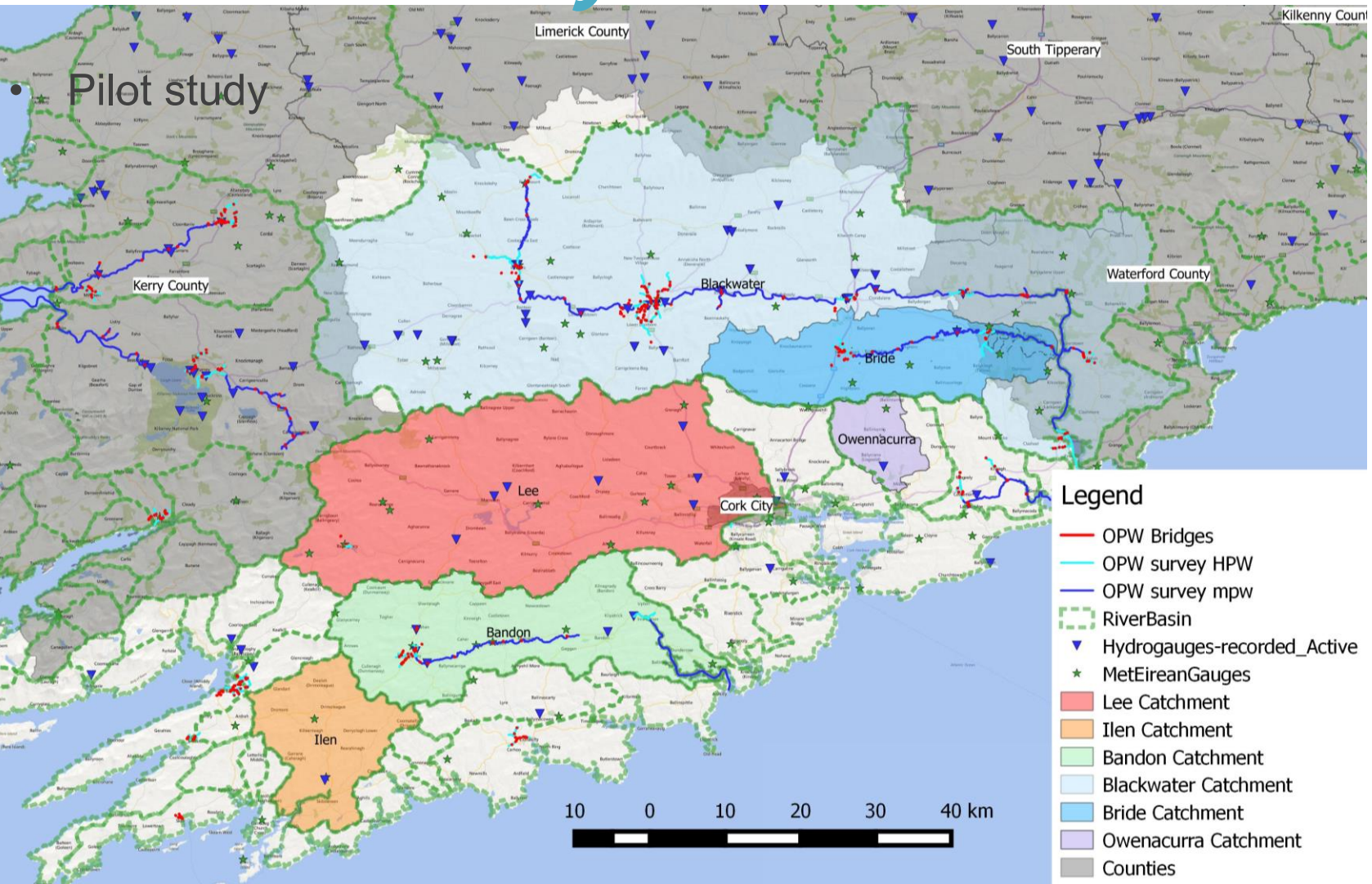
# SUMMARY OF *bridge<sup>sms</sup>*

- User interface





# SUMMARY OF *bridge<sup>sms</sup>*





# METHODOLOGY AND APPROACH

## Bridge SMS

### DSS 1 – Bridge Scour

DSS 1.1  
Static data

DSS 1.2  
Dynamic data

### DSS 2 – Bridge Structure

DSS 1 Decision and recommendation

DSS 2 Decision and recommendation

**Final Decision and recommendation**

# APPROACH

## a. QUALITATIVE scour risk QR

Derived from a qualitative risk matrix

Product of  $QR = L \times S$

- $L$ , Likelihood of occurrence of hazardous event
- $S$ , Severity of hazard consequence

4 classes of scour risk

Likelihood (L) and Severity (S) are obtained from the HYRISK methodology in the NCHRP report.

Qualitative Risk Matrix						
Likelihood of occurrence of hazardous event	<b>Frequent</b> The hazard will occur on a regular basis during the life of the asset / process / system / procedure. The hazard will be continually experienced	10	10 <i>Undesirable</i>	20 <i>Intolerable</i>	30 <i>Intolerable</i>	40 <i>Intolerable</i>
	<b>Probable</b> The hazard will occur several times during the life of the asset / process / system / procedure. – The hazard will occur often	7	7 <i>Tolerable</i>	14 <i>Undesirable</i>	21 <i>Intolerable</i>	28 <i>Intolerable</i>
	<b>Occasional</b> The hazard will occur a number of times during the life of the asset / process / system / procedure. – The hazard will occur infrequently	5	5 <i>Tolerable</i>	10 <i>Undesirable</i>	15 <i>Undesirable</i>	20 <i>Intolerable</i>
	<b>Remote</b> The hazard is likely to occur at some time during the life of the asset / process / system / procedure.	4	4 <i>Negligible</i>	8 <i>Tolerable</i>	12 <i>Undesirable</i>	16 <i>Intolerable</i>
	<b>Improbable</b> The hazard is unlikely to occur but possible at some time during the life of the asset / process / system / procedure– the hazard may occur in exceptional circumstances	2	2 <i>Negligible</i>	4 <i>Negligible</i>	6 <i>Tolerable</i>	8 <i>Tolerable</i>
	<b>Incredible</b> The hazard is extremely unlikely to occur during the life of the asset / process / system / procedure	1	1 <i>Negligible</i>	2 <i>Negligible</i>	3 <i>Negligible</i>	4 <i>Negligible</i>
			1	2	3	4
Severity of hazard consequence	Description		Insignificant	Marginal	Critical	Catastrophic
	Consequence to persons		Possible minor injury	Minor injury	Single Fatality or severe injury	Fatalities or multiple severe injuries
	Property loss and environmental Consequence		€20k	€200k	€2m	€20m

# METHODOLOGY AND APPROACH

- Likelihood of occurrence  $L$  depends on the *Lifetime Risk of Scour Failure* ( $P_{LT}$ ).
- $P_{LT} = 1 - [1 - P_A]^{LT}$ 
  - $P_A$  is annual probability of scour failure
  - $LT$  is provisional life of a bridge (100 years)
- Annual probability  $P_A$ 
  - Function of Overtopping frequency and Scour vulnerability.

<i>Lifetime Risk of Scour Failure <math>P_{LT}</math></i>	<i>Likelihood of occurrence of hazardous event <math>L</math></i>
1	10
0.999 - 0.400	7
0.399 - 0.100	5
0.099 - 0.010	4
0.009 - 0.001	2
<0.001	1

Table 14. NBI Annual probability of scour failure  $P_A$ .

<b>Scour Vulnerability</b> <i>(from Table 14)</i>	<b>Overtopping Frequency</b>		
	<i>Remote (R)</i>	<i>Slight (S)</i>	<i>Occasional (O)</i>
<i>(0) Failed</i>	1	1	1
<i>(1) Imminent failure</i>	0.01	0.01	0.01
<i>(2) Critical scour</i>	0.005	0.006	0.008
<i>(3) Serious scour</i>	0.0011	0.0013	0.0016
<i>(4) Advanced scour</i>	0.0004	0.0005	0.0006
<i>(5) Minor scour</i>	0.000007	0.000008	0.00004
<i>(6) Minor deterioration</i>	0.00018	0.00025	0.0004
<i>(7) Good condition</i>	0.00018	0.00025	0.0004
<i>(8) Very good condition</i>	0.000004	0.000005	0.00002
<i>(9) Excellent condition</i>	0.0000025	0.000003	0.000004

# METHODOLOGY AND APPROACH

- Presented as value of money in €.
- HYRISK equation the total cost of bridge failure

$$Cost = C_1 eWL + \left[ C_2 \left( 1 - \frac{T}{100} \right) + C_3 \frac{T}{100} \right] DAd + \left[ C_4 O \left( 1 - \frac{T}{100} \right) + C_5 \frac{T}{100} \right] \frac{DAd}{S}$$

- Cost - total cost of bridge failure (€)
- C- unit rebuilding cost from (€/m)
- e - cost multiplier for early replacement based on average daily traffic
- W - bridge width from NBI item 52 (m)
- L - bridge length from NBI item 49 (m)
- C- cost of running automobile from (i.e. €0.22/km)
- C- cost of running truck from (€1.02/km)
- D - detour length (km)
- A - average daily traffic (ADT) from NBI item 29
- d - duration of detour based on ADT from (days)
- C- value of time per adult in passenger car (€/h)
- O - average occupancy rate
- T - average daily truck traffic (ADTT) form NBI item 109 (10% of ADT)
- C- value of time for truck (€22.01/hr)
- S - average detour speed (typically 64 km/h)

# METHODOLOGY AND APPROACH

## b. QUANTITATIVE scour risk

- PRIORITY RATING (PR)
- Relative scour depth

$$D_R = D_T / D_F$$

–  $D_T$  = total depth of foundation

–  $D_F$  = depth of foundation

- Priority factor

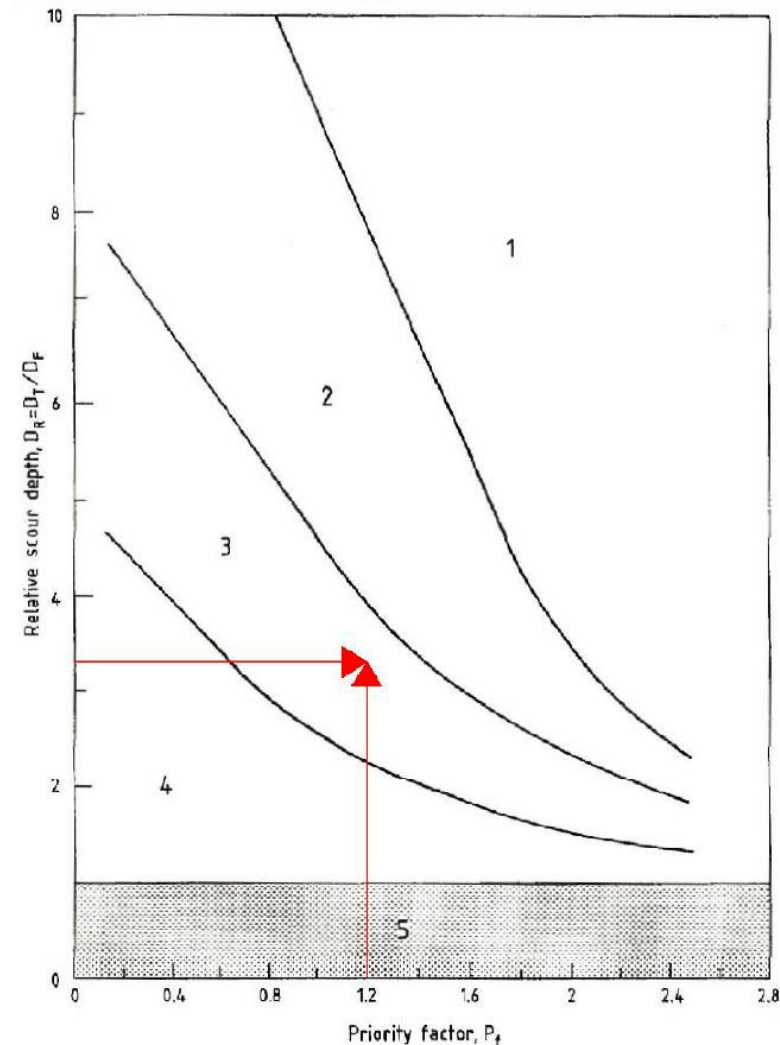
$$P_f = F \cdot H \cdot M \cdot T_R$$

– foundation type factor  $F$

– history of scour problem factor  $H$

– foundation factor  $M$

– type of river factor  $T_R$



# METHODOLOGY AND APPROACH - Mitigation measures

## 1. Inspections

- ☐ Two frequencies of Bridge inspections: after major floods or regular re-inspections.

## 2. Maintenance

- ☐ Minor works at and around the bridge
- ☐ Further studies are not required.

## 3. Bridge monitoring

- ☐ Implementation of procedures and tools for detailed monitoring of scour at the bridge site.

## 4. Studies and investigations

- ☐ More detailed studies and investigations undertaken by engineers specialising in the study of river engineering and scour problems

## 5. Scour protection works

- ☐ Scour reduction measures to improve flow conditions at a structure (streamlining of piers, river training, etc)
- ☐ Structural measures to withstand the predicted depths of scour, (underpinning foundations, reinforcement and extension of foundations, sheet piling, etc)
- ☐ Scour protection measures (riprap, gabions, etc)

## 6. Bridge replacement works

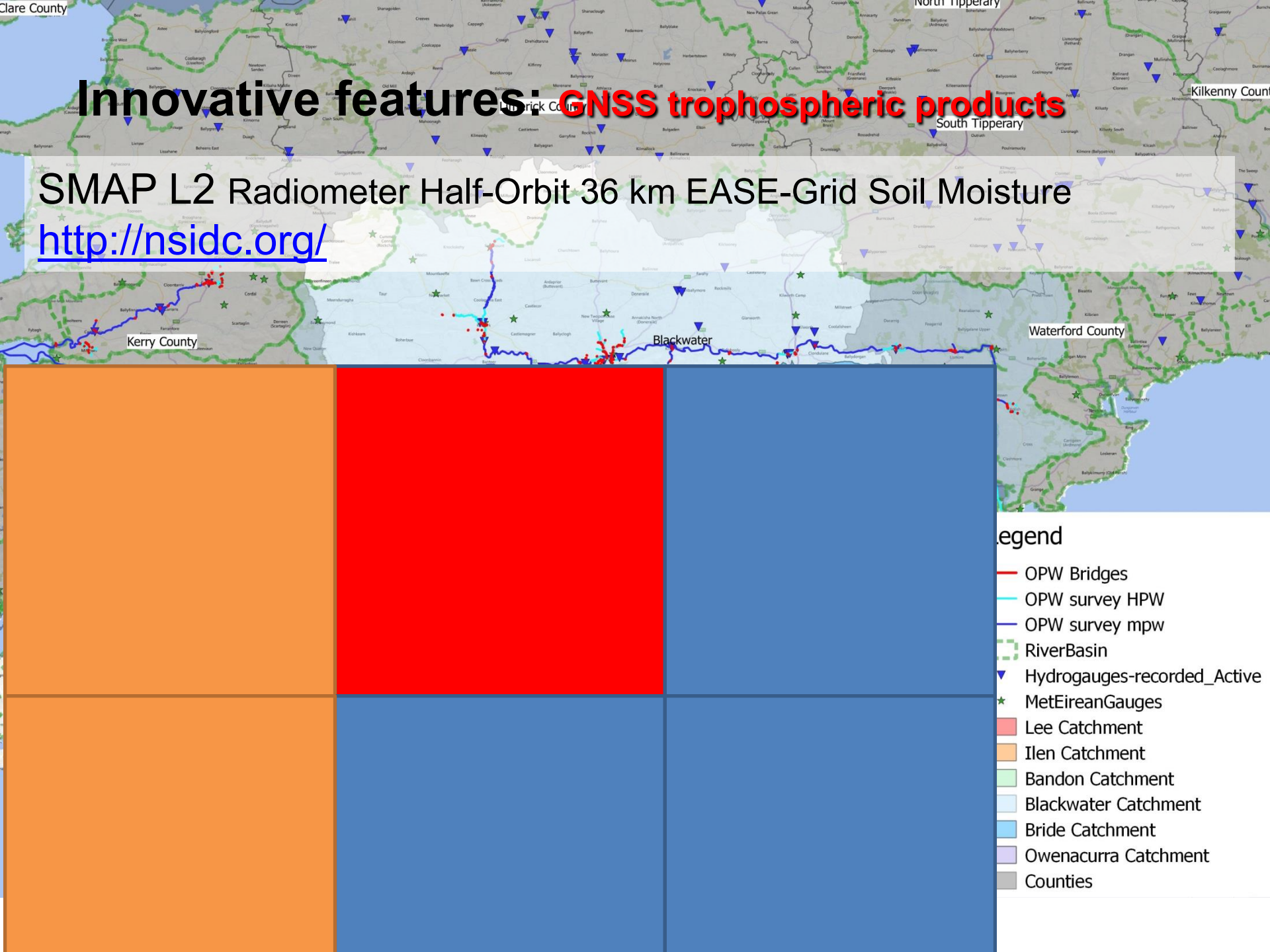
- ☐ Significant works for partial or complete replacement of the bridge



# Innovative features: GNSS tropospheric products

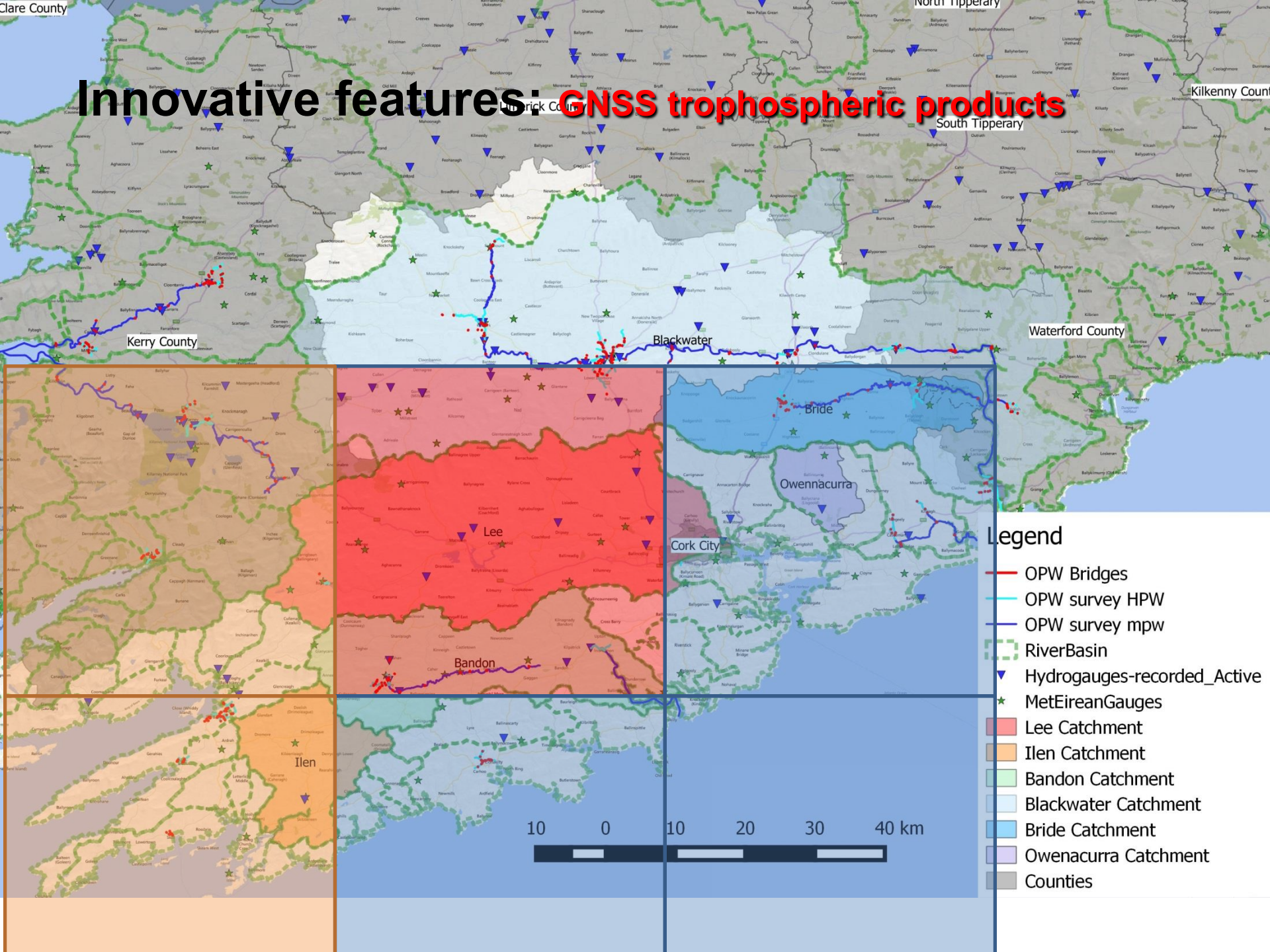
SMAP L2 Radiometer Half-Orbit 36 km EASE-Grid Soil Moisture

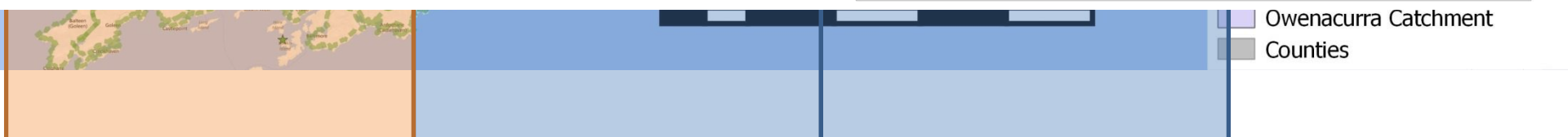
<http://nsidc.org/>





# Innovative features: GNSS tropospheric products



[illegible]



# Innovative features: GNSS tropospheric products

- expectations, availabilities, resources

Number of bridges for pilot, circa 10

## A. Real Time Data

### A.1. Rainfall

A.1.1 Rainfall (gauges)

A.1.2 Rainfall (Meteorological model)

A.1.3 Rainfall (Radar)

### A.2. Water levels (WL)

A.2.1 Hydrological gauges

A.2.2 Tides

### A.3. Other Meteorological data

A.3.1 Temperature

A.3.2 Pressure

A.3.3 Other

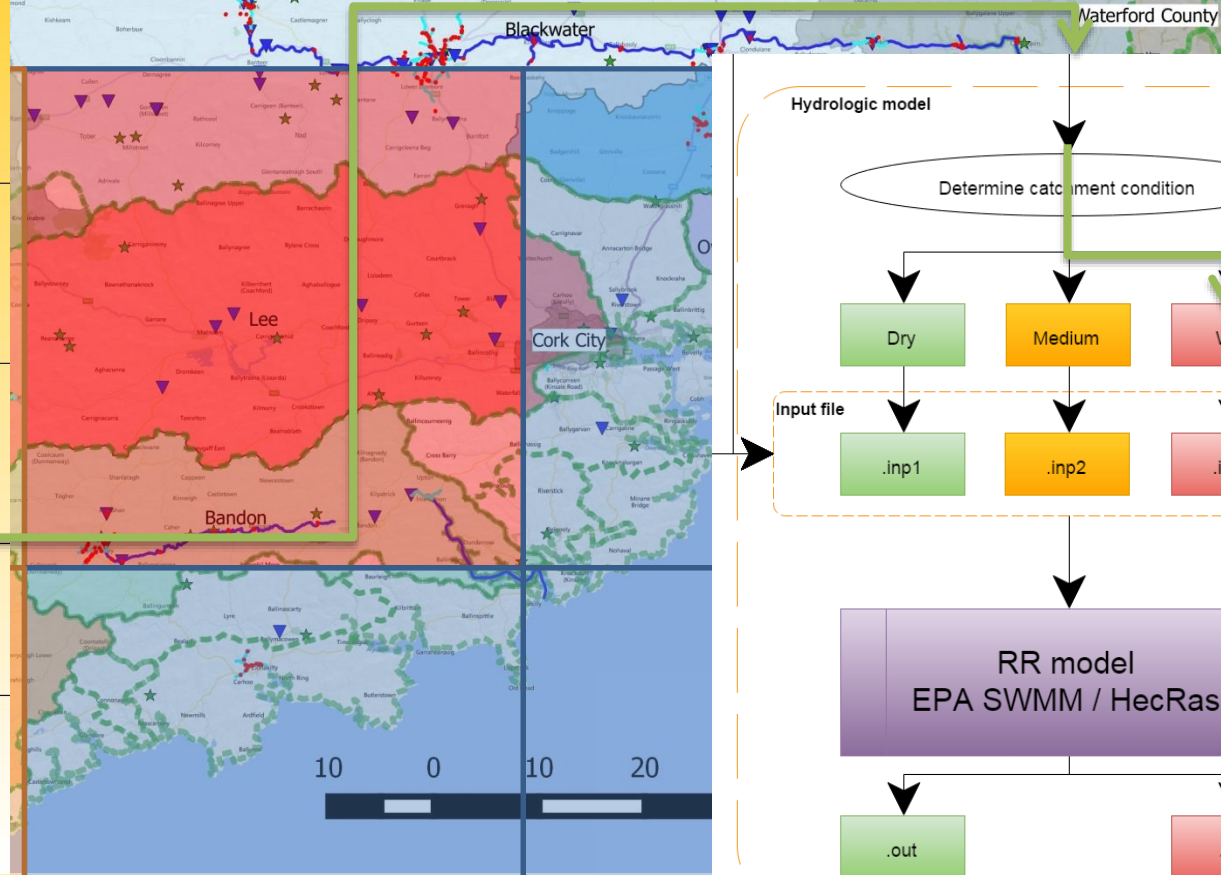
### A.4. Soil Moisture

A.4.1 Terrestrial sensors

A.4.2 Satellite sensors  
(GNSS COST Action)

### A.5. Scour Monitoring Equipment

### A.6. Traffic counter





# Innovative features: GNSS tropospheric products

## A. Re

### A.1. Rainfall

A.1.1 Rainfall (g

A.1.2 Rainfall (M

A.1.3 Rainfall (F

### A.2. Water levels

A.2.1 Hydrologi

A.2.2 Tides

### A.3. Other Meteor

A.3.1 Temperat

A.3.2 Pressure

A.3.3 Other

### A.4. Soil Moisture

A.4.1 Terrestria

A.4.2 Satellite s

(GNSS COSTA

### A.5. Scour Monito

### A.6. Traffic counter

## Dissemination

- **Website** <http://www.bridgesms.eu/>
- **Twitter** @BRIDGESMS\_MaREI  
[https://twitter.com/BRIDGESMS\\_MaREI](https://twitter.com/BRIDGESMS_MaREI)
- **Facebook** <https://www.facebook.com/Bridge-SMS-1603198356632504/timeline/?ref=hl>
- **Linkedin**  
[https://www.linkedin.com/grp/home?gid=8337384&trk=my\\_groups-tile-grp](https://www.linkedin.com/grp/home?gid=8337384&trk=my_groups-tile-grp)
- **Youtube**  
<https://www.youtube.com/channel/UCPAMvdlzSwQrpBfPQXcqVTA>





[link to paper](#)



## **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **The assessment method of Hungarian documents on bridge inspection**

**Zsuzsanna Pisch** – head of bridge department,  
Coordination Center for Transport Development / Hungarian Transport Agency, Hungary

[link to paper](#)



**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**

# ROAD BRIDGES IN HUNGARY

- In Hungary, **7 528** road bridges exist, more than half of them are located on the minor road network.

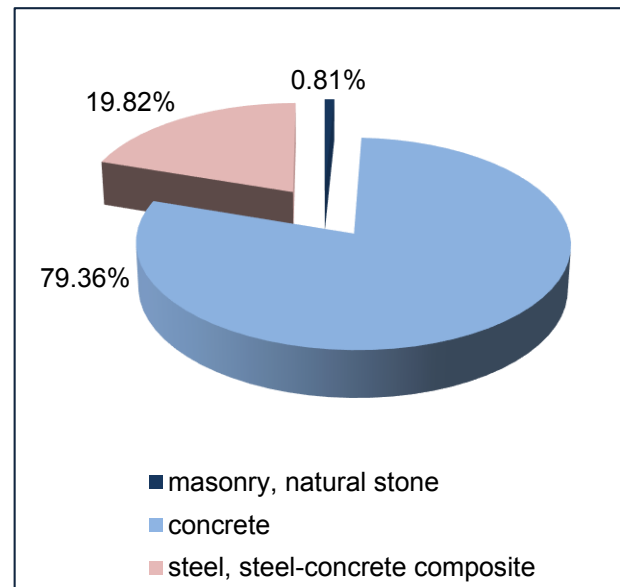
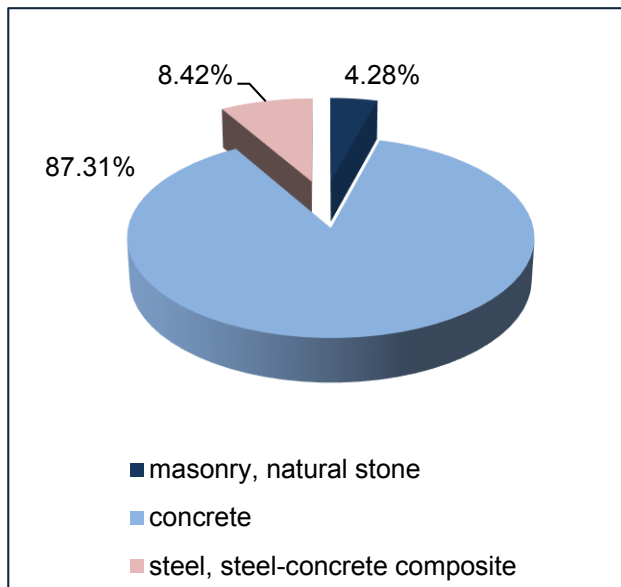
Road category	Number	Area ( $\times 1000 \text{ m}^2$ )	Length (m)
Motorway	1 586	1 350,25	95 731,57
Main road	1 799	583,92	44 802,61
Minor road	4 143	524,55	54 417,02
Together	7 528	2 458,72	194 951,20

The categorization and main data of road bridges



# ROAD BRIDGES IN HUNGARY

- Most of the bridges are made of concrete, approximately the quarter of them are made of steel and other.



Percentage ratio of bridge material according to  
a – number; b – area

# BRIDGE INSPECTION TYPES

- In Hungary 4 levels of bridge inspection are implemented in the relevant maintenance system.

	Regular checks		Annual inspection	Main supervision
Bridge type	all bridge	all bridge	all bridge	span length is more than 20 m; length of superstructure is more than 40 m; railway overpass of irrelevant length
Frequency	weekly	every half year	yearly	every 10 years
Type of inspection	visual inspection	visual inspection	visual inspection (measurement if necessary)	visual inspection and measurement
Focus	traffic safety, suitability for operation, presence of serious damage	traffic safety, suitability for operation, presence of damage, cleanness	all structural and non-structural parts	all structural and non-structural parts

Inspection levels in Hungary

# TECHNICAL SPECIFICATIONS OF ROADS

Complex collection of standards

9 main topics:

1. General
2. Traffic planning
3. Design of roads
4. Traffic control
5. Construction materials
6. Construction of roads
7. **Bridges and other load-carrying structures**
8. **Maintenance and operation of roads**
9. **Measurements and testing**





# TECHNICAL SPECIFICATIONS OF ROADS

## 7. Bridges and other load-carrying structures

- design
- construction
- bridge equipments
- protection against corrosion

## 8. Maintenance and operation of roads

- register and technical supervision of bridges
  - **Register and Technical Supervision of Highway Bridges**
  - **Technical Supervision of Highway Bridges. Additional Dates and Examination Points of View.**

## 9. Measurements and testing

- testing methods of concrete corrosion and waterproofing
- non-destructive testing methods

# THE SELECTED DOCUMENTS

## Register and Technical Supervision of Highway Bridges

- Expositis the different types of bridge inspection
- Aspects, but not assessment methods

## Technical Supervision of Highway Bridges, Additional Dates and Examination Points of View

- annual bridge inspection → **PONTIS-H bridge inspection guide**
- main supervision of bridges → aspects and detection methods

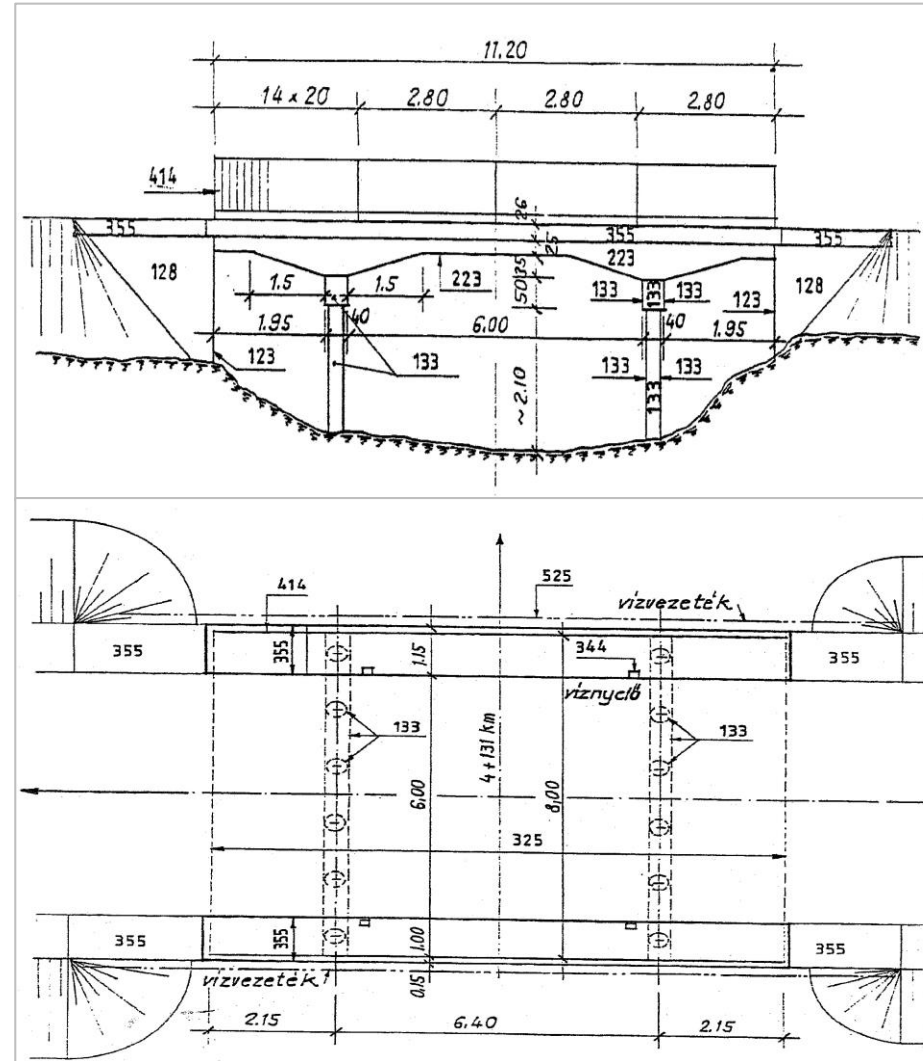


# PONTIS-H BRIDGE INSPECTION GUIDE

## 1. Defines the bridge elements of every bridge types

- 5 main structural parts
  - substructure
  - superstructure
  - bridge deck
  - bridge accessories
  - environment of bridge
- subparts (elements)
  - numerical code

123: reinforced concrete abutment (front wall)  
 128 reinforced concrete wing wall,  
 133 reinforced concrete pier,  
 223 monolithic concrete girders,  
 325 asphalt pavement  
 344 gully  
 355 any kind of pavement on footways  
 414 galvanized steel pedestrian guardrail  
 525 rainwater collecting pipe system



# PONTIS-H BRIDGE INSPECTION GUIDE

2. Methods for **calculating the area** of the elements

3. Defines the **typical damage and deterioration types** belonging to the five condition classes for each element

- 1: as if it were new (no significant deterioration has been observed)
- 2: initial defect (only minor surface defects)
- 3: average defect (more than surface defect)
- 4: serious defects (well-developed defect)
- 5: very serious defect (a defect that has influence on the load-bearing capacity of the structure and incorporates accident hazard)

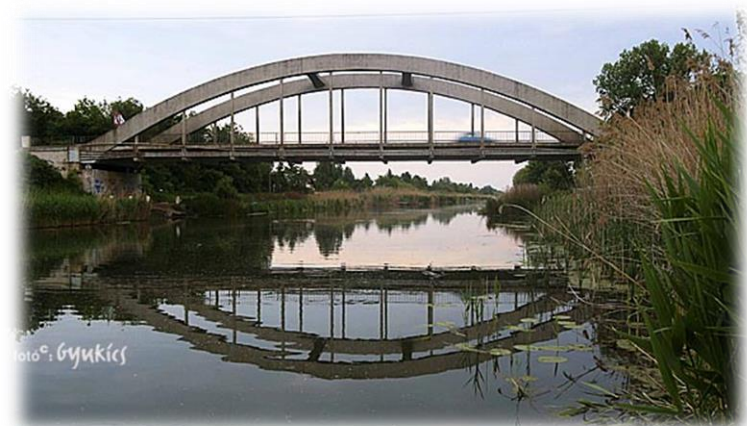


Inspector's name: .....				Date of inspection: .....								
Bridge name: .....				Road No., section: .....								
Superstructure material: .....												
Operator of bridge: .....								OMC: .....				
Spans: ... db		Max span: ... cm		Struct. Length: ... cm				Salt spreading: ...				
Bridge width: ... cm		Year of last encroachment: ...										
Surface: ... m <sup>2</sup>		Stand. load b. cap: ...		Limitation 1: ...								
ADT: 0 E/nap		Load b. cap.: ...		Limitation 2: ...								
Main grades: ..... Superstruct.: ..... Substruct.: ..... Br.accessories: ..... Pavement: ..... Br.environment: .....												
Note/Megjegyzés:												
Cod e Kód	Element name		Quant/ mennyiség	1+2	%	3	%	4	%	5	%	VT
113	Reinforced steel concrete foundation	m <sup>2</sup>										
123	Reinforced steel abutment	m <sup>2</sup>										
128	Reinforced steel wing wall	m <sup>2</sup>										
133	Reinforced steel concrete pier	m <sup>2</sup>										
248	Reinforced steel beam	m <sup>2</sup>										
320	Plastic and other kind of insulation	m <sup>2</sup>										
325	Asphalt and other pavement surface	m <sup>2</sup>										
335	Asphalt expansion structures	m										
344	Steel gulley, drainage, dewatering sys	db										
353	Material of reinforced steel supplementary lanes	m <sup>2</sup>										
355	Any kind of supplementary lane pavement	m <sup>2</sup>										
365	Backfill	m <sup>2</sup>										
419	Zinc layer steel barrier	m <sup>2</sup>										
422	Concrete (and other material) stairs	m <sup>2</sup>										
432	Concrete slope pavements	m <sup>2</sup>										



# SUMMARY

Specification	Regular checks	Annual inspection	Main supervision
Register and Technical Supervision of Highway Bridges	😊	😊	😊
Technical Supervision of Highway Bridges, Additional Dates and Examination Points of View		😊	😊 😊
PONTIS-H bridge inspection guide		😊 😊 😊	😊







[link to paper](#)



## **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **Development of a Quality Management Plan for Timber Bridges**

Prof. Dr. Steffen Franke – Bern University of applied sciences  
Daniela Grütter - Schweizerischer verein für schweisstechnik

[link to paper](#)

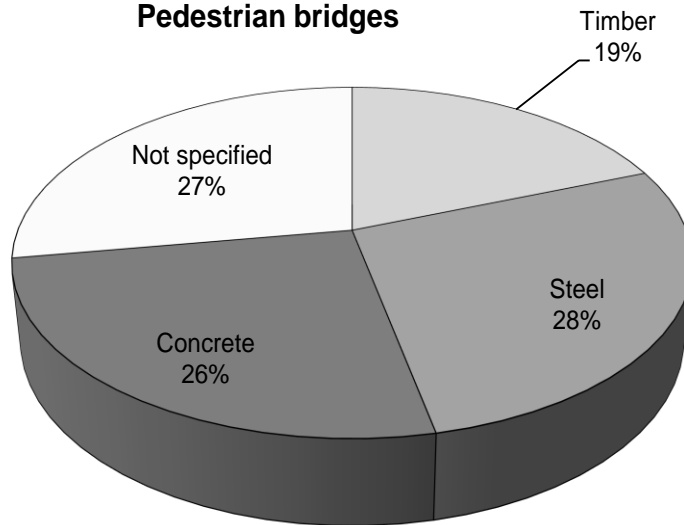


**30<sup>th</sup> March - 1<sup>st</sup> April 2016**  
**Belgrade, Serbia**

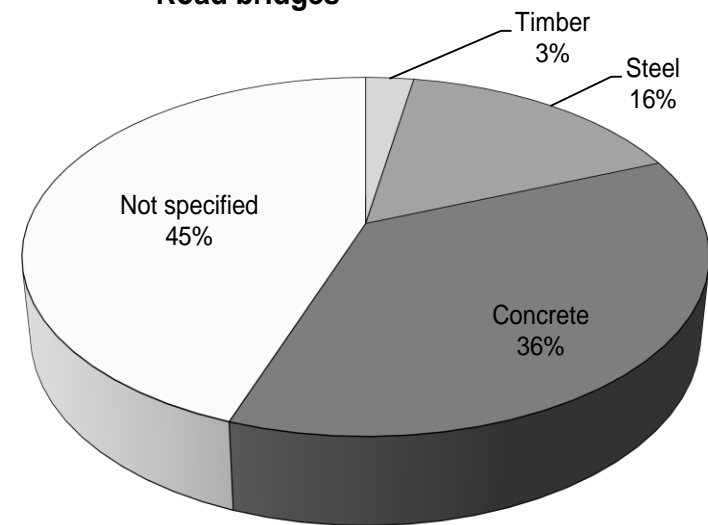
# Timber Bridges in Switzerland

- Building application for new bridges and renovation of bridges from 2010-2014

**Pedestrian bridges**



**Road bridges**



# Timber Bridges in Switzerland

- Connects two parts of the city
- Built: 1821/1991 (Fire)
- Covered bridge
- Truss frame
- Max load: 16 tons
- Length: 107 m
- Width: 4.8 m
- Height: 3.7 m
- Asphalted roadway





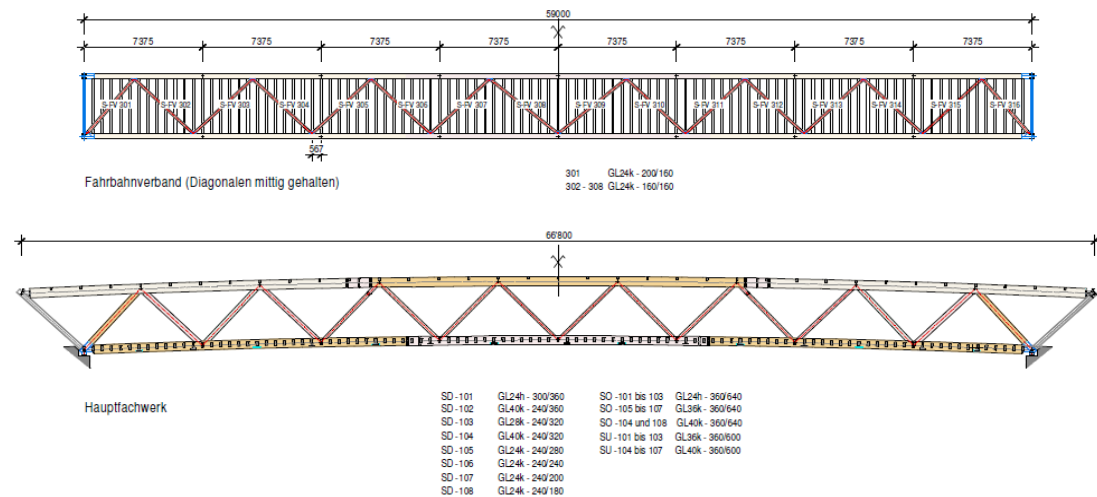
# Timber Bridges in Switzerland

- Built: 2013
- Covered bridge
- Framework
- Span: 59 m
- Width: 3.8 m
- Height: 3.6 m
- Oak decking roadway



# Timber Bridges in Switzerland

- Built: 2013
- Covered bridge
- Framework
- Span: 59 m
- Width: 3.8 m
- Height: 3.6 m
- Oak decking roadway





# Timber Bridges in Switzerland

- Built: 2007
- Open bridge
- Max load: 40 tons
- Length: 32 m
- Asphalted roadway
- Lifting bridge at high tide



# Timber Bridges in Switzerland

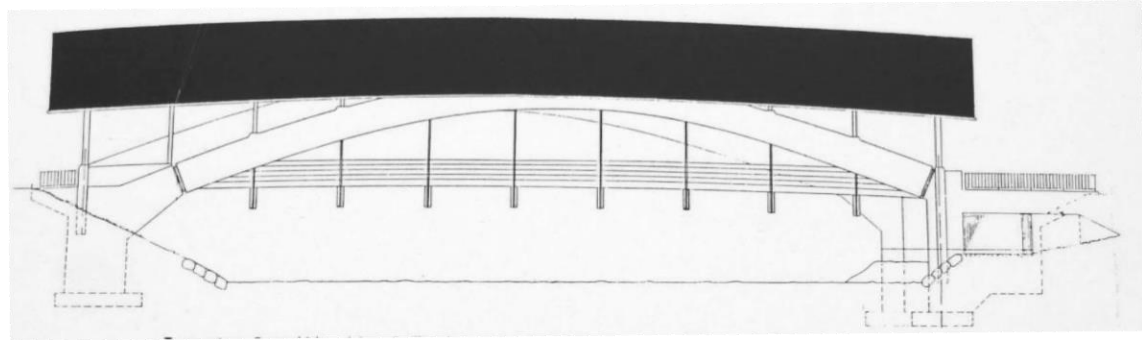
- Built: 1837/1988
- Covered bridge
- Arched girder
- Max load: 28 tons
- Length: 50 m
- Width: 7 m
- Height: 4.5m
- Asphalted roadway





# Timber Bridges in Switzerland

- Built: 1837/1988
- Covered bridge
- Arched girder
- Max load: 28 tons
- Length: 50 m
- Width: 7 m
- Height: 4.5m
- Asphalted roadway



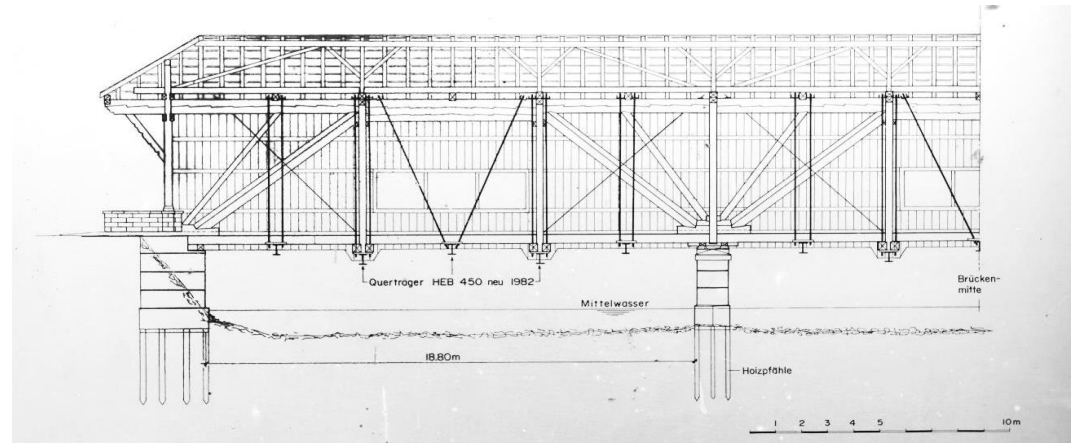
# Timber Bridges in Switzerland

- Built: 1846/1982
- Covered bridge
- Max load: 28 tons
- Length: 61.7 m
- Width: 5.6 m
- Height: 5.5 m



# Timber Bridges in Switzerland

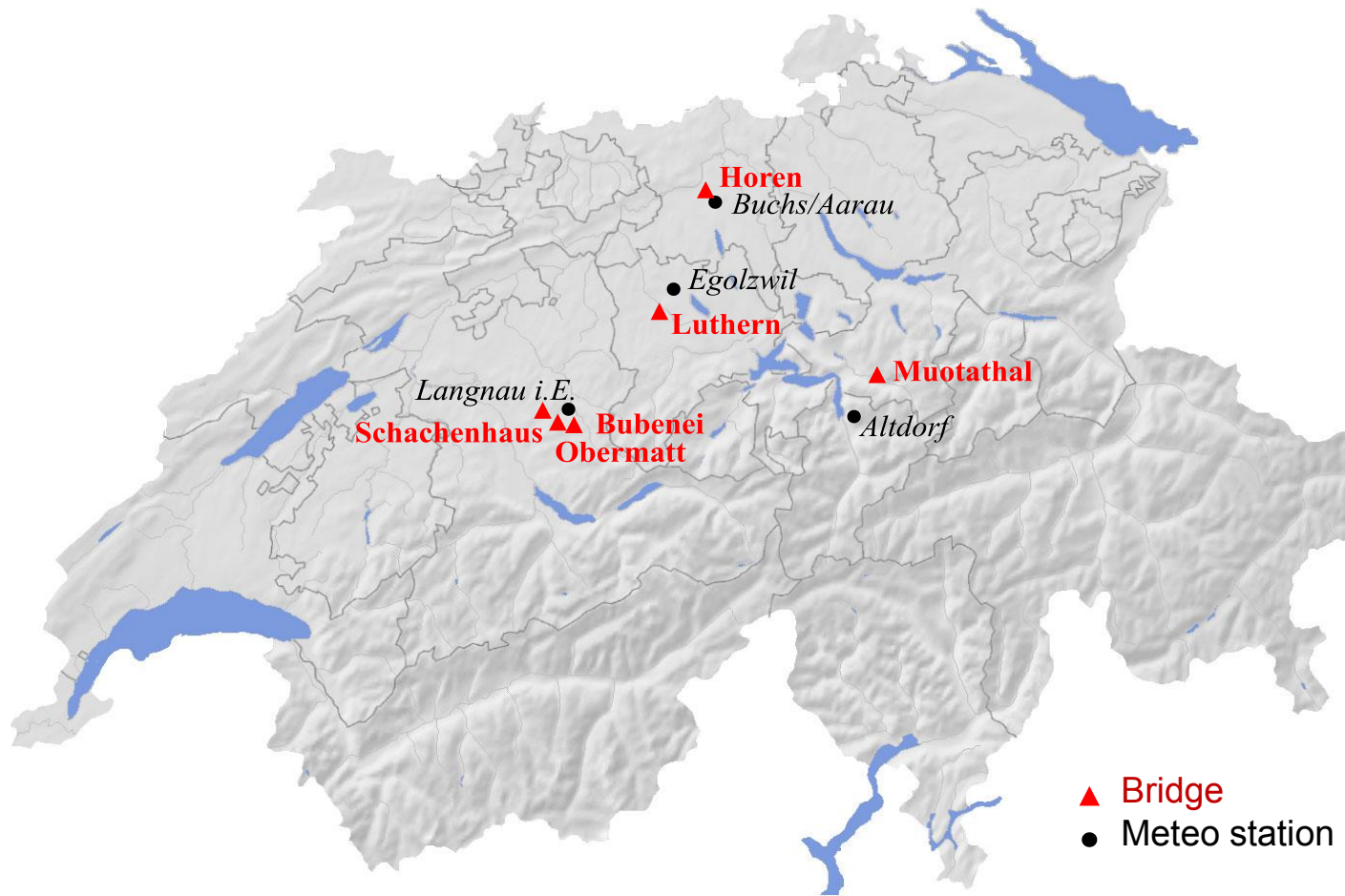
- Built: 1846/1982
- Covered bridge
- Max load: 28 tons
- Length: 61.7 m
- Width: 5.6 m
- Height: 5.5 m





# Timber Bridges

- Assessment and monitoring by BFH





# State of Art for Timber Bridges

- Road bridges, pedestrian and cycle path bridges, wildlife bridges
- National and regional network
- Requirements through hierarchic order and national law
  - Federal Roads Office (FEDRO)
  - SIA Standards
  - VSS Research and standardization for road and transportation
- Preservation of Bridges ASTRA 308.314, ASTRA 308.070
  - Maintaining the basis structure
  - Guaranteeing sufficient security
  - Ensuring serviceability
  - Economic optimization of maintenance of necessities
  - Detecting new potential risks
  - Reducing immediate action to minimum



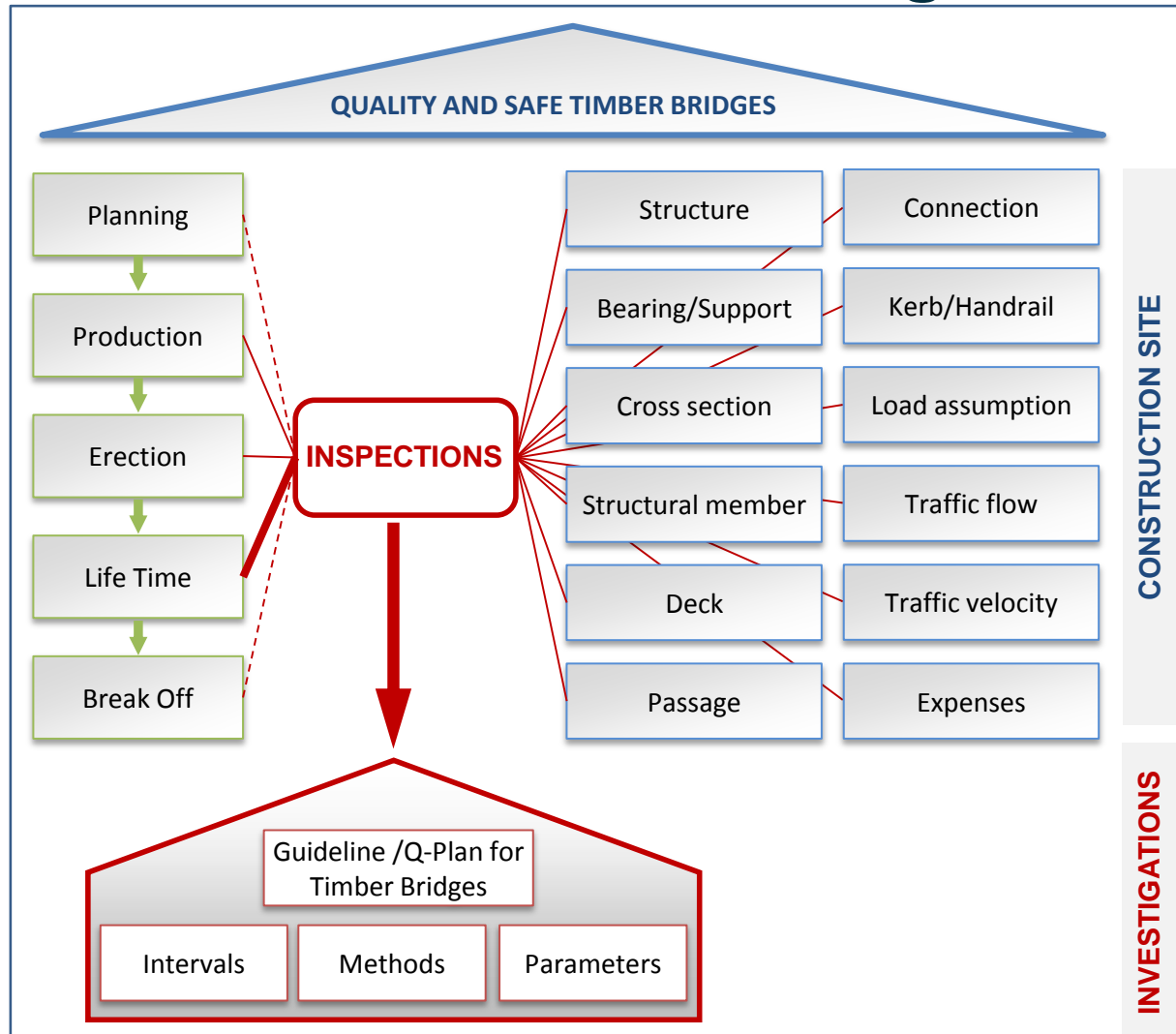
Schweizerische Eidgenossenschaft  
Confédération suisse  
Confederazione Svizzera  
Confederaziun svizra

VSS<>

sia

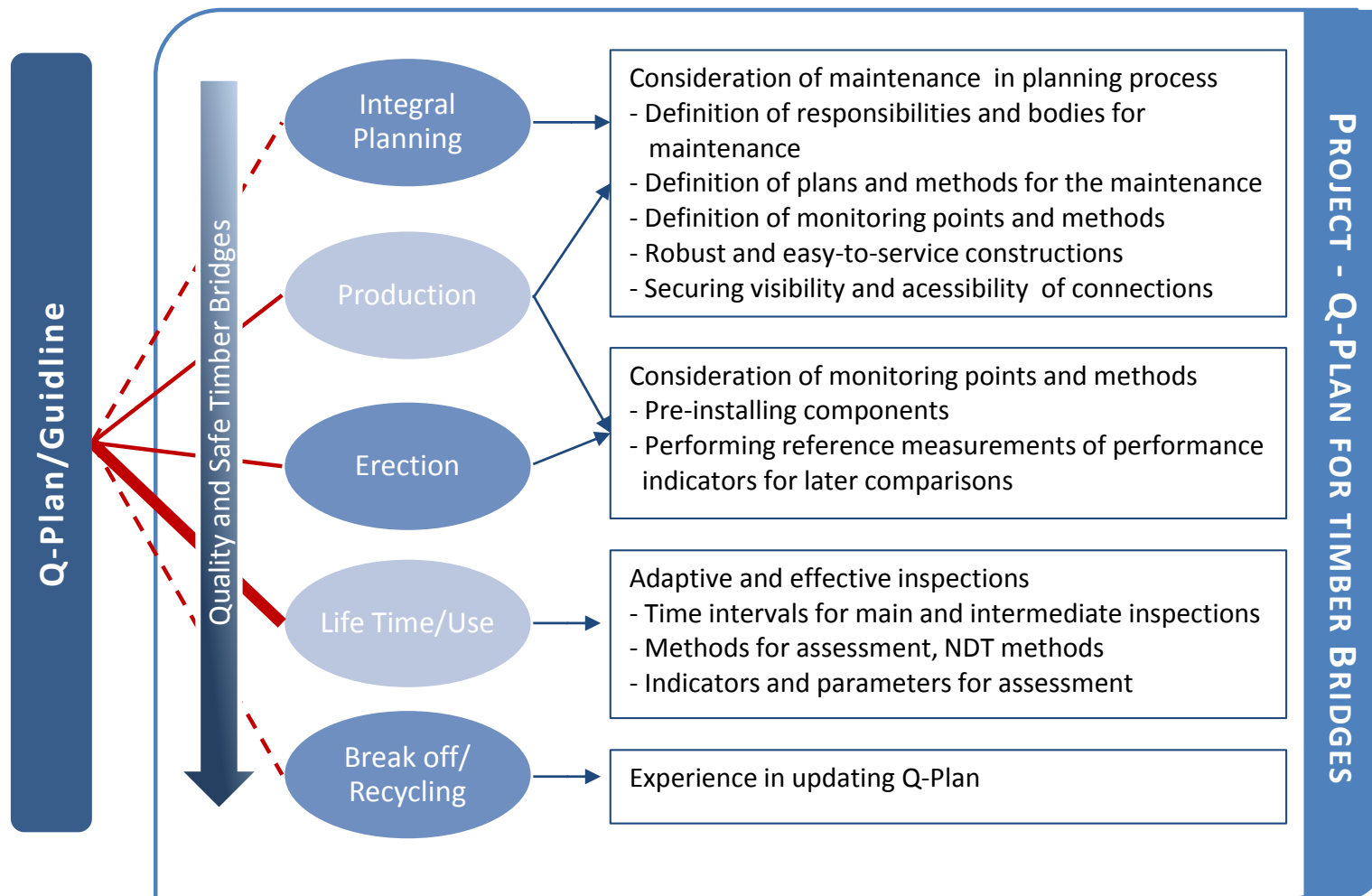
No specific  
regulations for  
timber bridges

# State of Art for Timber Bridges



# Research Project – Relevant Topics

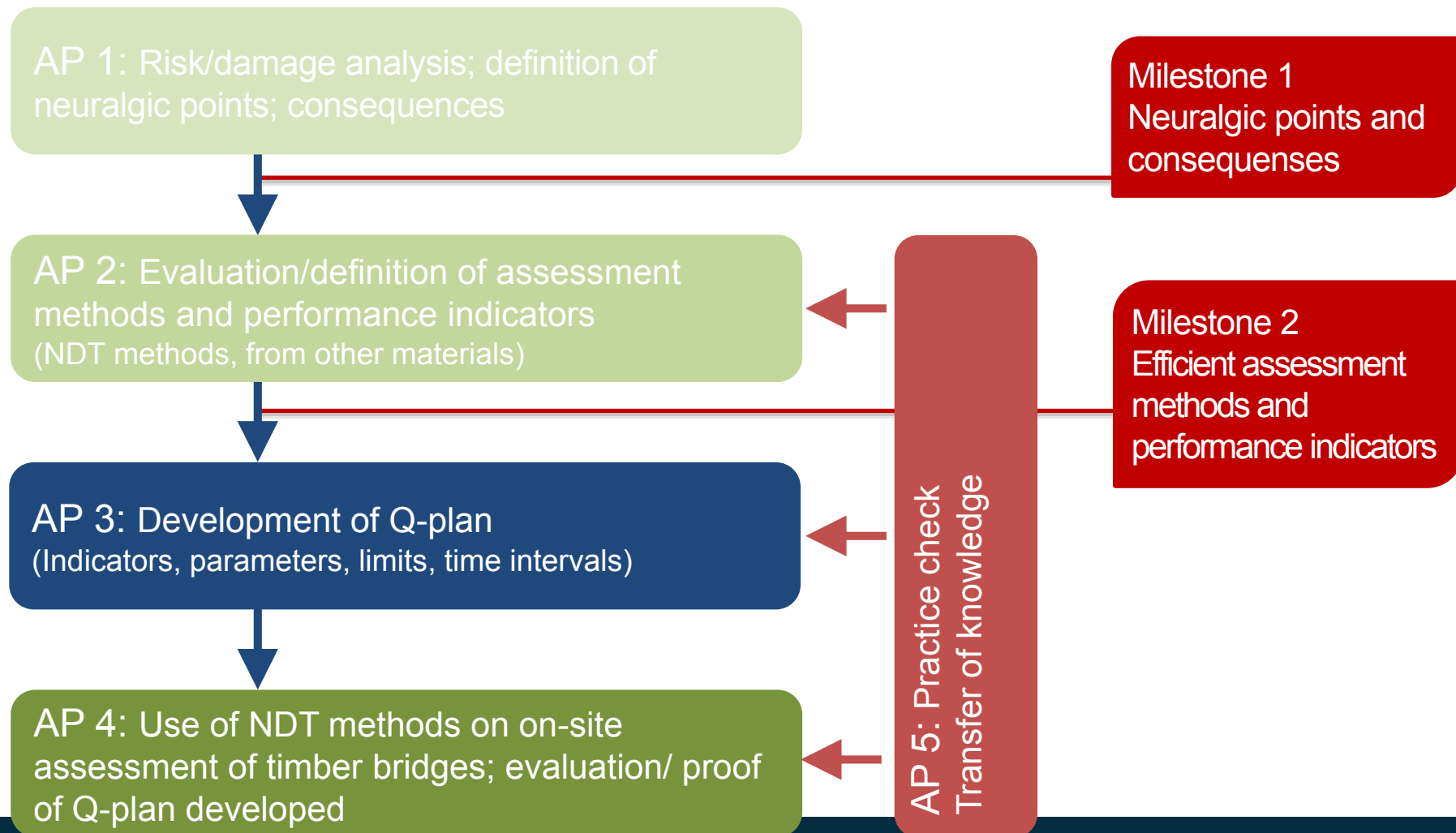
- Q-Plan for timber bridges



# Objectives and Methods

- Development of a template or catalogue of **neuralgic points** in combination with **efficient NDT methods and performance indicators**
- Definition and production of **reference standards, testing and inspection bodies** for the particular NDT methods for wood application and **indication of effectiveness**
- Development of an failure catalogue in order to ensure **reproducibility** and **reliability** in test performance
- **Development of Q-plan**
- Knowledge transfer

# Research Project - Objectives



# Methods for the assessment

- Indicate key factors and parameters
  - Moisture content of wood
  - Eigen frequency of bridge
  - Free visible marks (colour change of wood, cracks)
- Non destructive testing methods (NDT-methods) known for timber and steel
  - Application and key parameters
  - Adaption on timber
- Approaches for inspections or guidelines for other construction materials
  - Analysis of inspection intervals, methods and indicators
  - Background information from DIN 1076
  - Analysis of existing specific inspection plans for timber bridges
  - Performance of on site applications





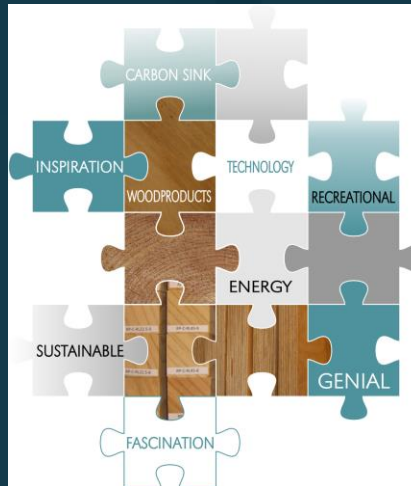
# Conclusions and View

- Research application handed in 29.02.2016 to State secretary for education, research and innovation (SERI) in Switzerland
- Evaluation period of 6 month, project duration of 24 months
- Targeting of representative timber bridges for assessment and monitoring
- Launch STSM and student projects for first assessment steps and on site experiences





**TU1406**  
COST ACTION



[link to paper](#)



### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **GUIDE FOR THE ASSESSMENT OF MASONRY BRIDGES – Technical Parameters**

**João Amado** - Infraestruturas de Portugal, Portugal

**Luís Freire** - Infraestruturas de Portugal, Portugal

**Anibal Costa** - Universidade de Aveiro, Portugal

[link to paper](#)

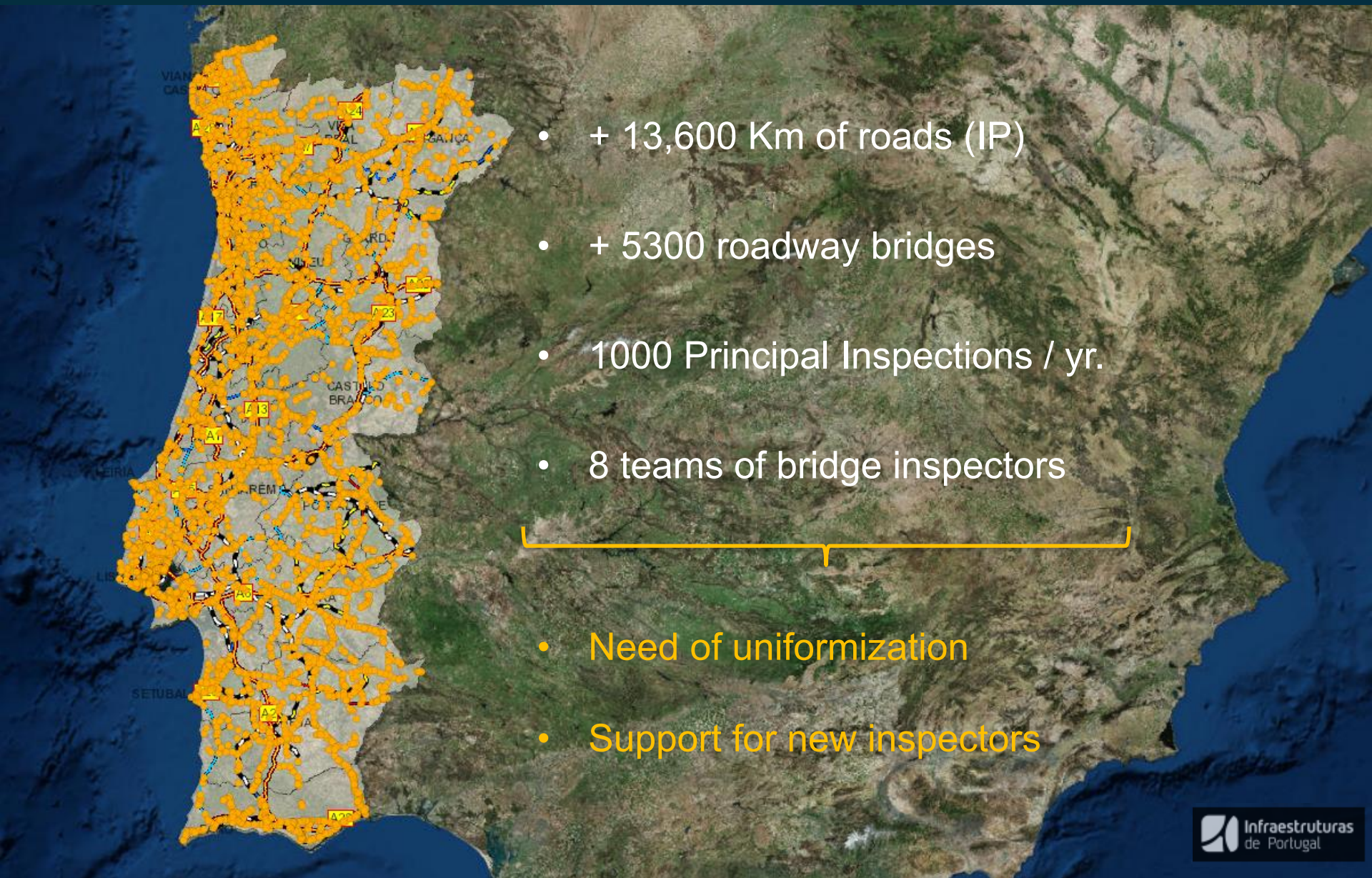


30<sup>th</sup> March - 1<sup>st</sup> April 2016  
Belgrade, Serbia

# CONTENTS

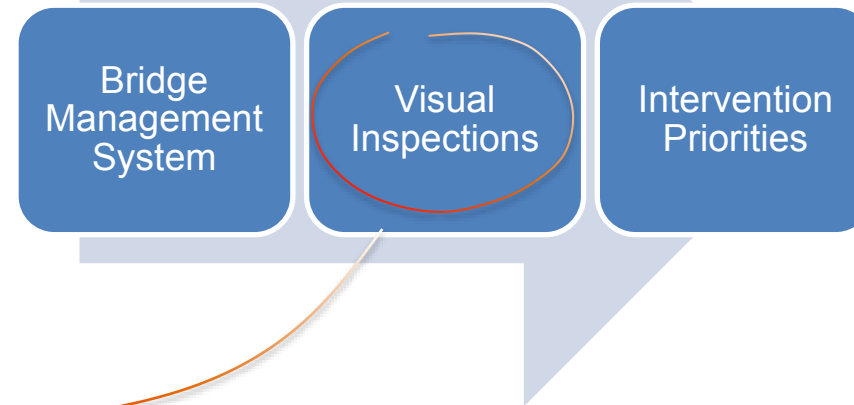
- Motivations
- Introduction to the Guides
- Guide for Masonry Bridges
- Technical Parameters
- Final Remark
- References





# INTRODUCTION

Infraestruturas de Portugal



**Threat:** ← **Opportunity:**

- Lack of documented support to a (visual) comprehensive assessment of bridges;
- Different interpretations and use of the Condition Rating Scale.

## Guides for the Assessment of Bridges

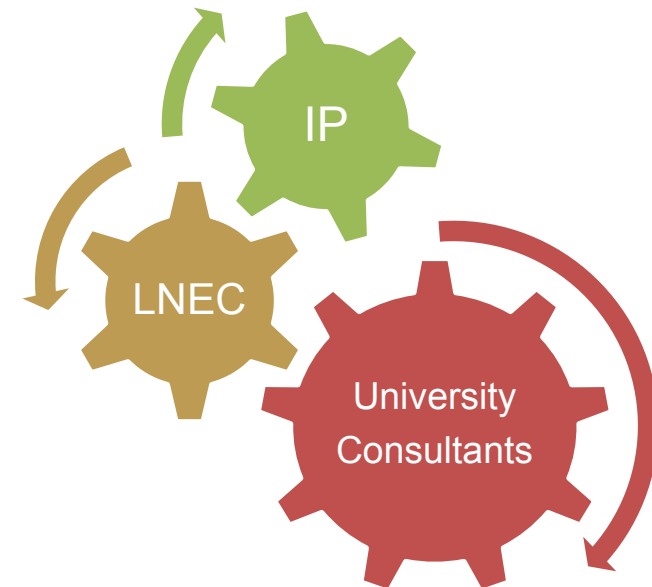
- Concrete bridges
- Metallic bridges
- Masonry bridges
- Geotechnical Structures
- Waterways
- Bridge Equipment



# GUIDE FOR MASONRY BRIDGES

- Historical Background
  - Building techniques
  - Evolution of codes
- Materials and Structural Systems
  - Masonry types and constitutive elements
  - Types of arches
  - Failure modes
- Defects, origins and condition assessment
  - Causes of defects
  - Common defects
  - Diagnosis and Condition assessment
- Tests, monitoring and rehabilitation techniques

6 Guides/  
Similar Approach



# GUIDE FOR MASONRY BRIDGES

- Historical Background
  - Building techniques



*Trajano Bridge*

Chaves, Portugal

Dated 2<sup>nd</sup> century

N.º of arches: 12

Total span: 140 m

# GUIDE FOR MASONRY BRIDGES

- Historical Background
  - Building techniques



Aqueduct

*Aqueduto das Águas Livres*

Lisbon, Portugal

Dated 1748

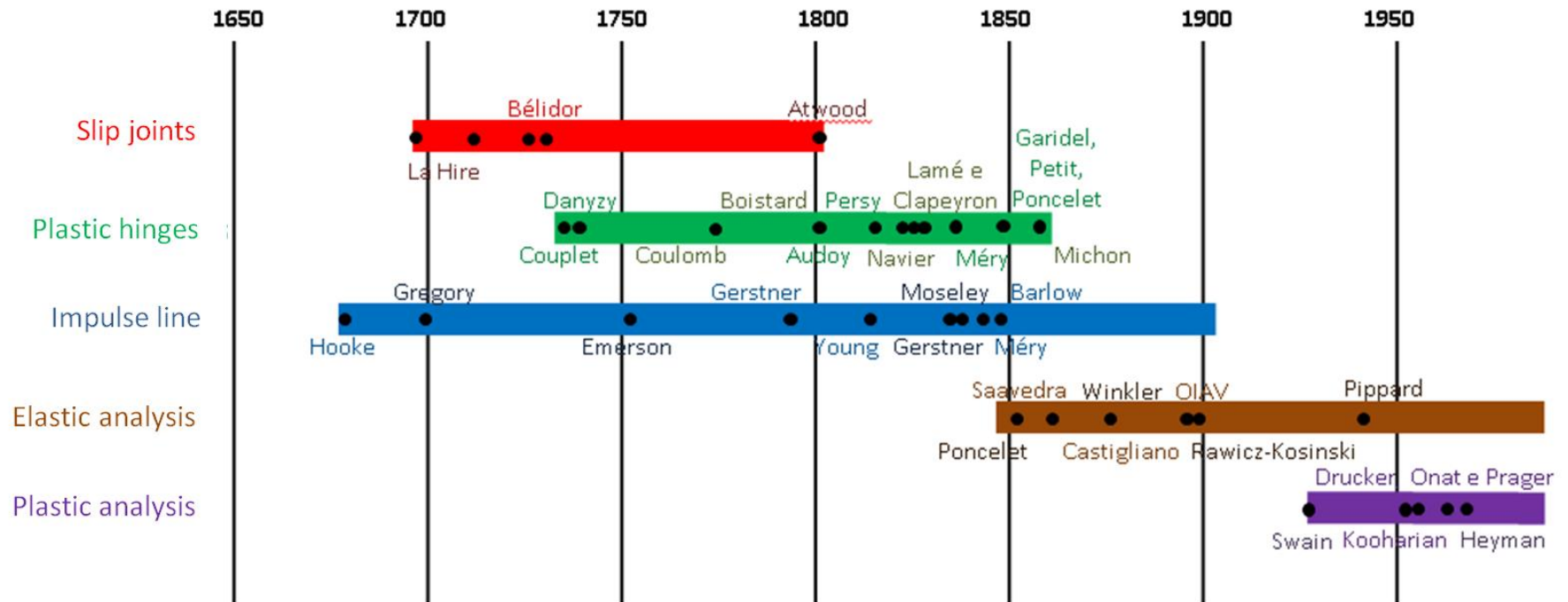
N.º of arches: 35

Max. height: 65m

Max. Span: 29m

# GUIDE FOR MASONRY BRIDGES

- Historical Background
  - Evolution of codes











Costa, 2009



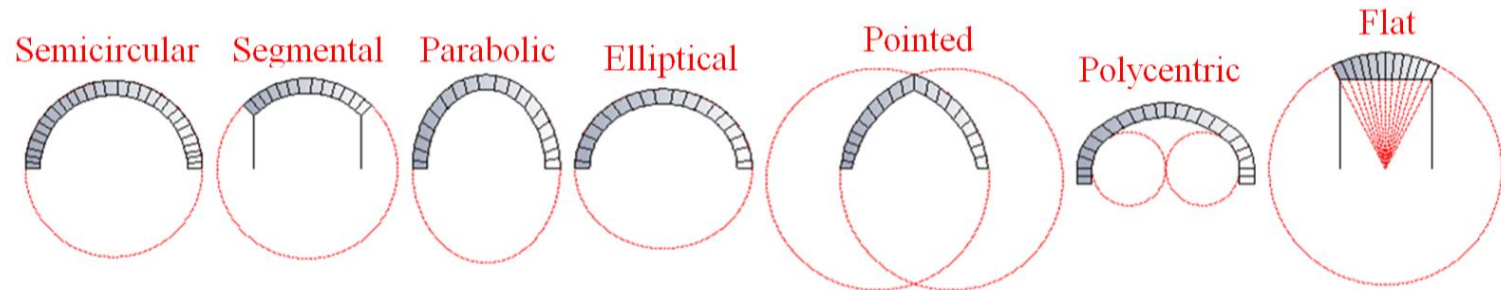
# GUIDE FOR MASONRY BRIDGES

- Materials and Structural Systems
  - Masonry types and constitutive elements

	Joints with mortar		Joints without mortar	
Regular masonry				
Irregular masonry				

# GUIDE FOR MASONRY BRIDGES

- Materials and Structural Systems
  - Types of arches



*Mirandela Bridge, Portugal*



# GUIDE FOR MASONRY BRIDGES

- Materials and Structural Systems
  - Structural failure modes in masonry arch bridges

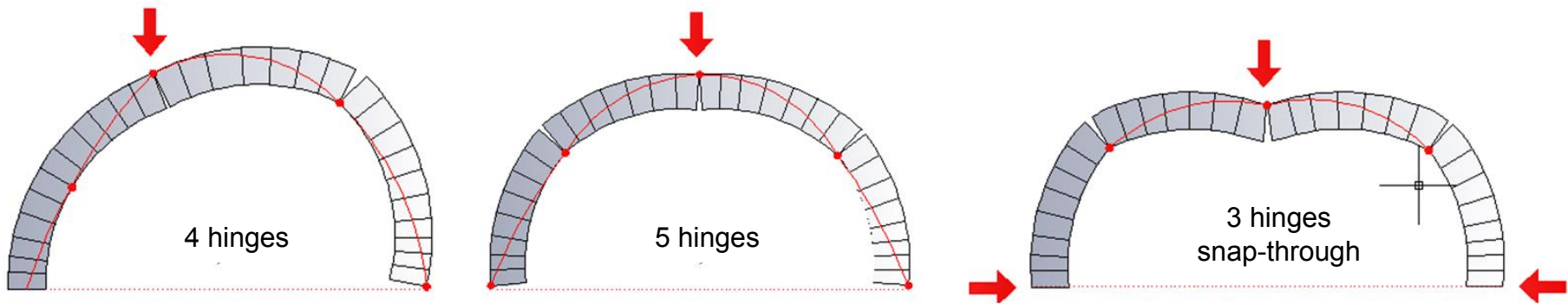
	Elements	Failure modes	Conditioning factors
Longitudinal	Arch	4 plastic hinges mechanism	Resistance, equilibrium
		5 plastic hinges mechanism	Resistance, equilibrium
		3 plastic hinges snap-through	Equilibrium
		Crush	Resistance
		Slip	Resistance
	Spandrel walls	Crush	Resistance
	Bridge	Global plastic hinges mechanism	Resistance, equilibrium
Transv.	Backfill, spandrels and arch	Longitudinal cracks in the vault	Resistance, equilibrium
		Bending and punching shear of the arc	Resistance

Costa, 2009

# GUIDE FOR MASONRY BRIDGES

- Materials and Structural Systems
  - Failure modes

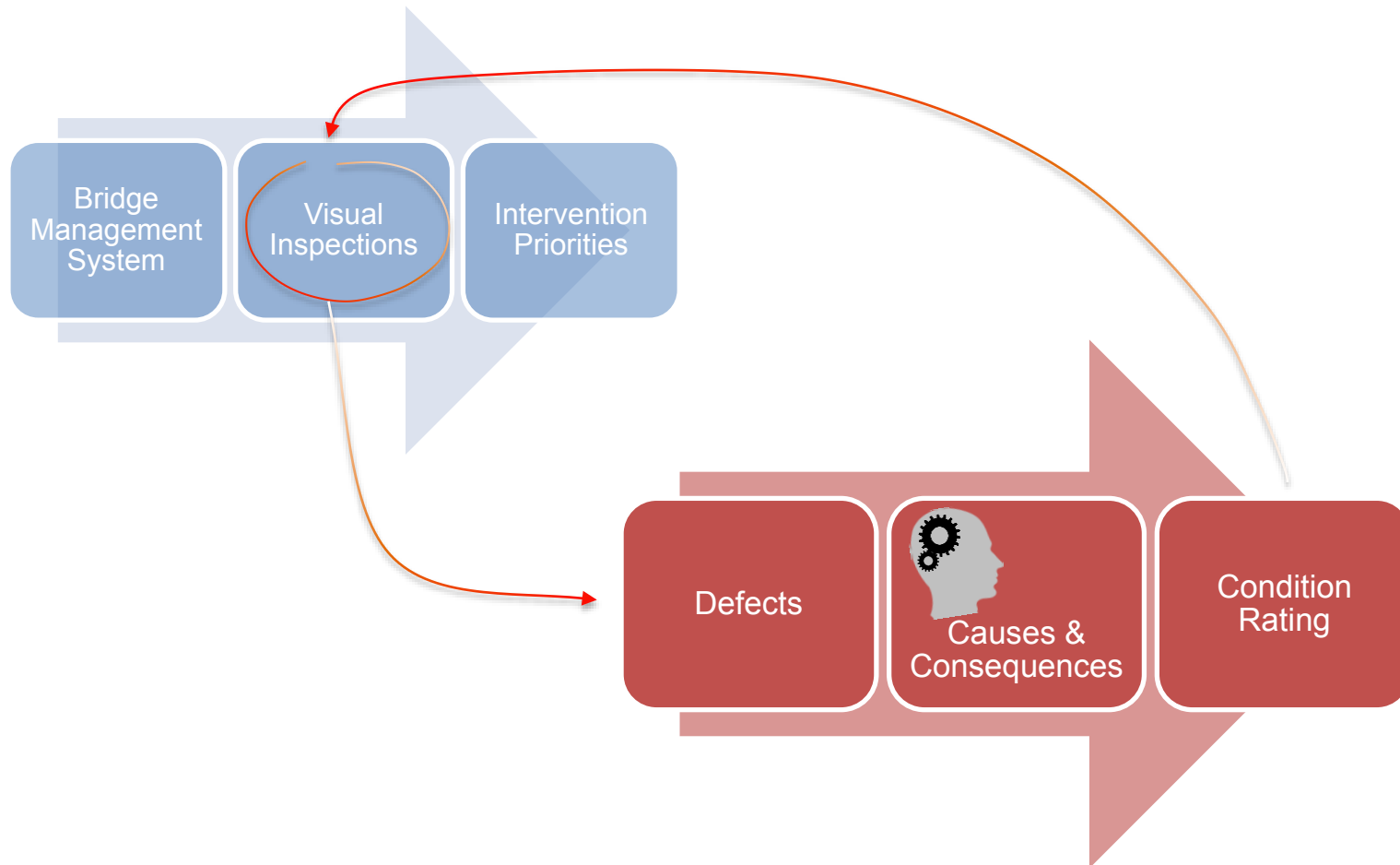
Longitudinal failure modes mechanisms:



Costa, 2009

# GUIDE FOR MASONRY BRIDGES

- Defects, origins and condition assessment



# GUIDE FOR MASONRY BRIDGES

- Defects, origins and condition assessment
  - Causes of defects

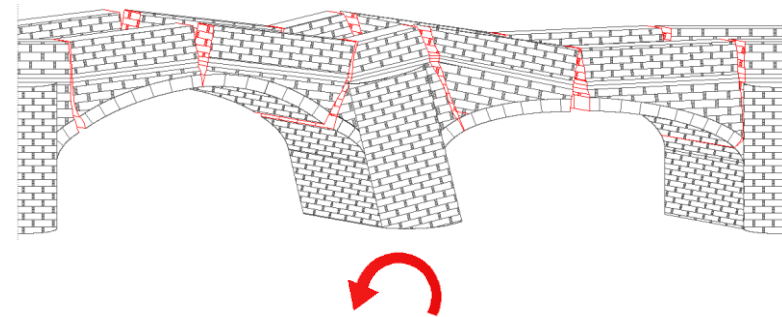
*Actions according to ICOMOS:*

Acting on the structure (Mechanical)	Static actions	Direct	Applied loads (e.g. permanent load, equipment, intrusive vegetation, etc.)
		Indirect	Applied strains (e.g. imposed deformations due to settlements, mortar shrinkage, etc.)
	Dynamic actions		Imposed accelerations (e.g. seismic action, wind, traffic, etc.)
Acting on the materials	Physical		Decay of material properties due to ambient factors (e.g. water, temperature gradient, moisture, pollution, etc.)
	Chemical		
	Biological actions		

# GUIDE FOR MASONRY BRIDGES

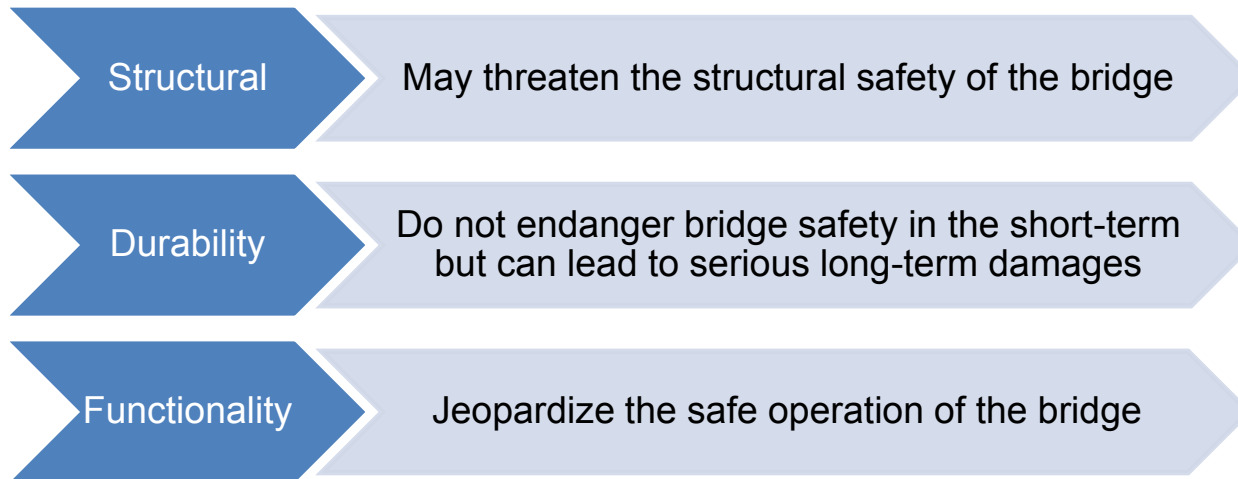
- Defects, origins and condition assessment
  - Causes of defects

Causes of defects	Effect on structure
Foundation movement	Equilibrium loss
Poor rigging	
Poor design or construction	
Collision of vehicles	
Excessive loads	Increased solicitations
Excessive vibrations	
Backfill decay	Strength loss
Previous interventions	
Material decay	



# GUIDE FOR MASONRY BRIDGES

- Defects, origins and condition assessment
  - Common defects





# GUIDE FOR MASONRY BRIDGES

- Defects, origins and condition assessment
  - Common defects

## Structural defects

May threaten the structural safety of the bridge

Localized defects in blocks

Longitudinal cracks

Transversal cracks

Oblique cracks

Vertical cracks

Loss of blocks or mortar

Geometric deviations outside the masonry plane

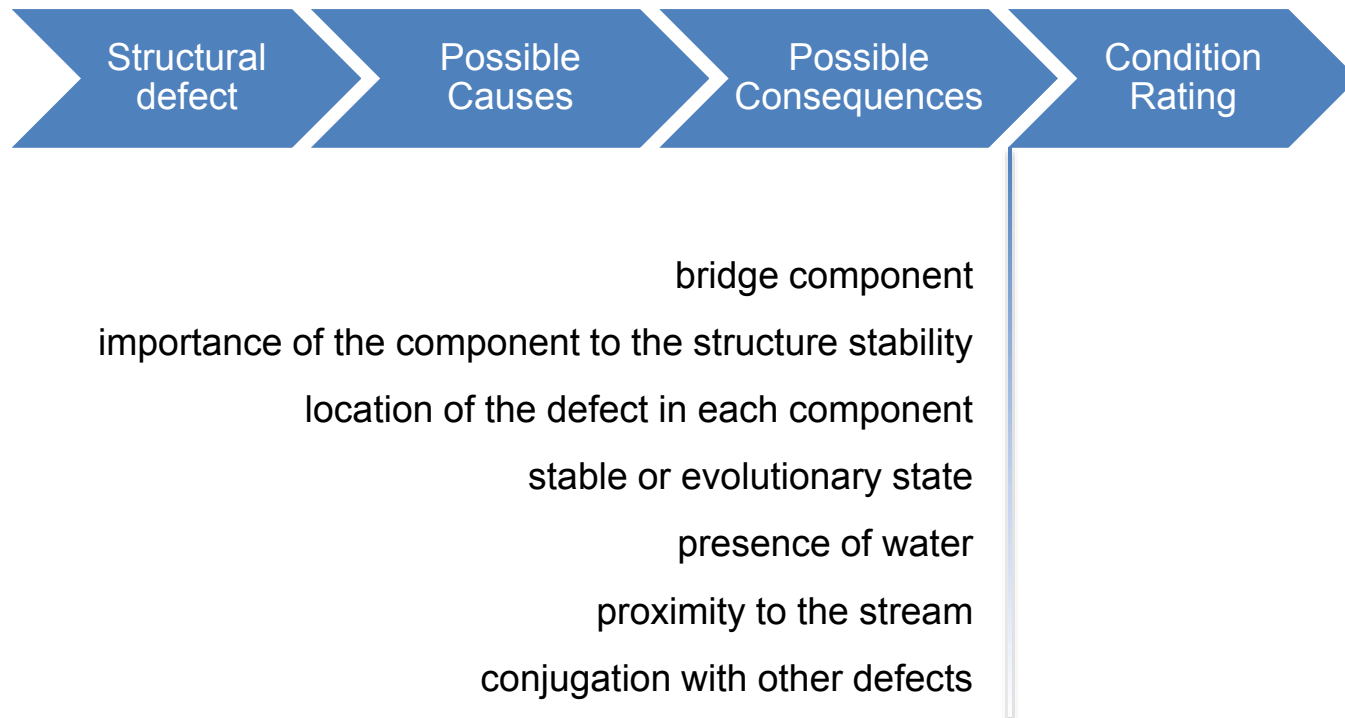
Geometric deviations in masonry plane

Settlement of piers/ abutments

Ruin

# GUIDE FOR MASONRY BRIDGES

- Defects, origins and condition assessment
  - Diagnosis and Condition assessment



# GUIDE FOR MASONRY BRIDGES

- Defects, origins and condition assessment
  - Example:

Crack/ opening  
below the  
spandrel wall

Description

Possible  
Causes

AA04	ANOMALIAS NO ARCO	
<b>FENDILHAÇÃO LONGITUDINAL, JUNTO À FACE</b>		
<b>Descrição</b>	Fendilhação longitudinal no intradorso do arco, entre a 1ª e 2ª fiada longitudinal de aduelas, a montante ou a jusante, que concretiza uma descontinuidade entre o arco e o paramento da estrutura. Esta anomalia tende a desenvolver-se ao longo das juntas da alvenaria e por vezes das aduelas, causando o seu seccionamento.	
<b>Causas</b>	CA03	Rigidez do arco inferior aos tímpanos e enchimento devido a erros de projeto ou execução.
	CA05 CA06	Vibração e cargas excêntricas, resultante da rodagem de veículos junto aos passeios, fixação de tubos e outros equipamentos ao longo do paramento da ponte - Mecanismo de transmissão dos impulsos horizontais.
	CA07 CA09	Rigidez do arco inferior aos tímpanos e enchimento, causada por degradação do enchimento e/ou do material.

# GUIDE FOR MASONRY BRIDGES

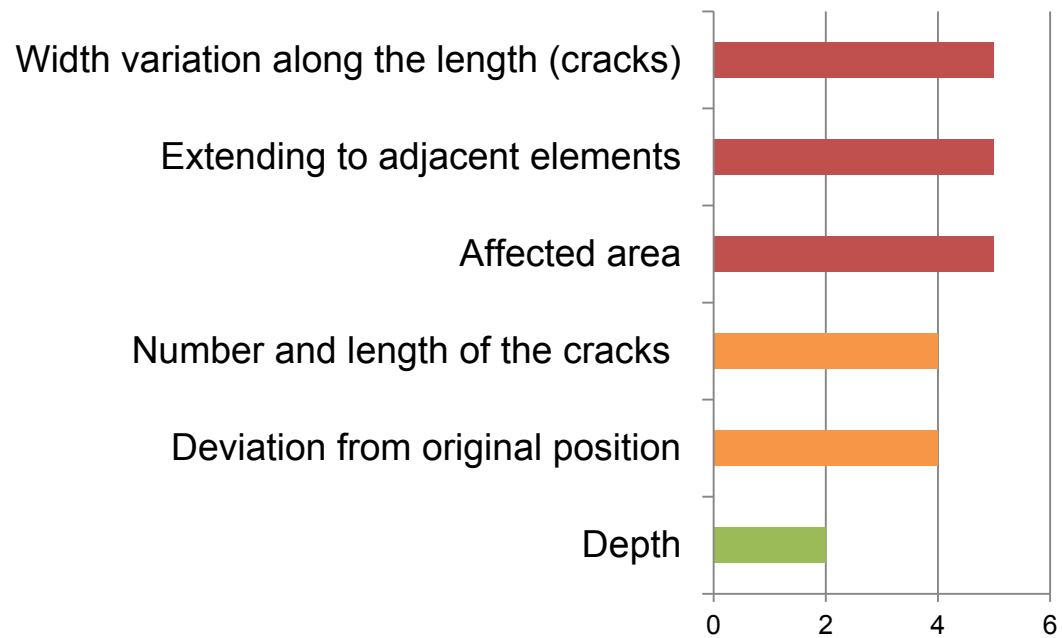
- Defects, origins and condition assessment
  - Example

Key observations	<b>Aspetos a inspecionar</b>	Avaliação da extensão da fendilhação (ex) e medição da abertura da fenda (a). Verificar a existência de fendilhação em elementos adjacentes (tímpanos e pilares). Avaliação do enchimento, cuja degradação pode ser verificada através do seu destacamento ou do destacamento/perda de aduelas.	
Test/ measurements	<b>Meios complementares de diagnóstico</b>	Régua de medição. Instrumentação com fissurómetros.	
Condition Rating	<b>Estado de Conservação</b>	2	ex < 50 % da imposta do arco.
		3	ex ≥ 50 % da imposta do arco; a < 5 cm; com fendilhação em elementos adjacentes (tímpanos e pilares).
		4	ex = 100 % da imposta do arco e a ≥ 5 cm; ou com degradação do enchimento.
Aggravating factors	<b>Fatores de agravamento</b>	Nos casos das pontes estreitas a passagem de veículos.	
Consequences	<b>Consequências</b>	Deficiente encaminhamento de cargas. Pode colocar em causa a estabilidade do elemento.	
Possible evolution	<b>Evolução</b>	Perda de argamassa, abertura de juntas, destacamento e perda de blocos, descompressão do enchimento, abatimento do arco. Favorece a infiltração de água e os depósitos de origem biológica.	
Risk mitigation	<b>Medidas mitigadoras de risco</b>	Condicionamento do trânsito. Remoção dos equipamentos fixados ao paramento da ponte.	
Repair technics	<b>Metodologia de reabilitação</b>	Preenchimento das fendas com argamassa compatível com os materiais existentes. Atirantamento transversal do arco e eventualmente dos tímpanos, se houver risco de descompressão do enchimento. Substituição ou consolidação do enchimento, em caso de elevada degradação deste elemento.	

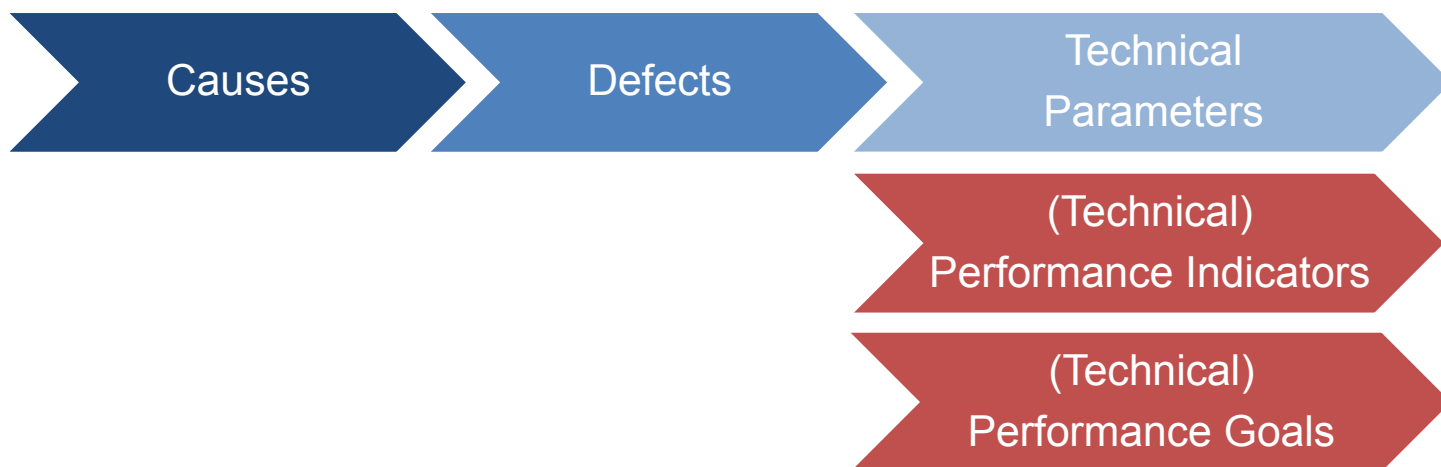
# TECHNICAL PARAMETERS

Structural Defects

Technical Parameters



# Final Remark





# References

Cristina Costa. *Análise numérica e experimental do comportamento estrutural de pontes em arco de alvenaria de pedra*. PhD thesis, Universidade do Porto, FEUP, Porto, 2009.

ICOMOS. Recommendations for the Analysis, Conservation and Structural Restoration of Architectural Heritage, Technical Report.

Aníbal Costa, Hugo Perneta, Cristina Costa, António Arêde, Humberto Varum, Guide for the Assessment of Masonry Bridges, Infraestruturas de Portugal, forthcoming.



[link to paper](#)



# **COST TU1402: Quantifying the Value of Structural Health Monitoring**

Sebastian Thöns

ERDA – Civil Engineering Risk and Decision Analysis  
Department of Civil Engineering, Technical University of Denmark

# Introduction and background

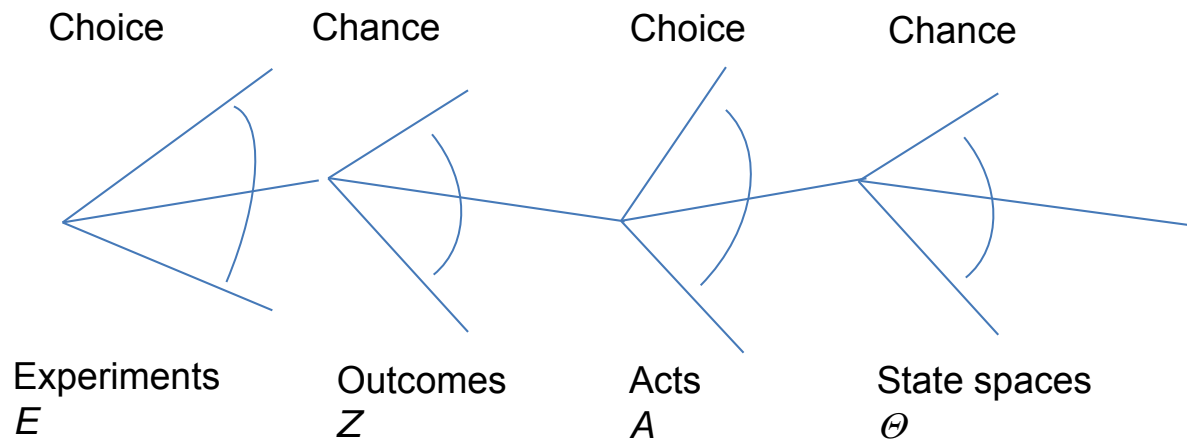
Structural Health Monitoring (SHM) constitutes an extensive research field over decades.

Despite the maturity of the research, infrastructure owners and operators are reluctant to invest in SHM systems as the utility of SHM systems is hardly known.

The utility of SHM systems can be quantified based on the Value of Information theory.

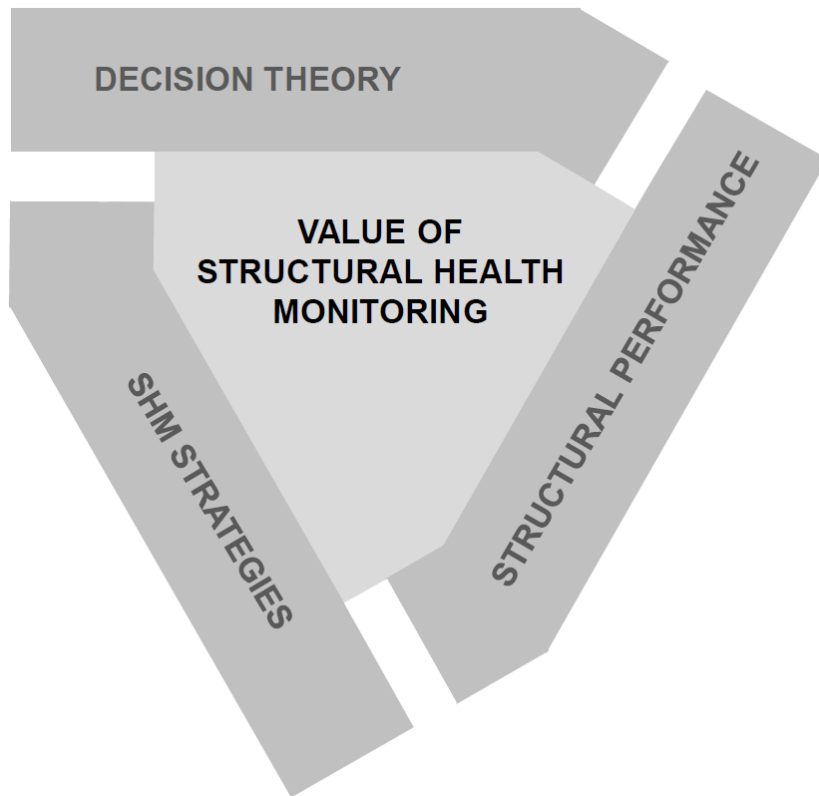
# Value of Information

- The Value of Information theory was formulated by Raiffa and Schlaifer (1961) on the basis of utility theory.



# Quantification of the value of structural health monitoring

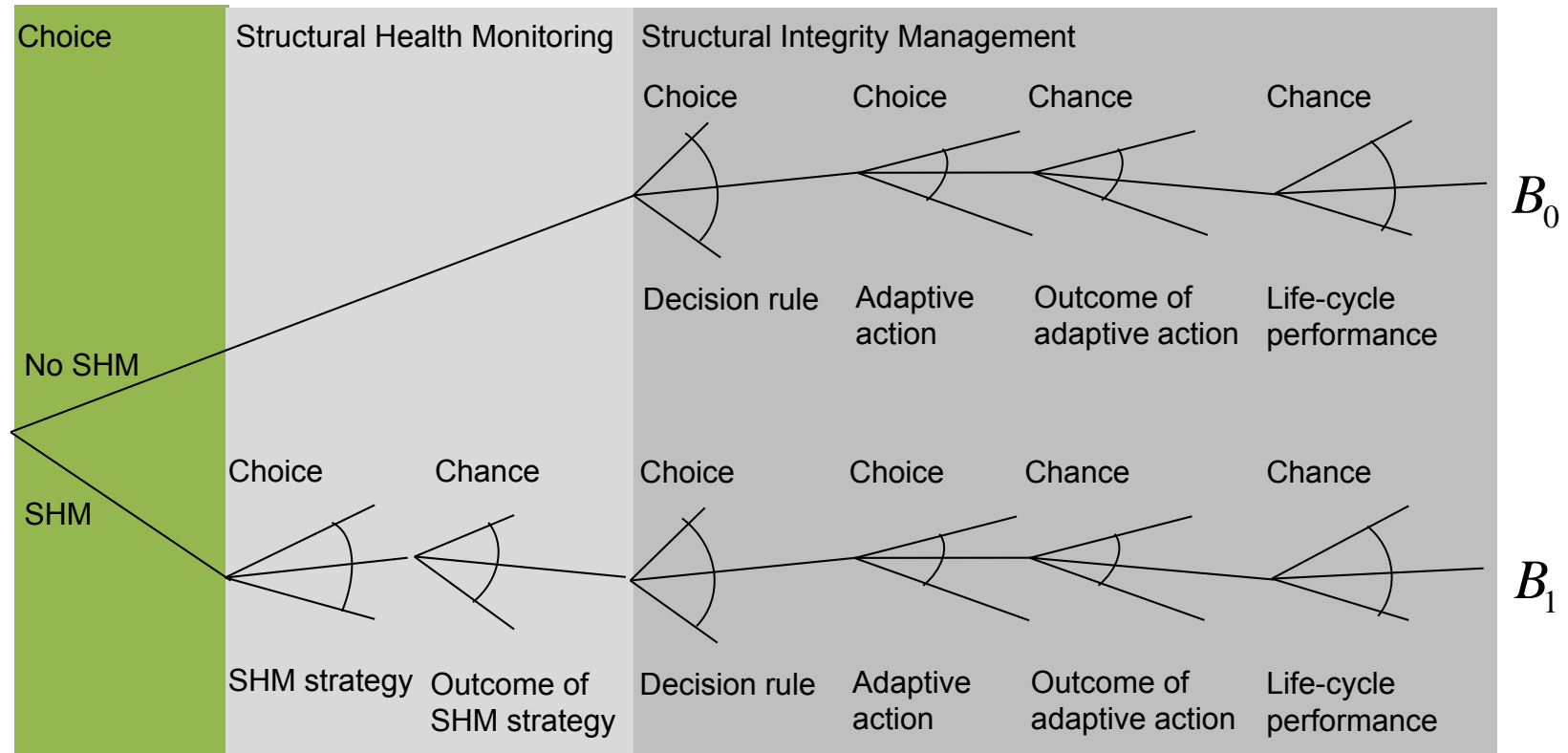
- The value of structural health monitoring is calculated as the difference between life cycle benefits  $B_1$  and  $B_0$ :



$$V = B_1 - B_0$$



# Quantification of the value of structural health monitoring



# Quantification of the value of structural health monitoring

Value of SHM:

$B_0$ : Life cycle benefit without SHM

$B_1$ : Life cycle benefit utilizing SHM

$$V = B_1 - B_0$$

Life cycle benefits:

$$B_0 = \max_{\mathbf{a}, \mathbf{d}} E_{\mathbf{Z}_E} \left[ E_{\mathbf{Z}_A} \left[ \mathbf{d}(\mathbf{a}, \mathbf{Z}_E, \mathbf{Z}_A), \mathbf{Z}_E, \mathbf{Z}_A \right] \right]$$

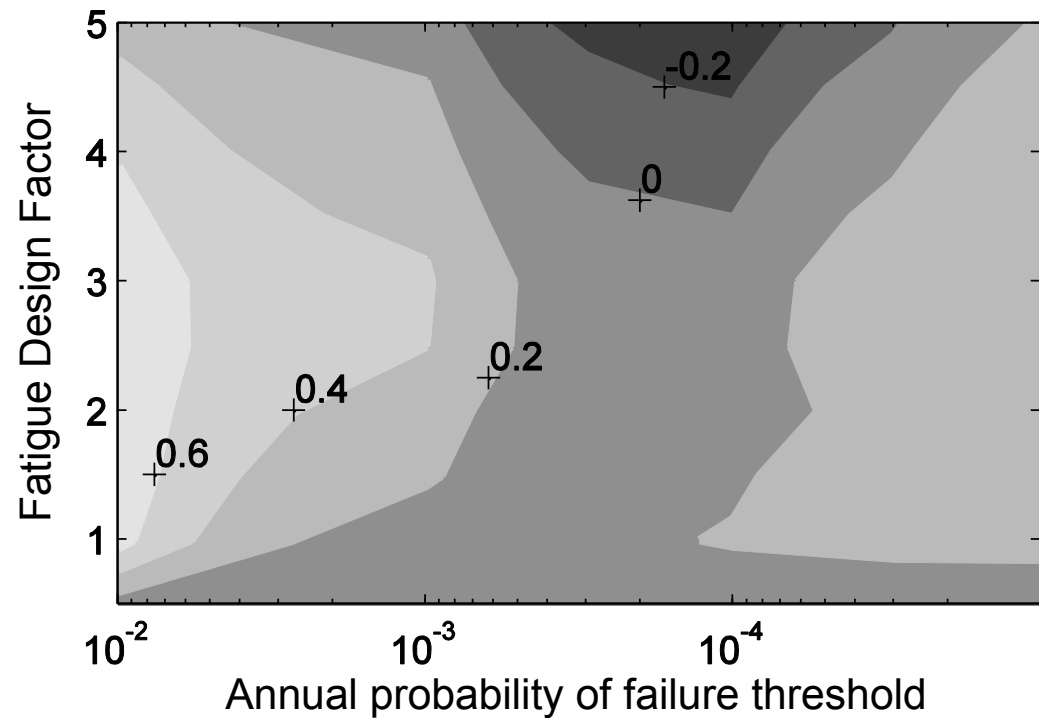
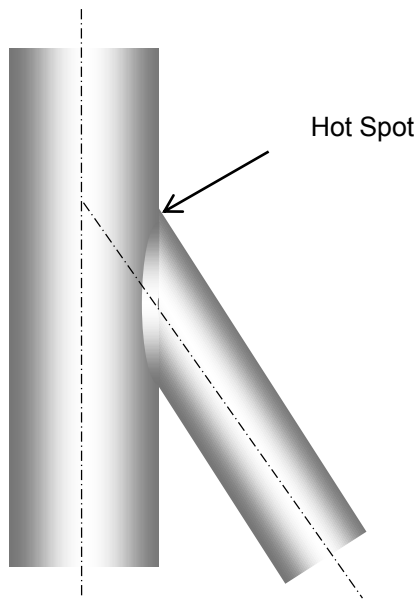
$$B_1 = \max_s E_{\bar{\mathbf{Z}}_E} \left[ E_{\bar{\mathbf{Z}}_A} \left[ \max_{\mathbf{a}, \mathbf{d}} E_{\mathbf{X}|\bar{\mathbf{Z}}_E, \bar{\mathbf{Z}}_A} \left[ \mathbf{X}, \bar{\mathbf{Z}}_E, \bar{\mathbf{Z}}_A, \mathbf{s}, \bar{\mathbf{d}}(\bar{\mathbf{a}}, \mathbf{X}, \bar{\mathbf{Z}}_E, \bar{\mathbf{Z}}_A) \right] \right] \right]$$

$\mathbf{X}, \mathbf{Z}_A, \mathbf{Z}_E$ : Random variables for uncertain monitoring results, aleatory and epistemic uncertainties

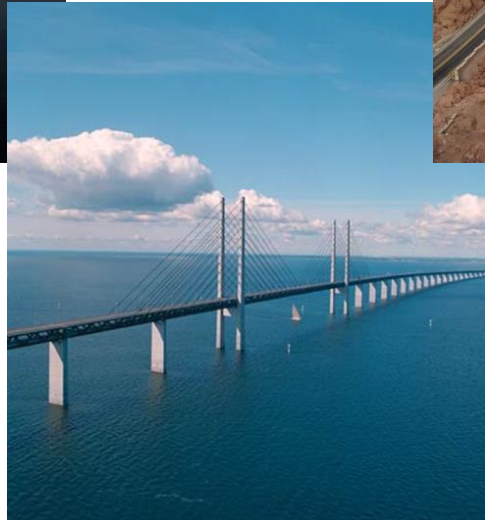
$\mathbf{s}, \mathbf{d}, \mathbf{a}$ : SHM strategies, decision rules and adaptive actions

# Examples

The value of SHM (normalised) in dependency of the design and the operation reliability.



# Potential application areas



# COST Action TU1402: Key deliverables

1. A library of tools and algorithms for the quantification of the Value of SHM.
2. A chapter to the Probabilistic Model Code of the JCSS.
  - Documentation the scientific framework and approaches
3. A guideline on the quantification of the value and optimization of SHM.
  - Detailed examples
  - For practising engineers
4. Dedicated dissemination activities.
  - E.g.: workshops, special sessions at international conferences, training courses, scientific missions
5. A well-developed homepage.
  - Activity documentation with videos, presentations and reports

# COST Action TU1402: Impact

The COST Action aims to impact science, industry and society.

Scientific impact:

- Development of the scientific field for quantifying the value of Structural Health Monitoring
- The network of this Action with experts in science, industry and stakeholders of structures and infrastructure systems will be utilized for developing project proposals
- The scientific field will be made accessible and practicable by dissemination including guidelines



# COST Action TU1402: Impact

European economy and society impact:

- Improved economic efficiency in the continued development, operation and maintenance and asset management of structures and infrastructure systems
- New business opportunities for European small and medium-sized (SME) and large industrial enterprises and the opportunity to create high quality jobs
- Increased competitiveness in the building, construction and structural engineering industry

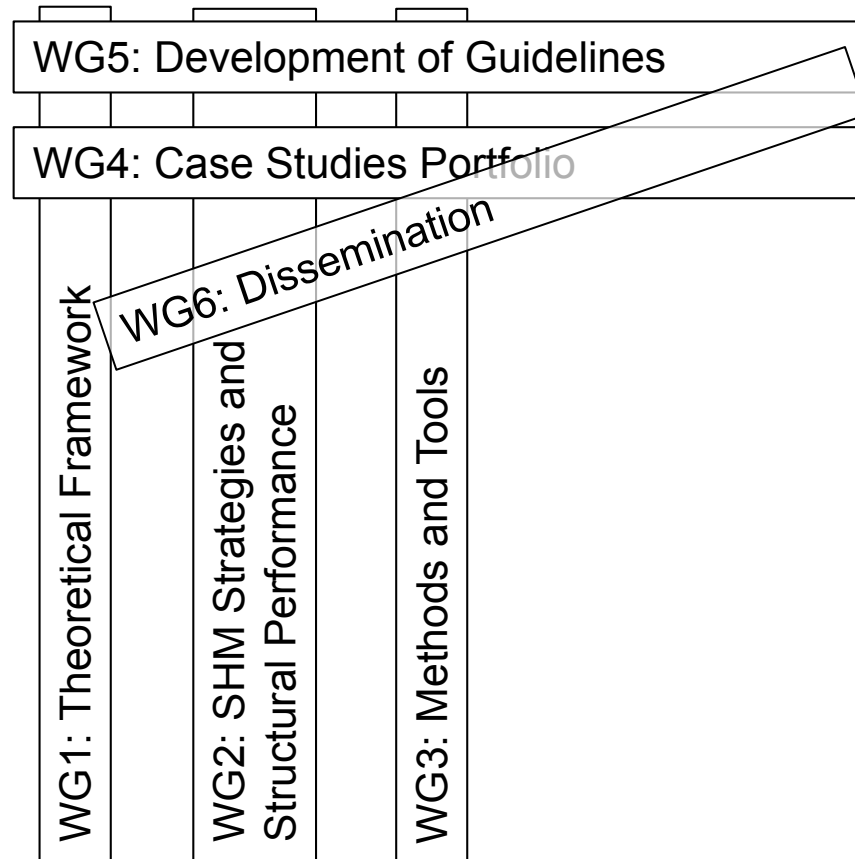
# COST Action TU1402: Scientific Program

The scientific focus of the Action is directed to the objective of quantifying the value of structural health monitoring before implementation.

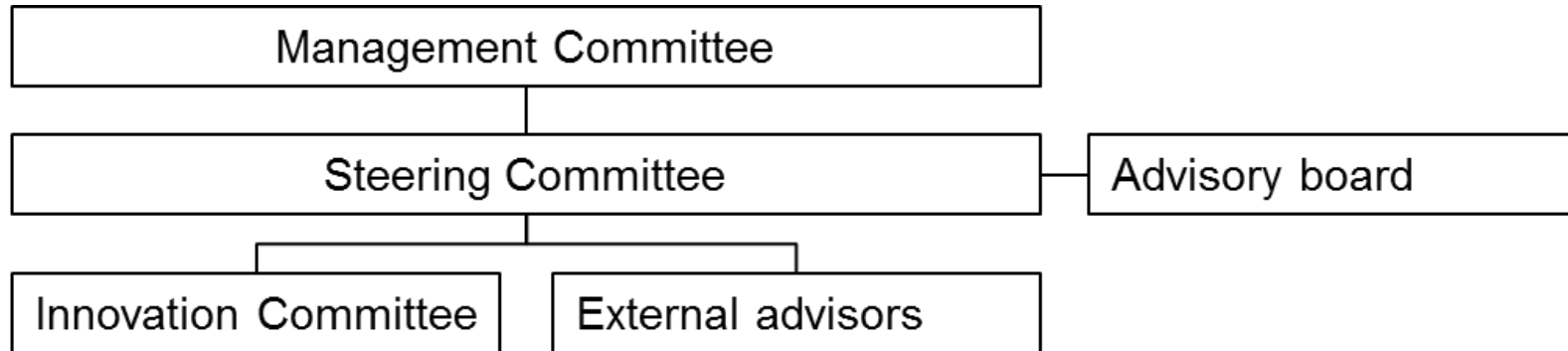
The COST Action comprises 5 Tasks:

1. Theoretical framework
2. SHM Strategies and Structural Performance
3. Methods and Tools
4. Case Studies Portfolio
5. Development of Guidelines

# COST Action TU1402: Organisation

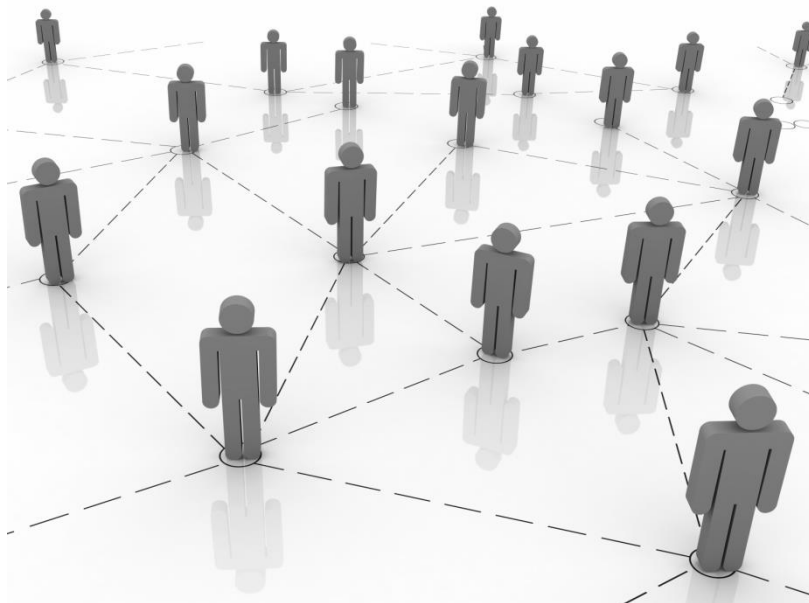


# COST Action TU1402: Organisation



# COST Action TU1402: Network

- The network comprises various research institutions, engineering consultants industrial enterprises as well as operators of infrastructures.



7 European countries

# COST Action TU1402: WG2 - Activities

- Working Group 2 on SHM Strategies and Structural Performance
  - Leader: Prof. Marios Chryssanthopoulos (University of Surrey, UK)



- Co-Leaders: Prof. Geert Lombaert (Katholieke Universiteit Leuven, Belgium) and Dr. Michael Döhler (Inria, France)





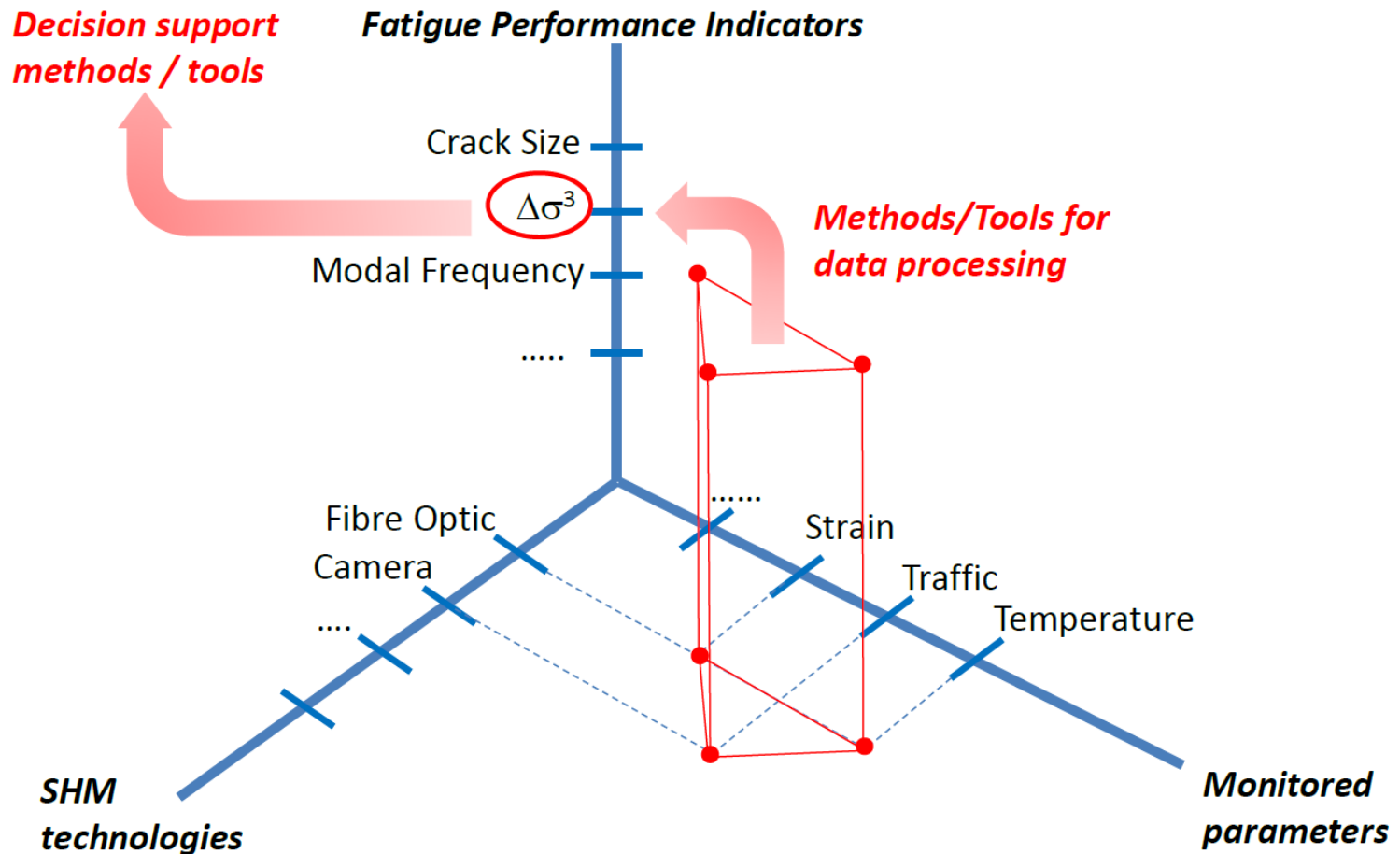
# Objectives

- Categorizes available **SHM technologies** with regard to the **measured quantity** and the related **structural performance** – collect and represent “best practice”
- Quantify links between measured quantities and structural performance of interest with consistent treatment of **uncertainties**.

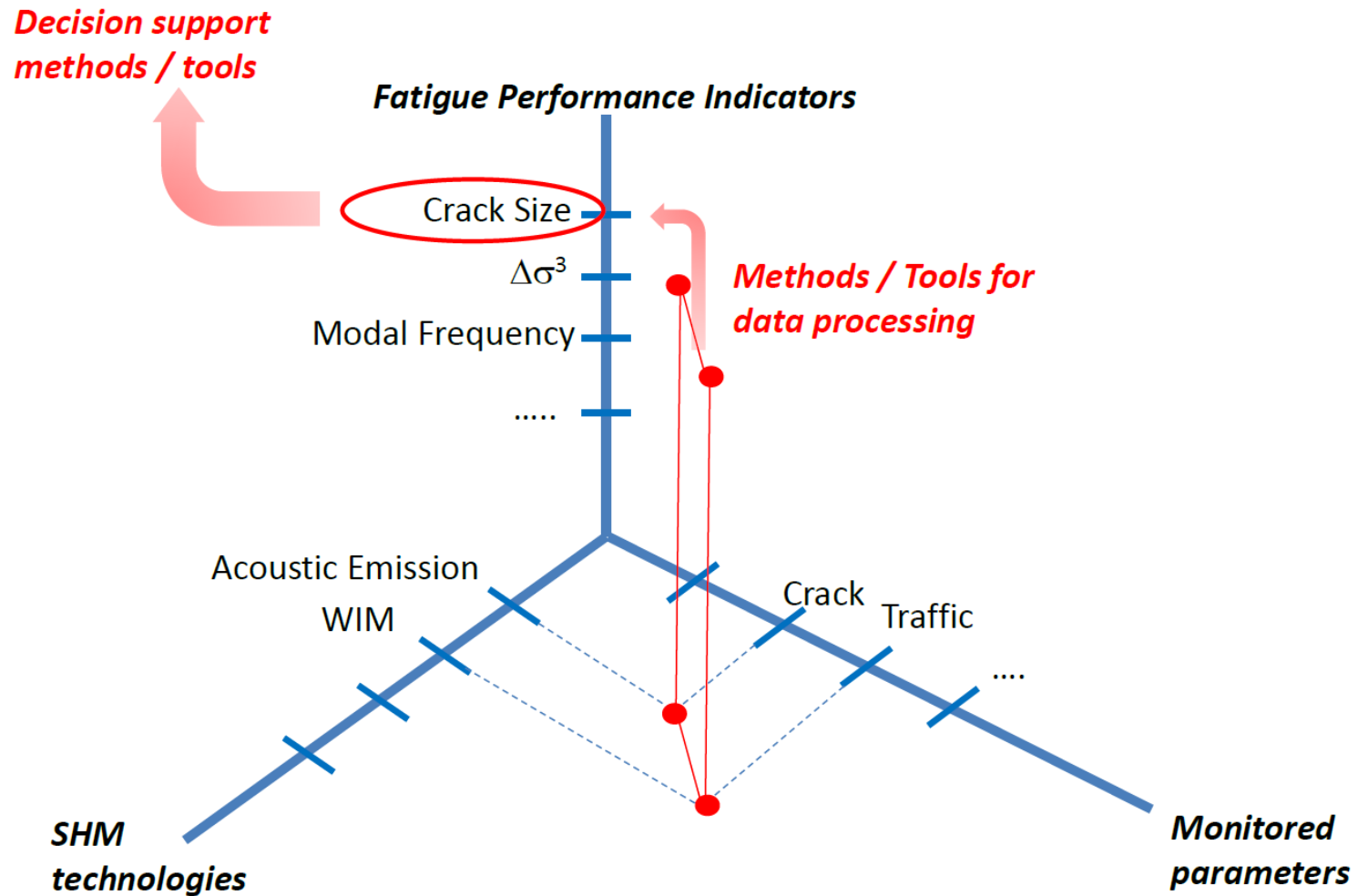
## Categorization

- SHM technologies can be categorized in many different ways:
  - Type of structural application
  - Type of data or features extracted
  - Global or local method
  - Model-based versus data-based
- In order to provide guidance in the selection of SHM technologies, it seems natural to depart from the **type of structure**
- The structure then defines relevant **types of performance**, e.g. for bridge:
  - Ultimate limit state
  - Durability
  - Serviceability
  - Fatigue
- The type of performance can be assessed through **indicators**, e.g. for durability:
  - Appearance (rust stains) - Ingress (chlorides, CO<sub>2</sub>)
  - Crack width
  - Loss of material
- **Threshold values** may be set to define the onset of further action. This requires monitoring and interpretation of indicators through an appropriate **SHM strategy**.

# A possible SHM strategy



# An alternative SHM strategy



## Structural Types

- Bridges
- Buildings
- Chimneys / Cooling Towers
- Dams (earth structures)
- Offshore Structures
- Nuclear structures

**System**

## Performance

- Serviceability
- Ultimate/Limit State
- Fatigue
- Reliability
- Resilience
- Sustainability

## Indicators

- Modal Frequencies/ Shapes
- Interstorey Drifts
- Stress ranges
- Crack widths
- Ductility
- Model Prediction Errors
- ....

**Performance**

## Observations

- Deflections
- Vibrations
- Chlorides
- Acoustic Signals
- Operational Loads
- Extreme Loads
- Strains
- Environmental Variations
- Cracks

## Technology

- FO sensors
- MEMs
- Laser
- GPR
- AE sensors
- Ultrasonic
- ...

**SHM**

## Decisions

- Safety
- Functionality
- Life Extension
- ...

## Actions

- Maintenance
- Inspection
- Repair
- Strengthening
- ....

**Life Cycle Assessment**

*...from observations to decisions...*

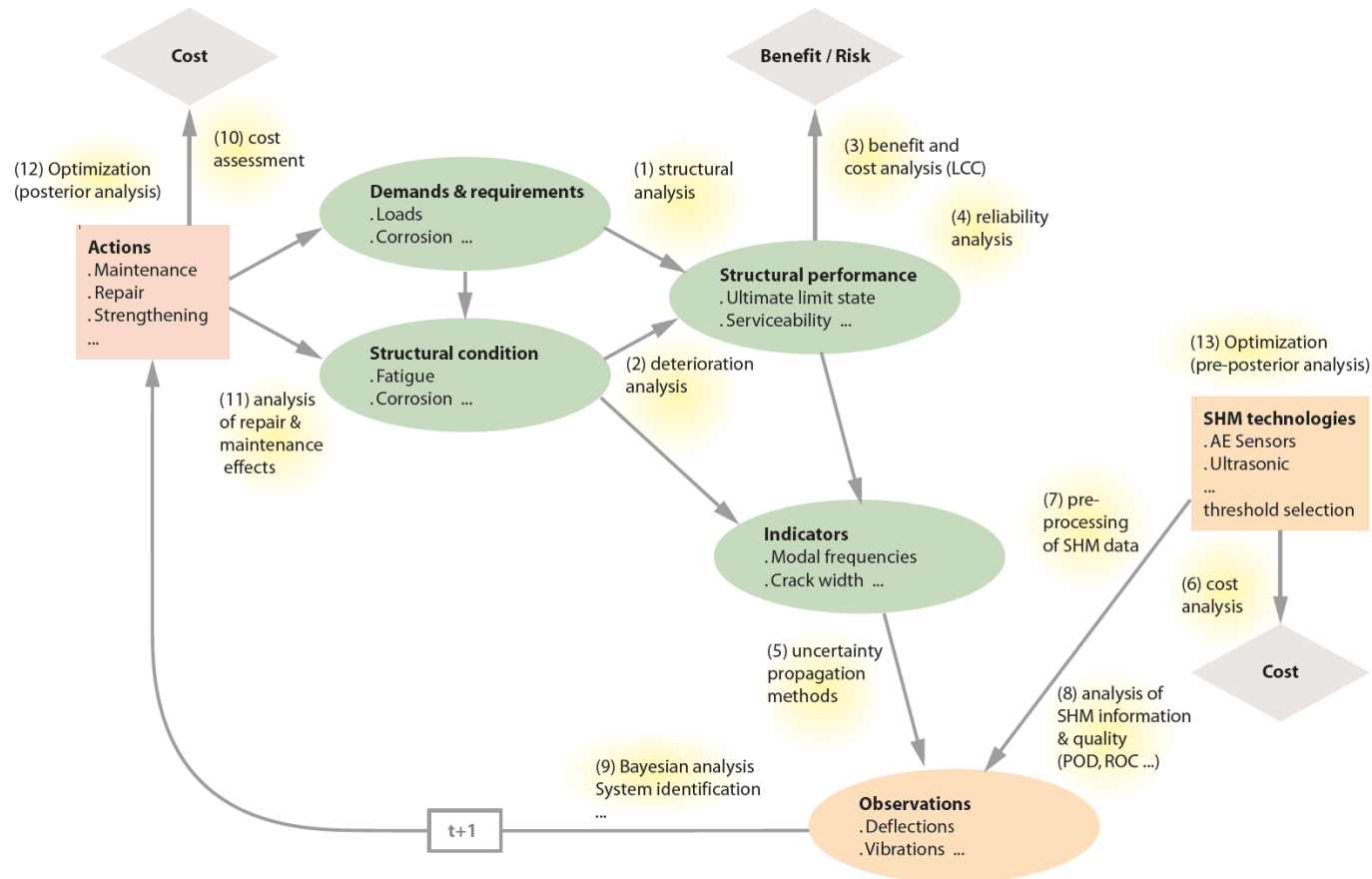
- 'Fixed' path
- Optional path 1
- Optional path 2

# COST Action TU1402: WG3 Activities

- Working Group 3 on Methods and Tools
  - Leader: Prof. Daniel Straub (Technical University of Munich, Germany)
  - Co-leader: Prof. Eleni Chatzi (ETH Zurich, Switzerland)



# COST Action TU1402: WG3 Activities





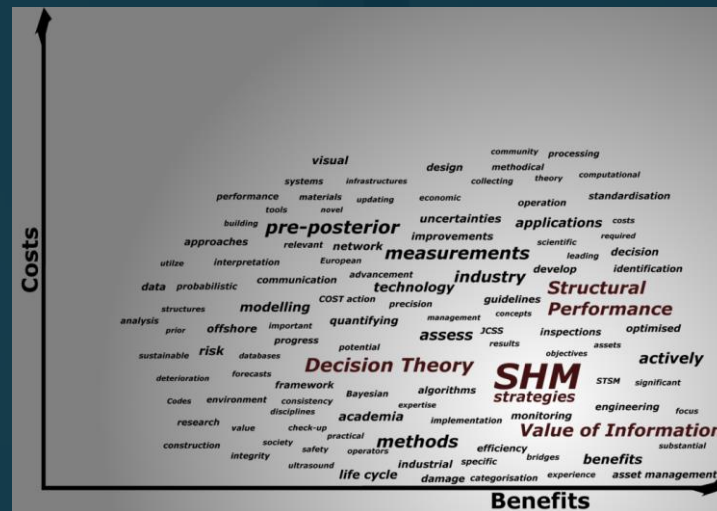
# Classification and documentation

Title:			
Classification		Specification	Reference
Case description	Structure		
	Structural performance model		
	SHM strategy		
	SHM strategy model		
	Technology readiness level		H2020
Value of Information	Results		
	Analysis type		

Title:			
Classification			
Case description	Structure		
	Structural performance model		
	SHM strategy		
	SHM strategy model		
	Technology readiness level		
Value of Information	Results		
	Analysis type		
Structural performance	Structural reliability		
	Structural Integrity Management		
	Consequences		
Measurement information	Type		
	Relation to structural performance		
	Temporal characteristic		
	Spatial characteristic		
	Precision	Measurement uncertainty	
		Operation uncertainty	
		Data analysis (model) uncertainty	
		Dependencies	
	Costs	Investment	
		Installation	
Operation and maintenance			
Replacement			
Measurement system deployment	System		
	Technology		
	Handling		
	Analysis		

# Liaison with COST Action TU1406

- Relating performance indicators to a Value of Information Analysis.
  - Quantification of the value of performance information.
- Joint case studies.
- Joint TU1406 TU1402 Workshop
  - 2<sup>nd</sup> and 3<sup>rd</sup> of March 2017, Zagreb, Croatia



Thank you for your attention.



## **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# Report from Working Group 1

**Alfred Strauss** - University of Natural Resources and Life Sciences, Institute of Structural Engineering, Austria

**Ana Mandić Ivanković** - Faculty of Civil Engineering, University of Zagreb, Croatia

30<sup>th</sup> March - 1<sup>st</sup> April 2016  
Belgrade, Serbia

# Status: Applied PI databases

Finished screening
Austria
Bosnia and Herz.
Croatia
Czech Republic
Denmark
Estonia
Finland
France
FYR Macedonia
Germany
Greece
Hungary
Ireland
Israel
Latvia

Lithuania
Netherlands
Norway
Poland
Portugal
Serbia
Slovakia
Slovenia
Spain
Sweden
Switzerland
Turkey
United Kingdom

Not finished
Belgium
Bulgaria
Cyprus
Italy
Luxembourg
Malta
Montenegro



# Status: people nominated for RD

Country:	Nominated Person
Austria	
Belgium	
Bosnia and Herz.	
Bulgaria	
Croatia	Ana Mandic Ivankovic
Cyprus	
Czech Republic	Pavel Ryjacek
Denmark	
Estonia	
Finland	
France	Andre Orcesi
FYRO Macedonia	Elena Dumova-Jovanoska
Germany	
Greece	Dimosthenis (Dimos) Kifokeris
Hungary	
Iceland	
Ireland	
Israel	

Country:	Nominated Person
Italy	Giuseppe Carlo Marano
Latvia	
Lithuania	
Luxembourg	
Malta	
Montenegro	
Netherlands	Giel Klanker
Norway	
Poland	
Portugal	Luís Oliveira Santos
Serbia	Nikola Tanasic
Slovakia	
Slovenia	
Spain	Juan Murcia-Delso
Sweden	
Switzerland	
Turkey	
United Kingdom	

# Completed processes

- **Homogenization and categorization**
  - of the **properties** of the **applied PI-database** (PI-DB)
  - of the **Table of Terms**

based on the findings from the screening process and code formulations
- **Homogenization, categorization and clustering**
  - **Performance Indicators**

(except the categorization assoc. with WG2 and WG3 requirements)
- **Homogenization and Harmonized-PI - extension**
  - of Croatian database

as the basis for the data base from an European perspective

# Upcoming process steps

- **Completion of the data base (homogenization, categorization, screening)**
  - the **Croatian database** with extended harmonized PI
  - the **harmonized Table of Terms**
  - the **updated Glossary**
  - the **country specific Databases** prepared for harmonization

will be sent to the nominated people with the request to support in the final harmonization

  - the harmonized 32 to 34 applied databases will be compiled to the database of an European perspective
- **Supplementing definitions**

the updated glossary will be sent to the MC and nominated people with the request to check the existing definitions

  - with respect appropriate formulations
  - missing definitions
  - definitions significant but not yet included
  - overlapping definitions

# Upcoming process steps

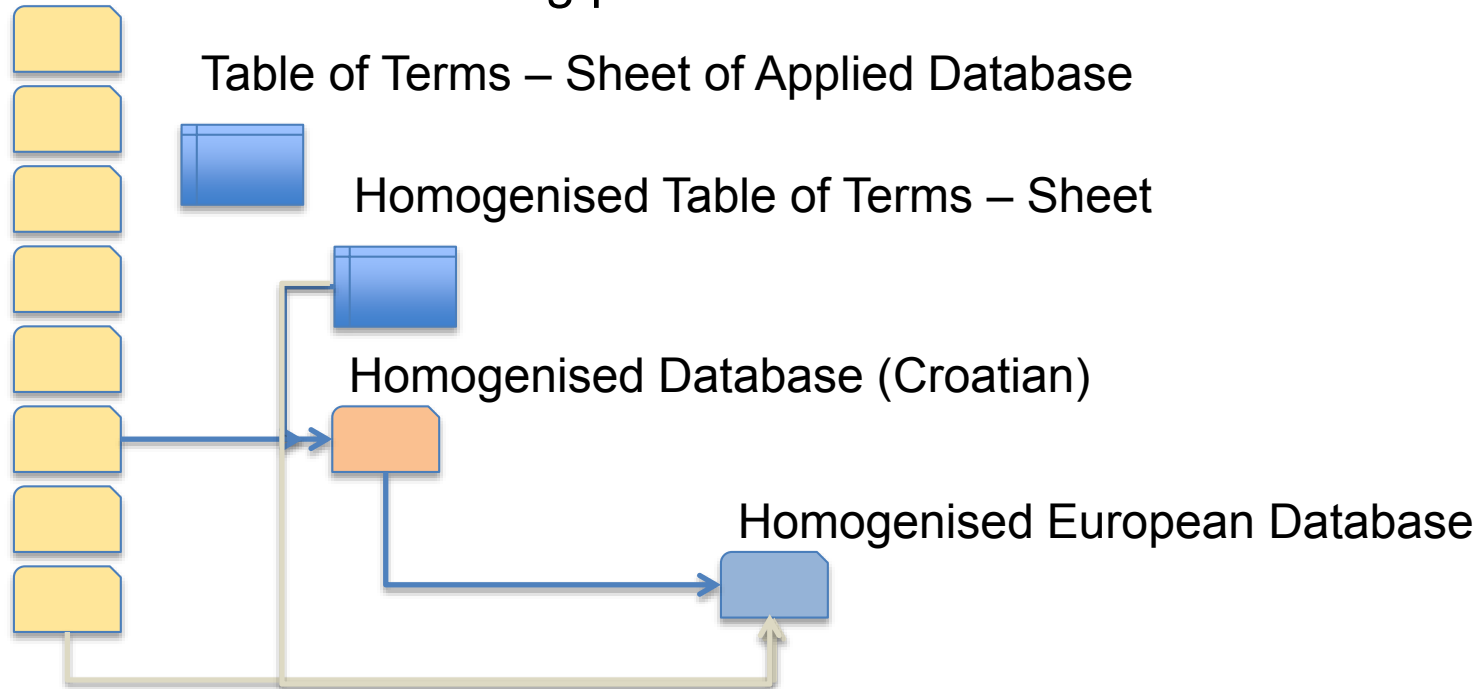
- **Homogenization, categorization and clustering**
  - Performance Indicators categorization associated with the requirements of WG2 and WG3
  - weighting the Pis (importance of PIs for WG2 and WG3) – “SPIDER”

# Upcoming process steps

- **Research data base**
  - reminder will be sent to the MC to nominated people for screening for the research paper
  - ?Library systems e.g. Endnote or Zotero?
  - ?Research gate?

# Homogenisation process

- Data bases – Screening process







### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **Report from WG 2 Performance goals**

Irina Stipanovic  
University of Twente, Netherlands

**UNIVERSITEIT TWENTE.**

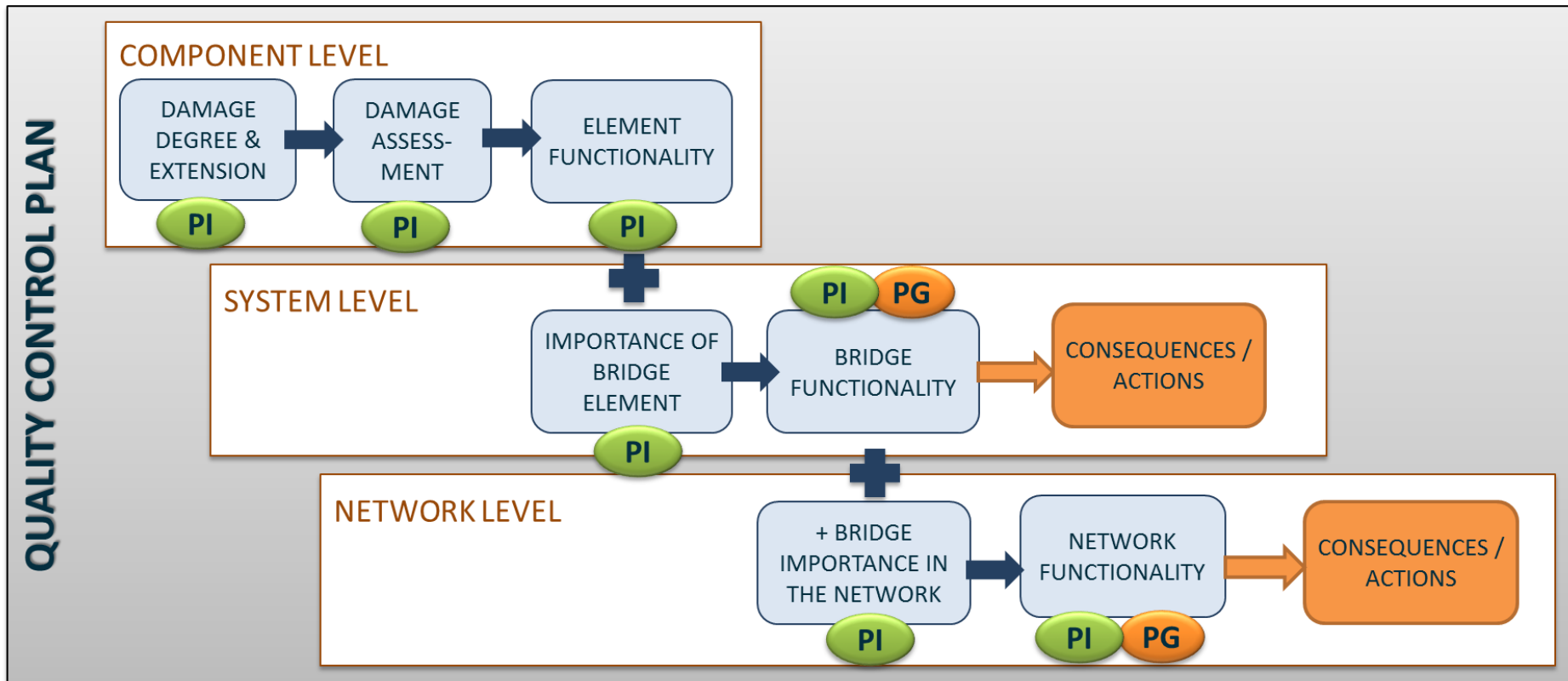
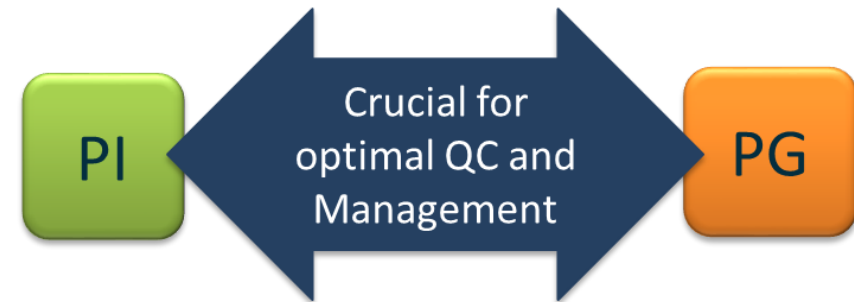
30<sup>th</sup> March - 1<sup>st</sup> April 2016  
Belgrade, Serbia

# Introduction

## Main objective of WG 2

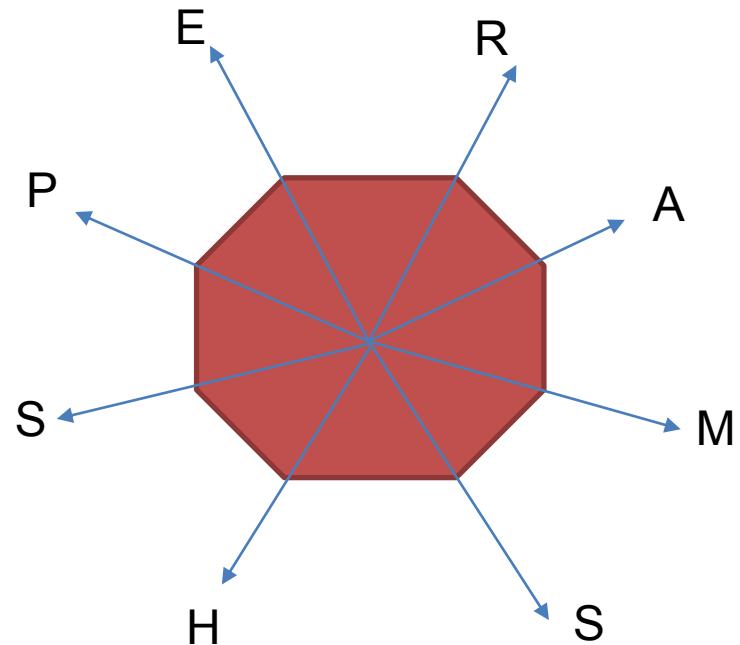
- to provide an overview of existing performance goals based on the indicators previously identified in WG1.
- These goals will vary according to technical, environmental, economic and social factors.
- Report which will specify the performance goals, linked to the Key Performance Indicators.

# Background Framework



## Performance Goals

- Different aspects of performance should be taken into account
  - Technical, sustainability and socio-economic aspects
  - The first draft of the PG aspects will be based on Dutch model, e.g.
    - Reliability
    - Availability
    - Maintainability
    - Safety
    - Security
    - Environment
    - Costs
    - Health
    - Politics
  - Literature survey in parallel



## WG 2 Objectives

- To identify different performance goals' aspects on the system and network level
- To define and determine the methodologies for PGs assessment / evaluation
- To link PGs with clustered PIs
- To collect several case studies (3 to 5) presenting bridge management maintenance system
  - Overview of the goals and indicators required by the agency
  - Decision making process for maintenance decisions
  - Costs
  - To put them against the proposed framework

## WG 2 Milestones

- Minutes of the meeting and conclusions how to proceed
  - First draft of the document
  - Contribution from WG members
  - Collection of case studies in the structured manner
  - Report content list
  - Report development
- 
- Presentation of the first results in Delft
  - WG 2 and WG 3 workshop in Delft



- **COST TU 1406 WG 2 and WG 3 workshop**
- **Bridge performance requirements and quality control plans**
- **20 – 21 October 2016, Delft, Netherlands**



# Agenda

- **Thursday 20/10/2016 (1 room)**
- Workshop, invited speakers and paper presentations
- Networking dinner
  
- **Friday 21/10/2016 (2 smaller rooms)**
- WG 2 and WG 3 workshop
  
- Call for papers by the end of April
- Deadline 1st July 2016



Thank you for your attention!

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### **WG MEETINGS & WORKSHOP**

An overview of Key Performance Indicators across Europe and Overseas  
The main findings from WG1 and other contributions from WG2 and WG3

# **Report from WG3 “Establishment of Quality Control Plans”**

Rade Hajdin - University of Belgrade, Serbia



Грађевински факултет

Универзитет  
у Београду

30<sup>th</sup> March - 1<sup>st</sup> April 2016  
Belgrade, Serbia

# QUALITY OF PRODUCTS

- Quality is often defined as fitness for **purpose**.
- In ISO 9000: Degree to which a set of inherent characteristics of a **product** or **service** fulfills requirements.
- Example: printer
  - Primary requirement (**purpose**): Printing documents
  - Operational Requirements (prerequisites): Format, Interface, Driver, etc.
  - Consumer requirements (demand): Intuitive handling, plug-n-play, all format, all operation systems, minimum costs
  - General requirements (regulation): Environmental protection, health protection, etc.
- Market forces will (theoretically) find the balance between the demand and supply (first two items).

# GENERAL PRODUCT REQUIREMENTS

- Requirements (=features) are set by the producers themselves and communicated to the consumers (advertisement)
- Product with the same purpose can fulfill different requirements or even purposes.
- Consumers can choose between different products and related requirements.
- Requirements (features) vs. costs (TCO)
- Consumers have differing requirements i.e. everybody can buy his/her own printer.
- Lack of quality of a product is characterized by non-fulfillment of communicated requirements (~fraud).



# QUALITY OF ROADS (AND ROAD BRIDGES)

- **Primary requirement (purpose):** Enabling vehicles to drive from origin to destination
- **Operational requirements:** GVW, Axle Loads, Width, Height, etc.
- **User requirements:** Safe, reliably and affordable travel
- **General requirement (regulation):** Environmental protection
- The first items define the supply side in economical terms
- The third items is demand side in economical terms
- The problem arises that different users cannot have different roads.
- It is not practicable nor sustainable to build a road for unique operational requirements -> natural monopoly
- One size fits all
- Pricing - always a challenge when there is no market.

# REQUIREMENTS FOR BRIDGES (ROADS)

- Which size fits all? - Economy and public long for:
  - Maximum (unrestricted) weight allowance
  - Maximum (unrestricted) clearance
  - Minimum (no) fatalities and/or injuries due to bridge collapse
  - Minimum (no) property damage
  - Maximum (24/7) availability
  - Minimum (no) noise
  - Minimum (no) pollution
  - Spotless visual appearance (no cracks, spalling, corrosion traces, etc.)
  - Minimum (no) costs for operation and MR&R
- These desires are contradictory and are resolved in a political process and set by the agencies in collaboration with professional organizations.

# BAD THINGS MAY HAPPEN ....

- Exceptional traffic loading
- Heavy traffic with snow and wind
- Hurricanes and tornados
- Earthquake
- Cyclic loading
- Damaging processes
- Settlements
- Scour
- Rockfall
- Landslides



# DESIGN

- The “bad things” that can happen are normally considered in a design process
- Currently, the bridges are designed for the service life of 100 or even 150 years.
- The list of scenarios that may render bridge unfit for its purpose (primary requirement) are considered in the codes of practice.
- Real scenarios are replaced by a fictitious scenario that is supposedly invisible than any real scenario with certain probability.
- If in these scenarios the bridge remains fit for its purpose than the quality requirements are fulfilled.
- Fulfillment of the requirements defined in the codes of practice means that the bridge is of sufficient quality.

# QUALITY CONTROL

- There are quite a few definitions reflecting the ambiguous definition of the word “control” as
  - Verify, check or inspect or
  - Command, direct or rule.
- In business the quality control is defined as:  
“The process of inspecting products to ensure that they meet the required standards”  
or  
“The activity of checking goods as they are produced to make sure the final products are good”
- Consumers may also conduct the quality control (check).

# QC FOR BRIDGES?

- “....checking goods as they are produced ....”
- Performed by designers and contractors during the design and construction.
- Owner (operator) sets the requirements but is not directly involved in controlling of their fulfillment.
- Before the acceptance (handing over the bridge to the owner) and commissioning the owner performs the quality control i.e. inspection. This includes but is not limited to:
  - Independent checking of code compliance
  - Material properties
  - Visual checking



# IS TU1406 NEEDED?

- The design codes are established and used in practice.
- The compliance to the code requirements means **quality**.
- So, it seems everything is clear and we should go home, right?
- Not quite:
  - For the industry product it is sufficient to prove quality before selling them. There is no guarantee that they will **perform** as desired after the warranty period or in different conditions.
  - Road and bridges are long living objects and even if they are of high quality at the acceptance, they may not meet quality requirements after some time due to change in traffic, deterioration, etc.

# QC FOR EXISTING BRIDGES?

- Seems quite easy: Check the bridge according to the current code.
- The detailed check is quite expensive (at the moment) so it should be performed only when really necessary.
- The necessity for the detailed check is to be determined by more simple means such as visual inspections.
- There is also a middle ground: combination of visual inspection with some more sophisticated investigation techniques.
- Even if the detailed check according to the current code fails the bridge may be perfectly fit for its purpose:
  - Real traffic loading is smaller than the code model
  - Code account for construction uncertainty, which can be eliminated on existing bridges

# QUALITY CONTROL PLAN

- So, quality control for existing bridges is necessary and so is also this COST action 😊
- QC plan should be based on multilevel procedure from simple visual inspections to in-depth investigations, based on the level of doubts with regard to the bridge performance.
- Quality control plan should define at which interval the quality controls are necessary and which condition the more detailed investigations or corrective actions are necessary.
- The inspections (incl. in-depth investigation) are meant to provide information on the actual bridge performance. The findings and measurement collected within inspections are regarded as **performance indicators**.

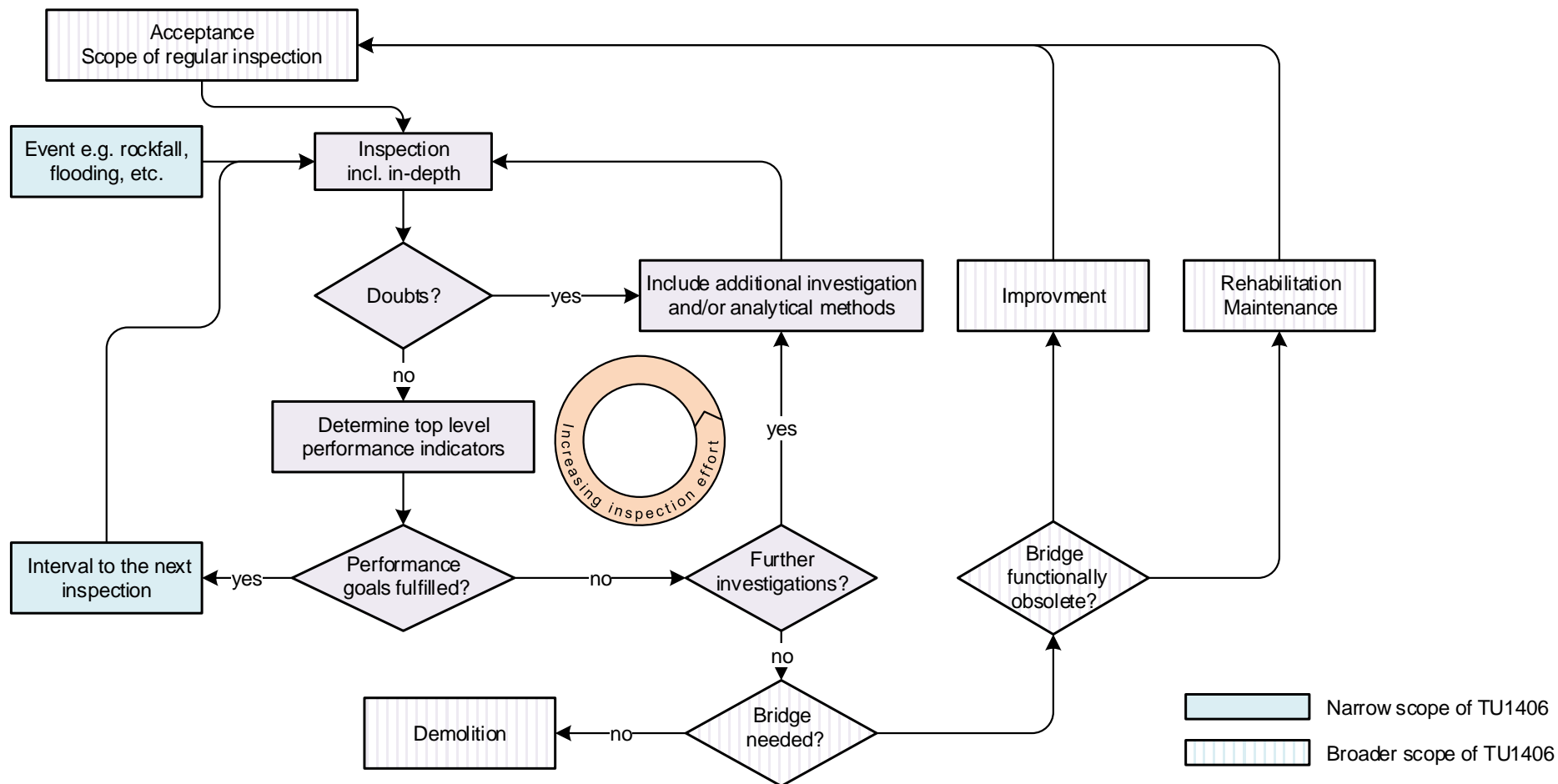
# PERFORMANCE INDICATORS

- Low-level
  - Findings: cracks, spalls, color change, leakage, efflorescence
  - In-situ measurement: crack width, half-cell measurements, sclerometer measurements, measurement of electrical resistance, geo radar map
  - Lab testing: results chemical analysis, mechanical testing on specimen
- Top-level (to be compared with performance goals)
  - Based on low-level indicators the top level indicators are obtained
  - Qualitative: condition rating
  - Quantitative: probabilities of undesired scenarios

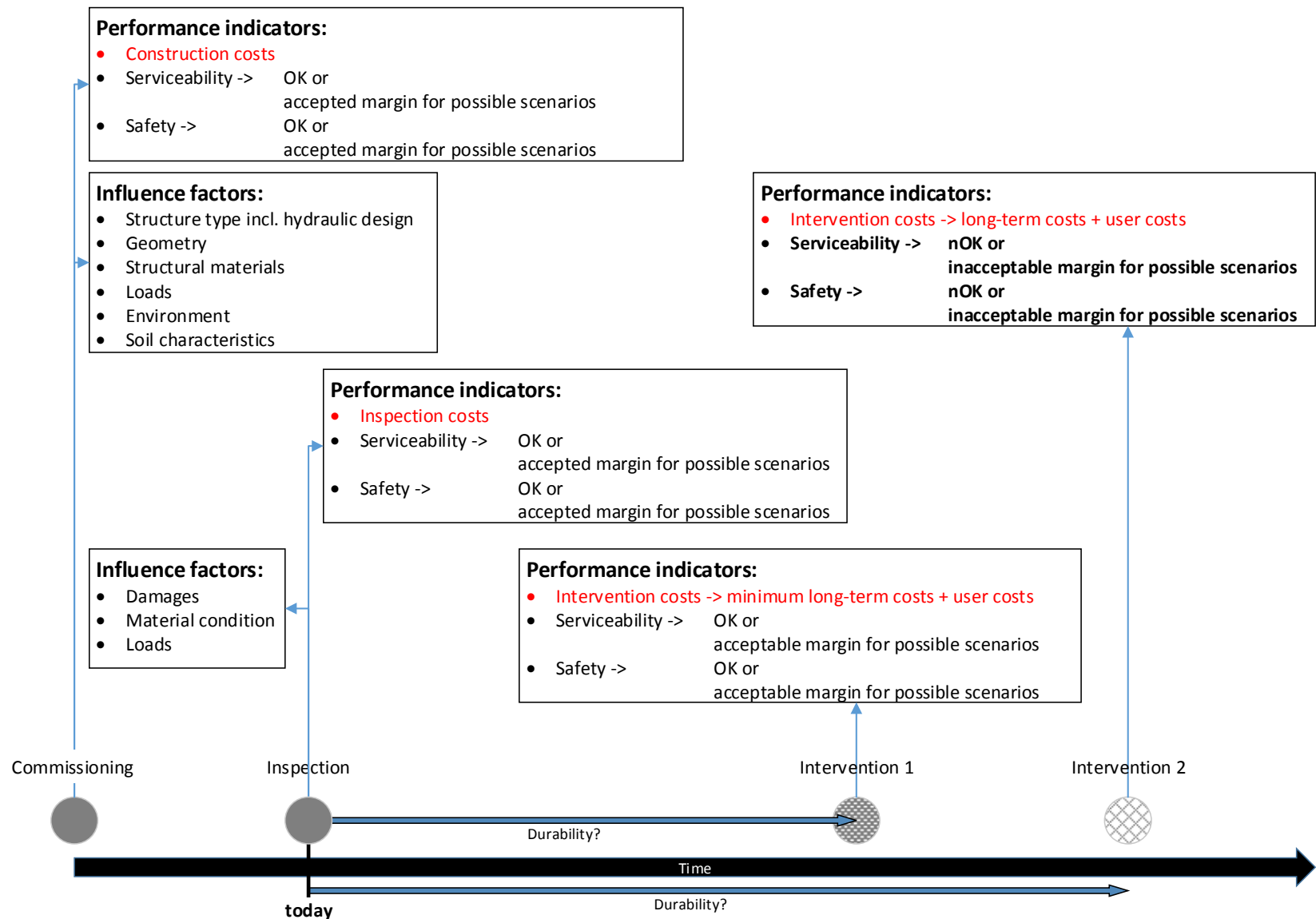
# PERFORMANCE GOALS

- Performance goals = quality requirements
- The term “performance goal” is more often used for existing bridges.
- It defines how the existing bridges should perform under current or future conditions and loadings.
- It can be expressed in term of limiting probabilities (return period) of undesired scenarios or deterministically as threshold condition rating.
- Performance goals should reflect the levels of quality control plans.
- Performance goals could be (1) satisfying or (2) extremizing.
- For the latter there are no threshold values as they should be maximized or minimized.

# GENERAL PROCEDURE







# OUR JOB

- Based on the results of the WG 1 and 2 as well as on survey of existing approaches in practice the objective of this group is to provide a methodology with detailed step-by-step explanations for establishment of QC plans for different types of bridges. The QC plans will address the dynamics and uncertainty of the processes that may significantly comprise the bridge performance.
- Guideline on inspection intervals and investigation methods and instruments.
- Criteria for triggering more detailed investigations, safety and serviceability checks or maintenance interventions
- List of investigation methods and statements on their reliability.
- Liaison with TU1402 “Value of Information”

# BREAKDOWN OF TASKS

- Focus on most common bridge types and systems
- No landmark bridges

			Girder bridges	Arch bridges	Frame bridges	Etc.
Interceptable processes (Observable processes)	Damaging processes	Corrosion	Task 2 (Masovic. Linneberg)	Task 3 (Amado)	Task 2 (Masovic, Linneberg)	
		Alkali Aggregate				
		Sulphate				
		Fatigue				
	Demand	Traffic volume				
		Traffic loading				
		Climate				
Non-interceptable processes	Sudden events	Earthquake	Task 4 (Tanasic)			
		Gravitational hazards				
		Fire				
		Accidents				
	Non-observable	Fatigue				
		Hidden damaging processes				

# TASKS

- **Task 1** (not presented on slide before) will deal with the quality of resources:
  - Quality of equipment and investigation methods i.e. reliability of obtained results  
This includes the measures to obtain the maximum quality
  - Quality of human resources (education, skills)  
This includes also the measures that are needed to educate HR adequately.

Lead: Matej Kušar

- **Task 2** – Lead: Snežana Mašović and Poul Linneberg
- **Task 3** – Lead: João Luís da Gama Amado
- **Task 4** – Lead: Nikola Tanasić
- The task groups 2,3 and 4 need to address the whole process described in the slide 15

# TIMELINE

ID	Task Name	2015			2016				2017				2018				2019
		Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
1	Survey of European QC Plans																
2	Ground work for task groups																
3	Task Groups Coordination																
4	<i>Matrix tasks 1 - N</i>																
5	Investigation techniques and their reliability																
6	Assessment methods																
7	Triggering criteria for more detailed investigations																
8	Triggering criteria for maintenance interventions																
9	Draft input for Guidelines																
10	Guidelines for the establishment of QC Plans																



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THANKS FOR YOUR ATTENTION!





# Quality Specifications for Roadway Bridges, Standardization at a European Level (BridgeSpec)

State of the Action TU1406

**Joan R. Casas** – Vice-Chair, UPC – BarcelonaTech, Spain



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 **cost**  
EUROPEAN COOPERATION  
IN SCIENCE AND TECHNOLOGY

# WHERE WE ARE ?

- At the end of the first year of the Action
- Data base of performance indicators used in 30 countries
- Glossary of terms (almost finished)
- Data base of research performance indicators (still in progress)
- Main effort on technical performance indicators. Not as much in other indicators (social, environmental,....)

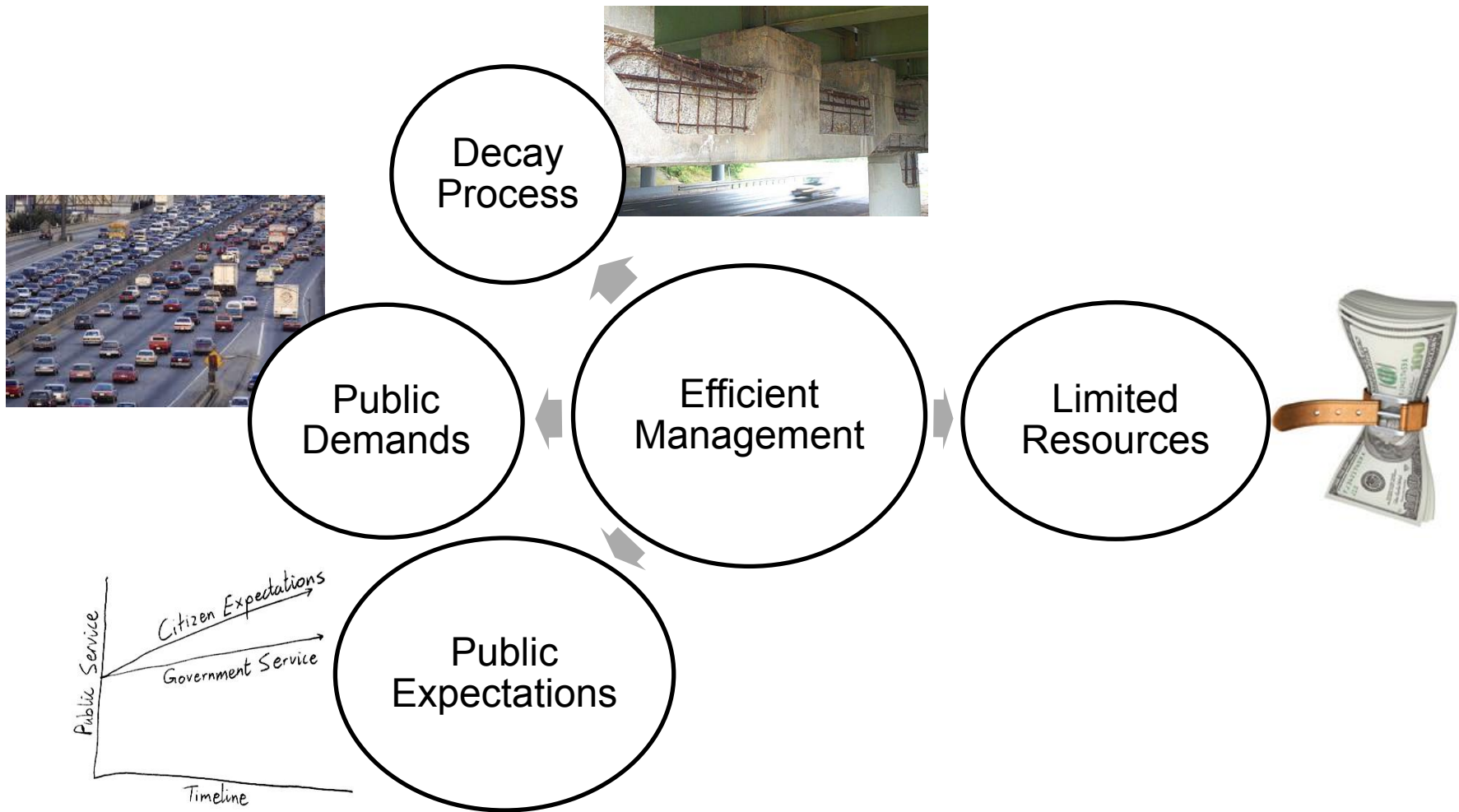
# WHAT DO WE HAVE ?

- Huge amount of information !!

# WHAT TO DO WITH THIS HUGE AMOUNT OF DATA

- Get lost into the data
- Get relevant results for general purposes
- Get relevant results for COST TU1406 (Our goal)

# 1. BACKGROUND



## 2. REASONS FOR THE ACTION



There is a **REAL NEED** to standardize the quality assessment of roadway bridges at an European Level



### 3. OBJECTIVES

#### Aim

The main objective of the Action is to

**develop a guideline for the establishment of QC plans  
in roadway bridges**

by integrating the most recent knowledge on performance assessment procedures with the adoption of specific goals. This guideline will focus on bridge maintenance and life-cycle performance

## OBJECTIVES

- Definition of quality: Degree to which a set of inherent characteristics of a product or service fulfills requirements (ISO 9000)
- **Quality control:**
  - Are the requirements fulfilled ?
  - Is the required performance achieved ?
- Decisions and actions (involving money) will result from the answer to those questions

## WHAT WE DO REFER WHEN TALKING ABOUT PERFORMANCE (REQUIREMENTS) ?

- In the case of bridges: What public desires ?
  - Safety (**both at system and component level**)
  - Serviceability
  - Availability
  - Economy (referred to life-cycle cost, and therefore including durability issues)
  - Environmentally friendly (including visual appearance )

## How do we measure performance and answer to the question: Is required performance achieved ?

- By defining the so-called “performance indicators”
- By **monitoring** them (Interaction with COST TU-1402)
- By comparing their actual value with defined “target values”
- Target values are defined in the **Quality Control plans**

## Which are the performance indicators to be monitored ?

- **Related to safety:**
  - Load factor
  - Safety factor
  - Reliability index (ULS)
  - Risk
- **Related to serviceability:**
  - Condition rating, condition index
  - Crack width
  - Deflection
  - Vibration intensity
  - Natural frequencies
  - Modal shapes

# Which are the performance indicators to be monitored ?

- **Related to availability:**
  - robustness
  - redundancy
  - resilience
- **Related to economy:**
  - Life-cycle cost
  - Difussivity coefficient of chlorides
  - Permeability
  - Concrete cover
  - Crack width
  - Remaining service life



## Which are the performance indicators to be monitored ?

- **Related to environment (including aesthetics):**
  - Crack pattern
  - CO2 equivalent
  - Resilience
- **Actually more than 200 identified in WG1**
- **Are all they really performance indicators ?**
  - Some of them just technical indicators ?
- **How can we select them ?**

# DEFINITION OF PERFORMANCE INDICATOR

- Parameter measurable and quantifiable related to the bridge performance that can be directly compared with a target measure of a **performance goal** (absolute measure of performance) or can be used for ranking purposes among a bridge population (relative measure of performance) in the framework of a **Quality Control Plan** or life-cycle management (decisions, actions involving economic resources )

# DEFINITION OF PERFORMANCE INDICATOR

- Value derived from a combination of different measurable parameters (variables)
- Sustainability Action: Initial list of 191 sustainable indicators. Final list of only 25
- TU1406: By now, more than 200 performance indicators identified.
- How many at the end ?

# EXAMPLE

- CRACK WIDTH:
  - Measurable ? YES
  - Quantifiable ? YES
  - Target value available ? YES
  - Valid for ranking purposes ? YES (locally)
  - Decisions with economic implications can be taken based on it ? YES

# EXAMPLE

- COMAC (Modal Assurance Criteria):
  - Measurable ? YES
  - Quantifiable ? YES
  - Target value available ? YES
  - Valid for ranking purposes ? NO
  - Decisions with economic implications can be taken based on it ? NOT YET (Research indicator)

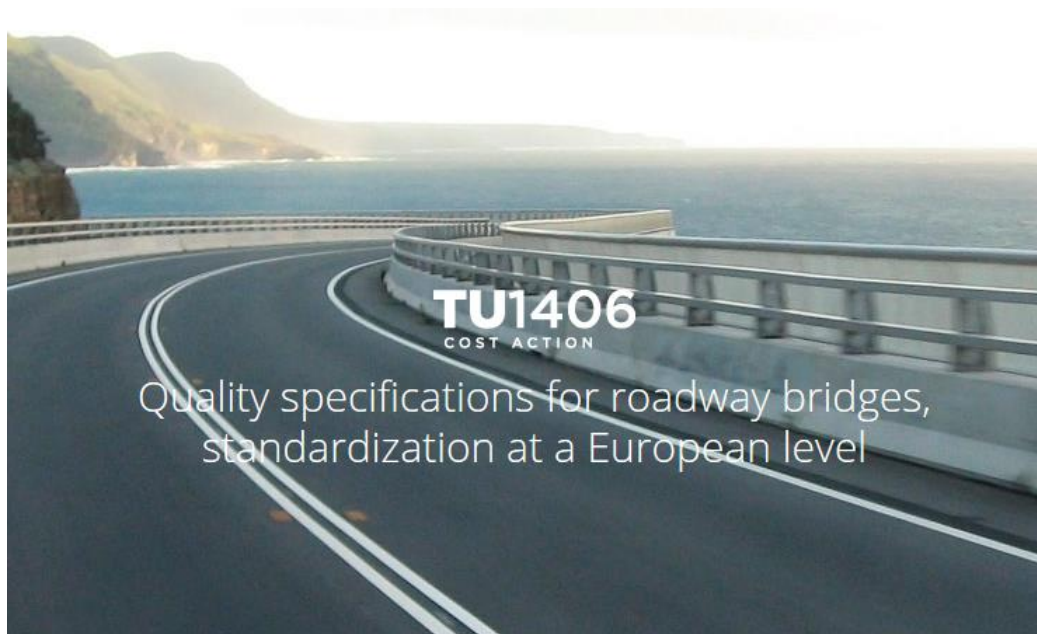
# EXAMPLE

- CONDITION RATING:
  - Measurable ? YES
  - Quantifiable ? YES
  - Target value available ? YES
  - Valid for ranking purposes ? YES
  - Decisions with economic implications can be taken based on it ? YES



# NEXT STEPS

- Interaction between WG's: Avoid overlapping of tasks (WG2 and WG3)
- Analysis of data base. Work in progress (WG1)
  - Take into account the input from owners, operators



Thank you  
for your  
attention



# Quality Specifications for Roadway Bridges, Standardization at a European Level (*BridgeSpec*)

**José C Matos** – Chair COST TU1406, ISE - University of Minho,  
Portugal  
([jmatos@civil.uminho.pt](mailto:jmatos@civil.uminho.pt))



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# CONCLUDING REMARKS



WG		Year 1				Year 2				Year 3				Year 4			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
WG1	Technical indicators	✖	✖	✖	X												
	Environmental indicators	✖	✖	✖	X												
	Other indicators	✖	✖	✖	X												
WG2	Technical goals					X	X	X	X								
	Environmental goals					X	X	X	X								
	Other goals					X	X	X	X								
WG3	Survey of European roadway QC plans	✖	✖	✖	X	X	X										
	Procedures for the establishment of a QC plan							X	X	X	X						
	Selection of case studies							X	X	X							
WG4	Benchmarking										X	X	X	X	X		
	Application on a QC plan											X	X	X	X		
	Standardized performance indicators				X	X	X	X									
WG5	Standardized goals								X	X	X	X					
	Standardized QC plan										X	X	X	X	X	X	X
WG6	Dissemination	✖	✖	✖	X	X	X	X	X	X	X	X	X	X	X	X	X

## CONCLUDING REMARKS

### **WG1 – Key Performance Indicators**

Report in Key Performance Indicators, including Operators and Researchers KPI Database:  
**Predicted date - end of April 2016.**

### **WG2 – Performance Goals**

Report in Performance Goals, including Operators and Researchers KPI Database:  
**Predicted date - end of April 2017.**

### **WG3 – Establishment of a QC Plan**

Report in Incorporation of Key Performance Indicators in a QC Plan: **Predicted date - end of April 2017.**

### **WG5 – Drafting of a guideline / recommendations**

Report in Standardization of Key Performance Indicators: **Predicted date - end of December 2016.**

## CONCLUDING REMARKS

**1<sup>st</sup> Training School**

**KTH, Stockholm, Sweden**

**12 to 16 September 2016 (Technical Visit on 17 September 2016)**

**LOS: Mohammed Safi (Folkbro)**





## CONCLUDING REMARKS

**Next WG meeting / Workshop**

**TNO, Delft, the Netherlands**

**20 and 21 October 2016**

**LOS: Irina Stipanovic (UTwente) and Giel Klanker (Rijkswaterstaat)**



## CONCLUDING REMARKS

The WG meeting/Workshop will focus on technical and non-technical bridge performance requirements, followed by quality control plans. Therefore we would like to invite COST TU 1406 members to submit short papers related to the following topics: (i) Evaluation of bridge performance (threshold values, requirements, goals); (ii) Technical, sustainability and economic bridge performance; (iii) Lifecycle Assessment; and (iv) Inspection and Maintenance plans.

The proposed manuscripts should be developed with the COST TU 1406 template (provided at [www.tu1406.eu](http://www.tu1406.eu) ) and with the length between 3 and 6 pages. Authors of selected excellent papers will be invited to do oral presentations of their work, being their travel expenditures reimbursed by COST (reimbursement is only applied for authors from COST Countries). The deadline for submission is **1<sup>st</sup> July 2016**.

## CONCLUDING REMARKS



*and see you in Delft ...*



**thank you for your attention**



# Workshop papers



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# Workshop Papers by sessions

## Session 1

[“Performance Indicators as Basis for Life-Cycle-Considerations”](#), by Mr. Ralph Holst, Federal Highway Research Institute (BASt), Germany

[“Structural robustness of bridges based on redistribution of internal forces”](#), by dr Tomasz Kamiński, Assistant prof. at Wroclaw University of Technology, Poland

[“Robustness as performance indicator for masonry arch bridges”](#), by dr José C. Matos, Assistant prof. at University of Minho, Portugal

[“Performance indicators for road bridges – categorization overview”](#), by dr Ana Mandić Ivanković, Associate prof. at Faculty of Civil engineering, University of Zagreb, Croatia

## Session 2

[“Structural behaviour of stone arch bridges”](#), by dr. Cristina Costa, Assistant prof. at Instituto Politécnico de Tomar, Portugal

[“Forecasting of performance indicators”](#), by dr Snežana Mašović, Assistant prof. at Faculty of Civil engineering, University of Belgrade, Serbia

[“Interface for collection of performance indicators for roadway bridges– STSM experiences”](#), by Ivan Zambon, PhD candidate at BOKU Wien, Austria

[“A new perspective for robustness assessment of framed structures”](#), by Hugo Guimarães, PhD. candidate at University of Minho, Portugal

[“Lifecycle-based discretization of bridge performance indicators”](#), by Mr. Dimosthenis Kifokeris, PhD candidate, Aristotle University of Thessaloniki. Greece



# Workshop Papers by sessions

## Session 3

[“The impact of the severe damage on the dynamic behavior of the composite road bridge”](#), by Dr Pavel Ryjáček, Associate prof. at Faculty of Civil Engineering, Czech Technical University in Prague

[“Effect of vehicle travelling velocity on bridge lateral dynamic response”](#), Dr Luke Prendergast, Postdoctoral research associate at University College Dublin, Ireland

[“Damage detection for bridge structures based on dynamic and static measurements”](#), by Dr Viet Ha Nguyen, Postdoctoral research associate at Faculty of Science, Technology and Communication, University of Luxembourg

[“Qualitative performance indicators for bridge management in Italy”](#), by Dr Mariano Zanini, University of Padova, Italy

[“Using an air permeability test to assess curing influence on concrete durability”](#), by Dr Rui Neves, Assistant prof. at Instituto Politécnico de Setubal – ESTBarreiro, Portugal

## Session 4

[“Consequence modelling for bridge failures”](#), by Dr Boulent Imam, Senior lecturer at University of Surrey, UK

[“Data collection on Bridge Management Systems”](#), by Dr Nikola Tanasić, Assistant prof. at Faculty of Civil engineering, University of Belgrade, Serbia

[“Scheduling bridge rehabilitations based on probabilistic life cycle condition information”](#), by Dr Dimos C. Charmpis, Associate prof. at University of Cyprus

# Workshop Papers by sessions

## Session 5

[“Environmental effects on bridge durability based on existing inspection data”](#), by Dr Ioannis Balafa, Special teaching staff at University of Cyprus

[“Development of the bridge management system under the project BridgeSMS”](#), by Mr Igor Kerin, Research Assistant at UCC / MaREI, Ireland

[“The assessment method of Hungarian documents on bridge inspection”](#), by Mrs. Zsuzsanna Pisch, Hungarian Transport Administration, Hungary

[“Development of a Quality Management Plan for Timber Bridges”](#), by Dr Steffen Franke, Assistant prof. at Bern University of Applied Sciences, Switzerland

[“Guide for the Assessment of Masonry Bridges – Technical Parameters”](#), by Mr. João Amado, Infraestruturas de Portugal, S.A.

## Performance Indicators as Basis for Life-Cycle-Considerations

Ralph Holst

*Federal Highway Research Institute (BASt), Bruederstrasse 53, D-51427 Bergisch Gladbach, Germany*

*E-Mails: Holst@bast.de*

**Abstract.** The present situation of the aging infrastructure requires the use of life-cycle considerations. This is necessary to keep the performance of the roads in spite of the necessary conservation actions. The measures themselves will thereby be reduced to a necessary minimum. The most important prerequisites for this result are the exact knowledge of the state of the bridges and the appropriate maintenance strategies. Therefore, the aspects life-cycle considerations, data collection and maintenance strategies are described in detail in the text.

**Keywords:** Bridge Inspection, Life-Cycle-Considerations, Bridge Data, Maintenance strategies

### 1 Boundary conditions

Germany is a very strong transit country, also following the enlargement of the European Union. In order to grow the economy in Europe, the security and ease of traffic has to be guaranteed at all times.

It should be noted, that important conditions have changed with time:

- Significant increase in traffic, particularly heavy goods traffic,
- Increase of total allowable weight of vehicles,
- Overloading of trucks,
- Increasing bridge ages (Fig. 1).

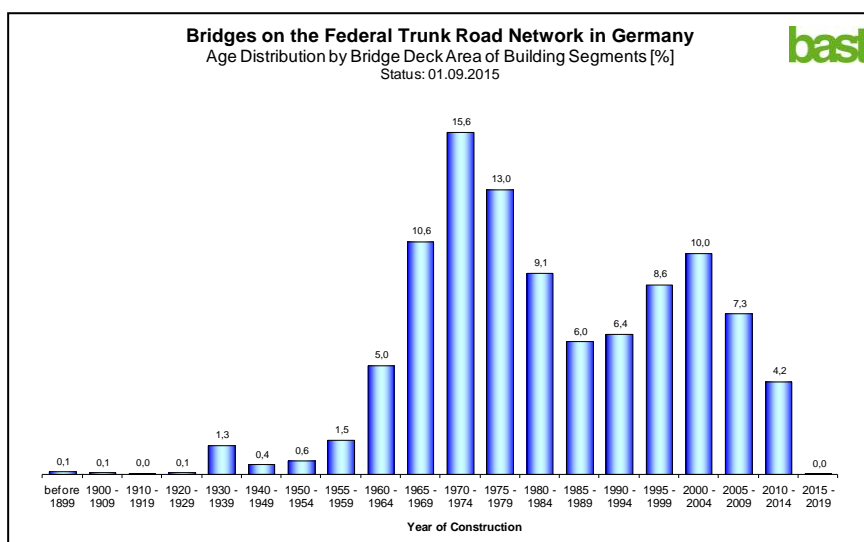


Figure 1: Age distribution (BASt)

These developments have left their visible marks on the bridge. Increasingly, concrete spalling, cracks and corroded reinforcement of the component parts.

Due to limited budget funds available and the fact that in the past very often new measures were given preference before maintenance measures in recent years has flowed too little money in the maintenance of bridges and engineering structures (Fig. 2).

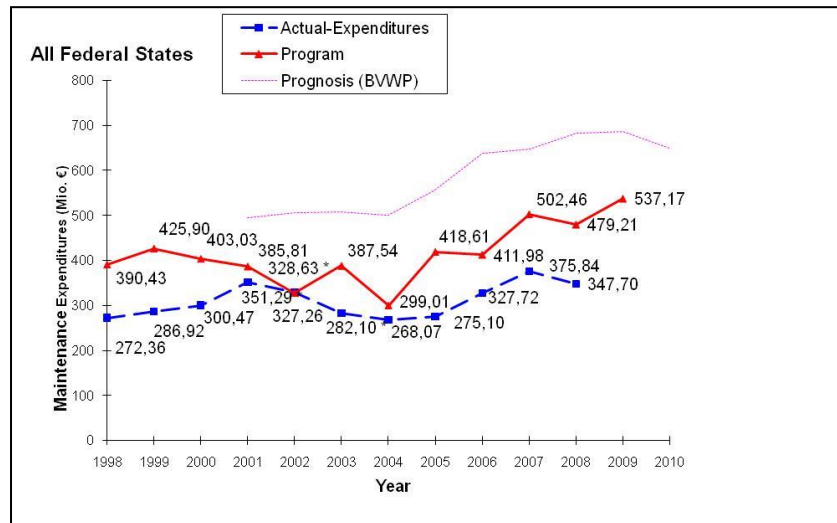


Fig. 2: Maintenance Expenditures (BMVBS)

Meanwhile there is a trend, that life cycle considerations find increasingly the way from the laboratories of universities and other research institutions into the daily practice. This happens thanks to the sustainability requirements of the political sphere.

## 2 Life cycle considerations

The task of a large number of management systems is to primarily produce technically feasible and economic maintenance measures. This is intended to ensure the safety and ease of transport and to use the financial resources, mostly public money, economically.

This view, however, considered only a portion of the entire service life of structures. From an economic perspective, it is however necessary to know how bridges behave during their entire lifetime and what maintenance measures are necessary to assure the ease and security of the traffic and at what total cost accumulate over this period.

In doing so, also external factors such as climate change and traffic forecasts play a major role.

Depending on the desired information, there are different ways to perform life cycle considerations (Schmellekamp unpubl.).

The best known are

- LCA, Life Cycle Assessment is a systematic analysis of the environmental impacts of products throughout the life cycle or until a certain time of processing.
- LCC, Life-cycle costing, is a cost management method that considers the whole life cycle of a building. It includes the construction, operation, maintenance and End-of-life phases. Here, only the direct costs are of interest.
- LCP, the life cycle performance of mechanical systems describing the performance of a system, based on the costs of manufacture to disposal. Among the economic efficiency while providing the highest possible availability, yield, quality and flexibility is to be understood.

It is necessary to distinguish which periods should be considered. It may be meant the period from the initial planning to commissioning or the time from start to adhere to basic repairs.

The life cycle considerations that should be examined hereafter refer to the period of manufacture to the demolition of bridges.

Thus, studies have sufficient significance, it is necessary to provide a variety of construction related data:

- Design information,
- Damage data,

- Useful life or damage models for different damage for different components,
- Maintenance measures with costs and useful lives,
- Traffic-/traffic volume data,
- Decision rules for the implementation of measures.

The goal is, to show the future behavior of the bridge regarding to the important parameters realistically in relation to the desired information.

It has been established here that the following parameters are important or necessary:

- Classification of the bridge components or component groups with regard to a similar, future behavior,
- Calculation of the masses of individual components or component groups, divided according to different materials, in order to take into account ecological and economic effects during the manufacture of these materials,
- Component or component group-related damages with damage assessments and information on the extent of damages,
- Component or component group-related behavior models for a variety of major construction materials that allows to determine the right time for maintenance measures and also to represent the behavior after the measure,
- Component or component group-related direct costs for maintenance measures,
- Indirect costs (from traffic)
- Roads and traffic volume data to assess the impact of maintenance measures,

### **3 Bridge data as an important basis for life cycle considerations**

The bridge inspection in Germany is based on DIN 1076 "Highway Structures – Testing and Inspection" (DIN, 1999).

The objective of this standard is to identify defects and damages at an early stage, to give the authorities the possibilities to take actions before major damage occurs or when the safety is compromised.

For this purpose, the bridges and other engineering structures are divided into components and component groups. For bridges, these are:

- Superstructure,
- Substructure,
- Bearings,
- Expansion joints,
- Pavement,
- Waterproofing,
- Cap,
- Protection device (railing, safety barriers),
- Pre-stressing,
- Foundation,
- Soil and rock anchors,
- Bridge ropes and cables.

At these component groups any defect / damage is evaluated regarding to the three criteria “stability”, “traffic safety” and “durability” with a rating on a scale from 0 to 4.

Here "0" means that this defect / damage has no effect on the component or the structure. By contrast, the stability rating "4" indicates that the stability of the component and also the total bridge no longer exists and immediate action (up to blocking of the building) is required.

Using the individual damage assessments, the condition index of the bridges is calculated with the uses of the maximum principle. The maximum principle states, that the highest condition index of a single damage leads to the condition index of the whole bridge (Holst 2010b).

All bridges in the course of roads will undergo a major inspection every 6 years. Thereby every damage/defect is tested and evaluated in a hand-near distance by the bridge inspection team. This test is primarily a visual inspection. In the event that a bridge inspector may not have a final assessment of damage or the cause of the selfsame can't be resolved without a doubt, there is the possibility of a so-called "object-related damage analysis" to be carried out. These special reports can either be carried out by the bridge inspector itself or from third parties. Here, the whole range of additional studies is possible, from the sampling site and the investigation in the laboratory to non-destructive methods, e.g. with the aid of ultrasonic or radar.

Before a new bridge is approved, the so-called structure log will be created in the program "SIB-Bauwerke". This structure log describes the materials used and dimensions of the different components, the contractors and the construction costs. "SIB-Bauwerke" has been developed and financed jointly by the federal ministry and the 16 states. It is based on a component-related acquisition of construction and damage data of bridges and other engineering structures in the course of roads.

With each test or repair action this structure log will be updated, so that at any time all necessary information about the bridge is available. The encryption is based on the "Road Information Database Instructions - sub-structures (ASB-ING)". (BMVI 2013)

#### 4 Maintenance strategies

Apart from purely technically oriented specifications, the goals of the road authorities play a very important role. It can be distinguished three fundamentally different strategies.

- Preventive maintenance,
- Systematic conservation and
- "targeted aging."

These strategies reflects the respective weightings of the road owners with regard to following criteria (Fig. 3)

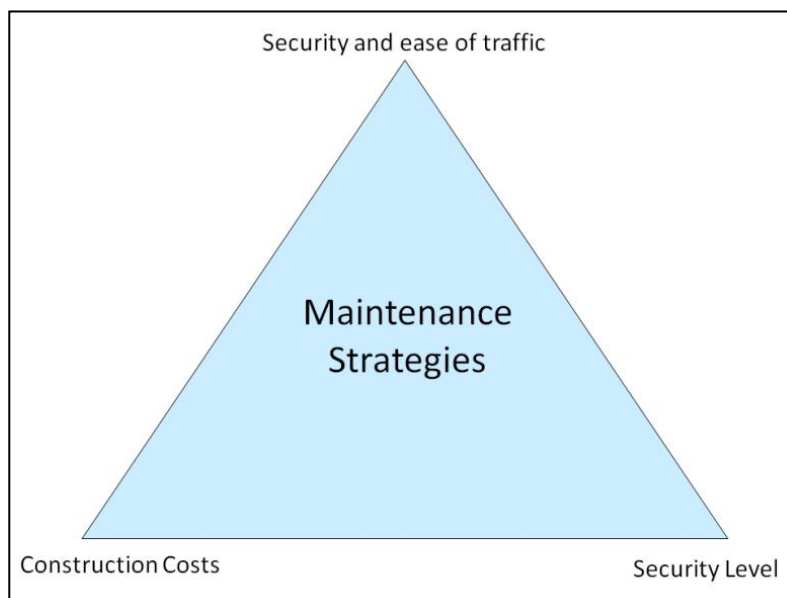


Fig. 3: Influencing factors (Holst)

- Intervention in the road; "Security and ease of traffic",
- Security level of the bridge or other engineering structure,



➤ Construction Costs.

A national road authority, for which the safety level of its buildings is the most important criteria, is expected to select a preventive maintenance strategy. This means that there shan't in any cases be a critical condition at the building. This also means that either more robust structures must be chosen which are more resistant to external stresses or preventive maintenance measures shall be taken at regular intervals, but even before the onset of visible damage. This increases the encroachment on the road by a significantly larger number of maintenance measures during the period of use of the bridge or it must give the possibility of temporary detouring. All these measures increase the costs of the bridge.

The opposite of this strategy described is the possibility of "targeted aging." Here, the structure is maintained by minimal cost maintenance measures in such condition that it just reaches the user requirements and the prescribed period of use. Then the structure is demolished or completely renovated. This strategy has the disadvantage that it is very susceptible to unforeseen events. This can, in extreme cases, lead to short-term blocking or the collapse of the bridge. Succeeds in bringing a bridge in this manner over the useful life without major loss events occur, it can be assumed that the total cost to other structures turn out to be low in comparison.

Both mentioned strategies have their advantages but also disadvantages. For this reason there is a third option.

This is an optimum balance between the three criteria:

- Interventions in the road should be minimal,
- Construction and maintenance costs should be minimized,
- It's at any given time to ensure the required level of security and
- The useful life should be guaranteed.

An important prerequisite for this method is that the road authorities have the opportunity to respond to changes in the structure.

Bridges are, in general, in spite of prescribed rules and standards requirements, unique items that behave in very different ways during the life time.

The main factors that influence the behavior of bridges over time are:

- Planning and manufacturing defects,
- Material mistakes,
- External influences (temperature, precipitation, wind, chlorides, carbonation ...),
- Traffic, in particular the heavy and heavy load traffic,
- Structural changes (conversion, expansion measures),
- Exceptional events (accidents, floods, fires ...).

These factors are sometimes stationary (e.g. manufacturing defects), others are changing over time.

Thus, it is necessary to be able to represent changes to the structure over time to get adjusted maintenance strategies.

## **5 Summary and Outlook**

Thus the availability of roads is also guaranteed in the future, the aging transport infrastructure must be systematically maintained. This task can't be fulfilled without extensive construction works on the bridges and other engineering structures of the roads. Since each maintenance project is an intervention in the safety and ease of traffic, these interventions over the lifetime of the bridges must be reduced as far as possible on the number and duration. Thus it is necessary for this purpose to make appropriate life-cycle considerations. The base here forms an early and comprehensive knowledge of the structure and of the current state of the bridges. In addition, appropriate conservation strategies need to be developed and object-based adapted, enables both early intervention, as well as subsequent measures. It is always the whole life cycle of both the individual bridge, as

well as the associated route included in the evaluation. Only then it'll be possible to make the transport infrastructure fit for the future, while ensuring the function as a road.

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# Structural robustness of bridges based on redistribution of internal forces

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**Abstract.** In the paper a new method of the structural robustness evaluation is proposed which is based on redistribution of internal forces at some failure scenario. It represents a consistent approach applicable to any type of structure. Two measures of robustness are applied differing in relative level of bending resistance assumed in calculations. Two case studies of beam bridges with the main girder failure (a hinge formation) in the mid-span are presented. Some conclusions and comparison of the proposed measures are provided.

**Keywords:** bridge, robustness, redistribution, damage, failure, FEM

## 1 Structural robustness definition

There are a number of approaches to the structural robustness evaluation proposed in literature (see Biondini & Restelli, 2008, Cavaco, 2013 or Kamiński, 2014). The method presented within the paper refers to an energetic approach defined by (Starossek & Haberland, 2008) where for simplification of calculations instead of energy the internal forces are used. Precisely, the bending moments in selected sections are analysed. Two approaches are applied differing in relative level of bending resistance considered in calculations. In the first case, the robustness  $R$  is defined as follows:

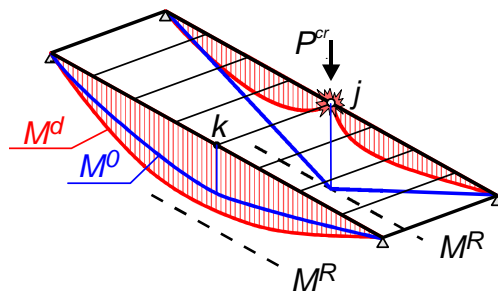
$$R = 1 - \max_k \left( \frac{\Delta M_{k,j}}{\Delta M_k^R} \right) \quad (1)$$

where  $\Delta M_{k,j}$  – increase of the bending moment in section  $k$  after failure (hinge formation) in section  $j$ , Nm,  $\Delta M_k^R$  – increase of the bending moments in section  $k$  required to reach its ultimate load capacity, Nm,

Practical calculation of the robustness can be carried out by means of the following formula:

$$R = 1 - \max_k \left( \frac{M_{k,j}^d - M_{k,j}^0}{M_k^R - M_{k,j}^0} \right) = \min_k \left( \frac{M_k^R - M_{k,j}^d}{M_k^R - M_{k,j}^0} \right) \quad (2)$$

where  $M_{k,j}^0$  – bending moment in section  $k$  of the intact structure triggered by the critical load  $P_j^{cr}$ , Nm,  $M_{k,j}^d$  – bending moment in section  $k$  after failure of section  $j$  triggered by the critical load  $P_j^{cr}$ , Nm,  $M_k^R$  – bending resistance of the section  $k$ , Nm.



**Fig. 1.** Redistribution of bending moments in a 2-girder structure at failure in section  $j$

Graphical interpretation of the analysed problem is presented in Fig. 1 for a 2-girder span at failure in section  $j$ .

As the critical load, the most unfavourable and effective in reaching the bending resistance of the section  $j$  loading scenario is assumed. Therefore a concentrated force  $P_j^{cr}$  located over the considered section  $j$  (on the extreme ordinate of the influence surface for the bending moment  $M_j$ ) is applied.

In the linear-elastic models satisfying the superposition principle it is possible to apply a further simplification to carry out analysis with a unit force  $P$ . Then the formula takes a form:

$$R = 1 - \max_k \left( \frac{M_{k,j}^{d,1} \cdot k_j - M_{k,j}^1 \cdot k_j}{M_k^R - M_{k,j}^1 \cdot k_j} \right) = \min_k \left( \frac{M_k^R - M_{k,j}^{d,1} \cdot k_j}{M_k^R - M_{k,j}^1 \cdot k_j} \right) \quad (3)$$

$$k_j = \frac{M_j^R}{M_{j,j}^1} \quad (4)$$

where  $M_{k,j}^1$  – bending moment in section  $k$  of the intact structure triggered by a unit load  $P_j = 1$ , Nm,  $M_{k,j}^{d,1}$  – bending moment in section  $k$  after failure of section  $j$  triggered by a unit load  $P_j = 1$ , Nm,  $k_j$  – multiplier of a unit force  $P_j$  required to reach the ultimate load capacity of section  $j$ .

When the sections  $j$  and  $k$  are with the same properties and resistance Eq (3) can be independent of the section resistance, as follows:

$$R = 1 - \max_k \left( \frac{M_{k,j}^{d,1} - M_{k,j}^1}{M_{j,j}^1 - M_{k,j}^1} \right) \quad (5)$$

In the second approach the robustness  $R'$  is calculated in a similar way, however instead of increase of the bending moment  $\Delta M_k^R$  given in denominator of Eq (1), just the section resistance  $M_k^R$  is applied. The formulas corresponding to Eqs (3) and (5) are then following:

$$R' = 1 - \max_k \left( \frac{M_{k,j}^{d,1} \cdot k_j - M_{k,j}^1 \cdot k_j}{M_k^R} \right) \quad (6)$$

$$R' = 1 - \max_k \left( \frac{M_{k,j}^{d,1} - M_{k,j}^1}{M_{j,j}^1} \right) = 1 - \max_k \left( \frac{\Delta M_{k,j}^1}{M_{j,j}^1} \right) \quad (7)$$

It is visible that the difference between  $R$  and  $R'$  is related to the relative level of resistance included in denominators of Eq (5) and (7) coming from assumed initial level of the bending moment acting in section  $k$  (prior to failure) and thus defining its remaining load carrying capacity. It can be also noted that the measure  $R$  is higher than zero if  $M_{j,j}^1 > M_{k,j}^{d,1}$ .

## 2 Case studies

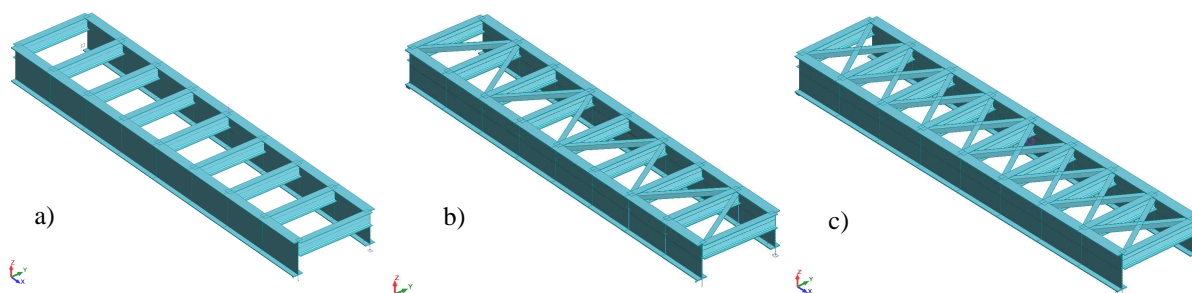
Within the paper two types of beam bridges are analysed: a simply supported 2-girder one as well as a continuous 2-span 6-girder structure. The study is based on a numerical analysis carried out by means of linear models of Finite Element Method.

### 2.1 Simply supported 2-girder bridge

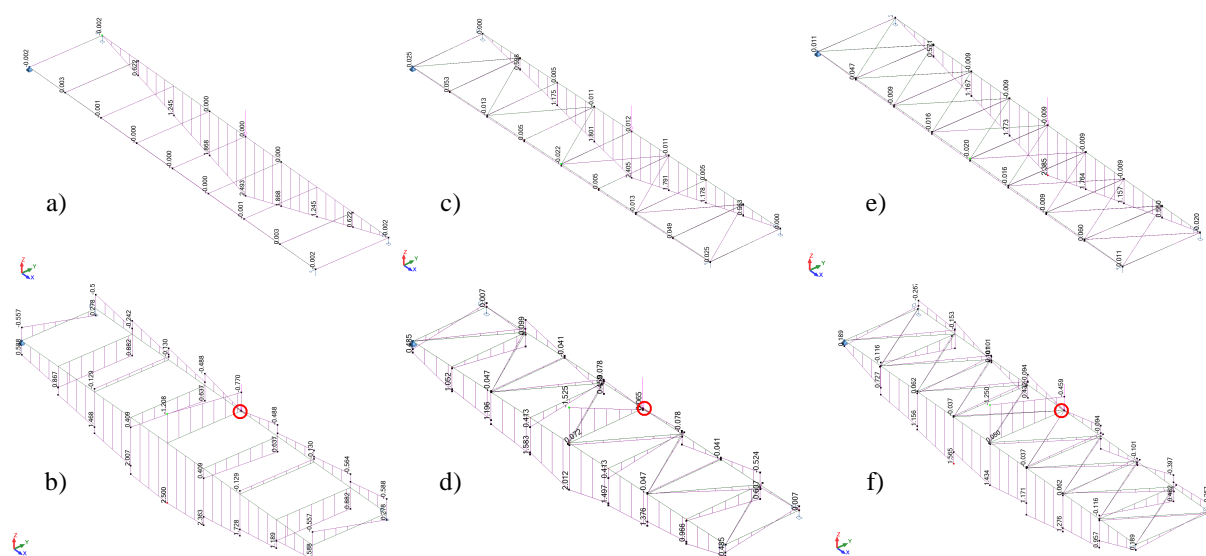
Analysed structure corresponds to typical 10 m span railway bridge with plate girders 900 mm high. Three variants of the bracing system are considered (according to Fig. 2):

- I. cross-beams only (IPE 360),
- II. cross-beams (IPE 360) with N-system of horizontal bracing (L 120x120x10),
- III. cross-beams (IPE 360) with X-system of horizontal bracing (L 120x120x10).

Robustness analysis is carried out assuming flexural yielding of a girder in the mid-span section. Such a failure is represented in the bridge model by definition of a hinge in the damaged section. Results presenting distribution of bending moments triggered by a single force located in a position of the damaged section before and after the failure are shown in Fig. 3.



**Fig. 2.** FE models of the considered variants of the 2-girder simply supported bridge: a) variant I, b) variant II, c) variant III.



**Fig. 3.** Bending moments before/after failure for: variant I: a) / b), variant II: c) / d), variant III: e) / f)

The measures of robustness  $R$  and  $R'$  for the variant II calculated according to Eq (5) and (7) respectively, are:

$$R = \min_k \left( \frac{M_{j,j}^1 - M_{k,j}^{d1}}{M_{j,j}^1 - M_{k,j}^1} \right) = \frac{2.40 - 2.01}{2.40 - 0.08} = 0,168$$

$$R' = \min_k \left( \frac{M_{j,j}^1 - M_{k,j}^{d1}}{M_{j,j}^1} \right) = \frac{2.40 - 2.01}{2.40} = 0,196$$

Results for all the variants are given in Table 1 below.

**Table 1.** Robustness analysis results for the 2-girder simply supported beam.

variant	$M_{j,j}^1$ kNm	$M_{k,j}^1$ kNm	$M_{k,j}^{d1}$ kNm	$R_j$	$R'_j$
I	2,50	0,00	2,50	<b>0,000</b>	<b>0,000</b>
II	2,40	0,08	2,01	<b>0,168</b>	<b>0,196</b>
III	2,38	0,09	1,43	<b>0,415</b>	<b>0,437</b>

The presented results indicate that the variant III is characterised by the highest robustness (confirmed by the both measures) what is caused by the effective contribution of that most complex bracing system in redistribution of

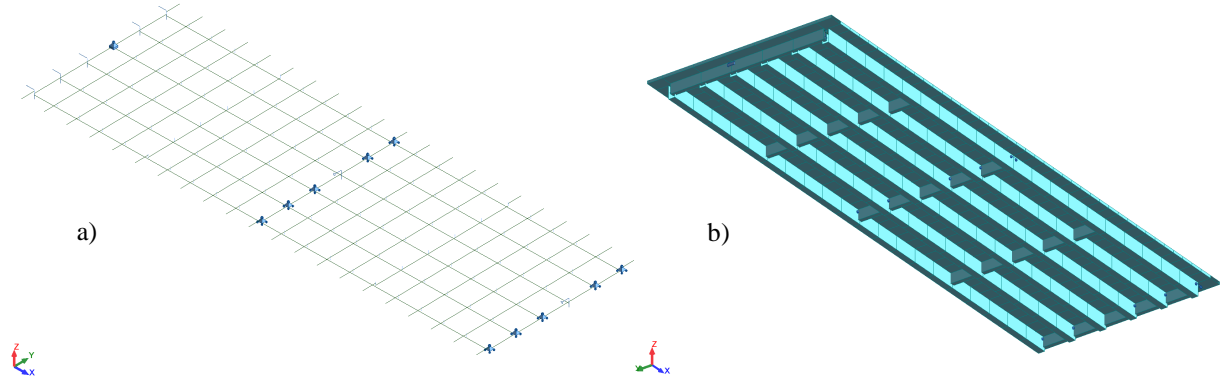
bending moments from the damaged to the intact girder. In the variant III the load is redistributed over the largest length of the intact girder and therefore it leads to reduction of the bending moment in analysed section  $k$ .

## 2.2 Continuous 2-span 6-girder bridge

The second case is a 2-span continuous beam structure with spans: 25 + 25 m. The beam and slab section type is composed of six RC girders 150 cm high and 60 cm wide as well as RC slab 25 cm thick. Its model applied in analysis is shown in Fig. 4.

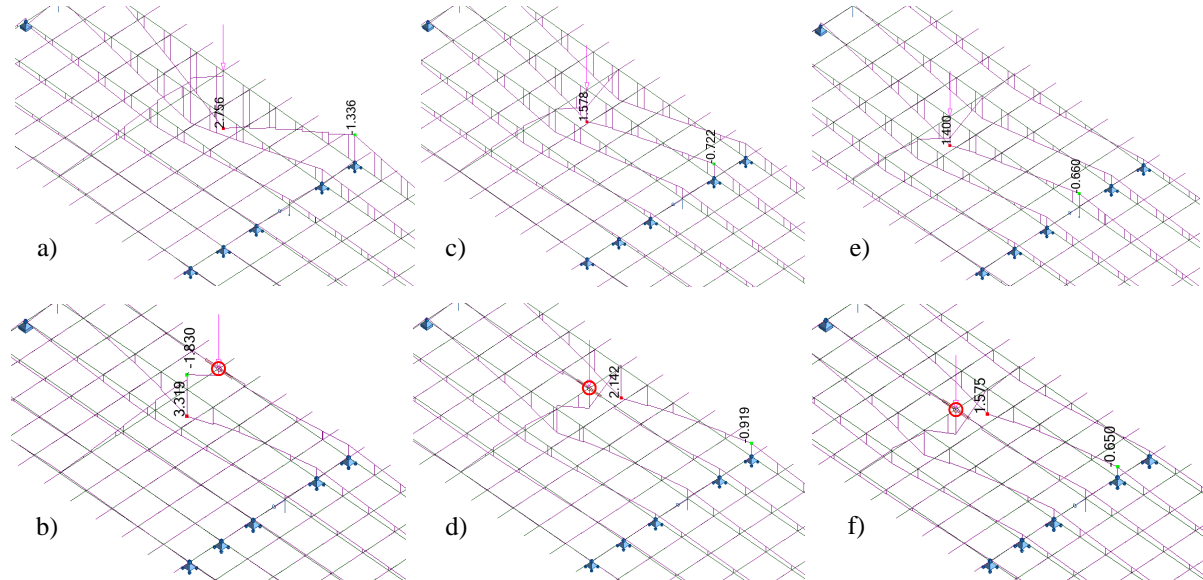
The robustness is checked considering three separate cases of failure (flexural yielding) in the mid-span section of various main girders:

- A. the edge girder,
- B. the second girder from the edge,
- C. the third girder from the edge.



**Fig. 4.** Numerical model of the 2-span bridge: a) geometry and boundary conditions, b) bottom view with section shapes

Results presenting distribution of bending moments triggered by a single force located in a position of the damaged section before and after the failure are shown in Fig. 5 (for enlarged part of the structure).



**Fig. 5.** Bending moments before/after failure in section A: a) / b), section B: c) / d), section C: e) / f).

At the failure in section A (the edge girder) the largest internal forces appear in section B (the second girder). In this case the measures of robustness  $R$  and  $R'$  are equal to:

$$R = R_{B,A} = \frac{M_{j,j}^1 - M_{k,j}^{d1}}{M_{j,j}^1 - M_{k,j}^1} = \frac{2.756 - 3.319}{2.756 - 1.474} = -0.439 < 0$$



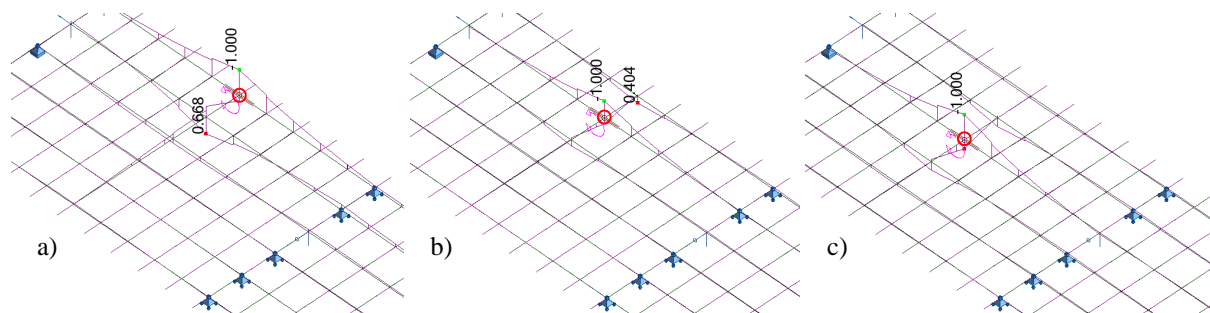
$$R' = R'_{B,A} = \frac{M_{j,j}^I - M_{k,j}^{dI}}{M_{j,j}^I} = \frac{2.756 - 3.319}{2.756} = 0,331$$

Results for all the cases of failure are collected in Table 2 where the damaged  $j$  and corresponding checked  $k$  sections are given. Each time the checked sections are assumed in a girder neighbouring to the damaged one and located closer to the edge.

**Table 2.** Robustness analysis results for the 6-girder continuous beam.

damaged section $j$	checked section $k$	$M_{j,j}^I$ kNm	$M_{k,j}^I$ kNm	$M_{k,j}^{dI}$ kNm	$R_j$	$R'_j$
A	B	2,756	1,474	3,319	<b>-0,439</b>	<b>0,331</b>
B	A	1,578	1,504	2,142	<b>-7,622</b>	<b>0,596</b>
C	B	1,400	1,097	1,575	<b>-0,578</b>	<b>0,659</b>

Physical interpretation of the quantity  $(\Delta M_{k,j}^I / M_{j,j}^I)$  included in robustness  $R'$  measure Eq (7) is a participation of the section  $k$  in redistribution of the lost bending resistance in section  $j$ . Therefore, except Eq (7),  $R'$  can be found also within an analysis with application of unit bending moments to the damaged section, as it is shown in Fig. 6. By means of such an analysis it is more clear which elements take the loads (manifesting by bending moments) and thus are the most vulnerable to overloading after failure of the section  $j$ .



**Fig. 6.** Redistribution of bending moments after failure in: a) section A, b), section B, c) section C.

As it is given in Table 2 the robustness expressed as  $R$  is lower than 0 for all the cases, what means progressive development of the failure in the following girders. This effect arises from the robustness  $R$  definition based on external loading scenario assuming presence of the critical load  $P_f^{cr}$  (expressed in Eq (5)) before and after failure of the section  $j$ . This is the most unfavourable as well as the least probable case. An opposite approach is represented by the second robustness measure  $R'$  where neither external loading scenario nor initial bending moment in section  $k$  are considered.

### 3 Conclusions

The proposed method of the structural robustness evaluation represents a consistent and complete approach applicable to any type of structure – with arbitrary static system, structural form and material. Given measures  $R$  and  $R'$  get values close to 1 for robust system and close to 0 for non-robust ones. In case of  $R$  the negative values can appear what indicates a threat of progressive collapse.

Within the case studies two types of beam bridges are analysed. Robustness of the structures is checked with consideration of a specific main girder failure (a hinge formation) in the mid-span. Thanks to the applied measures it can be quantified and compared for various cases. In case of the 2-girder structure robustness evaluated by means of both  $R$  and  $R'$  measures reflects effectiveness of various layouts of the bracing systems in agreement with expectations and intuition. Analysis of the 6-girder structure reveals essential dependence of measures  $R$  and  $R'$  to the assumed loading scenario and to the initial level of internal forces in the checked section.

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## Robustness as performance indicator for masonry arch bridges

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**Abstract.** Masonry arch bridges date from past centuries, being preserved over the years due their historical importance. According to the Sustainable Bridges Project, around 40% of all European bridges are masonry arch bridges. However, some of these bridges have suffered deterioration over time and, in some cases, safety can be compromised. In order to avoid such desirable events, the concept of robustness arises. Structural robustness has gained a high interest after the collapse of the World Trade Centre. In fact, robustness can be defined as the ability of a structure to support a certain amount of damage without global collapse occurrence. A structure is considered robust when it is designed with very resistant components and presents a progressive collapse when one of these components fails. Over the last years, several methods have been proposed to quantify the robustness, namely: (1) risk-based robustness index; (2) reliability-based robustness index; (3) deterministic robustness index based on experimental data. This work aims to present the quantification of the robustness index for a masonry arch bridge in order to assess its structural condition.

**Keywords:** Masonry arch bridges, Railway bridges, Robustness Index, Limit analysis, Safety assessment,

### 1 Introduction

Masonry arch bridges (MAB) are important linking elements of transportation network. Although they were built in the past centuries, MAB have been proving to possess excellent in-service performances and an extraordinary ultimate load-carrying capacity, as demonstrated by several authors (Casas, 2011, Melbourne et al., 2007, Moreira, 2014). This is indeed remarkable once they were designed for much lower loads, being rarely retrofitted or strengthened despite the deterioration and possible damages from accidents during its lifetime. Combining both degradation and damages, this may result in severe reduction of the overall structural safety. Hence, it of paramount importance to assess if these damages compromise the structural capacity to support a certain amount of damage without occurring global collapse, i.e., a local collapse which cannot compromise the global safety and integrity. In this way, concepts like structural robustness arises in order to investigate such performance to certain damage scenarios.

In this paper, a methodology for robustness-based assessment of existing MAB, which may be applied to railway and roadway MAB, based on the ultimate load-carrying capacity and multiple damage scenarios is presented. To determine the load-carrying capacity, a limit analysis approach, based on mechanisms, will be employed. The presented robustness approach throughout this paper will be tested and applied to an existing Portuguese railway MAB.

### 2 Structural robustness

Structural robustness has been recognized over the years as a theme of high interest due to the collapse of big structural systems, which started by small damages and resulted in catastrophic consequences. World Trade Centre collapse has triggered the renewed interest in the study of structural robustness. In addition, the following facts like: i) failures due to unforeseen loads; ii) design and execution errors; and iii) undetected deterioration and reduced maintenance, also triggered the investments in this area.

## 2.1 Background and concepts

Starossek and Haberland (2010) presented several definitions of robustness in civil engineering domain by several authors. One of those definitions is the one presented by ASCE, which states that progressive collapse may be defined as the spread of an initial local failure of a member, being this damage transmitted to surrounding structural members, whose fail one after one until the global collapses occurs (disproportionate failure). Also, Starossek and Haberland (2010) pointed out that there are another structural terms that should be considered in structural robustness assessments such as exposure, vulnerability, damage tolerance, redundancy, ductility and reliability.

## 2.2 Brief overview on robustness indexes

Over the years, several methods and robustness indexes (RI) have been presented to quantify the robustness being distinguished three main types, namely: i) risk-based RI; ii) reliability-based RI; and iii) deterministic RI. The following works are the most relevant ones: Frangopol and Curley (1987), Biondini and Restelli (2008), Starossek and Haberland (2011), Cavaco (2013), Fu and Frangopol (1990), Lind (1995), Ghosn and Moses (1998) and Baker et al. (2008). A short review of these works is presented below.

### 2.2.1 Deterministic approach

Frangopol and Curley (1987) indicate that redundancy is a representative RI, being developed a deterministic indicator. Robustness assessment proposed by Biondini and Restelli (2008) is normally associated to accidental actions such as explosions or impacts. Nevertheless, this index may be applied to material deterioration situations. The approach proposed by Starossek and Haberland (2011) is based on the progressive collapse to assess how robust the structure is. The authors also divide the progressive collapse caused by the impact and by redistribution. Cavaco (2013) proposed a new RI based on a damage spectrum, which is proper for the evaluation of structures under harsh environments such as deterioration.

### 2.2.2 Probabilistic approach

Frangopol and Curley (1987) and Fu and Frangopol (1990) proposed some probabilistic indexes to measure structural redundancy that can assess the RI. This RI gives a measure of the robustness of a structural system. Lind (1995) proposed quantitative measures either for vulnerability and damage tolerance of a system. Ghosn and Moses (1998) focused on bridges where the redundancy was defined as a capacity to redistribute the applied loads after the ultimate capacity of the members being reached. Hence, the authors proposed a complete framework to structural assessment considering bridges as a structural system.

### 2.2.3 Risk-based approach

Baker et al. (2008) proposed a risk-based robustness assessment, based on direct risk (direct consequences) and indirect risk (indirect consequences), being possible to consider multi-hazard scenarios and different type of damages. Once this RI considers direct and indirect consequences, is highly dependent on social and economic environment and cannot be considered a structural property. Thus, two similar structures can present different RI.

## 3 Framework for MAB structural robustness index

### 3.1 Description

MAB are structures composed by the association of voussoirs, being their Ultimate Limit State (ULS) attained, not by depletion of load capacity (ULS:STR), but by formation of sufficient internal releases, such as plastic hinges of sliding planes, resulting in the dismantlement of masonry units (ULS:EQU). Once MAB structural behavior may not be analytically defined, their performance is, generally, expressed by Eq. (1):

$$f = R - S, \quad (1)$$

where  $R$  is the resistance curve, which is the MAB ultimate load-carrying capacity, and  $S$  is the applied loads (Casas, 2011, Melbourne et al., 2007, Moreira, 2014).

For the structural analysis, RING software will be employed (Gilbert et al., 2014). This software idealizes MAB as an assemblage of rigid blocks, with a rigid-plastic constitutive behaviour. The spandrel walls are not considered and the fill material is simulated by “filling elements”, which only react when compressed, having no tensile capacity. Passive restraining, caused by filling material, was obtain by application of Rankine’s Theory. For the dispersion of live loads, Boussinesq’s distribution theory is employed.

The applied load model is the one presented in the EN 1991-2 (CEN, 2003), namely the LM71 load model. This model is composed by 4 single loads and 2 optional uniformly distributed loads. Once the 2 uniformly distributed loads increase the failure load factor of MAB (Santis, 2011), they will not be considered in this analysis. The

presented values for the 4 single loads are the characteristic ones (250 kN), being these values corresponding to the 98<sup>th</sup> percentile of a Normal probabilistic density function (Moreira, 2014). Thus, it is obtained a mean value of 207,4 kN, being the failure load factor expressed in terms of this value.

In order to assess MAB robustness, it will be employed the RI proposed by Cavaco (2013). According to this author, robustness is presented as a performance evaluator since it evaluates the variation of structural performance indicator under a certain damage scenario. Within this method, both structural performance and damage are normalized, being the RI, for a specific performance and damage type, given by the area below the curve defined by Eq. (2):

$$RI = \int_{D=0}^{D=1} f(D)dD, \quad (2)$$

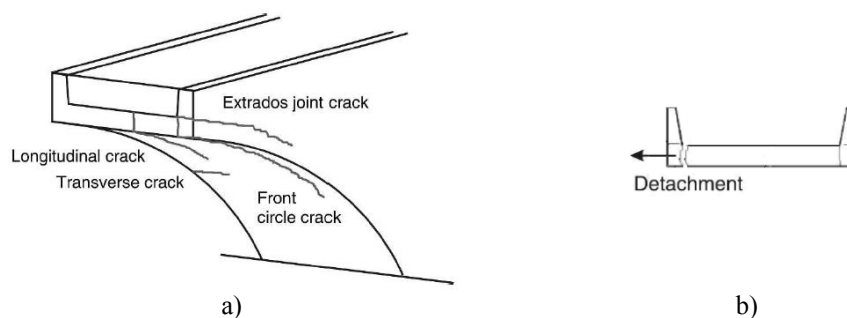
where  $f(D)$  is the normalized structural performance and  $D$  is the normalized damage. The robustness varies between zero and one, for null and full robustness, respectively. In this work, RI represents the average normalized ultimate load-carrying capacity of the damaged MAB.

### 3.2 Damage scenarios

The majority of MAB heritage is older than a century and, in most cases, the material and structural defects are notorious and therefore it must be taken into account in the safety assessment. Additionally, the lack of maintenance aggravates their condition. All these facts culminate in diminishment of the ultimate load-carrying capacity of the bridge and it is of upmost importance to guarantee the required safety levels.

#### 3.2.1 Longitudinal cracking

Longitudinal cracks may appear in any section of the arch (**Fig. 1a**). Cracks decreases the bearing capacity due to the fact that applied loads cannot be distributed throughout the arch and then to the piers and abutments. Another source of cracking is the detachment of spandrel walls. When spandrel walls move outward of the arch, it leads to the cracking of the arch and a consequent reduction in the ultimate load-carrying capacity is verified. Also, the isolation of the spandrel walls reduces the arch support to bear applied loads, see **Fig. 1b**) (Melbourne et al., 2007, Gilbert et al., 2014, Costa, 2009).



**Fig. 1.** Defects in MAB (adapted from Proske and Gelder (2009)): (a) MAB cracks; (b) Spandrel walls detachment

#### 3.2.2 Transversal cracking

Transversal cracks may be originated by detachment of spandrel walls or support settlement, see **Fig. 1**. In some cases, masonry voussoirs of the arch may loss its mortar, resulting in the displacement of it. The significance of transversal cracks in MAB performance depends on several factors. One example is the fact that it may lead to the deterioration of fill material and surrounding voussoirs (Melbourne et al., 2007, Gilbert et al., 2014, Costa, 2009).

#### 3.2.3 Spalled masonry arch voussoirs

In old MAB, spalled masonry voussoirs are always present. Generally, they do not compromise structural integrity. However, in cases of mortar loss, mortar wash-out and/or widespread spalled voussoirs, the effective arch thickness may be severely reduced and consequently the ultimate load carrying capacity (Gilbert et al., 2014, Costa, 2009).

### 3.2.4 Masonry deterioration and fatigue

Masonry is greatly affected by the phenomena of degradation and fatigue. Concerning fatigue, tests conducted by Clark (1994) and Roberts et al. (2006) indicated that brick masonry's fatigue strength may reach 50% of its quasi-static compressive strength. In respect to deterioration, it is mainly related to environment, physical and chemical attacks, such as moisture, thermal gradients, freeze-thaw cycling and sulfate attack. Also, masonry's porosity is highly propitious to the penetration of chemical substances, contributing to the degradation. All these facts result in the reduction of its mechanical properties, especially in its compressive strength (Costa, 2009).

## 4 Application to a case study

### 4.1 The Calharda viaduct

The Calharda viaduct (**Fig. 2a**) was built in 1882 and it is located in Beira Alta railway line. It is composed by five full-centered arches, each one with a free span of 12,00m and a maximum height of 20,0m. Its total extension is of 86,50m with a top width of 4,00m and it is all built of rough dry joint masonry. All piers have the same geometry, with exception of their heights, being the cross section in longitudinal and transversal directions, variable (linear variation). **Fig. 2b** presents the geometric details of Calharda viaduct. For material properties, **Table 1** presents the considered mean values for the following structural parameters. The mean values are the ones considered instead of the characteristic ones, once no partial safety factors will be employed in the present work.



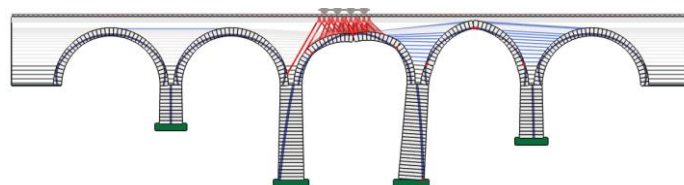
**Fig. 2.** Calharda Viaduct: (a) perspective; (b) elevation view (dimensions in [mm])

**Table 1.** Material properties.

		$x_m$
Masonry	Density, $\gamma_m$ (kN/m <sup>3</sup> )	25
	Compressive strength, $f_c$ (MPa)	20
	Friction coefficient, $\mu$ (-)	0,58
Fill material	Density, $\gamma_f$ (kN/m <sup>3</sup> )	20
	Angle of friction, $\phi$ (°)	30
	Cohesion, $c$ (kPa)	0
Ballast	Density, $\gamma_b$ (kN/m <sup>3</sup> )	17,66
Track	Track load per unit area, $T_L$ (kN/m <sup>2</sup> )	1,42

The failure mechanism of Calharda viaduct is the 7 plastic hinges mechanism, being the middle span where the collapse occurred, see **Fig. 3**. Accordingly, 3 hinges have formed in the loaded span, another three in the next span and the remaining hinge on the adjacent pier's base. The adjacent pier to the third span is slender and, due to this fact, there is interaction between the two piers and the loaded span. It is noted that this situation is the one that no damage is considered, being obtained a failure load factor of 4.09.





**Fig. 3.** Calharda Viaduct collapse: 7 hinges mechanism.

## 4.2 Damage scenarios. Robustness index

As presented in the previous section, the considered damage scenarios (DS) were the following: i) longitudinal cracking due to spandrel wall detachment (DS1), in which a 10% maximum damage is considered; ii) transversal cracking along the arch (DS2), which considers 10% maximum damage; iii) spalled masonry arch voussoirs, for the third (DS3) and middle span (DS4) sections, which both situations will simulate the reduction of the arch thickness in 10% in those sections; and iv) masonry deterioration and fatigue (DS5), being simulated the reduction of compressive strength for a maximum of 20% of its initial value. The percentage of damage considered took into account the values of 0 %, then 10%, 25%, 50% and 100% of the studied scenarios. These percentages were based on expert judgement. **Table 2** shows the load-carrying capacity obtained for the different damage scenarios as well as the corresponding normalized load factor and RI. Between brackets are presented the normalized failure load factors in terms of the no-damage situation.

**Table 2.** Damage Scenarios and corresponding failure load factors and RI.

DS	Max damage	0%	10%	25%	50%	100%	RI
1	500 mm	4.09 (1.00)	4.09 (1.00)	4.09 (1.00)	4.09 (1.00)	4.09 (1.00)	1.00
2	87 mm	4.09 (1.00)	4.07 (1.00)	4.03 (0.99)	3.77 (0.92)	3.61 (0.88)	0.94
3	87 mm	4.09 (1.00)	4.08 (1.00)	4.07 (1.00)	4.04 (0.99)	3.95 (0.97)	0.99
4	87 mm	4.09 (1.00)	4.06 (0.99)	4.01 (0.98)	3.89 (0.95)	3.57 (0.87)	0.94
5	5 MPa	4.09 (1.00)	4.08 (1.00)	4.07 (1.00)	4.04 (0.99)	3.99 (0.98)	0.99

## 5 Conclusions

Obtained RI for the different scenarios of damage indicate that all the five scenarios present a high robustness index, once obtained values are close or equal to one, leading to the conclusion that the bridge guarantees its safety. The analysis of each damage scenario and corresponding RI allows to point out that:

- In respect to bridges effective width for load transversal dispersion (DS1), it is verified that the bearing capacity has not been affected. Even for the situation of 500mm width reduction, the failure load factor is not affected, and therefore it is concluded that this width is not used for the dispersion of applied loads for the critical positions, thus the unitary RI;
- The reduction of the effective arch thickness due to transversal cracking (DS2) has some influence in Calharda viaduct behavior. According to obtained failure load factors, it is observed that in situation of 100% of maximum considered damage, the reduction of bridges performance reaches 12%. In this situation, if the damage is only 10% of the arch thickness, the RI decreases to 0.94, pointing out that the arch is a crucial element in MAB and if it is damaged, the MAB safety may be compromised;
- Localized cracking in the third section of the span-length (DS3) has practically no effect on Calharda viaduct overall safety. This is somehow expected once the failure mechanism occurs according to a 5 hinges collapse mechanism, being the critical section the middle-span one. However, it could be possible that the MAB would fail for this situation, once it is easy to develop a 4-hinges mechanism due to the damage and it is typically a critical section;

- For the situation of localized damaged in the middle span section (DS4) of the third span, it is possible to verify that a reduction of bridges performance is affected. In fact, when maximum damage is considered, the Calhorda viaduct failure load factor is reduced in 13%. This is significant, once only one section of the arch is considered to be damaged. Considering the obtained collapse mechanism, it is expected that the localized damage in the middle section would decrease the bearing capacity, once the failure mechanism is attained more easily and therefore the decreasing in the RI;
- The degradation of masonry due to fatigue and biological/chemical attacks (DS5) reaching 20% of its original value has minor influence in the overall performance and therefore obtained RI is nearly the unit, not being affect structural robustness. Even when the damage reaches its maximum value, the reduction if the failure load factor is minimum, indicating that masonry compressive strength is not an influent parameter in the overall behavior.

This framework is being extended to a set of MAB belonging to the Portuguese Railway company, REFER, where more detailed techniques and different approaches of robustness are also being discussed.

## Acknowledgements

This research was funded by project PEst-C/ECI/UI4029/2011 (FCOM-01-0124-FEDER-022681), from Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement No 606229 and by the Portuguese Science and Technology Foundation through project UID/ECI/04029/2013. Also the collaboration and information provided by the Portuguese railway network (REFER) is gratefully acknowledged.

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## Performance indicators for road bridges – categorization overview

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**Abstract.** An overview of the performance indicators' categorization based on results of the screening process of the inspection and evaluation documents for roadway bridges performed under the auspices of COST action TU 1406 is proposed. Additionally research based indicators are contemplated in order to raise existing European maintenance practice to a higher level.

**Keywords:** performance, indicators, thresholds, detection, evaluation, technical, sustainable, socio-economic.

### 1 Introduction and motivation

Management of road bridges comprises coordinated activities to realize their optimal value which involves balancing of costs, risks, opportunities and performance goals.

Performance goal may be considered as type of bridge property or behavior that is required during its lifetime. Different types of performance goals need to be reached at different levels of a roadway bridge asset, as a part of its efficient and effective maintenance strategy. For example, functionality of a specific bridge element (such as the stability of abutment, bending capacity of a main girder or retention level of a safety barrier) is a performance goal at the component level. Adequate seismic performance of a complete bridge structure is a goal at the system level, but taking into account the consequences of its collapse it becomes the goal at the network level.

Whether the goal is achieved or not, may be assessed through the evaluation of various performance indicators which additionally implies knowledge of their respective levels of influence to an observed performance goal.

Performance indicator may be defined as superior term of a bridge characteristic that have the possibility to indicate the condition of a bridge. It can be expressed in the form of a dimensional performance parameter or as a dimensionless performance index. The former is measurable/testable parameter that quantitatively describes certain performance aspect (for example crack width) and the second one is qualitative representation of performance aspect (for example importance of a bridge component in the whole bridge structure or importance of a bridge in the complete network).

To evaluate certain performance indicator, performance thresholds or criteria must be set. Threshold value constitutes a boundary for purposes such as: a) monitoring (e.g. an effect is observed or not), b) assessing (e.g. an effect is low or high), and c) decision-making (e.g. an effect is critical or not). A criterion is a characteristic that is relevant for the choice between processes e.g. such as maintenance actions or others.

Although the interaction of different performance indicators is inevitable, their categorization into technical, sustainable and socio-economic indicators through component, system and network level is proposed in order to more easily identify methods for their quantification and level of their influence to a certain structural performance goal. This categorization should contemplate the origin of indicators, level and extend of their influence.

Besides related detection methods, performance thresholds and evaluation methods, interactions between performance indicators and performance goals will be contemplated as they are in general crucial for optimal quality control and management of road bridges.

## 2 Performance indicators at the component level

Bridge inspection is general carried out by bridge elements (components) forming three main bridge sub-systems: substructure, superstructure and roadway (Croatian roads ltd. 2014 & Croatian highways ltd. 2010 a). Bridge components including constitutive materials are given in table 1.

**Table 1.** Bridge elements for categorization at the component level

Substructure	Superstructure	Roadway + equipment
Foundations (concrete)	Superstructure (reinforced concrete)	Pavement
Deep foundations, piles (concrete)	Superstructure (prestressed concrete)	Curb & Cornices
Deep foundations, piles (steel)	Superstructure (steel)	Railings & railing anchorage, barriers
Deep foundations, piles (timber)	Superstructure (composite)	Sidewalk (Pedestrian walkway)
Abutments (concrete)	Superstructure (timber)	Bearings
Abutments (masonry)	Superstructure (brick)	Expansion joints
Piers (concrete)	Superstructure (stone)	Drainage
Piers (steel)	Arch (concrete)	Lighting
Piers (masonry)	Arch (masonry)	Signalization
...	...	...

### 2.1 Technical indicators

At the bridge component level, one of the important performance goal to be reached is damage assessment. This implies detection of damages but also their identification and evaluation. Damage of a bridge element is physical disruption or change in its condition, caused by external actions, such that some aspect of, either the current or future performance of the component (and perhaps consecutively a complete structure) is impaired.

**Table 2.** Example of categorization of damage degree or extend as a primary performance indicator for concrete superstructure

Damage type (characteristics)	Damage indicator	Damage detection	Damage threshold	Damage evaluation
Abrasion	Affected area (m2) + Affected depth (cm)	Visual inspection + Direct measurement	Classes / upper value + damage phase duration	Grades according to handbook of damages
Cavities		Acoustic emission		Acoustic emission analysis
Corrosion	Affected area (m2)	Visual inspection + Direct measurement	Classes	Grades according to handbook of damages
	Percentage of damaged cross section of reinforcement (%)	Specialist detailed inspection	Upper values of the phase + damage phase duration	Grades according to handbook for assessment
	Physical parameter	In situ testing		Testing analysis
Cracks	Crack width (mm)	Visual inspection + Direct measurement	Classes / upper value + damage phase duration	Grades according to handbook of damages
		Monitoring		
Delamination	Affected area (m2) + Affected depth (cm or mm)	Visual inspection + Direct measurement	Classes	Grades according to handbook of damages
Insufficient concrete cover	Affected area (m2)	Visual inspection + Direct measurement	Classes	Grades according to handbook of damages
Insufficient concrete quality	Physical parameter	Probing		Probing analysis
Spalling	Affected area (m2) + Affected depth (cm or mm)	Visual inspection + Direct measurement	Classes	Grades according to handbook of damages
.....				

Four main approaches in damage detection are visual inspection, nondestructive testing, probing and structural health monitoring. In addition to damage detection and characterization, damage identification includes ascertaining the cause of the damage and its consequences and damage evaluation comprises degree or/and extend with respect to the set threshold value. Besides most commonly set up upper limit, additional threshold in the damage assessment may be duration of damage phase, which will give a clue in which phase of damage progress the element is find: low, moderate or high. The former will request the protection from further progression, the second one will require a routine repair and the last one requests more detailed inspections and testing leading to a routine or special repair. Upon assessing damages of a particular bridge element, the component functionality level may be evaluated. Element may be evaluated in best condition when no damage is detected, with unquestionable function when damage is in initial phase, with function not been compromised when damaged is moderate and with questionable function or element is out of function when damage has high degree and/or extend.

## **2.2 Socio-economic indicators**

At this level socio-economic aspects are to be included. A ratio of sum of costs for repair of individual damages and price of the new element is an indicator of the element's general condition assessment. Threshold for this indicator may be set as quantitative scale of value showing gradation of element condition assessment. For all elements for which this ratio is above 1.0 replacement with a new element should be predicted.

## **3 Performance indicators at the system level**

In order to assess the impact of the damaged element functionality to the entire structure, the importance of bridge element is to be evaluated according to following criteria: structural safety and serviceability, traffic safety and durability (Croatian highways ltd. 2010 b). Qualitative scale of values may show how the collapse of a particular element would affect each criteria. Besides technical indicators, at this level sustainability and socio-economic indicators will assume essential impact to performance requirements.

Additionally, indicators related to scientific achievements in, for example, testing and monitoring, dynamic behavior and reliability of bridge structures should be included at this level, as well. Some contemplation on those indicators will be given after the survey of research based indicators at the European level. For example, bridge reliability assessment will require adequate knowledge level on bridge properties such are for example stiffness changes and realistic traffic loading which requires investment in additional inspection, testing or monitoring method, advanced modeling techniques and updating data on bridge resistance and loads.

### **3.1 Technical indicators**

Technical indicators at this level are those related to bridge safety and serviceability as main performance goals used in existing inspection and evaluation documents. Based on this criteria, it may be decided that collapse of particular element will have no influence to safety and serviceability of the bridge, has influence to a part of a bridge structure or has influence to an entire bridge structure.

### **3.2 Sustainable indicators**

When meeting performance requirements is evaluated, under given condition during a given period of time, sustainability issues occur. Therefore durability may be considered as sustainable performance goal which needs to be included as a criteria for condition assessment of bridge sub-systems comprising roadway, substructure and superstructure and for entire bridge condition assessment. Based on durability criteria, it may be decided that collapse of particular element will have no influence to durability of other components or contrary that collapse of particular element will cause reduced durability of other components.

### **3.3 Socio-economic indicators**

Traffic safety may be considered as socio-economic performance goal. Namely, as criteria for condition assessment of bridge sub-systems or entire bridge condition assessment, it is expressed in levels of traffic limitation or congestion: collapse of a particular element has no influence to traffic flow, causes speed limitation, causes local traffic redirection or complete traffic suspension.

Additional indicator to be raised at the system level is element general condition assessment, which will help to assess the condition of a sub system and entire bridge.

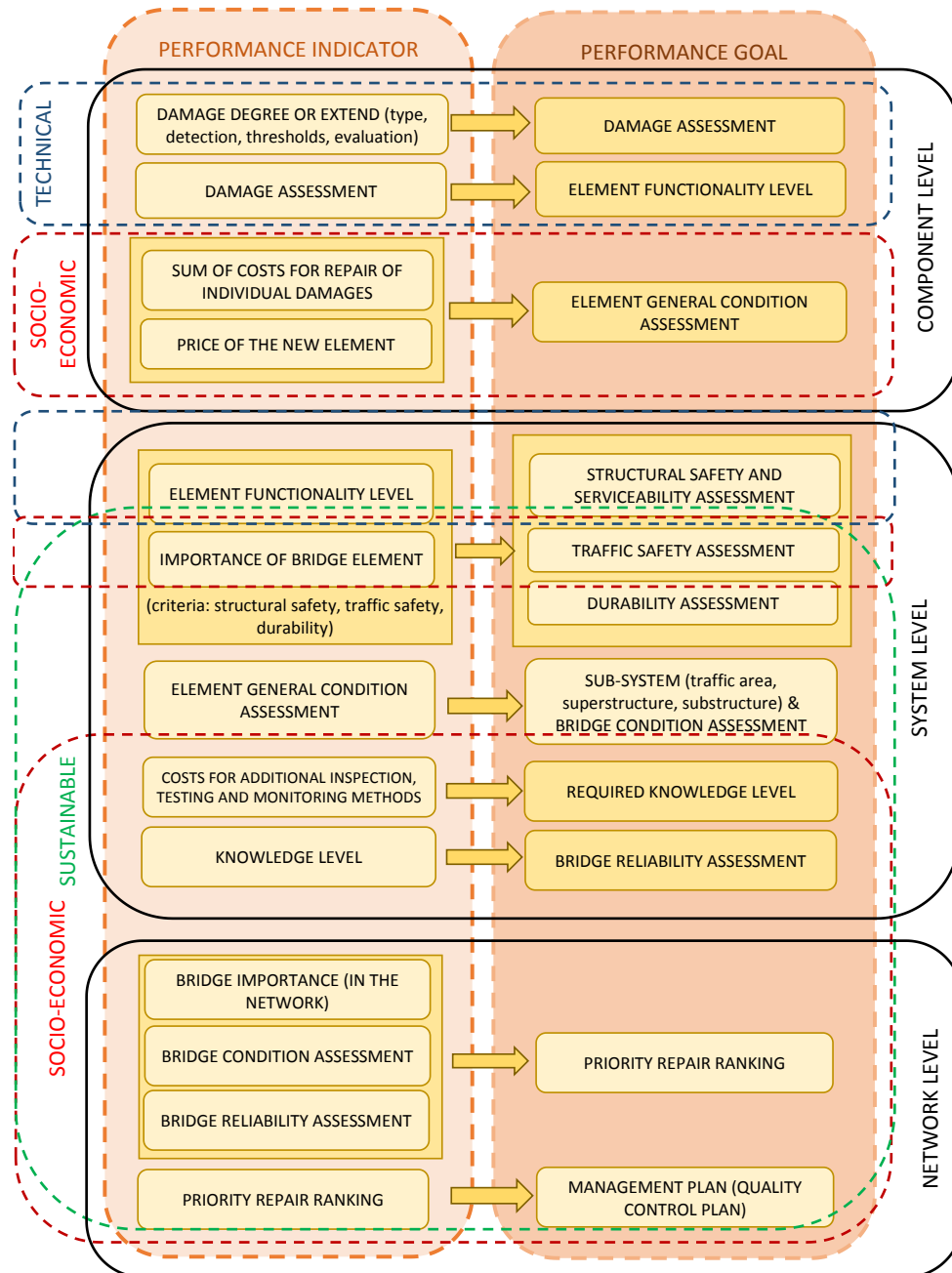


Fig. 1. Interaction of performance indicators and performance goals

#### 4 Performance indicators at the network level

At the network level, based on the bridge condition assessment gained through standard inspection and evaluation procedures with additional evaluation of bridge importance in the network, the primary goal to be reached is priority repair ranking.

Bridge condition assessment based on four criteria: structural safety and serviceability, durability, traffic safety and general bridge condition, may be contemplated as sustainability indicators at the network level. On the other hand, bridge importance in the network, which is based on five criteria - road category, annual average daily traffic, detour distance, largest span, total length - may be considered as socio-economic indicator. Criteria related to bridge condition are based on damage assessment procedure overviewed in this paper based on existing inspection and evaluation documents. The first three criteria related to bridge importance - road category, annual average daily traffic and detour distance - are mutually independent and equally important for decision on bridge importance. Criteria of the largest span and criteria of the total length describe the common demands on the construction and property value and therefore their importance in total may be considered as equal to other criteria. Criteria are reduced to the comparable values with the help of preference functions and adequate threshold of



indifference and preference for each criteria (Croatian highways ltd. 2008). At this level indicators related to scientific achievements such is bridge reliability assessment, should be continuously developed from previous level and included into priority repair ranking.

Priority repair ranking, at the same time, is essential indicator for final goal: optimal management plan of roadway bridges, which is to be evaluated through decision ranking (by power and weakness of decisions).

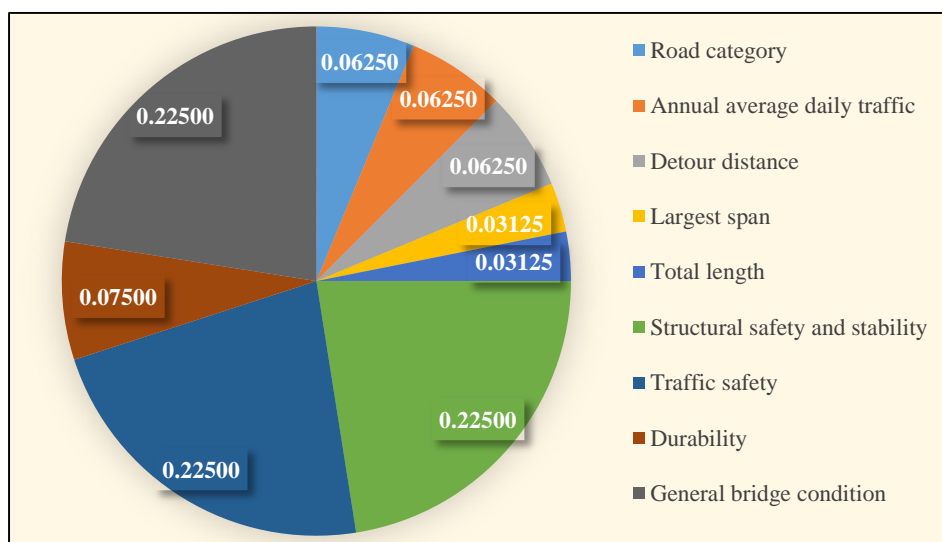


Fig. 2. Example of weight of performance criteria for performance goal - priority repair ranking

## 5 Performance indicator Data Base from an European perspective

One of the main objectives in the COST TU 1406 action is to build a performance indicator data base that supports in the objectives of WG2 to WG3. This process included (a) a survey process through understanding regarding performance indicators / goals / thresholds etc. among the participants of the COST action, (b) the creation of a glossary associated with the components, damages, performance of bridge structures, (c) the screening of national inspection and evaluation documents (see Fig. 3) with respect to performance- indicators, thresholds, goals etc. and (d) the definition of the structure of the performance indicator database, as shown in Fig. 4. (see also Casas 2016, Strauss et al. 2016, Strauss and Mandic Ivankovic 2016).

Country	Document	Doc. Type	Author	Year
Austria	Quality Assurance for Structural Maintenance - Suveillance, Checking and As	Inspection	BMVIT	2011
Bosnia and Herz.	ZAKON O CESTAMA FEDERACIJE BOSNE I HERCEGOVINE / LAW ON ROADS OF	Inspection	Parlament Federacije BiH / Federation Parli	2010
	Odluka o kategorizaciji cesta u autoceste i brze ceste, magistralne ceste i re	Inspection	Vlada FBiH / Government of FBiH	2014
	Pravilnik o održavanju javnih cesta / Regulations the maintenance of public	Inspection	Federalnom ministarstvu prometa i komun	2010
	SMJERNICE ZA PROJEKTOVANJE, GRAĐENJE, ODRŽAVANJE I NADZOR NA CE	Inspection	RS-FB&H/3CS – DDC	2005
	UPUTSTVO ZA INSPEKTORE MOSTOVA / INSTRUCTIONS FOR INSPECTORS OF	Evaluation	BCEOM Societe Francaise D'Ingenere	2004
	MOSTOVI / BRIDGES	Research	Prof. Boris Kobojević, Prof. Bisera Kara	1994
	Inspekcijski formular za pregled mosta / The inspection form for an overvie	Inspection	Prof. Bisera Karalić-Hromić	2004
Croatia	Handbook of damages on bridge elements	Evaluation	Hrvatske ceste d.o.o., dr.sc. Danijel Tenžera	2014
	Guidelines for bridge inspections	Inspection	Hrvatske ceste d.o.o.	2014
	HRMOS manual – Bridge management	Inspection	Hrvatske ceste d.o.o.	1999
	HRMOS manual – Bridge management – General bridge inspection	Inspection	Hrvatske ceste d.o.o.	1999
	Handbook of damages on bridges	Inspection/evaluati	Hrvatske Autocese d.o.o.	2010
	Guideline for bridge evaluation	Evaluation	Hrvatske Autocese d.o.o.	2010
	Bridge Management Planning	Background docume	Hrvatske Autocese d.o.o.	2008
Czech Republic	ČSN 73 6221 Inspection of road bridges	Inspection	UNMZ Ústav pro technickou normalizaci, mé	2011
	ČSN 73 6222 Load capacity of road bridges	Evaluation	UNMZ Ústav pro technickou normalizaci, mé	2009
	Catalouge of the bridge damages and defects	Inspection	Pontex spol. s r.o.	2008
	TP72 Diagnostics of road bridges	Inspection	Pontex spol. s r.o.	2008
	TRP201 Measuring and monitoring of the cracks in the concrete bridges	Inspection	CTU in Prague, Klokner institute	2008
	ČSN 73 6209 Load tests of bridges	Evaluation	UNMZ Ústav pro technickou normalizaci, mé	1996
	Damages of railway bridges	Inspection	SŽDC TÚDC	2009
	Rules for the assesment of the load capacity of railway bridges	Evaluation	SŽDC TÚDC	2014
	SŽDC S5 management of bridges(railway)	Inspection	SŽDC TÚDC	2012
	TP120 Maintenance, repairs and refurbishment of concrete road bridges	Inspection	Pontex spol. s r.o.	2010
	TP175 Evaluation of the remaining life of concrete road structures	Evaluation	SVUOM s.r.o.	2006
	TP215 The application of the modal analysis for the road bridges evaluation	Evaluation	CTU in Prague, Faculty of civil eng.	2009

Fig. 3. Cutout of codes and guidlines used for the performance indicator database



## Structural behaviour of stone arch bridges

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**Abstract.** This paper is part of the studies of the StoneArcRail project aimed at the experimental and numerical characterization of the structural behaviour of stone arch bridges. The project focused on the analysis of the vibration effects caused by railway traffic and the evaluation of the influence of traffic loading parameters on the bridge behaviour and assessment of structural and track safety and users comfort. The study involves a few bridge cases which can be considered representative of the most common and important typologies of masonry bridges in service in the national railway network.

**Keywords:** stone arch bridges; experimental assessment; model calibration; numerical modelling

### 1 Introduction

The interest in study the structural behaviour of stone masonry arch bridges relates to the fact that currently there are a considerable number of cases of this type of bridges in operation in the rail and road infrastructures and many of them with several years of age (Olofsson *et al.*, 2007). The need of identifying operating limits of masonry arch bridges within the national railway network is also recognized by the public body responsible for the Portuguese infrastructures' network (IP-Infrastructures of Portugal; ex-REFER). In this context, this project aimed at contributing to, yet not solving, the following open issues: identification of exploitation limits (loads and train speeds) for in-service masonry arch bridges; establishing safety and comfort criteria, specifically adapted for this type of bridges; definition of measures to mitigate the effects caused by train-induced vibrations in the masonry arches which can be considered the first key structural elements of these bridges.

In order to accomplish these objectives, the study was based on three bridge cases focused on the following main streamlines: a broad experimental campaign on a bridge case study with just one arch (Fig. 1a), about 8 m span, located at PK124 of the Minho line, near São Pedro da Torre (next to the North Portugal-Spain border, close to Valença) complemented by detailed numerical modelling; a more restricted experimental campaigns and less detailed numerical modelling of two other larger bridge cases involving several arches, though with different longitudinal and height wise characteristics, namely the Durrães bridge (Fig. 1b), still in the Minho Line, and the Côa bridge (Fig. 1c) in the Beira Alta Line towards the Vilar Formoso East Portugal-Spain border.



**Fig. 1.** Case studies: a – PK124 bridge; b – Durrães bridge; c – Côa bridge

### 2 Experimental assessment

The experimental component of the project comprised testing activity in-situ and in lab, and the corresponding result analysis. The objective was to obtain realistic data from in-situ and lab tests, feeding the bridges' numerical models, both detailed and more simplified ones, all duly calibrated based on experimental measurements. One freight railway vehicle was also tested aiming for the identification of vehicle modal parameters.

## 2.1 Geometric survey

The geometric characterization of the bridges was based on laser scanning survey and Ground Penetrating Radar tests (GPR) performed on two of the bridge cases, namely the Durrães and PK124 bridges, as well as visual inspections and details from the design drawings available for all bridge cases. GPR tests were made in order to deeply understand the bridge geometry, including the facing stones' thickness in piers, abutments and spandrel walls, and study the properties of foundations. In addition, four penetrometer Dynamic Probing Super Heavy tests (DPSH) were performed at ground level of Durrães bridge at the same locations where GPR tests were done in order to correlate the results from both test types. The results of both GPR and DPSH tests shown good correlation allowing estimating the depth of the firm of the Durrães bridge (Arêde *et al.*, 2015) which is close to 10 m in location of 3 tests (corresponding to the zones of the arches 3-to-8) and close to 4 m in the location of test 4 (corresponding to the zone of the arch 13).

## 2.2 Dynamic tests

Dynamic tests were made allowing identifying modal properties of the bridges, particularly, natural frequencies, vibration modes and damping coefficients. For Durrães and Cõa bridge ambient vibration tests were made, while for the PK124 bridge forced vibration tests were adopted due to the poor signal provided from ambient vibration. Forced vibration was induced using a structural exciter materialized by a mechanical device, provided with a mass of approximately 130 kg suddenly released at 1.50 m high. The tests on Durrães bridge involved 32 points of measurement (Fig. 2a) allowed identifying 11 vibration modes, characterized by their frequencies (from 1.851 to 5.916 Hz), damping ratio and mode shapes (six of them shown in Fig. 2b, Costa *et al.*, 2014), obtained by the enhanced frequency domain decomposition method (EFDD) available in ARTeMIS® software. The same was done for Cõa bridge, allowing characterizing 7 vibration modes in the frequency range between 1.14 and 7.75 Hz (Costa *et al.*, 2013 and Jorge *et al.*, 2016). For PK124 bridge 8 vibration modes were obtained with frequencies from 10.45 to 32.12 Hz, using both output-only and input-output data analysis methods (Costa *et al.*, 2015a).

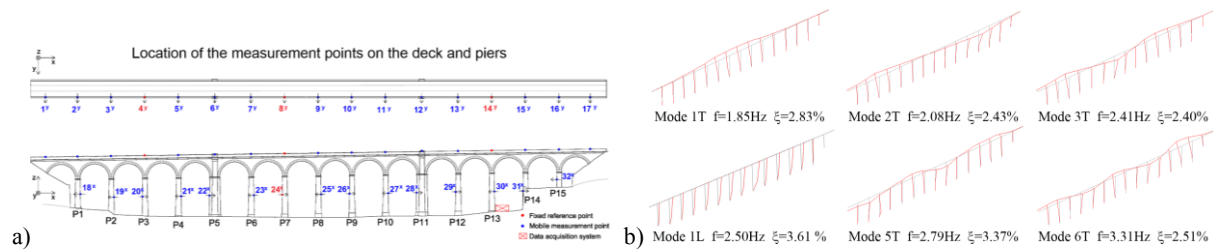


Fig. 2. Modal identification of Durrães bridge: a – test setup; b – modal parameters

Forced vibration tests made on a freight railway vehicle provided acceleration outputs from which the identification of vehicle modal parameters was carried out through the EFDD method, both in loaded and empty vehicle conditions. For the former, 6 natural vibration modes were obtained (2.69 Hz to 8.11 Hz) while for the later condition (empty) 11 modal parameters were captured with frequencies between 3.42 Hz and 26.49 Hz.

## 2.3 Material testing

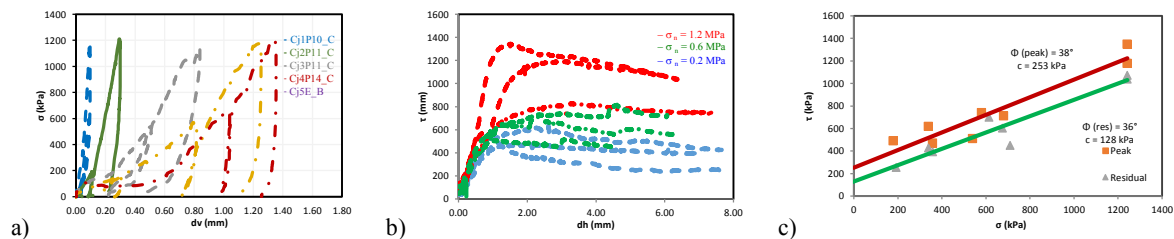
The experimental campaign involved in-situ activities, including flat-jack and Ménard pressuremeter tests carried out for PK124 and Durrães bridges and lab tests performed on the collected samples (Arêde *et al.*, 2015). For the lab tests, cores were drilled and samples were extracted from points that wouldn't compromise the bridge aesthetics and resistance, yet allowing a good characterization of the different components. Stone and stone-to-stone block joint samples were taken at the surface of piers, spandrel walls and abutments. The corresponding boreholes were used for the pressuremeter tests.

The flat-jack technique was successfully used as a non-destructive option to characterize in-situ vertical stress and deformation of the masonry structure. However, the difficulties found in applying this technique to large masonry blocks (0.5 m high, Fig. 3a) and joints of reduced thickness (1-2 mm) involving high axial loads, allowed exploring the very limits of this type of test (which is not usual for the tested masonry type) thus yielding results that must be carefully explored. The tests with Ménard pressuremeter led to good results for mechanical parameters of the infills. The adoption of this technique in horizontal boreholes (Fig. 3b), with materials stronger than common soils, was a challenging alternative use of this type of equipment; nevertheless, the results have shown good applicability of this technique to the study of these materials. The experimental results in terms of the range of average values of masonry and infill deformability obtained in-situ with flat-jacks and pressuremeter tests are included in Fig. 3c.



**Fig. 3.** In-situ material testing: a – flat-jacks; b – pressuremeter test; c – estimated deformability results

Concerning lab tests, cyclic compression tests were carried out, enabled to record the evolution of compressive stress with the vertical displacement and evaluate the variation of the joint normal stiffness caused by successive loading-unloading cycles (Fig. 4a). As for behaviour of masonry joints in the tangential direction, shear tests were made in a shear-test box machine, by applying a normal constant pressure at three different levels (0.2, 0.6 and 1.2 MPa), from which results were obtained in terms of peak and residual shear strength and elastic stiffness (Fig. 4b). Based on normal and shear peak and residual strength values, Mohr-Coulomb envelopes were determined for both peak and residual conditions (Fig. 4c). The results shown Fig. 4 were obtained for Durrães bridge. The normal and shear stiffness obtained for joint samples of PK124 and Durrães bridges are summarized in Table 1.



**Fig. 4.** Stone-to-stone joints behaviour of Durrães bridge samples: a – normal stress vs. vertical displacement; b – shear stress vs. horizontal displacement; c – Mohr-Coulomb failure envelope

The range values obtained for the stone mechanical characterization which comprised the determination of the compressive and tensile strength and Young modulus, using standard testing, are included also in Table 1. The results obtained with the tests permitted a detailed characterisation of the constituent materials of the bridges and thus the values obtained for the mechanical properties have been used in numerical simulation.

**Table 1.** Physical and mechanical parameters of masonry joints and granite stone blocks

	Normal stiffness MPa/mm	Shear stiffness MPa/mm	Compressive strength MPa	Tensile strength MPa	Young modulus GPa
Durrães	0.83-1.8	0.63-0.83	34.8-59.4	3.7-5.4	20.0-23.5
PK124	0.5-2.5	0.07-0.63	35.9-81.4	2.3-5.2	6.8-10.9

### 3 Numerical modelling

The numerical study was focused on definition and calibration of numerical models for the three bridges and two considered trains, one freight train and another passenger train. Both, finite element method (FEM) and discrete element method (DEM) were used to perform the structural analysis resorting to usual commercial computer codes, namely the FEM based CAST3M® and ANSYS®, and the DEM based UDEC® and 3DEC®.

#### 3.1 FEM based continuous models

For the three bridges, FEM based models (Fig. 5) were developed considering elastic materials. For typically non-homogeneous bridge materials such masonry and infills, equivalent homogeneous and continuous materials were considered with linear elastic mechanical properties duly calibrated based on the test results reported in Section 1. Based on first estimates of material parameters bounded by experimental data, numerical modal configurations



were obtained and compared with experimentally obtained ones, in terms of frequency and Modal Assurance Criteria (MAC) values. In order to improve matching of numerical and experimental modal results, an existing calibration procedure was adopted, based on the ambient vibration test results and involving two stages: a sensitivity analysis (to select the most influencing parameters) and an optimization process (mainly involving as optimizing variables, the parameters selected in the sensitivity analysis).

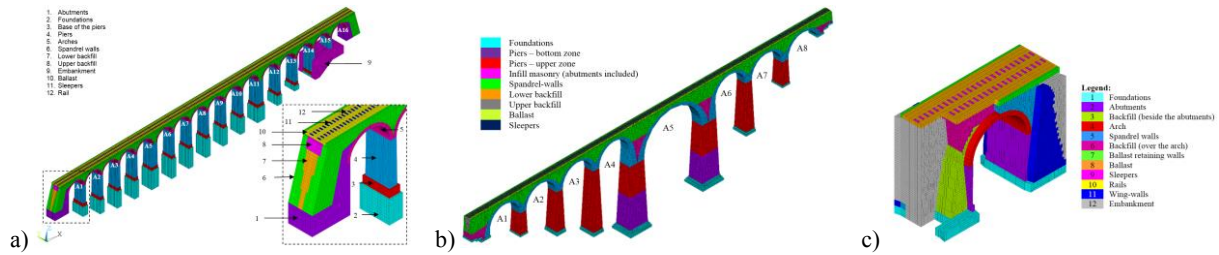


Fig. 5. FE global models: a – Durrães bridge; b – Côa bridge; c – PK124 bridge

The calibration methodology consisted on an iterative method based on genetic algorithms, originally developed by Ribeiro (2012) and used with quite good results also in the bridge models of Durrães (Costa *et al.*, 2014), Côa (Costa *et al.*, 2013 and Jorge *et al.*, 2016) and PK124 (Costa *et al.*, 2015). These calibrated numerical models were then used for the bridges' dynamic analyses, wherein train-bridge interaction was also considered.

### 3.2 Detailed FEM and DEM based discrete models

Further detailed FEM and DEM modelling strategies, already used with good results in other previous studies (Costa *et al.*, 2015b, 2015c), were developed for PK124 bridge to allow performing more refined analyses wherein the non-linear behaviour was considered for assessing load carrying capacity of the bridge under incremental static loads. The masonry bridge components (arches, spandrels, abutments and backfill behind abutments) are represented by micro modelling strategies, in the case of FE models (Fig. 6a) using solid elements to define the individualized blocks and joint elements at their interfaces (stone-to-stone joint type) and in the DE models (Fig. 6b) using deformable blocks and nonlinear contacts. The backfill is also modelled with solid elements or deformable blocks connected to joint elements (in FE models) or contacts (in DE models) in the interfaces between the infill and stone masonry, with different characteristics for the infill-to-stone joint type.

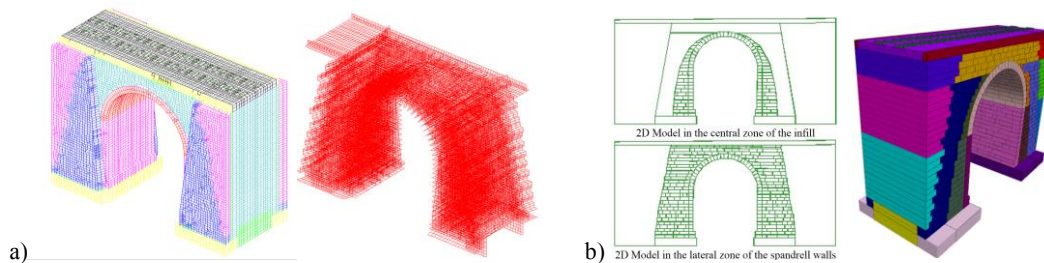


Fig. 6. Detailed models of PK124 bridge: a – 3D FE model (solid and joint elements); b – DE models (2D and 3D)

For comparative purposes, and to achieve better confidence on the results of load carrying capacity, similar constitutive models and material parameters were defined in both FE and DE models. Thus, the contact elements are controlled by a nonlinear Mohr-Coulomb friction model without dilatancy and the Drucker-Prager model is used to represent the infill material behaviour. The stone blocks were considered with linear elastic behaviour. The values the elastic parameters of blocks, joints and infill materials were defined based on the material tests and modal identification results presented in Section 2, while stress-displacement curves to define the nonlinear constitutive models were based on material behaviour recorded in material testing.

## 4 Numerical assessment

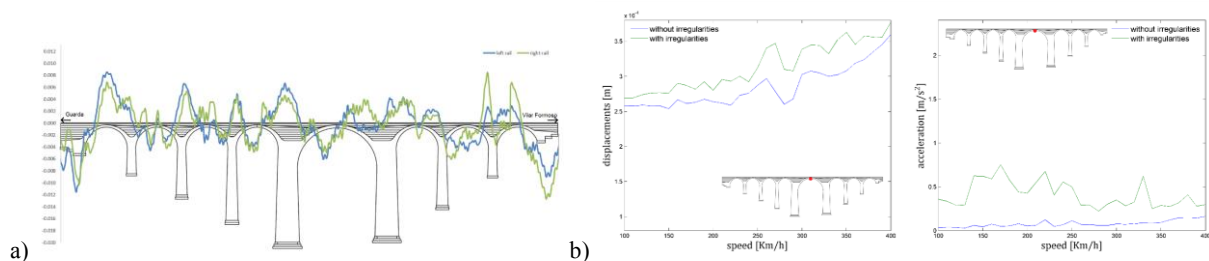
The numerical part of the project aimed at addressing the behaviour assessment of both the bridges and the trains, due to the dynamic effects caused by interaction between them and by track irregularities, as well as the assessment of the limit loading applied statically on the bridge models.

### 4.1 Dynamic effects

The dynamic responses were derived from TBI software (Ribeiro *et al.*, 2012) developed in Matlab® which efficiently performed the dynamic analyses considering the train structure interaction and including track



irregularities. The software uses the modal superposition method for solving the dynamic equilibrium equations of the bridge, and a direct integration method (Newmark method) for the train. The dynamic analyses were made considering the two simulated trains, passenger (Alfa-Pendular) and freight ones. This allowed obtaining bridges' accelerations, displacements and strains, as well as accelerations in train vehicles, in order to assess passenger comfort or stability of the carried load (in freight trains). Train speed ranges were assumed as 100 to 400 km/h and 80 to 220 km/h, respectively for the passenger and freight trains. The track irregularities were obtained based on records provided by the track inspection. Fig. 7a illustrates the longitudinal levelling profiles of the C  a bridge. These records consider the contributions related to wavelengths between 3 and 70 m. The maximum amplitude equal to 12.7 mm appears essentially at the abutments of the bridge. For the Durr  es and PK124 bridges, considering the freight train action, there were no vertical accelerations exceeding the code-standard limit ( $3.5 \text{ m/s}^2$ ) for the assumed speed range. For the C  a bridge loaded with the passenger train, this limit is reached in several locations at 220 km/h of speed. Fig. 7b shows the vertical response at the centre of the principal arch in terms of displacements and accelerations for the range of speed considered in the dynamic analysis. The contribution of 83 vibration modes for the response of the bridge, with frequencies between 1.09 and 30 Hz, was considered in this bridge analysis. The time step of the analysis was equal to 0.001 s. The adopted values of the damping coefficients were equal to the values of those obtained from an ambient vibration test (Jorge *et al.*, 2016).

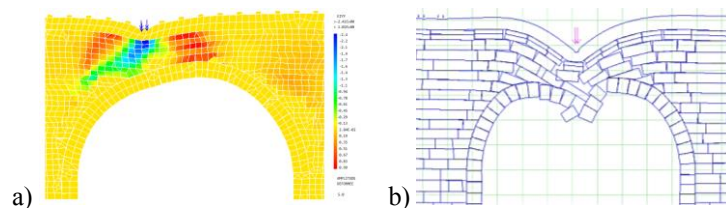


**Fig. 7.** Numerical results of the C  a bridge: a – longitudinal levelling profiles of the left and right rail; b – vertical response at the centre of principal arch A5 in terms of displacements and accelerations

Regarding the effects on the studied vehicles, the freight one reached high acceleration values; however, since no information is available on code-standard limit acceleration values for freight vehicles, no explicit conclusion can be drawn thereof. As for the passenger train in the C  a bridge, high accelerations are also obtained such that, according to applicable code-standard (EN1990-Annex A2) limits of vertical acceleration in the passenger car body, for very good passenger comfort level the speed limit at which the train can run is 120 km/h, while for good and satisfactory comfort levels the speed limit is 160 and 240 km/h, respectively.

## 4.2 Load carrying capacity

Aiming for the evaluation of the maximum load applied statically on the on the detailed models of PK124 bridge (presented in Section 3.2), the most unfavourable train positions (passenger and freight) were obtained so as to induce the arch failure associated with the formation of hinge mechanisms, which were evaluated on the basis of global FE analysis under moving loads presented in Section 4.1. Then, for the same train positions, increasing load levels were considered in order to obtain the final collapse load. The analyses of such models' response, throughout the incremental load history, allowed identifying the damage evolution in bridge models associated with masonry joint opening and sliding as well as infill material yielding as shown in Fig. 8a. Fig. 8b shows the deformed configuration of the DE models after the maximum intensity level 10 of the freight train was reach which correspond to the maximum load applicable on the DE model satisfying the equilibrium conditions.



**Fig. 8.** Numerical results of PK124 bridge: a – plastic deformation distribution (%) on the infill FE 2D model for the vehicle intensity level of 5; b – deformed configuration of the 2D DE model after the maximum intensity level of 10

It was found that very high values are required for the load factor of the nominal train loading in order to develop a collapse mechanism in the bridge. The analysis of the 3D models allowed evaluating the bridge response under the action of the freight train loading until the intensity level of 10P without the formation of any hinge in the arch. For the 2D DE models the maximum multiplier applied with the Alfa-pendular loading was 70 and for the freight train loading the value of the multiplier was 10.

## 5 Conclusions

The previous sections focused on a research project aiming at assessing the structural response of stone arch bridges under traffic loadings based on experimental and numerical studies. A comprehensive experimental campaign, including laboratory and in-situ tests, was performed on three bridges in operation in the Portuguese railway network. Material testing and in-situ dynamic identification tests have been used as complementary techniques, thus allowing merging the results obtained from in-situ and laboratory sample testing with the results drawn from global testing of the whole structure. The numerical study involved modelling strategies suitable for the simulation of the dynamic response of the bridges under the traffic loading as well as for the simulation of the load carrying capacity.

## Acknowledgements

This work includes research conducted with the financial support of FCT through the PTDC project/ECM-EST\_1691/2012-Experimental and Numerical Characterisation of the Structural Behaviour of Arch Stone Masonry Bridges under the Action of Railway Traffic - Application to Portuguese Existing Bridges (StonArcRail). The authors thank engineers Ana Silva, Hugo Patrício and Nuno Lopes from IP-Infrastructures of Portugal for all their collaboration and the information provided on the bridges and professors Rui Calçada, Diogo Ribeiro, José Meneses, António Gomes and Rui Gonçalves and engineers Pedro Jorge, Ruben Silva, Maria Morais and Nuno Pinto and Mr. Valdemar for all their collaboration as members of the researcher team.

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## Forecasting of performance indicators

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**Abstract.** State of the art Bridge Management Systems generally comprise a deterioration model to predict condition development and a preservation optimization model to determine the optimum preservation policy. The condition of the bridge elements is revealed through visual inspections and usually evaluated using a discrete scale. For modeling the uncertain progress through the discrete condition scale used for bridges, a Markov chain model is the reasonable choice. Furthermore, the popularity of Markov Chains in the Bridge Management is based on the ability to obtain preservation policies for each element using the Markov Decision Process. To predict future performance, given that performance indicator is represented through a qualitative discrete scale, Markov Chain model can effectively be used. Brief review of Markov process for modeling bridge elements deterioration is given and similar model to forecast performance indicators is proposed.

**Keywords:** Bridge Management Systems, deterioration model, Markov process.

### 1 Introduction

Bridge Management Systems (BMS's) are established to support agencies to track and forecast the condition of bridges in inventory and to plan maintenance, rehabilitation, and replacement activities on bridges. To fulfill that goal state of the art Bridge Management Systems comprise a tightly coupled deterioration model, to predict condition development, and a preservation optimization model, to determine the optimum preservation policy.

The importance of the deterioration model in BMS should not be underestimated. In practice, mathematical models, used to predict the deterioration (or the future condition state), can be classified into two groups: deterministic models and stochastic models. Analytical models for deterioration based on actual physical and chemical processes involved in deterioration are rather complex including various uncertainty. On the other hand, available historical records about bridge elements condition, stored in bridge inspection databases, can be used to formulate stochastic model based on statistical methods.

A deterioration model in bridge management is not an end in itself but rather an essential ingredient for planning maintenance interventions. The popularity of Markov process, for modeling condition development, in Bridge Management is based on the ability to obtain preservation policies for each element using the Markov Decision Process by the means of linear program.

### 2 Markov process

A Markov process allows modeling the uncertainty in many real-world systems that evolve dynamically in time. The field of their application includes biology, computer science, engineering, operations research, game theory etc.

The basic concepts of a Markov process are those of a state and of a state transition. Markov process is a stochastic process distinguished by Markovian property that states that knowledge of the present state is sufficient to predict the future stochastic behavior of the process (the future states/performance are independent of the history of the state/performance). There are four basic types of Markov processes: discrete-time discrete-state (Markov chain), continuous-time discrete-state, discrete-time continuous-state and continuous-time continuous-state. The first one, Markov chain model is extremely useful in wide variety of practical problems, despite (or maybe thanks to) its very simple structure.

When value of performance indicator can be discretized in countable number of states, discrete state Markov process is a reasonable choice. Such discretization is detected in most of the manuals for visual inspection containing photos and descriptive aids to help the inspectors to classify the observed damages.

An example of state discretization is shown in figure 1, representing various stages of corrosion.

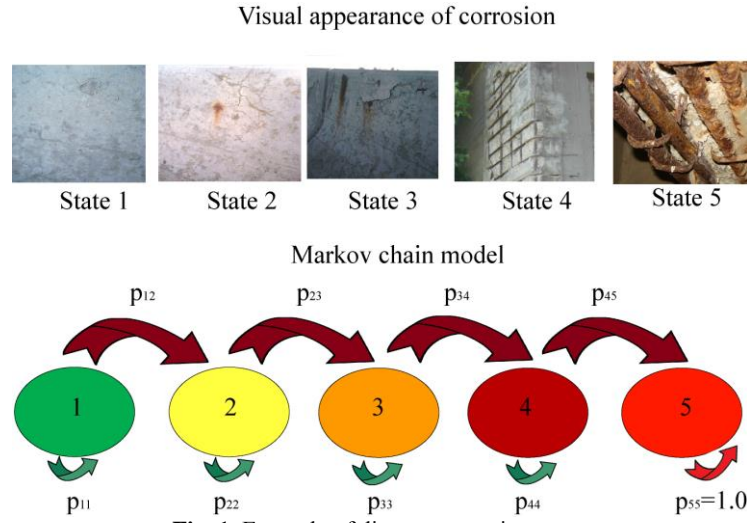


Fig. 1. Example of discrete corrosion states

For the time discretization, the simplest way is to choose the unit time step,  $\Delta t$ . Time step is usually chosen in agreement with the phenomena of interest. It seems reasonable to choose a year time step to describe development of bridge state/performance.

## 2.1 Markov chain

Transition between states in each time step occurs with probability  $p_{ij}(t)$  that generally depends on time. When transition probabilities do not depend on time (in every time step the probability of transition from state  $i$  to state  $j$  is the same), the process is called stationary and the Markov chain is homogeneous ( $p_{ij}(t) = p_{ij}$ ). It is usual to express the state transition probabilities as the entries of a  $k \times k$  transition matrix  $\mathbf{P}$  (where  $k$  is the number of discrete states). The form of the matrix can be simplified since it is accepted that deterioration is a one-way process. Since improvement of the condition cannot be achieved without maintenance all elements which indicated a backward process are assumed to be zero. Furthermore it is commonly assumed that an element can only either stay in its current state or move to the next state in one time step. This is based on having relatively long expected lifetimes (e.g. 75 years) compared with the model's time step (e.g. one year). The "failure" state, labeled by an integer  $k$  in Eq (1), presents an absorbing state in deterioration model.

With these assumptions, a one-year transition probability matrix for a homogeneous Markov chain, with  $k$  states, takes the form - Eq (1):

$$\mathbf{P} = \begin{bmatrix} p_{11} & p_{12} & 0 & \cdots & 0 \\ 0 & p_{22} & p_{23} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & 0 \\ \cdots & \cdots & 0 & p_{k-1,k-1} & p_{k-1,k} \\ 0 & \cdots & \cdots & 0 & 1 \end{bmatrix}, \quad (1)$$

The time that the process spends in the each condition state prior to transition is known as the sojourn time in this condition state. Homogeneous Markov chain assumes that the sojourn time in one state before transitioning to another follows an exponential distribution for continuous-time or a geometric distribution for discrete-time. Expected value of the sojourn time in state  $i$  before the transition in state  $j$ , for discrete-time homogeneous Markov model is given by:

$$E(\tau_{i,j}) = \frac{1}{p_{i,j}}, \quad (2)$$

where  $E(..)$  – indicates expected value;  $\tau_{i,j}$  – sojourn time in state  $i$  before the transition in state  $j$ , years;  $c - p_{ij}$  transition probability from state  $i$  to state  $j$  in time step.

It is obvious that Eq (2) is quite useful in obtaining transition probabilities for discrete-time homogeneous Markov chain based on the expert's judgments. Recently several methods were proposed for estimation transition probabilities using available historical data obtained by visual inspections. Nevertheless, the model can be updated when the new data becomes available.

### 2.1.1 Forecasting condition state using Markov chain model

The transition probabilities  $p_{ij}$  are one-step transition probabilities. The  $n$ -step transition probabilities ( $p(n)_{ij}$ ) are a conditional probability of the Markov chain transition from state  $i$  to state  $j$  after  $n$  time steps (commonly – years). Transition probability matrix, after  $n$  time steps is simply calculated as  $n$ -th power of one step transition matrix. Calculation of condition distribution at integer value of time steps  $Q^{(n)}$  ( $t = n$  years), is quite simple, given the initial state vector at time  $t=0$  is  $Q^{(0)}$  - Eq (3).

$$\begin{aligned} Q^{(n)} &= Q^{(0)} \cdot P^n, \\ Q^{(0)} &= \{ q_1^{(0)}, q_2^{(0)}, q_3^{(0)}, \dots, q_k^{(0)} \}, \end{aligned} \quad (3)$$

where  $q_i^{(0)}$  is the percentage of elements in state  $i$  at time  $t=0$  / probability that the element is in state  $i$  at time  $t=0$ .

For example, if the process starts from the best condition (new bridge/element) initial state vector is:

$$Q^{(0)} = \{ 1.0, 0.0, 0.0, \dots, 0.0 \}, \quad (4)$$

## 2.2 Semi Markov model

Markov chains models are often criticized in the literature because they fail to reflect that the transition probability is likely to increase with the sojourn time spent in a given condition state. Indeed, it sounds reasonable that the probability of staying in the same state decreases in the course of time. To improve the model semi Markov process has recently received interest in infrastructure management.

Similar to Markov process, semi-Markov process makes transitions from state to state but the sojourn time in each state is an arbitrary random variable and its distribution is governed by the next state the process will enter. In that sense, Markov processes is a special case of semi Markov process which assumes that the sojourn time in one state before transitioning to another follows an exponential distribution for continuous-time and a geometric distribution for discrete-time. The conditional sojourn time in state  $i$ , given that the process goes to the next state  $j$  is denoted by  $T_{ij}$ , which is a random variable. For semi Markov bridge elements deterioration model the second index can be omitted since an element can only either stay in current state or move to the next worse state, so, random variable  $T_i$  presents the sojourn time in the state  $i$ . It was suggested to adopt Weibull distribution, which is able to model a range of shapes by varying just two parameters, for sojourn time  $T_i$  in condition state  $i$ :

$$f(t_i) = \frac{\beta_i}{\mu_i} \left( \frac{t_i}{\mu_i} \right)^{(\beta_i-1)} e^{-\left( \frac{t_i}{\mu_i} \right)^{\beta_i}}, \quad (5)$$

where  $f(t_i)$  - Weibull distribution of random variable  $T_i$ ;  $\beta_i$  – shape parameter of Weibull distribution of  $T_i$ ;  $\mu_i$  – scale parameter of  $T_i$ .

Expected value of sojourn time in state  $i$  is:

$$E(T_i) = \frac{\mu_i}{\Gamma\left(1 + \frac{1}{\beta_i}\right)}, \quad (6)$$

where  $\Gamma(..)$  – is the gamma function.

### 2.2.1 Forecasting condition state using semi Markov model

In comparison with Markov chain mode, calculation of condition state distribution in any instance of time  $t$ , pose significant mathematical complexity when semi Markov model is used. It involves convolution integral/sum (Ibe, 2009.). The program was written in Wolfram Mathematica in other to estimate condition state distribution of semi Markov process for this purpose (Mašović, Stošić & Hajdin, 2015).

### 2.3 Illustrative example

This simple example is intended to demonstrate the usage of Markov processes that were previously discussed. According to experts judgment expected value of sojourn time in corrosion state is adopted as in Table 1. Expected time to reach the “failure” state is a simple sum of expected values of sojourn time in all previous states. In this illustrative example it is 20.5 years, when starts in best condition state.

Transition probabilities assuming Markov chain model are than calculated (table 1.)

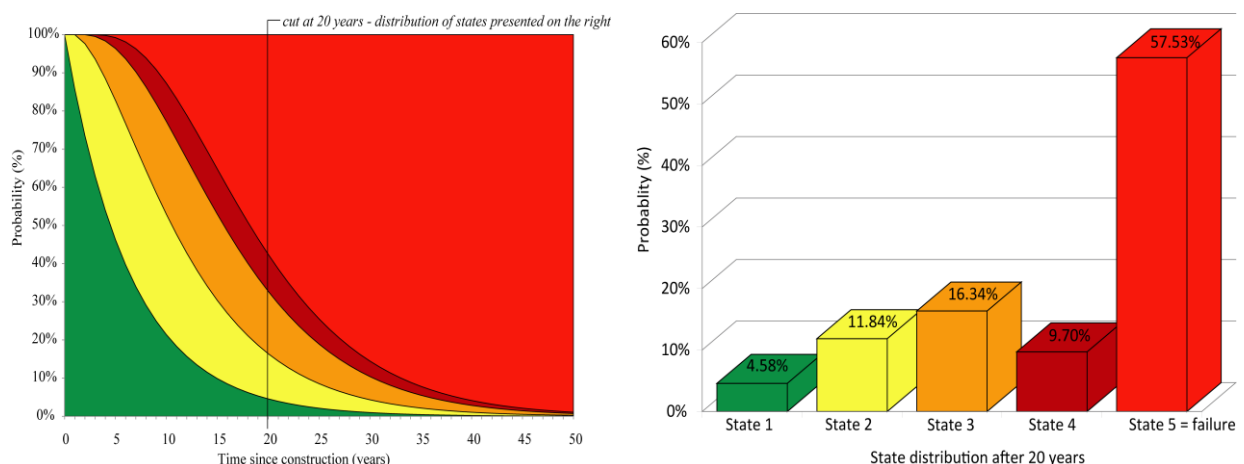
For semi Markov model Weibull distribution of sojourn time is used. The parameter  $\beta_1$  is chosen to be 2.0 to highlight that the probability of staying in the best state decreases in the course of time. For all other states exponential distribution is used as a special case of Weibull distribution when shape parameter  $\beta_i$  ( $i \neq 1$ ) equals 1.0. The scale parameters ( $\mu_i$ ) were calculated so that the mean value of the sojourn time in the condition states equals those obtained by experts election (Table1). This approach is justified since the dependency of transition probability on sojourn time in the best/initial condition state has been already modeled in literature with the Weibull survival function because it was observed, compare to the historical data, that geometrical distribution has fairly rapid initial deterioration.

**Table 1.** Characteristics of Markov and semi Markov model for corrosion states.

Corrosion state No.	$E(\tau_i)$ years	Markov model		Semi Markov model	
		$p_{i,i+1}$	$p_{i,i}$	$\beta_i$	$\mu_i$
State 1	7.00	0.14286	0.85714	2.00	7.89
State 2	6.00	0.16666	0.83333	1.00	6.00
State 3	5.00	0.20000	0.80000	1.00	5.00
State 4	2.50	0.40000	0.60000	1.00	2.50

Assuming that process starts from the best condition (new bridge/element) with appropriate initial state vector, Eq (4), distribution of states is calculated in course of time for both models.

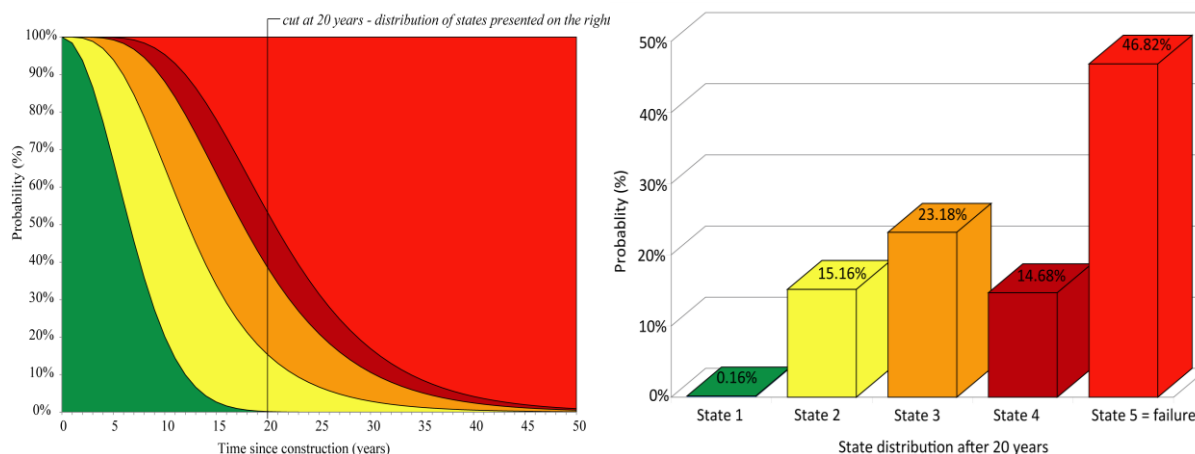
Distribution of states for Markov model is presented in Figure 2. It can be noticed (figure 2b) that in 20 years probability of failure is 57.53%. More interesting is that there is 4.58% probability that the element remains in the initial condition.



**Fig. 2.** Distribution of states in course of time for Markov chain model:  
a – deterioration curves; b – cut at 20 years – distribution of states at 20 years



Distribution of states for semi Markov model is presented in Figure 3. It can be noticed (figure 3b) that in 20 years probability of failure is 46.82% which is significantly smaller than for Markov model. On the other hand, probability the element remains in the initial condition is only 0.16%.



**Fig. 3.** Distribution of states in course of time for semi Markov model:  
a – deterioration curves; b – cut at 20 years – distribution of states at 20 years

To answer the question which model better fit the observed phenomena, data analysis from historical records should be undertaken.

### 3 Conclusions

In the paper stochastic model is proposed for forecasting performance indicators. This model is already successfully used in state of the art bridge management systems for prediction of the future condition state of bridge elements. Two types of Markov processes are described (Markov chain, and semi Markov model). Both models are data-driven so significant amount of data is needed to estimate parameters of sojourn time distribution, especially for semi Markov model. To overcome this problem, until the available historic data meet the need for a reliable estimation of sojourn time distribution, a large number of agencies are still using expert elicitation.

Although the semi Markov approach may seem more appropriate from a physical point of view, there is no strong evidence in its favor. There are rather significant obstacles for using semi Markov model: the absence of the memoryless property poses severe mathematical complexity especially for determination of optimum policy for finite time horizon.

### Acknowledgements

The work reported in this paper is a part of the investigation within the research project TR 36002 - The planning and management of transport and communications using the methods of computational intelligence, supported by the Ministry of Education and Science of the Republic of Serbia. This support is gratefully acknowledged.

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## Interface for collection of performance indicators for roadway bridges – STSM experiences

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**Abstract:** The ultimate goal of the COST TU1406 Action is to elaborate and standardize quality specifications for roadway bridges based on bridge performance indicators. The main tasks of the Work Group I is to carefully plan the procedure and conduct the process of the applied indicators' collection and classification. In this paper, the experience and work carried out during the two Short Term Scientific Missions is presented. In these missions the main tasks were related to setup and dissemination of the interface for collection of performance indicators. The main difficulties in screening of the relevant national documents and solutions for structuring the adequate interface features are explained. Here it was essential to elaborate the Tutorial to aid the interface users in the process of data screening. The process of interface testing and dissemination as well as feedback implementation was elaborated. Additional to applied, the research performance indicator database was introduced. After the interface was structured, the processes of its testing and dissemination were performed. By the end of the second scientific mission the feedback was received from 11 out of 34 COST participant countries, and the work of the authors continue on the analysis of the obtained results.

**Keywords:** Performance indicator database, Interface for data screening, quality specifications for roadway bridges

### 1 Introduction

The COST TU1406 Action aims to bring together, for the first time, both research and practice community in order to accelerate the establishment of a European guideline for quality specifications for roadway bridges based on bridge performance indicators (PI). The Action is divided into 6 Working Groups (WGs), with 34 European countries being represented.

The main tasks of WG1 is to collect, delineate and classify both applied and research performance indicators for roadway bridges. Thus, creating the path for the work of subsequent working groups. Shortly after assembling the Action, WG1 started with collection of all the documents envisaged for screening from different countries. The act of collecting documents started before the Geneva Workshop (Sept. 2015), until when more than 100 documents was collected. The starting idea was that the members of core group of WG1 screen all the documents and extract the key performance indicators (KPI).

Eventually, at the Geneva Workshop, the main concept for the key performance indicator database structure has been presented by the WG1 team. Based on the participants' suggestions at the workshop, the conclusions were drawn that the further work related to development of the KPI database should comprise the following tasks:

1. Elaboration of simple, user friendly interface to aid in the screening of the data from relevant national documents and elaboration of a tutorial for its application
2. Analyze/Control of the gathered data and consideration of the users feedback on the interface

These are the key tasks set before WG1, which were planned to be executed during the two Short Term Scientific Missions (STSM). The first STSM was performed by the WG1 team and N. Tanasic at the

Institut für Konstruktiver Ingenieurbau (IKI) at Universität für Bodenkultur Wien (BOKU) on the task one. Here, it was crucial to define and test the structure of an interface which in turn was going to be operated by the COST participant countries. The German document (Straßenwesen, Berichte der Bundesanstalt für Strassenwesen, 2015) and two Austrian documents (Bundesministerium für Verkehr, Innovation und Technologie a), 2011) and (Bundesministerium für Verkehr, Innovation und Technologie b), 2011) were used as starting points. The Tutorial, which comprised explanation of the interface concept and a few examples of data input, was prepared at the end of the first STSM.

The goal of the second STSM, performed by I. Zambon at the University of Minho, Guimarães in Portugal was related to the task two. Here it was of the outmost importance to provide constant assistance to the users of the interface and support screening of the relevant Portuguese documents. Following the end of the second STSM, the interface specifically for research documents was tailored. Also, the feedback from participating countries was recorded successfully. Finishing the second STSM, filling the interfaces was still in the process.

## 2 The Interface structure

The primary task of the STSM at BOKU comprised elaboration of a user interface that is going to be compatible for screening of KPI-s in any type of national document. The proposed concept of the interface, which enables free input, was to reveal the relationships between the key terms Performance Indicators/Methods/Index/Thresholds/Goals/Criteria, as some of these are not clearly defined in documents. The interface structure is set in MS Excel, which is presented in Figure 1. First, a user enters general data about the documents which are going to be screened (GeneralData\_sheet). The process of screening is performed in separate sheets (i.e. Cou\_1 sheet), where the main data structure is organized in the four groups: Performance Level, Damage, Performance Indicator/Index and Performance Assessment. Here, the input of data is realized row-by-row, following the chapters/paragraphs in a document, where the information for each data group is selected from the drop-down lists. Also, there is an opportunity to add additional references and specific information about the elements in groups and their evaluation process.

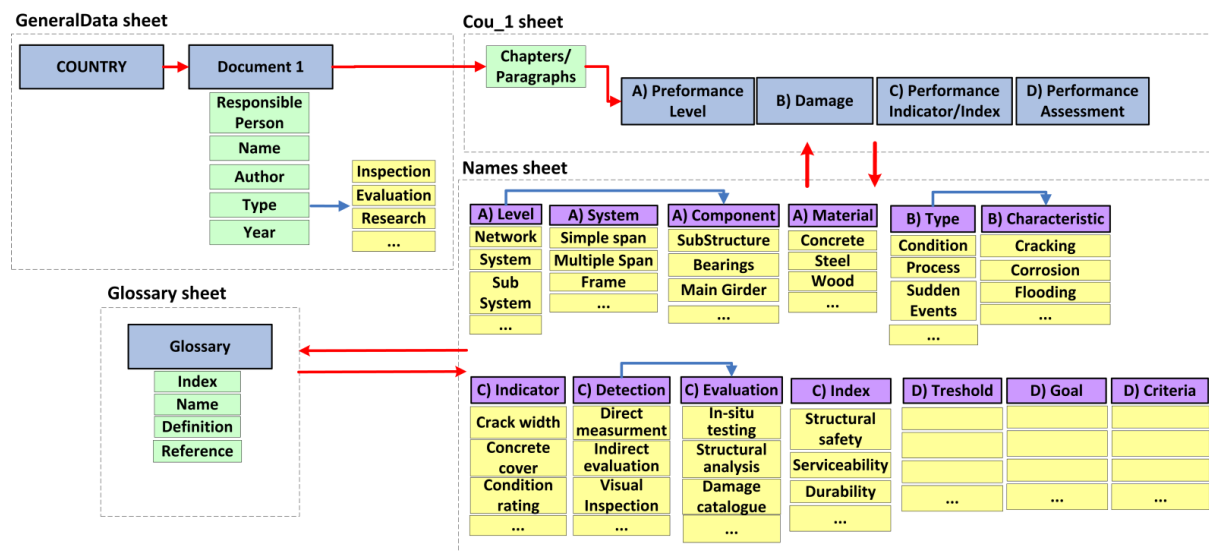


Fig. 1. The structure of the interface and the main connections between data fields and sheets

The Names\_Table sheet stores the information on the drop-down lists, and the suggestion is to update it during the surveying process by every user. In order to support the interface, the Glossary of key terms is structured. Initially it was supplied with data from the documents (County Surveyors Society CSS a), 2004) and (County Surveyors Society CSS b), 2004). In the screening process, it is essential to update the Glossary with country specific definitions of the key terms given in national documents. The tutorial for application of the user interface (Strauss, Vidovic, Tanasic, & Zambon, 2015) has been prepared to give instructions on how to perform extraction of information from relevant documents. There are two examples given, which will aid in the screening process.

### 3 Example of screening process

For structuring the KPI database, the first task was systematic and comprehensive screening of relevant national documents. It was taken into consideration that the amount and level of information varies between documents, even in those of same type. In general, documents address the key terms differently, thus one of the main requirements for the user interface was to allow an unrestricted data input in order to gather as much as information available.

The inspection document from Austria (Bundesministerium für Verkehr, Innovation und Technologie a), 2011) was taken as a basis for the interface structure. The general connections between the key terms that may be extracted in this document are presented in Figure 2. The most of information in the document points to connections between Perf. Level and Damages. However, more connections between key terms may be found on the damage processes of corrosion, and for structural component - bearings (Chapters 5, 6 in Figure 2). In the chapter where the main inspection equipment is discussed, valuable information on some connections between the terms may be found as well. Here, mostly the assessment and estimation Methods for certain types of Damage are discussed. The rating system for bridges given in this document also provides essential relationships between the key terms. The Damage degree on a bridge structure and its elements, which is observed during the inspection, may be connected both with Perf. Index and Perf. Indicators. However, the precise information on Perf. Thresholds/Criteria/Goals are not found while screening this document.

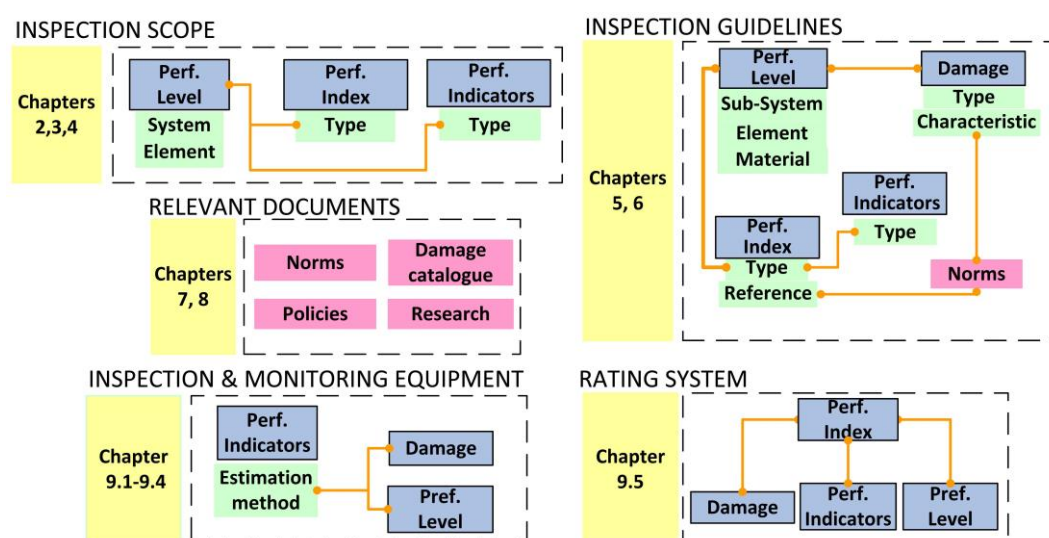


Fig. 2. Extracting the information on the key terms from documents – an example

### 4 Dissemination of interfaces

After successful elaboration of interfaces prepared for screening of national documents, the turn came to second STSM during which the tasks were dissemination and application of these interfaces. The dissemination was envisaged through the process of naming one responsible person per country and naming one responsible Management Committee (MC) Member per country. The task set for the MC members was to contact roadway owners and operators and to purchase the documents used. The tasks of the country responsible persons were to screen the national documents for performance indicators by using the provided interfaces.

During the STSM it was crucial to ensure that the documents prepared for screening were examined and improved, as well as that the responsible persons gets familiar with philosophy of screening. Also, the important part of STSM was to transfer the ideas from the leaders of the Action to the nominated persons and to work as a link between the designers of screening documents and nominated persons in order to

remove all the bugs and errors in the interfaces. During management of responsible persons' work several smaller errors in the database excel emerged and were pointed out, but were soon fixed.

One of the tasks performed during the STSM was assisting the responsible persons from Portugal in processes of document screening and filling the interfaces. The procedure consisted of breaking down document into relevant chapters and assign terms into interfaces.

By the end of the STSM 11 of 34 countries had already finished filling process and submitted their databases. Since rest of the countries either just started or still did not start the screening procedure, the managing the progress of the database was continued after the STSM.

## 5 Research database

The final task of STSM was to prepare the research database. It was envisaged as a database for all performance indicators that are in the stage of research and are still not approved or applied. The related interface, shown in the Figure 3, is very similar to the applied database interface, especially regarding to the philosophy of adding new entries. Here, there was no need for robust "Names\_Table", rather the performance indicators were directly entered. As for the applied, also for the research database, responsible persons from particular countries were nominated.

**SURVEY OF RESEARCH PERFORMANCE INDICATORS**

Article	Performance assessment of concrete structures based on probabilistic prediction models and monitoring information
Author	Strauss, Zambon, Vidovic, Grossberger, Bergmeister
Year	2015
Abstract	An efficient evaluation and prediction of time variable mechanical and chemical degradation processes is fundamental requirement for life-cycle analysis as well as for the complete assessment of concrete structures... Important tools and
Journal	IABSE Conference – Structural Engineering: Providing Solutions to Global Challenges; September 23-25 2015, Geneva, Switzerland
Keywords	life-cycle analysis; performance indicators; probabilistic performance prediction; efficient maintenance

Performance Indicator	Young modulus
Type of Indicator	Material property
Mathematical Formulation	
Threshold	
Intentions (where to apply)	In order to evaluate the fatigue performance of the critical cross-sections
Level of maturity	Research stage
Case study	STRABAG test foundation in Cuxhaven
Performance Indicator	Reliability index
Type of Indicator	Reliability
Mathematical Formulation	
Threshold	
Intentions (where to apply)	In order to evaluate the fatigue performance of the critical cross-sections
Level of maturity	Research stage
Case study	STRABAG test foundation in Cuxhaven

**Fig. 3.** Austrian example of research database

The article (Strauss et al., 2015) was screened and forwarded to research database responsible persons as an example. In the article the emphasis was set on the Young modulus and the reliability index as two performance indicators connected with existing concrete structures (Figure 3).

## 6 Conclusions

The main goal set before the Working Group 1 (WG1) of the COST TU1406 project was to preform screening of relevant national documents in order to point out key performance indicators. The first task here was to make a concept and subsequently the structure of a simple yet comprehensive user interface to perform screening of various types of documents - evaluation, inspection and research documents. The second task comprised testing of the interface features, its dissemination and analysis of the feedback from COST countries. These two tasks were set before the authors as primary goals of their

Short Term Scientific Missions (STSM), which they performed at BOKU University in Vienna and the University of Minho in Portugal, respectively.

By the end of the first STSM, the structure of the interface was set in MS Excel where emphasis is on free data input in predefined fields. The concept of interface was based on screening of relevant German and Austrian documents from which the relevant terms were supplied. Also, the tutorial was prepared which is aimed at country representatives – users of the interface. During the second STSM, the interface was bug-tested and disseminated to COST countries to perform the screening of their national documents. By the end of this mission, the concept and interface for screening of research documents was also prepared.

Currently, the feedback on the screening process was received from 11 out of 34 COST countries. The analysis of these results is underway and the work on the management of the performance indicator database continues.

## Acknowledgment

First and foremost authors would like to acknowledge the COST framework for the possibility of participating in the STSMs. Also, authors would like to acknowledge IKI at BOKU University and the University of Minho for hosting them as well as Prof. Alfred Strauss and Prof. Jose Matos for being their hosts. In addition, the concept of interface was prepared by Prof. Strauss, the leader of the WG1, which authors would like to acknowledge. The authors would like to specially thank Ms Anja Vidovic from BOKU University for her immense work on the Tutorial and preparation of related examples.

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## A new perspective for robustness assessment of framed structures

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**Abstract.** Robustness has been recognized as interesting research topic due to several collapses that have been occurring over last years. Indeed, this subject is related with global failure or collapse. However, its definition is not consensual since several definitions have been proposed in the literature. This short-paper aims to present a framework for assessing bridge's robustness as a probabilistic performance indicator. In this study, a non-linear model of a clamped beam with two point loads using DIANA software was developed to validate the framework presented. By means of a probabilistic approach, the load carrying capacity and structural safety were evaluated. In this regard, special focus is placed on an adaptive Monte Carlo simulation procedure to achieve a proper meta-model.

**Keywords:** Robustness, Probabilistic Techniques, Non-linear Analysis, Performance Indicator, Structural Safety.

### 1 Introduction

The concept of structural robustness received significant attention around 40 years ago due to the partial collapse of Ronan Point building in London. This subject began to be seriously studied after the massive disaster of World Trade Centre collapse. In addition, several structural failures triggered by unexpected loads, severe human errors during design or execution and lack of maintenance contributed to this increased interest in this topic (Canisius et al., 2007). In this context, a workshop carried by JCSS in collaboration with IABSE at the Building Research Establishment in London, UK (December 2005) gathered 50 experts, from research institutions, companies and government, to discuss issues related with robustness. The conclusions led to a general consensus that the present situation with regard to ensuring sufficient structural robustness through codes and standards was highly unsatisfactorily. As a consequence, a joint European project in Robustness was created, namely the COST action TU06010 – Robustness of Structures.

The present work aims to develop a reliability-based robustness assessment framework to evaluate bridge's safety. In this way, a non-linear finite element model (FEM) combined with advanced reliability methods was used in order to validate the proposed framework.

### 2 Robustness

In general, robustness can be defined as the ability of a certain structure to resist without disproportionate damage to either abnormal events or given damage. However, it is well known that there are several definitions of robustness proposed by several authors over the literature. Starossek and Haberland (Starossek & Haberland, 2010) in their work present several definitions of robustness in civil engineering domain. The same authors also discuss several terms related with robustness, such as:

- *Exposure* – possibility of a structure to be affected by a threat during its life-cycle;
- *Vulnerability* – susceptibility of a structure to be damaged by an exposure;
- *Damage tolerance* – ability of a structure to survive once it is damaged;
- *Redundancy* – availability of alternative paths for a load to be transferred from a point of application to a point of resistance;

- *Ductility* – ability of a structure to suffer plastic deformations without occurring rupture;
- *Reliability* – ability of a structure to perform its intended function for a specific period of time under certain conditions.

Regarding the quantification of robustness, they have been proposed several approaches by different researchers that evaluates the robustness in a deterministic, probabilistic and risk-based way. Concerning the deterministic approach, the most relevant works are presented by Frangopol and Curley, 1987 (Frangopol & Curley, 1987), Biondini and Restelli, 2008 (Biondini & Restelli, 2008), Starossek and Haberland, 2011 (Starossek & Haberland, 2011) and Cavaco, 2013 (Cavaco, 2013). In what concerns the probabilistic approach, the most relevant works are presented by Frangopol and Curley, 1987 (Frangopol & Curley, 1987), Fu and Frangopol, 1990 (Fu & Frangopol, 1990) Lind, 1995 (Lind, 1995) and Goshn and Moses, 1998 (Goshn & Moses, 1998). Lastly, in risk-based approach the most relevant work can be consulted in Baker et al., 2008 (Baker et al., 2008).

### 3 Proposed framework

Despite this intense effort of the research community, both structural reliability analysis and robustness assessment require a comprehensive understanding of crucial topics, hindering their practical application in real situations. Indeed, the most complete approach, namely, the risk-based robustness, usually overtakes the structural engineers scope. Besides that, ranges of existing robustness indexes still need to be normalized from 0 to 1, facilitating comprehension and comparison. In this sense, herein, a reliability-based robustness assessment framework is introduced, seeking to combine the existing knowledge, in order to obtain a new robustness index to be applied at two performance levels: structural behavior at ultimate or service limit states.

The proposed robustness index aims to depict the structural performance by assessing a selection of four key attributes traditionally related with robustness. In this approach, robustness is computed as equal to the area of a quadrilateral, whose sides' lengths represent a performance indicator according to Table 1. In order to obtain these indicator, deterministic analysis on design points are carried out.

**Table 1** – Adopted performance indicators.

Attribute	Performance Indicator	Reasoning
Reliability	$P_{\beta} = \frac{\beta_{dam}}{\beta_{int}}$	Reliability indexes
Damage tolerance	$P_{Dt} = \frac{LF_{dam}}{LF_{int}}$	Load factors
Redundancy	$P_R = \frac{\int M(\phi)_{dam}}{\int M(\phi)_{int}}$	Moment curvature areas
Ductility	$P_{\phi} = \frac{\phi_u / \phi_y _{dam}}{\phi_u / \phi_y _{int}}$	Flexural curvature ductility factor

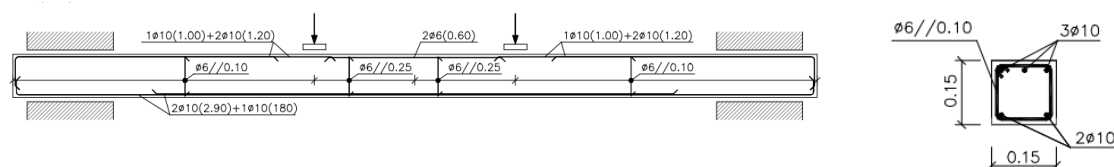
With regard to structural reliability, since the expected probability of failure is low, crude Monte Carlo requires a large number of numerical simulations in order to solve the convolution integral. To tackle this, the performance limit function is approximated by the so-called meta-models, namely, quadratic response surfaces, polynomial chaos, and so on. Herein, quadratic response surfaces (RS), which are able to efficiently cope with highly non-linear relations between inputs and outputs, are used.

To do so, an adaptive procedure based on Monte Carlo realizations inspired on schemes proposed by Bucher and Bourgund (Bucher & Bourgund, 1990) and also Rajashekhar and Ellingwood (Rajashekhar & Ellingwood, 1993) is accomplished. In this approach, a stepwise regression, which combines forward and backward regression methods to select the most important terms according to their statistical significance, is used to minimize the approximation error. This RS is built based on an initial experimental design (ED), a Monte Carlo sample, whose realizations are dispersed around the mean value according to their bias. Both design point coordinates and probability of failure are computed through the first reliability method (FORM). Regarding the following steps, new sampling points are added to enrich the ED around the design point. The procedure is stopped when a

convergence criterion is satisfied, which is based on reliability index relative error tolerance between consecutives iterations. In this procedure, the limit state function can be defined according to problem definition. Herein, a performance limit function based on the difference of resisting and acting loads,  $G(X) = R(X) - S(X)$ , is highlighted.

#### 4 Case Study

The present case study aims to assess the safety of a clamped beam as it can be seen in figure 1a, longitudinal view, and figure 1b, cross section. This beam was designed according with Eurocode 2 for an  $F_{sd}$  of 27kN. The reinforcing was performed in order that, in yielding state, the bending moment in support could redistribute the loads to the mid-span in order to equalize the bending moments in an ultimate limit state.



**Fig. 1** – Clamped Beam:  
a – longitudinal view; b – Cross section

Concerning its analysis, a non-linear finite element analysis were made through DIANA software. About the type of analysis, a 2D non-linear structural analysis was performed with class III beam elements based on Mindlin-Reissner theory with incremental load steps until its failure. The adopted method to solve the non-linear problem was the Modified Newton-Raphson method.

Regarding the definition of the constitutive laws for the materials, for concrete, a total strain fixed crack model was adopted in which for tensile behavior a linear ultimate strain based was used and an ideal behavior for compression. For the reinforcing steel, a tri-linear diagram was carried out.

The probabilistic values for the mechanical properties of the materials and applied loads are presented in table 2 as well as their mean values, coefficient of variation (CoV) and distribution functions.

**Table 2** – Material Properties and applied Loads.

Random Variable	Mean Value	CoV	Distribution Function	Reference
<b>Material Properties</b>				
Compressive strength ( $f_c$ )	30 MPa	12%	Normal	(Wiśniewski, 2007)
Tensile strength ( $f_{ct}$ )	2.9 MPa	20%	Log-Normal	(Wiśniewski, 2007, EN CEN 1992, 2010)
Young modulus ( $E_c$ )	32 GPa	8%	Normal	(Wiśniewski, 2007)
Steel yielding strength ( $f_{sy}$ )	460 MPa	6.5 %	Normal	(JCSS, 2001)
Steel ultimate strength ( $f_{su}$ )	530 MPa	7.5%	Normal	(JCSS, 2001)

Applied Loads				
Permanent load (G)	10 kN	9.5%	Normal	(Wiśniewski, 2007, JCSS, 2001)
Additional load (Q)	9 kN	15%	Gumbel	(JCSS, 2001)

#### 4.1 Damage Scenarios

Both idealized damage scenarios are formulated assuming a degradation of reinforcing steel cross-section area. Knowing that beam is designed to redistribute bending moments between critical cross sections, the main goal is to analyze the ability of forming plastic hinges. Indeed, according to deterministic analysis, beam presents a ductile behavior since rupture is ruled by steel yielding. The restrained cross-sections evidence a moment-curvature diagram with well-defined losses of stiffness. Since the structure does not present fragile ruptures, namely, a single plastic hinge, two scenarios involving a reduction of steel cross section are assumed. The first appoints to general degradation phenomena with a percentage of loss near 25%. A localized reduction of steel cross section area up to 40% regarding top layers at beams ends is also considered.

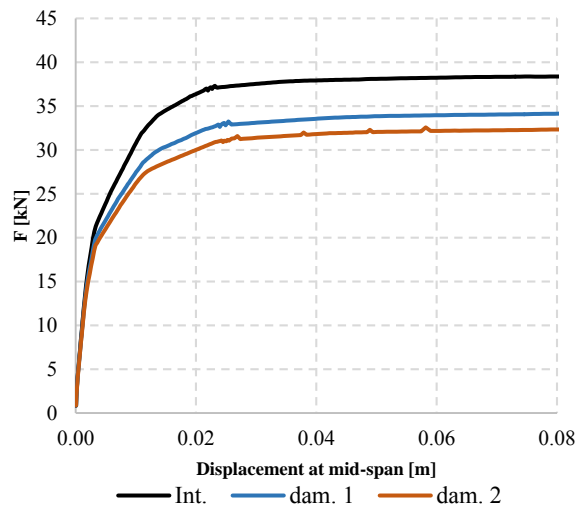
#### 4.2 Obtained Results

The adaptive Monte Carlo procedure used to achieve a quadratic response surface considered an initial sample  $N$  equal to  $N = 3 \cdot M$  with  $M$  input random variables. For further iterations, the same sample size is added. A MATLAB built-in function, stepwiselm, is used to select potential model terms according to different criteria (eg. sum of squared errors, AIC, BIC,...). Finally, the best model is chosen based on log-likelihood value. Both simulations converged quite rapidly due to the existence of well-defined failure mode. In fact, after four iterations the RS presented interesting approximation errors in which engineering reasoning validate mathematical models.

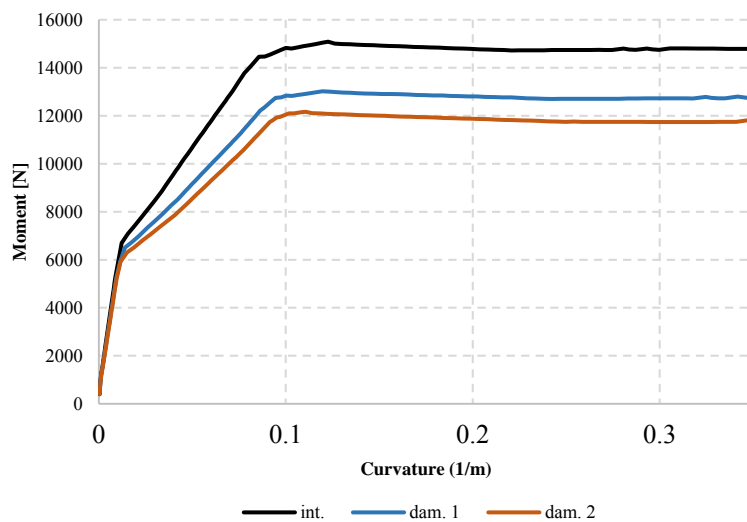
In the following, deterministic analysis of design values for intact and damage scenarios are presented. Design points coordinates, reliability index, load factor are shown in Table 3. Displacement at mid-span is schematically presented in figure 2. Herein, three different phases regarding structural performance can be distinguished, namely, initial elastic phase, cracking phase and plastification of steel, i.e. yielding phase. Indeed, this behavior is well depicted in the moment-curvature diagram at beam end shown in figure 3.

**Table 3** – Results for intact and damage scenarios.

	int.	dam. 1	dam. 2
fc	16.3	16.2	15.6
fct	1.7	1.7	1.6
Ec	23.3	23.2	22.8
fsy	371.7	398.0	403.5
fsu	399.7	436.8	444.0
G	11.2	11.2	11.2
Q	27.3	23.2	21.5
$\beta$	8.78	7.83	7.58
LF	38.5	34.4	32.5
$\phi_y$	0.016	0.014	0.012



**Fig. 2** – P-delta curve

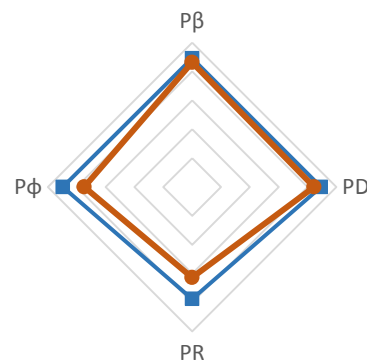


**Fig. 3** – Moment curvature diagram

According to the proposed methodology, robustness index is given by the area of quadrilaterals which are schematically represented in figure 4. Although both scenarios led to similar reliability indexes, the robustness indicator is worsen by the reduction of ductility and redundancy. However, a high robustness indicator is achieved in both cases, since this structure has the ability of redistributing forces, specially due to small cross-section height and good ratio of steel/concrete area.

**Table 4** – Robustness Assessment

$P_{\beta}$	0.892	0.863
$P_{Dt}$	0.892	0.845
$P_R$	0.775	0.627
$P_{\phi}$	0.896	0.748
Robustness	0.74	0.58



**Fig. 4** – Performance Indicators in robustness assessment

## 5 Conclusions

A reliability-based robustness assessment framework to evaluate bridge's safety is introduced. Herein, a simple example concerning a clamped beam with two point loads is used to validate the proposed methodology in order to extent its application to a real bridge. Indeed, this paper presents some preliminary studies concerning reliability analysis and robustness assessments. The main goal is to facilitate the understanding of some attributes regarding robustness, aiming to propose a versatile framework to evaluate robustness according to a choice of key performance indicators. The methodology seeks not only to obtain a normalized robustness index but also to visualize the influence of different attributes. Regarding reliability analysis, used approach intends to reduce computational time and also to reproduce an explicit limit state function avoiding overfitting and diminishing approximation error. In fact, this methodology can be improved by introducing some features: i) use of pseudo random-generators to populate region of failure; ii) establishing cross-validation procedures; iii) considering model

error as random variable; iv) bootstrap sampling to estimate boundaries of probability of failure. Finally, the application of these framework with additional improvements is to be applied in a near future.

### Acknowledgements

The authors would like to thank ISISE – Institute for Sustainability and Innovation in Structural Engineering (PEst-C/ECI/UI4029/2011 FCOM-01-0124-FEDER-022681), FCT– Portuguese Scientific Foundation for the research grant PD/BD/113677/2015. This study also received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under grant agreement No. 606229. Also the collaboration and information provided by the professor António Abel Henriques is gratefully acknowledged.

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## Lifecycle-based discretization of bridge performance indicators

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**Abstract.** The research concerning the performance of large infrastructure, and especially bridges, is extensive. Most prominent topics are those investigating the static, dynamic and seismic performance of bridges and all their constituent parts. The associated performance indicators include mainly the damage degree, bearing structure ductility, fragility frequency, SSI (soil-structure interaction), vulnerability, fragility, and resilience of bridges. Whereas the various indicators can be divided into certain indices groups (cost efficiency, safety, serviceability etc.), a discretization taking into account a holistic approach to lifecycle infrastructure management has not yet taken place. This paper presents such an attempt based on the key bridge performance indicators proposed by researchers in Greece, a country with important experience in this type of infrastructure. Following a targeted literature review, a conceptual schema is presented that showcases the interconnections between fundamental notions of lifecycle project management (namely constructability, sustainability and risk analysis). Then, an integrated discretization of the found grouping performance indices according to the aspects of the schema is depicted. The utility of this discretization is that the key aspects of studied research efforts concerning bridge performance indicators can be incorporated into the interconnection schema, which constitutes the first part of a, currently under development, holistic lifecycle management methodological framework. This incorporation does not only serve as an indicator regularization according to the key aspects of lifecycle project management, but also as a verification test for the schema itself in the case of certain aspects of bridges and large infrastructure in general.

**Keywords:** Bridge performance indicators, discretization, life cycle management, constructability, sustainability, risk analysis

### 1 Introduction

Civil engineering researchers have been investigating and publishing results on various aspects of large infrastructure for decades. However, firstly implicit and gradually more explicit studies on Bridge Performance Indicators (BPIs) started to emerge mainly in the early 1990s. The research output has been qualitatively and quantitatively increasing ever since, resulting in numerous cutting-edge insightful studies. However, these BPIs have never been wholly incorporated into a holistic framework transpiring the complete project lifecycle. Cognitive relations between the indicators can be logically deduced and a coarse grouping be constructed, but a de facto discretization according to prominent notions of the project lifecycle management does not exist.

In this paper, a targeted literature review is conducted to obtain the most deeply researched BPIs. Then, these are coarsely grouped in categories of performance indices. The fundamental notions of constructability, sustainability and risk analysis are showcased and their importance in the achievement of the highest level of project performance is noted. Then the lack of their holistic integration is documented by mentioning extended reviews of the relative literature and a novel conceptual schema showcasing their interconnections and interfaces is depicted. According to the schema, the earlier defined groups of performance indices are discretized. Finally, the importance of such a discretization and the utility of the schema and a generalized holistic framework in the lifecycle management of bridges are discussed.

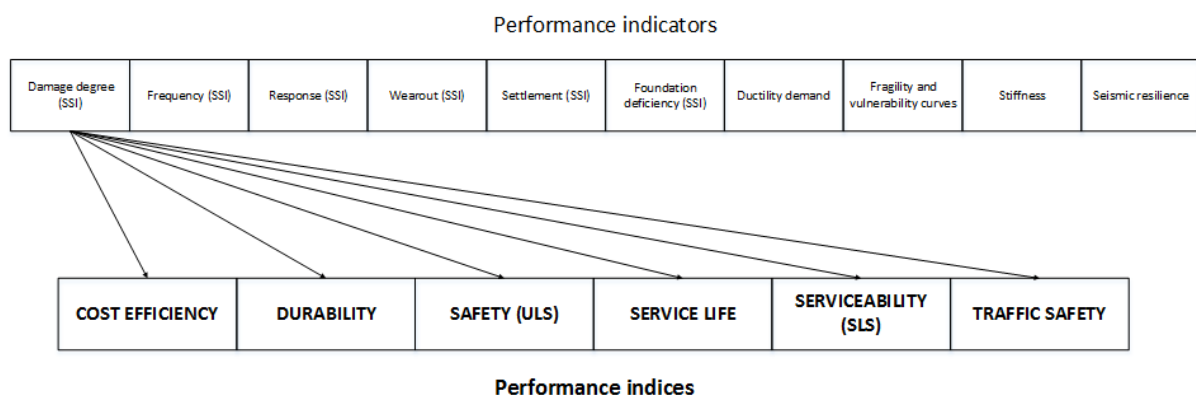
## 2 Bridge performance indicators in targeted literature review

TU1406 Cost Action's scope is the standardization, at a European level, of quality specifications for the design and construction of roadway bridges. In this context, the creation of a database of BPIs and relative notions, like performance indices and performance levels was planned and performed, based on official technical manuals and experts' knowledge. Furthermore, a second database was created comprising BPI-related research efforts at a national level. This paper expands the exploitation of the collected data for the second database by using them for the development of a lifecycle-based discretization of BPIs.

The full research output concerning implicitly or explicitly BPIs is, as a whole, too large for the scope of this paper. Consequently, the following filters were applied for the output of the targeted relevant literature review that is hereby showcased: (a) when several papers are concerned with the same or similar subjects (written by the same team of authors or not), only the most influential and cited ones are noted; (b) only papers published in the last decade (2006-2016) are reviewed and mentioned; (c) newer, more encompassing research efforts taking into account and incorporating earlier ones, even in the time period designated earlier, are generally favored; (d) papers too ambiguously and loosely connected with BPIs are generally discarded in favor of the ones characterized by a more explicit connection; (e) in case of a mixed Greek and non-Greek co-authoring team, only papers having the first author affiliated with a Greek institution are selected. As a result, the following targeted and filtered list of BPIs prominently researched in the recent relevant Greek literature is conducted:

- Damage degree, frequency, response, wearout, settlement and foundation deficiency of the constituent bridge parts due to SSI (soil-structure interaction) during ground motions (Manos, Kourtides & Sextos 2008, Kotsoglou & Pantazopoulou 2010, Sextos et al. 2011, Farantakis, Kotsoglou & Pantazopoulou 2014, Lesgidis, Kwon & Sextos 2015, Sextos, Mylonakis & Mylonas 2015)
- Ductility demand (Papanikolaou & Kappos 2009a,b, Manos, Katakalos & Kourtides 2013, Pilitsis et al. 2015)
- Fragility and vulnerability curves, most often interconnected (Moschonas et al. 2009, Tsionis & Fardis 2012, Taskari & Sextos 2015)
- Stiffness (Katsaras, Panagiotakos & Kolias 2009, Taskari & Sextos 2015)
- Seismic resilience (Paraskeva, Kappos & Sextos 2006, Timosidis & Pantazopoulou 2007, Mitoulis & Tegos 2010, Tegou, Mitoulis & Tegos 2010, Bardakis & Fardis 2011, Kappos et al. 2012, Mitoulis, Titirla & Tegos 2012, Fardis & Tsionis 2013, Moschonas & Kappos 2013)

From the respective analyses conducted in the previous research efforts and through logical deduction, it can be inferred that each of the BPIs belong in all the performance indices groups shown in Figure 1.



**Fig. 1.** Performance indices grouping for the most researched performance indicators in the recent relevant Greek literature

In Figure 1, while all BPis belong to all performance indices groups (as mentioned earlier), only the connecting lines of the first were depicted, for the sake of clarity. The performance indices groups were drawn from the development of the first database mentioned above.

### 3 Conceptual schema of the interfaces between constructability, sustainability and risk analysis and lifecycle-based discretization of BPis

Constructability is most widely known as “the optimum use of construction knowledge and experience in planning, design, procurement and field operations to achieve overall project objectives” (CII 1986). Sustainability is the notion of promoting the development that meets the needs of the present without compromising the ability of future generations to achieve their own (WCED 1987). Risk analysis is the collective methodology of risk assessment, through a systematic process of decision-making in order to accept a known or assumed risk and/or reducing the harmful consequences or probability of occurrence of the risk (Singh et al 2007). All three notions are prominent in lifecycle project management towards achieving the highest level of project performance, which can be understood as the level of the desirable success in meeting the stated technical performance specifications and the mission to be performed (Angelides 1999). The most commonly considered success determinants are the cost and time of project completion and the quality of deliverables (De Wit 1986). Additional determinants, like safety (Lam & Wong 2009) can be considered separately or as constituent elements of quality, accounting for the general definition of the latter as the conformance to all the specified requirements (Crosby 1979). The theories and methodologies incorporated by constructability, sustainability and risk analysis seek to optimize the aforementioned success determinants, with each notion targeting at certain aspects. Thus, for a holistic, all-encompassing and all-optimizing lifecycle management framework, the interconnection, integration and utilization of all three notions is desired.

Following a thorough review of the relevant literature, it was realized that all three notions have not yet been wholly integrated to one another, with only one-to-one intertwinements being the rule (Kifokeris & Xenidis 2016). As a first step to overcome this lack of integration, a conceptual schema of the interfaces and the interconnection links is shown in Figure 2.

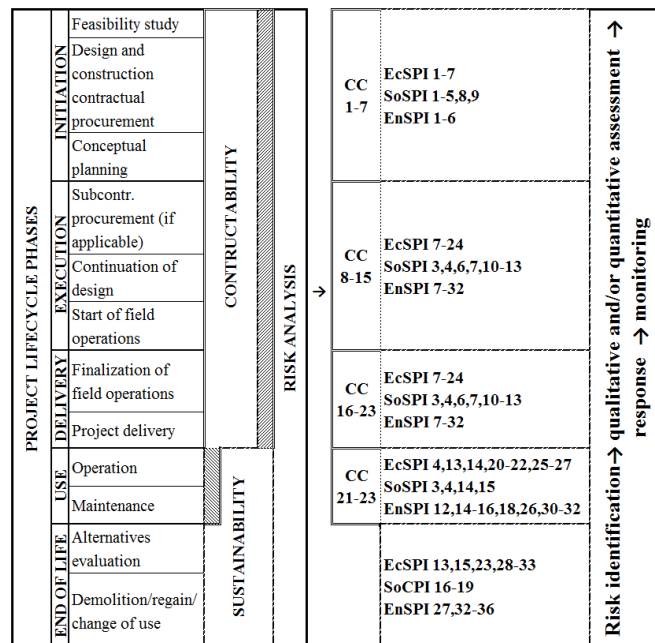


Fig. 2. Interconnections and interfaces between constructability, sustainability and risk analysis (Kifokeris & Xenidis 2016)

In the schema, the project lifecycle from its conception to its discharge is divided into five distinct phases with their corresponding subphases. Constructability pertains heavily the lifecycle phases up to project delivery, with a modest extension to operation and maintenance phase, while sustainability is prominent also in the pre-delivery phases, but much more in the post-delivery ones (Kifokeris & Xenidis 2016). Risk analysis and its procedures transpire the whole project lifecycle (Kifokeris & Xenidis 2016). Constructability is facilitated through the implementation of a constructability program, which is transpired by certain guidelines known as Constructability Concepts (CCs). The 23 most widely used Concepts (Nima 2001) are distinctly divided per phase. Implementation of sustainability can be checked through a series of unique and/or overlapping performance indicators, namely 32 economic (EcSPI), 19 social (SoSPI) and 36 environmental ones (EnSPI) (Shen et al. 2007). The SPIs are also divided per phase. It is shown that each CC per phase is transpired by all the relevant EcSPIs, SoSPIs and EnSPIs (Kifokeris & Xenidis 2016). The individual delineation of both the CCs and the SPIs is beyond the scope of this paper, but the reader can refer to the corresponding cited research efforts.

By merging Figures 1 and 2, the lifecycle discretization of the noted grouping indices of the BPIs can be logically deduced. The results are shown in Figure 3.

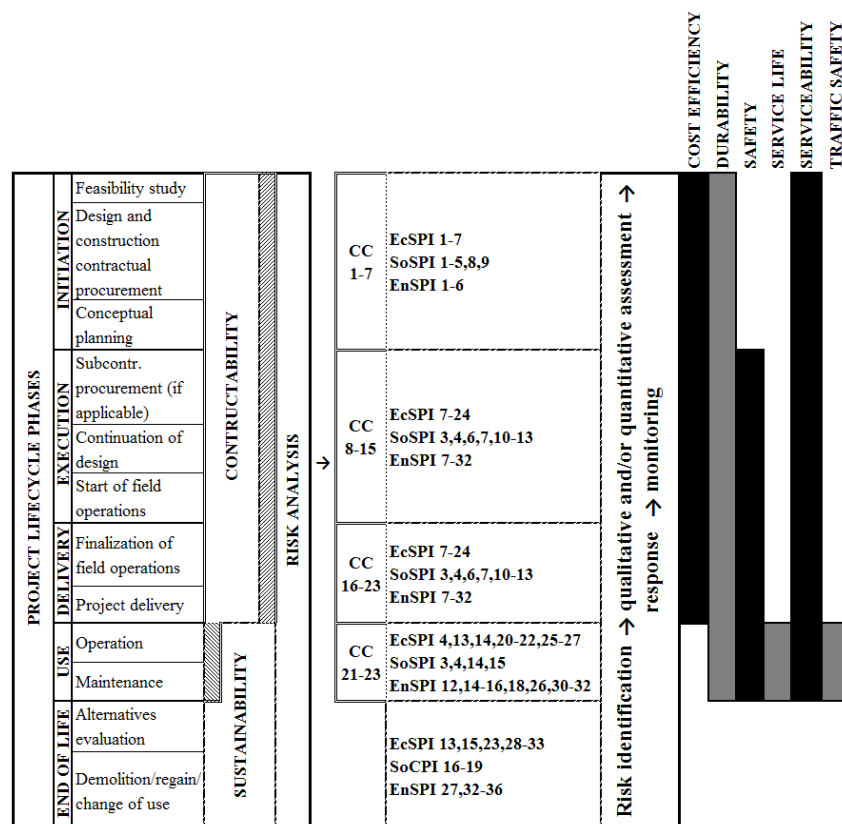


Fig. 3. Discretization of performance indices and BPIs according to the conceptual schema

Since each index encompasses all the noted in the previous section BPIs, all of them should be checked for the corresponding lifecycle phases pertained by the index (in conjunction with the overlapping SPIs and taking into account the guidelines provided by the CCs) and incorporated in an all-inclusive risk analysis procedure. Where the indices overlap, the corresponding BPIs should be multiply checked under the light of every index.

#### 4 Conclusions

A true holistic lifecycle management for bridges has to incorporate, interconnect and integrate the distinctive BPIs, grouped under the corresponding performance indices, along with the SPIs, CCs and risk analysis procedures. Taking full account of all of the above, the prospect of project success in the case of bridges is materialized in a more structured and robust way.

In the recent relevant Greek literature, the most commonly researched BPIs account mainly for the cost efficiency, durability, safety, service life, serviceability and traffic safety of a bridge. These BPIs are grouped along with the relevant SPIs and CCs to form interconnected grouping indices with clear interfaces between them.

The discretization and integration of BPIs, SPIs and CCs could expand to cover more data and include also several types of new indicators drawn from various case studies. In this way, a general approach for enhanced lifecycle management for bridges can be produced towards the standardization of quality standards for bridges at the European level.

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# The impact of the severe damage on the dynamic behavior of the composite road bridge

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**ABSTRACT:** Several studies of dynamic behavior of road bridges were done lately in the Czech Republic. This paper describes result of one experimental and theoretical study of dynamic behavior of a road bridge. The study was carried out on the composite slab-on-girder bridge, which was damaged by a heavy vehicle. An experimental modal analysis was carried out twice on this bridge – for the damaged state and for the state after its reconstruction, respectively. In addition, the comparison of the modal analysis results for the damaged state and the state after the reconstruction of the composite bridge was done. The FEM model identification was done for both states of this bridge. The experimentally obtained results were compared with theoretically determined modal parameters for both states.

## 1 INTRODUCTION

The ability to monitor deterioration degree and detect damage of a structure at the earliest possible stage is very important. Current damage detection methods require that the vicinity of the damage is known a priori and that the portion of the inspected structure is readily accessible. The need of techniques that can be applied to complex structures led to the development of methods that examine changes in the vibration characteristics of the structure. It is suitable to check these methods and techniques on simple structural elements as well as on entire structures where we know the level of damage. These methods can also be used for verification and identification of FEM models of investigated structures.

## 2 THE BRIDGE NEAR VRÁŽ

### 2.1 Description of the bridge near Vráž

The investigated composite slab-on-girder bridge is situated across the highway D5 near the village Vráž in the Czech Republic (Fig. 1). The bearing structure of the composite bridge consists of a reinforced concrete slab on four main steel I-girders. It is a three-span continuous bridge with spans  $11.7\text{m} + 35.1\text{m} + 11.0\text{m}$ . In March 2001 the bridge was damaged by crash accident. A heavy vehicle (an excavator) ferried on D5 clashed into its two main girders. Consequences of this crash were permanent buckle of the main girder (15 cm in the place of the impact) and

damage of the connection between the main girder and the crossbeam (Fig. 2).

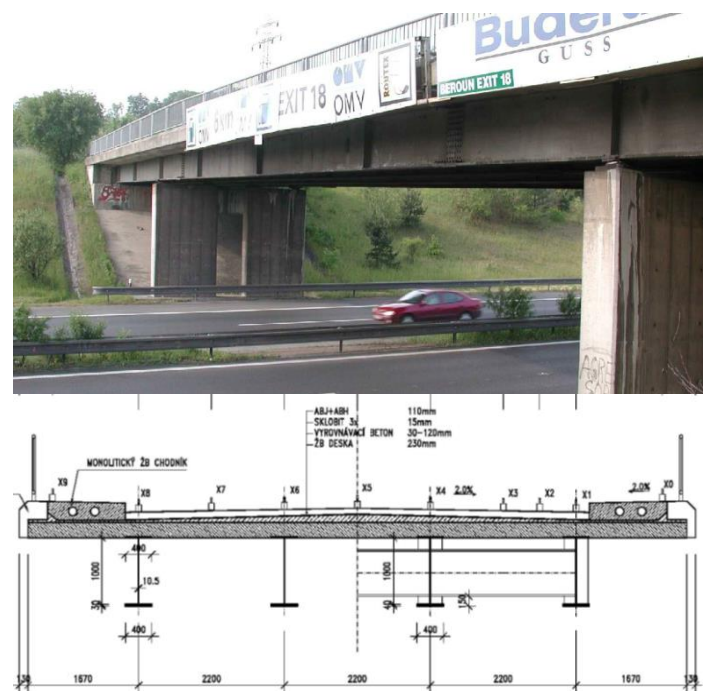


Figure 1. The slab-on-girder bridge near Vráž, cross section

### 2.2 Experimental modal analysis

Experimental modal analysis was carried out twice on this bridge – for the damaged state and for the repaired state of the bridge. The arrangement of the measurement was the same for both modal analyses.



Figure 2. The slab-on-girder bridge near Vráž, view on the damaged girder

Table 1. The comparison of experimental and theoretical natural frequencies using  $\Delta f_{(j)}$  – the damaged state

The damaged state - June				
Measurement		Model		$\Delta f_{(j)}$
(j)	$f_{(j)}$ [Hz]	(j)	$f_{(j)}$ [Hz]	
1	3,26	1	3,24	-0,62
2	3,41	2	3,60	5,28
3	8,16	3	7,88	-3,55
4	8,42	7	9,97	15,55
5	10,21	6	9,67	-5,58
6	12,01	10	12,02	0,08
7	13,74	11	13,33	-3,08
8	14,72	14	14,17	-3,88

Table 2. The comparison of experimental and theoretical natural frequencies using  $\Delta f_{(j)}$  – the repaired state

The state after reconstruction - October				
Measurement		Model		$\Delta f_{(j)}$
(j)	$f_{(j)}$ [Hz]	(j)	$f_{(j)}$ [Hz]	
1	3,38	1	3,27	-3,36
2	3,65	2	3,66	0,27
3	8,54	3	8,08	-5,69
4	8,95	4	8,29	-7,96
5	10,86	5	9,74	-11,50
6	11,39	6	10,05	-13,33
7	14,18	10	13,39	-5,90
8	15,89	13	14,73	-7,88

The electrodynamic shaker TIRAVIB 5140 was used for the excitation of the bridge. The excitation force was measured by three force transducers S-35 LUKAS, which were interconnected to show directly the whole driving force. The response of the bridge was measured by ten inductive accelerometers B12/200 HBM.

Vibration control system 2550B Spectral Dynamics with control computer Sun was used for data acquisition and data analysis.

The bridge was excited by random driving force of white type noise of the frequency range from 0 to 20 Hz. The driving force was controlled by signal generator SG 450 ONO SOKKI.

The response of the bridge was measured only in the vertical direction in a chosen net of points (280 points – 28 cross sections and 10 points in each one) on the upper face of the bridge.

Program STAR Spectral Dynamics was used for the off line evaluation of the natural frequencies and natural modes of vibration

### 2.3 Results of the Experimental modal analysis

Eleven natural frequencies, mode shapes and damping frequencies were evaluated after the first stage (the damaged state) of the experimental bridge monitoring and twelve natural frequencies, model shapes and damping frequencies were evaluated after the second stage (the state after reconstruction).

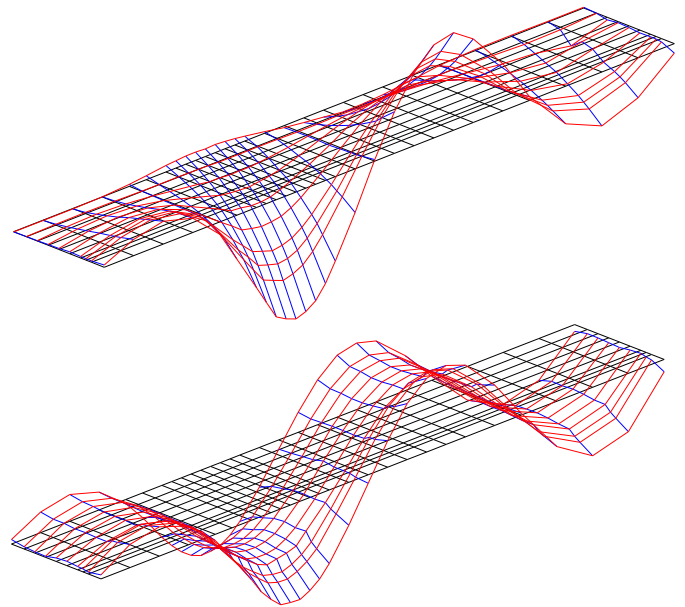


Figure 3. Visual comparison of the real parts of the third mode shapes for the damaged state (upper one) and for the state after reconstruction (lower one)  $MAC_{(3,3)}=0.618$ .

### 2.4 Comparison of the experimental results

Modal characteristics evaluated for the both verified states of the bridge were mutually compared.

Just from the visual comparison of characters of natural modes evaluated in damaged and repaired states (Fig. 3) it is clear that their changes caused by reconstruction of the damaged girder are substantial.

The change of the mode shapes was so large that Modal Assurance Criterion (MAC) had to be used to find corresponding modes and frequencies for comparison.

Changes of natural frequencies and damping frequencies were computed during the investigation of

the influence of the bridge damage on its modal characteristics. Coefficients  $MAC_{(j,j)}$ , Coordinate Modal Assurance Criterion  $COMAC_{(p)}$  (Fig. 4), the change of the curvature of natural mode shapes  $CAMOSUC_{(j),x}$  (Fig. 5 and 6) (recommended in Frýba and Pirner (2001)), changes of a modal flexibility matrix  $\Delta[\delta]$  and the 2<sup>nd</sup> derivative of changes of diagonal members of a modal flexibility matrix  $\Delta[\delta]''$  (Fig. 7) were used for comparison of natural modes.

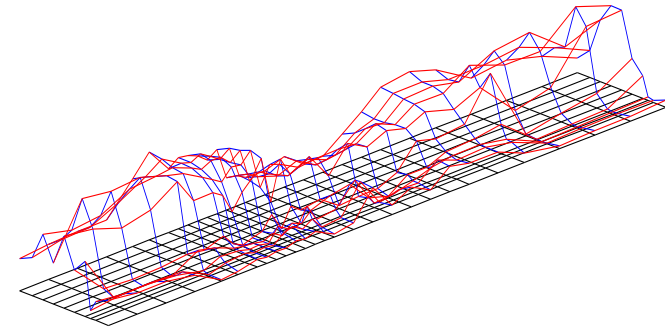


Figure 4. The change of the dynamic behavior of the bridge (damaged state – repaired state) described by function (1-COMAC), max. value shown in the figure is 0,887 (i.e.  $COMAC_{(128)} = 0,113$ ).

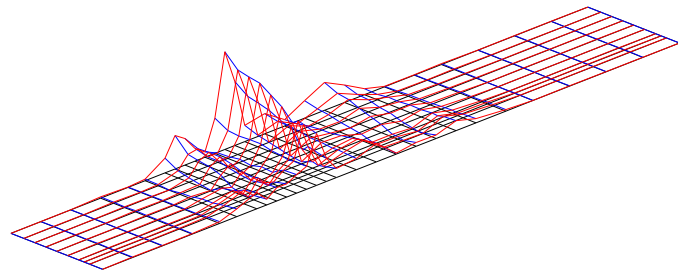


Figure 5. The change of the dynamic behavior of the bridge (damaged state – state after reconstruction) described by the change of the curvature of the 1<sup>st</sup> natural mode  $CAMOSUC_{(1)}$  calculated in longitudinal direction of the bridge

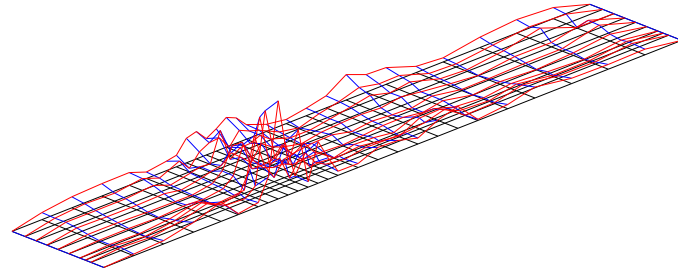


Figure 6. The change of the dynamic behavior of the bridge (damaged state – state after reconstruction) described by the change of the curvature of the 3<sup>rd</sup> natural mode  $CAMOSUC_{(3)}$  calculated in longitudinal direction of the bridge.

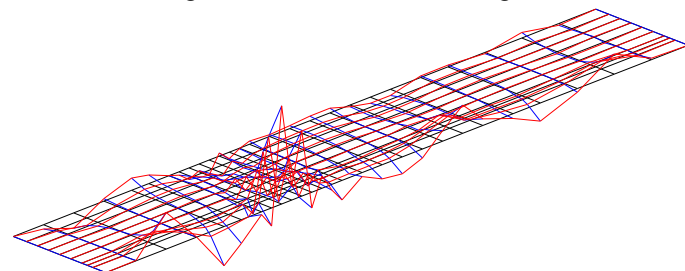


Figure 7. The change of the dynamic behavior of the bridge (damaged state – state after reconstruction) described by the second derivative of the diagonal members of the modal flexi-

bility matrix  $\Delta\delta''$  computed in longitudinal direction of the bridge.

From evaluated results, there can be found that damage of the main girder and its reconstruction significantly influence the dynamic behavior of the investigated bridge across the highway D5 near Vráž. The largest values of the  $CAMOSUC_{(1)}$  (Fig. 5),  $CAMOSUC_{(3)}$  (Fig. 6) and  $\Delta\delta''$  (Fig. 7) correspond to the repaired place of the main girder. Ascertained changes of modal characteristics are significant and confirm the improvement of the structural state of the bridge after the reconstruction of the main girder.

## 2.5 Verification of the FEM model of the bridge

Model of the bridge was created in program NEXIS 32 as a space model using shell, flat and beam elements. All geometric characteristics were included into the model according to the documentation and to the measurement done by authors in situ (Fig. 8).

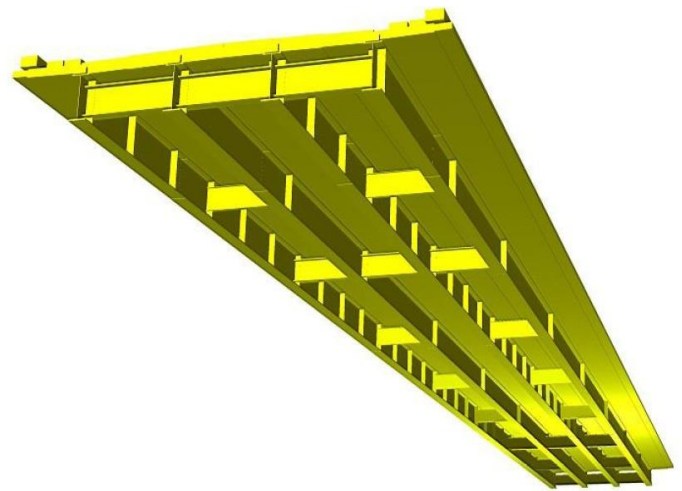


Figure 8. FEM model of the investigated bridge

FEM model of the bridge was verified and modified based on MAC and COMAC comparison between calculated and experimentally obtained modal characteristics to reach the best agreement between the model behavior and the real bridge behavior.

From the verification, it results that road layers, pavements and concrete leveling topping have to be included to the stiffness. The influence of these layers was important for the dynamic behavior of the structure.

Final comparison of the theoretical and experimental modal characteristics was done (Fig. 9-10) after verification of the model. It can be seen on Figure 10 that the torsional stiffness of the bridge model increased in the middle span of the bridge after the reconstruction.



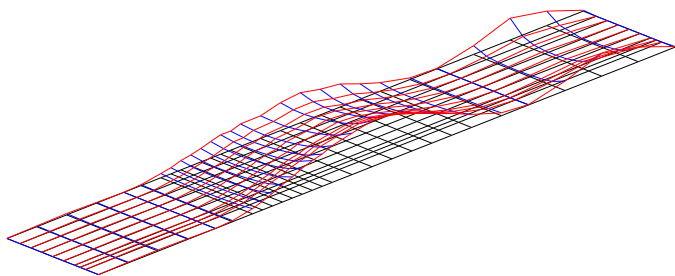


Figure 9. The comparison of the dynamic behavior between the real bridge and its model - damaged state. The differences in a modal flexibility matrix  $\Delta\delta$ .

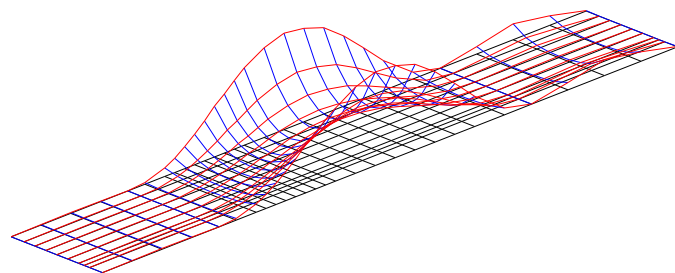


Figure 10. The comparison of the dynamic behavior between the real bridge and its model – state after the reconstruction. The differences in a modal flexibility matrix  $\Delta\delta$ .

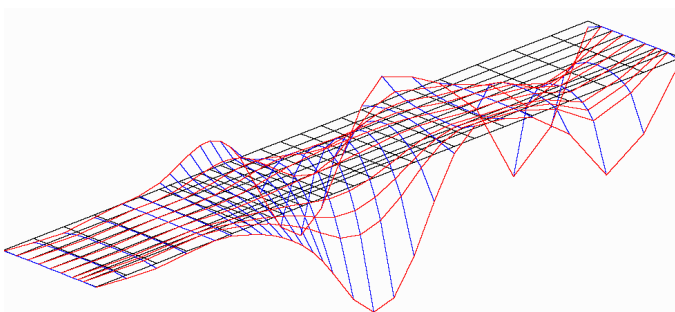


Figure 11. The comparison of the dynamic behavior of the model – damaged state  $\times$  state after the reconstruction. The differences in a modal flexibility matrix  $\Delta\delta$ .

### 3 CONCLUSION

From evaluated results of the measurement done on the bridge across the highway D5 near Vráž there can be found that damage of the main girder and its reconstruction significantly influence the dynamic behavior of the investigated bridge. Ascertained changes of modal characteristics are significant and confirm the improvement of the structural state of the bridge after the reconstruction of the main girder.

The change of the mode shapes was so large (Fig.3) that coefficient MAC had to be used to find corresponding modes and frequencies for comparison. For damage detection and localization on this bridge the use of natural frequency changes, changes of a mode surface curvature  $\text{CAMOSUC}_{(j),x}$  (Fig. 5-6), changes of a modal flexibility matrix  $\Delta[\delta]$  and especially the second derivative of changes of diagonal members of a modal flexibility matrix  $\Delta[\delta]''$  (Fig. 7) proved to be appropriate.

It seems that for damage localization on large structures using  $\text{CAMOSUC}_{(j),x}$  not only the first natural mode [Plachý (2003)] but also the higher ones (Fig. 6) can be used. Especially there is suitable to use combination of the values of  $\text{CAMOSUC}_{(j),x}$  computed in longitudinal and transversal direction of the bridge.

The FEM model verification was done the bridge. From this verification, it results that road layers, pavements and concrete leveling topping have to be included to the stiffness. The influence of these layers was important for the dynamic behavior of the structures.

Final comparison of the theoretical and experimental modal characteristics was done after verification of the models for the investigated bridge (Fig. 9-10) using the same methods as for comparison of experimental results obtained on the damaged and repaired bridge near Vráž.

It can be seen on the Figure 11 that the torsional stiffness of the bridge model increased in the middle span of the bridge near Vráž after the reconstruction.

### ACKNOWLEDGEMENT

The investigation of methods for damage detection and localization and methods for model verification was supported by Ministry of Education, Youth and Sports of Czech Republic as a part of the project CEZ:J04/98: 210000030.

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## Effect of vehicle travelling velocity on bridge lateral dynamic response

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**Abstract.** Vibration-based Structural Health Monitoring (SHM) is an area of ongoing research and has received much attention from researchers in recent years. Online damage detection methods for bridges rely on placing sensors on the structure to detect anomalies in measured parameters such as acceleration, frequency or displacement among others. Changes in these parameters can be used to infer the presence of damage such as cracking in bridge beams, foundation scour etc. These methods mostly rely on using the signals arising on a bridge from ambient traffic or environmental loading. For foundation scour detection purposes, the lateral response of a bridge is of particular interest in that this has been shown to be particularly sensitive to the scour phenomenon. Vehicle-Bridge Interaction (VBI) effects can have a significant influence on the condition of output vibrations from a bridge element. In this paper, the effect of vehicle travelling velocity on the lateral response of a typical highway two-span integral bridge is investigated. It is shown that depending on the velocity of the vehicle relative to the oscillatory period of the bridge it traverses, the bridge's dynamic response is either amplified or diminished by varying degrees. This phenomenon could influence the accuracy of a particular damage detection method relying on output system vibrations to infer damage.

**Keywords:** Bridge Dynamics, Damage Detection, Vibration, SHM

### 1 Introduction

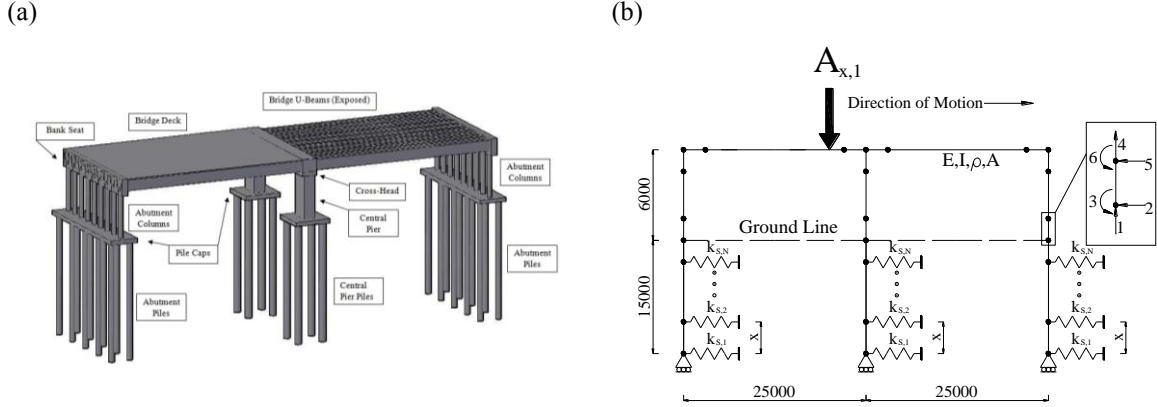
Vibration-based Structural Health Monitoring (SHM) is the art of monitoring the condition of a structure over its lifetime by monitoring dynamic properties with a view to preventing excessive damage from accumulating. Foundation scour is the term given to describe the process of soil erosion that can occur around bridge foundations due to adverse hydraulic action (Hamill 1999). Applying SHM techniques to scour detection has gained significant traction in recent years (Prendergast et al. 2013; Prendergast et al. 2015; Ju 2013; Foti & Sabia 2011; Prendergast et al. 2016; Klinga & Alipour 2015; Briaud et al. 2011; Elsaid & Seracino 2014). A common conclusion among researchers in this field is that the lateral response of a bridge sub-structural component (piles, pier) is the most sensitive to scour in terms of changes in modal properties (Prendergast et al. 2016; Prendergast et al. 2013; Elsaid & Seracino 2014; Briaud et al. 2011). It is therefore of interest to investigate phenomena that can affect the lateral dynamic response, or more specifically, impede the ability for a sensor located on the structure to effectively detect this response. The most practical way to excite a bridge (for vibration-based damage detection applications) is to use ambient traffic (Farrar et al. 1999). In this paper, the effect of vehicle travelling velocity as it traverses a bridge is investigated to highlight the significant effect that this can have via interaction with the bridge's own oscillatory motion. The type of bridge investigated is two-span integral bridges, due to their increasing popularity and prevalence.

### 2 Numerical Modelling

The issue relating to a vehicle travelling velocity across a two-span integral bridge is investigated using numerical modelling approaches in MATLAB. Various aspects of the model are discussed in the following sub-sections. Section 2.1 briefly describes different types of integral bridges and section 2.2 describes the mathematical approach taken to model the bridge, the foundation soil and the vehicle load in this paper.

## 2.1 Types of Integral Bridge

Integral bridges are becoming increasingly popular as they do not require a conventional expansion joint and this can reduce maintenance costs significantly. There are four main types of integral bridge (Prendergast et al. 2016): (1) Frame Abutment type; (2) Bank Pad Abutment type; (3) Flexible Abutment type and (4) Semi-Integral Abutment type. In this paper, type (3), a bridge with flexible support abutments, is modelled. A schematic of this type of bridge is shown in Fig. 1.



**Fig. 1.** Model schematics  
a – bridge elements; b – numerical schematic

## 2.2 Mathematical Considerations

The bridge is modelled using 6-degree-of-freedom (6-DOF) Euler-Bernoulli (2D) frame elements, the mass  $[M_b]$  and stiffness  $[K_b]$  matrices are available in Kwon & Bang (2000). The foundation soil is modelled using a Winkler philosophy which models the continuous soil layers as discrete, mutually independent and closely spaced springs (Dutta & Roy 2002; Winkler 1867). Standard properties are adopted to model the integral bridge in this paper and these properties are available in Prendergast et al. (2016), see Fig. 1(b).

To model the foundation soil, the approach described by Prendergast et al. (2015); Prendergast et al. (2016) and Prendergast & Gavin (2016) is used. This approach considers each soil spring as a linear-elastic element (strain-independent  $k_{s,i}$ ) and uses small-strain soil stiffness parameters ( $G_0$ ,  $E_0$ ) to characterize the response. In this paper, the bridge is assumed to be founded in loose sand.

Global mass  $[M_G]$  and stiffness  $[K_G]$  matrices are assembled for the full structure according to the procedure in Kwon & Bang (2000). The dynamic response of the bridge structure can be obtained by solving the second-order matrix differential equation of motion, see Prendergast et al. (2016) using the Wilson- $\Theta$  integration scheme. The damping matrix  $[C_G]$  is determined assuming a Rayleigh damping approach (Yang et al. 2004) and a damping ratio ( $\xi_1 = \xi_2 = \xi$ ) of 2% is assumed.

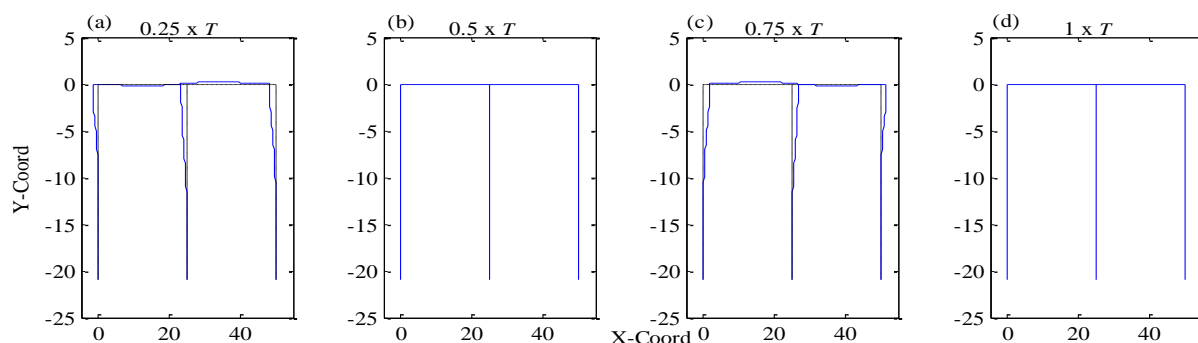
## 3 Velocity Effects

In this section, the interaction effects between a vehicle's travelling velocity over the bridge and the resulting impact on the bridge's own oscillatory motion is investigated. Section 3.1 presents an analysis of the mode shape of the bridge pertaining to lateral sway motion and section 3.2 investigates the effect of a single vehicle load traversing the bridge.

### 3.1 Global mode shape of bridge

An eigenvalue analysis is conducted in MATLAB to obtain the system eigenvalues and eigenvectors, which correspond to the un-damped frequencies and mode shapes of the model. The fundamental mode shape of the integral bridge is a global lateral sway mode, with a frequency of 1.5643 Hz and a corresponding period ( $T$ ) of 0.639 seconds. The bridge modal shape at four vibration stages corresponding to  $0.25 \times T$ ,  $0.5 \times T$ ,  $0.75 \times T$ , and  $1 \times T$  is shown in Fig. 2. Fig. 2 provides a pictorial view of the displaced shape of the given mode at a particular stage of vibration over one cycle. The time it takes for the given shape to arise and the direction of motion is displayed in Table 1. Interaction effects between the bridge's dynamic motion and the rate of load traversing are investigated in the next section.





**Fig. 2.** Bridge mode at various ratios of natural period  
a –  $0.25 \times T$ ; b –  $0.5 \times T$ ; c –  $0.75 \times T$ ; d –  $1 \times T$

**Table 1.** Bridge motion – direction and arrival times.

Fig. 2 Image Ref	Arrival Time (s)	Motion Direction
(a)	$0.25 \times 0.639 = 0.16\text{s}$	Stationary (will move right)
(b)	$0.5 \times 0.639 = 0.32\text{s}$	Swaying to right
(c)	$0.75 \times 0.639 = 0.4795\text{s}$	Stationary (will move left)
(d)	$1 \times 0.639 = 0.639\text{s}$	Swaying to left

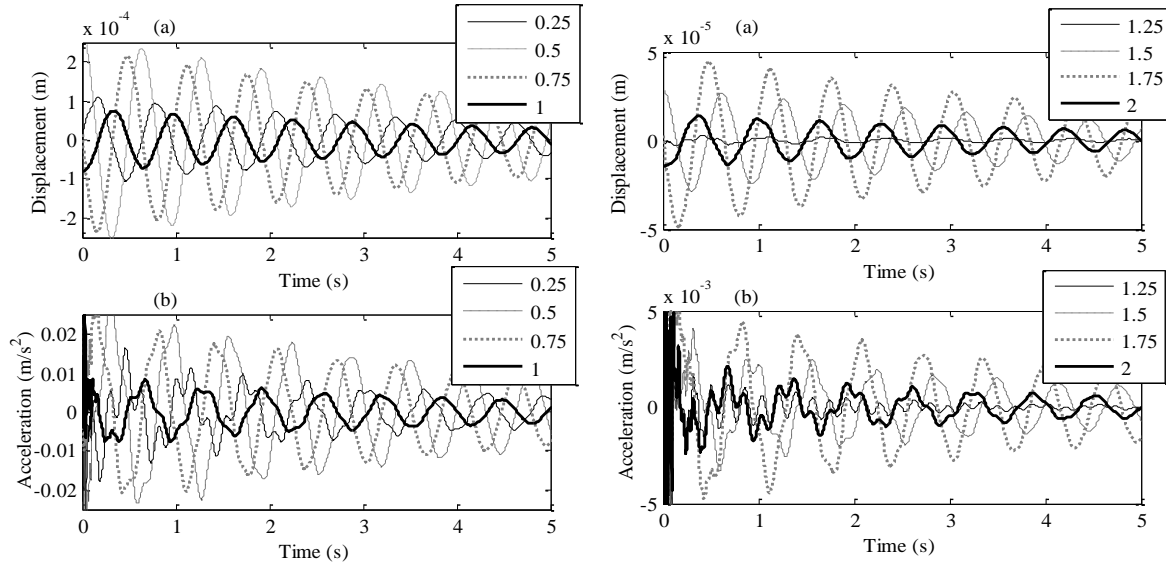
### 3.2 Single traversing load

While the bridge undergoes global sway at the first natural frequency (see Fig. 2), it first sways to the left (say) with span 1 deflecting downward, then sways right with span 2 deflecting downward. If we consider a single load ( $A_{x,1} = 100 \text{ kN}$ ) traversing the bridge while it undergoes motion at its own natural frequency, the rate at which the load traverses will interact with the amplitude of the bridge's lateral motion. It is postulated in this paper that maximum amplification of the response should occur if the load traverses the first span in the time it takes for the bridge to undergo one half of its vibration cycle (i.e. reaching the pier when the bridge is in condition (b) of Fig. 2). This means that the load will be on the left span when it naturally deflects downwards and on the right span when this naturally deflects downwards due to the bridge's periodic motion, thus amplifying this response. The opposite situation (maximum diminishing of signal) should occur if the load traverses span 1 in the time it takes for the bridge to undergo a full vibration cycle (i.e. condition (d) in Fig. 2). To investigate this, an analysis is conducted herein. For the analysis in this paper, only the free vibration signal after the vehicle (load) leaves the bridge is produced. A single load traverses the bridge with a velocity ( $v_s$ ) such that it crosses the first bridge span (25 m) in a time that is a given ratio of the bridge's natural period, see Table 2. The results of this analysis should confirm that a load traversing the bridge span 1 in a time that equates to half of the bridge's natural period is the most beneficial in terms of signal amplification (free vibration) while a load traversing the span 1 in a time equating to the full bridge period will impede the vibration the most. Establishing the effect at multiples of the bridge period (i.e. ratios  $> 1$ ) is also undertaken to observe if the effect is any different and also to see how the system reacts with more realistic loading velocities. Table 2 outlines the crossing times and required velocities for the analysis.

**Table 2.** Load velocities to traverse span 1.

Span (m)	$T$ (s)	Time to cross Span 1 $T_v$ (s)	Ratio $T_v/T$	Load $v_s$ (m/s)
25	0.639	0.16	0.25	156.43
25	0.639	0.32	0.5	78.22
25	0.639	0.4794	0.75	52.14
25	0.639	0.639	1	39.11
25	0.639	0.799	1.25	31.29
25	0.639	0.959	1.5	26.07
25	0.639	1.118	1.75	22.36
25	0.639	1.278	2	19.56

The results for the analysis are shown in Fig. 3. Fig. 3(left) shows the lateral pier top displacement and acceleration responses in free vibration for velocity ratios  $\leq 1$ . Fig. 3(right) shows the lateral pier top displacement and acceleration responses in free vibration for velocity ratios  $\geq 1$ . Five seconds of free vibration is analysed. In Fig. 3(left) it is evident that the maximum amplification of the free vibration response signals occurs for a load traversing the first span in the time it takes the bridge to undergo 0.5 times its vibration cycle. It is also shown that the lowest amplification of the signal occurs when the load traverses the first span in the time it takes the bridge to undergo a full cycle. The other ratios give intermediate results and the results are the same for both displacement and acceleration. This is sensible (and expected) as it indicates that when the load is completely in phase with the bridge motion (i.e. pushing down on span 1 as it naturally deflects downwards due to periodic motion, then moving to span 2 as this naturally deflects downwards) we achieve maximum amplification. When the load acts to resist the bridge's own oscillatory motion, we achieve the lowest amplification.



**Fig. 3.** Lateral pier top signals for load traversing span 1 in specified ratio.  
left – ratios  $< 1$ , right – ratios  $> 1$

Fig. 3(right) shows the results for the load traversing span 1 in a time that is multiples of the bridge's natural period. The amplitude results in this case are almost an order of magnitude less pronounced (to be expected as there is an element of the load acting against the bridge movement for every case). The results for Fig. 3(right) indicate a different outcome than those in Fig. 3(left). The maximum signal amplification occurs when the load reaches the end of span 1 in a time that is 1.75 times the bridge's period as opposed to 1.5 times which might have been expected from the first set of results. Also the lowest amplification occurs for the load traversing span 1 in 1.25 times the bridge period as opposed to 2 times, as might have been expected. The amplitude of the free vibration is a function of the bridge displacement, velocity and acceleration at the point when the load leaves the bridge and this can have a significant effect on the amplitude of the signal in free vibration. The results are less intuitive than when the load traverses in a specified ratio less than 1 of the bridge period as in this case it is easy to see when the load will act to impede the bridge motion. For ratios greater than 1, there is a trade-off effect in place as at some stage during the loading, the load will always be 'working against' the bridge motion to some degree. These results highlight the complicated interaction process at play in this problem and moreover show that using vehicle-induced vibration signals for bridge damage detection could potentially lead to issues with time-domain based SHM techniques.

#### 4 Conclusion

Vibration-based Structural Health Monitoring is a growing research area. In this paper we describe the application of the approach to investigate reliable methods to detect damage arising in bridge structures using dynamic response measurements. For scour detection using vibration-based methods, the lateral response of a bridge sub-structural element has been shown to be most sensitive to scour. Obtaining dynamic signals from a bridge is mostly undertaken by monitoring its response to ambient traffic loading. Therefore, it is of interest to study potential effects that could arise from the interaction between the rate of loading a two-span integral bridge and the measured response. In this paper, vehicle velocity effects were investigated in terms of how they can amplify or diminish the dynamic response of a bridge. The results show that the response magnitude in free vibration can vary significantly depending on how the load interacts with the bridge in terms of its own oscillatory motion. The results

in many cases may not be intuitive and this study aims to highlight potential disparities that can arise. This phenomenon could become an issue for time-domain related SHM techniques, as a diminished signal magnitude could become absorbed into the noise band of a standard sensor for example. Signal clarity can be a serious issue for many of these methodologies.

## Acknowledgements

The authors wish to acknowledge the support of the European Union H2020 project DESTination RAIL (Project No. 636285) and the Geological Survey of Ireland (GSI) Short-Call 2015 (Project No. 2015-SC-035) .

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## Damage detection for bridge structures based on dynamic and static measurements

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### Abstract

Some results of damage detection for real bridge structures are reported in the present paper based on both dynamic and static measurements. Dynamic analysis relates to the identification of modal parameters and deduced variables... The processing of static data is based on the analyses of deflection line and its derivatives, i.e. slope and curvature.

Detection methods were applied in several real concrete bridges in Luxembourg. The results are encouraging and useful for Structural Health Monitoring in civil engineering structures.

**Keywords:** bridge, damage, modal identification, deflection, temperature

### 1 Introduction

As bridges are structures of big size and subjected to varying temperatures, their structural health monitoring is quite difficult. Typically their inspections are done visually and static load testing is sometimes performed. Furthermore, especially in the last years, monitoring of modal features like eigenfrequencies, mode shapes or damping ratios is in vogue. These features can be used for subsequent analyses like model-updating and stiffness or flexibility assessment to identify and localize stiffness changes (Reynders & De Roeck, 2010; Huth et al., 2005; Nguyen & Golinval, 2010), even to predict remaining life (Khan et al., 2015). On the other hand, static load tests providing important information on deformation, displacement, tilt and strain (Inaudi, 2010) are still an appropriate alternative with a long tradition.

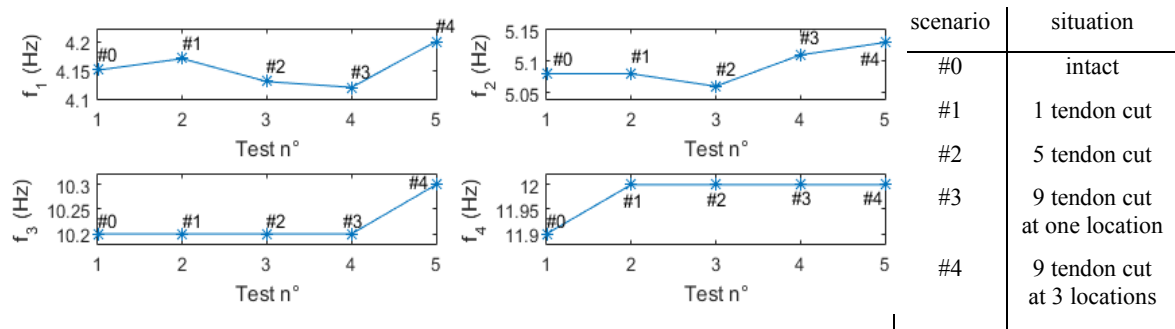
In the last decade, the Research Unit in Engineering Sciences at the University of Luxembourg had the opportunity to investigate several real bridges as well as to analyze the consequence of artificial introduced and hence known damages prior to their final demolition for different reasons. Some revealed issues are reported in the present paper, including both static and dynamic analysis. Different damage detection methods were tested and some results are reported in the present paper, including both static and dynamic analyses.

### 2 Dynamic investigation

Since corrosion and fatigue can induce cracking in concrete and hence stiffness reduction, the health condition of a structure may be reflected via its modal parameters, namely eigenfrequencies, mode shapes, modal masses and damping ratios. For example in any numerical model, damage or a reduction of structural stiffness normally leads to a reduction of eigenfrequencies. However, for real bridges, the damage detection based on the variation of eigenfrequencies is not always straightforward, because the reduction of frequency due to damage may be even lower than its variation due to environmental influences or due to measurement noise. It is for instance known that temperature influences Young's modulus of asphalt or bearings including the sub-soil, which hence changes considerably the stiffness. This can be illustrated by the two following examples.

The "Deutsche Bank" Bridge (Maas et al., 2012) was a three-span concrete bridge with a total length of 51m, post-tensioned by 29 tendons with subsequent grouting. In order to simulate damage, several prestressed tendons were cut according to 4 damaged scenarios #1 to #4 (1 to 27 of 29 tendons locally cut) and scenario #0 denotes the intact state. Under the excitations of an electric shaker with swept sine excitation of constant amplitude, vibration

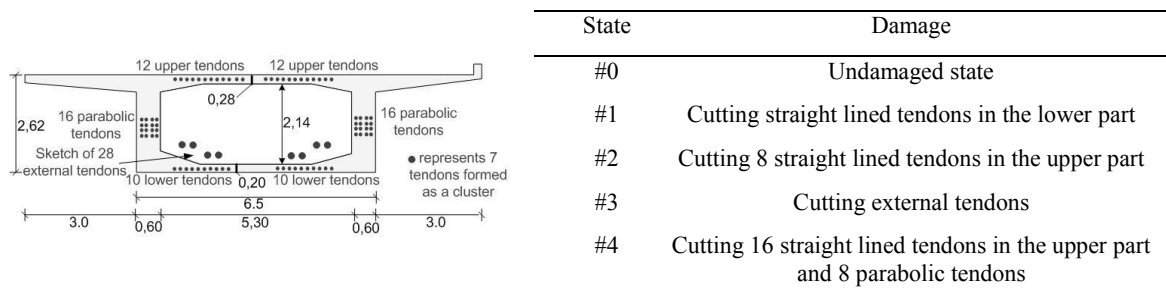
responses of the bridge were captured by 12 sensors allocated on two sides of the bridge deck. Eigenfrequencies identified for the first 4 modes are depicted in Fig. 1.



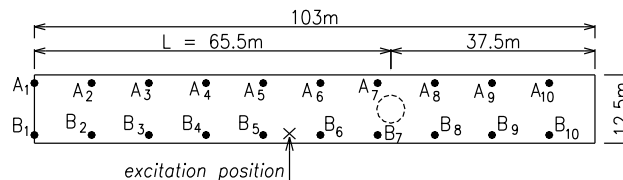
**Figure 1** : “Deutsche Bank” Bridge – eigenfrequencies measured for healthy state and increasing levels of damage

Though considerable local damages from condition #1 to #4 were stepwise increased, the eigenfrequencies do not reveal obvious decrease, above all as no visible cracking in concrete was observed.

In a second example, the Champangshiel-Bridge, artificial damages induced cracking in concrete but no monotonous decrease of eigenfrequencies. It was a pre-stressed concrete bridge that the total length is 102 m with two spans of 37 m and 65 m (Nguyen et al., 2014). A cross-section of the bridge is given in Fig. 2 and the position of sensors in Fig. 3; the distance between them along the bridge’s length was about 10 m. Before its complete destruction, the bridge was monitored and a series of damages were artificially introduced as summarized in the table in Fig. 2.



**Figure 2** : Schematic cross section of the box girder with location of the tendons and the execution of damages in the Champangshiel bridge



**Figure 3** : Location of the sensors on the deck of the Champangshiel bridge

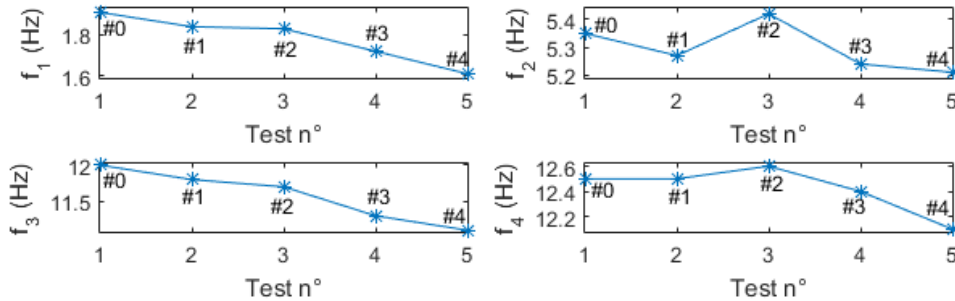
Vibration monitoring under swept sine and impact excitation were performed for the healthy structure and for each damage state. The identification of eigenfrequencies from these two types of excitation gave quite similar results which are shown in Fig. 4.

For this bridge, reduction of the eigenfrequencies due to damages is clearly visible, though not strictly monotonous. Especially for damage scenario #2, an increase of the eigenfrequencies  $f_2$  and  $f_4$  is apparent.

These two examples show that the detection by simple observation of frequencies is not always evident. Furthermore it should be noted that any perturbation due to excitation was avoided because the structures were always excited with the same manner and level. But for instance temperature variation was unavoidably present, due to the size of the bridge, due to solar radiation and day-night changes.

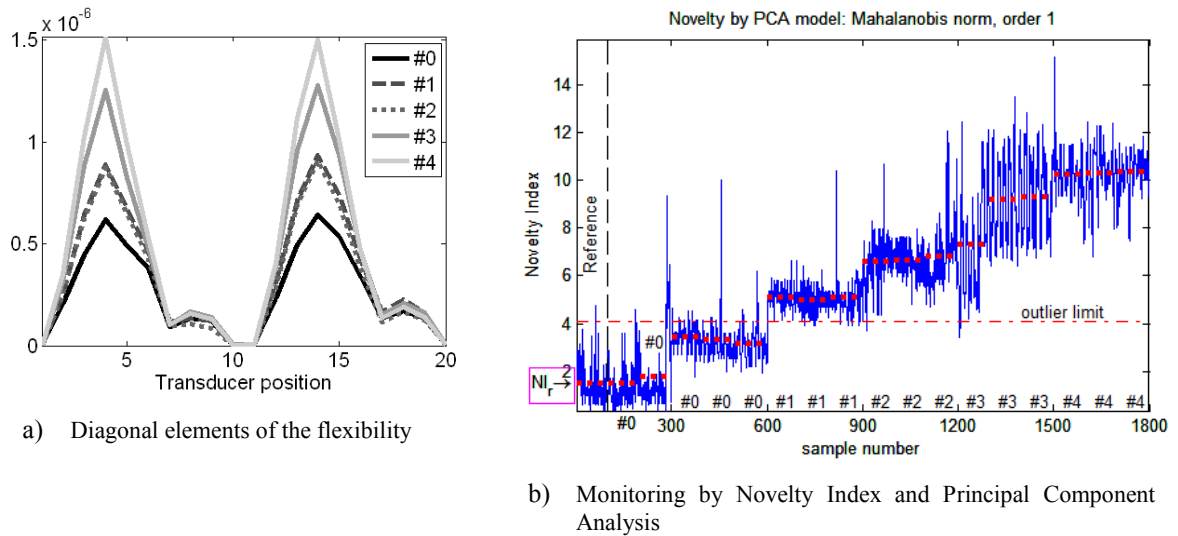
Other useful alternative can be the analysis of deduced dynamic features, e.g. the flexibility matrix or the use of Principal Component Analysis (PCA), a statistical method to remove noise and even temperature influence. Mode shapes are known as less sensitive to global change (e.g. due to temperature) but more perceptible to local change (e.g. due to damage). The flexibility matrix, i.e. the inverse of the stiffness matrix, is often computed in practice based on a limited number of measured eigenfrequencies, mode shapes and modal masses. This may allow

observing an increase of flexibility of structure with damage. As presented in Fig. 5a, the diagonal elements of this matrix show clearly the distinction between the different levels of damage (Mahowald et al., 2012).



**Figure 4 :** Champangshiehl bridge - eigenfrequencies measured for every state

Principal Component Analysis (PCA) is a statistical method that enables damage detection including environmental effects by considering for instance dynamic features as input, for example the identified eigenfrequencies (Nguyen et al., 2014). A particular advantage of this method is its ability to separate ambient influence from changes caused by damage, provided the number of samples is sufficient. A damage indicator called Novelty Index can be used as efficient tool for evaluating the difference between healthy and damaged states. Fig. 5b presents the PCA detection based on the first four eigenfrequencies and 300 samples in any damage scenario. In order to enable the detection on a broad basis and to avoid false alarm, the data in the healthy condition #0 are enriched and gathered from different days and different excitations (hammer impact and swept sine). The damaged states are examined under the swept sine excitations with constant excitation force amplitude. In total, Novelty Index  $NI$  is computed for 1800 samples for all the states. A red bold dotted line shows the mean value of every 100 samples. The dash-dot horizontal line indicates a statistical outlier limit  $OL = \overline{NI}_r + 3\sigma$  where  $\overline{NI}_r$  and  $\sigma$  are the mean value and the standard deviation of Novelty Index in the reference state.



**Figure 5 :** Damage detection for the Champangshiehl bridge

An overall look at Fig. 5b reveals an interesting result: despite the variation of the  $NI$  for the undamaged state #0 (which results from the variation of the eigenfrequencies with the temperature), most of the  $NI$  values lie below the outlier limit line. The few samples crossing this line are influenced by other factors, e.g. the presence of nonlinear effects or measurement noise. The small variation of the mean values in the healthy state #0 comes from simply the difference of excitations. On the contrary, all the damaged states are clearly detectable by exceeding the outlier limit. They are well classified and increasing in accordance with the respective damage levels.

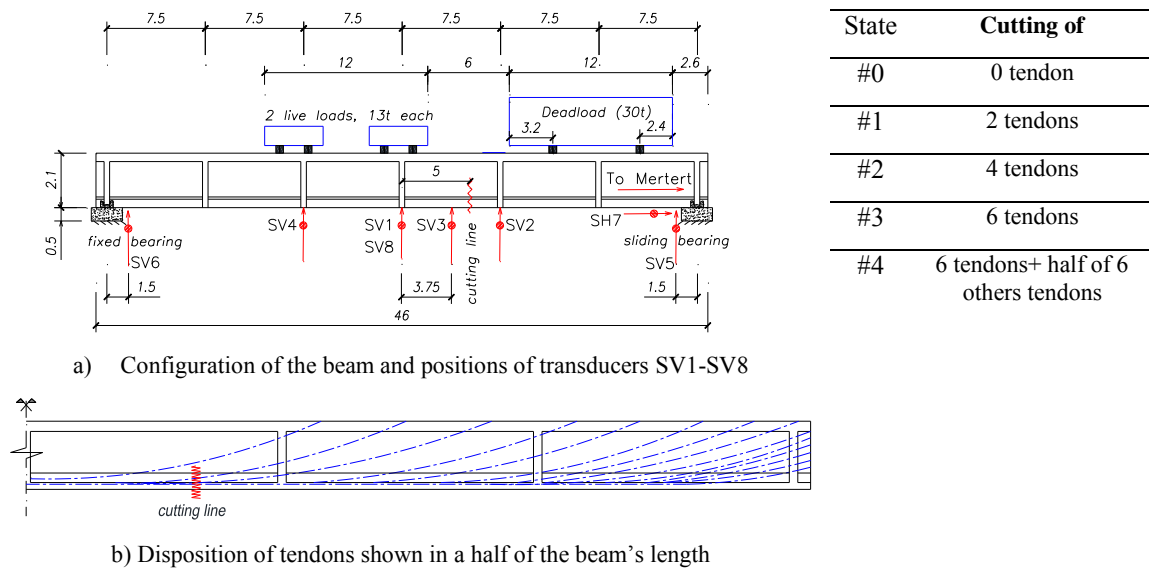


### 3 Static investigation

Beside vibrational inspection, static testing provides helpful and reliable information for assessing the actual condition of a bridge by discovering local change of stiffness through shape deformation and through the absolute values of deflection line for a given loading.

It consists in register displacements at several points in the structure and thus the deflection line is established for every state. This method is subsequently illustrated by a third test-object, the Grevenmacher-Bridge. The old bridge had 5 independent fields that each consisted of 5 parallel pre-stressed concrete beams. It was demolished in 2013 and two of these beams each with a length of 46 m and a mass of about 120 tons were shipped to a nearby port for test purposes.

In order to simulate the loading situation during its operational life, the dead-load of asphalt, pavement, guard railing, etc. had to be modeled. Hence one beam was cut in pieces and used for charging the second one, our test-object (Fig. 6.). One fixed and one sliding bearings were realized by cast-in-place concrete onto nearby railroads, which provided a solid foundation.



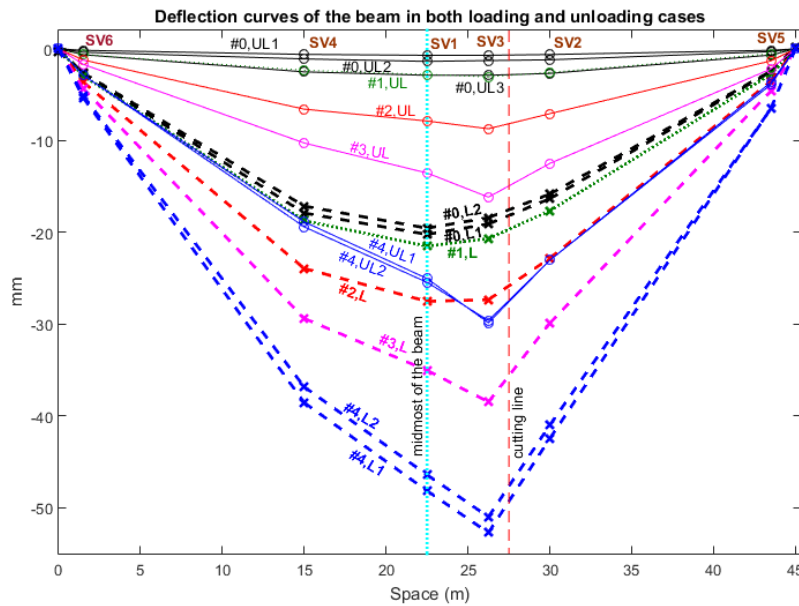
**Figure 6 :** The test set-up of the beam and description of damage scenarios #0 - #4

So to simulate this additional dead load, a part of the second beam with a mass of approximately 30t was set on the top of structure. This mass stayed onto the beam during the whole test period and is therefore referred to as permanent load. Although it was not distributed over the whole beam like an asphalt layer, it was considered as an admissible approximation. Additionally, two concrete blocks, each with a mass of 13t, were used to represent live loads due to high traffic loading on the bridge. They were put on for static tests and removed again after at least 24 hours. Displacements due to these loads were recorded in several locations, as detailed in Fig. 6a, along the vertical (SV1-SV6, SV8) and horizontal directions (SH7).

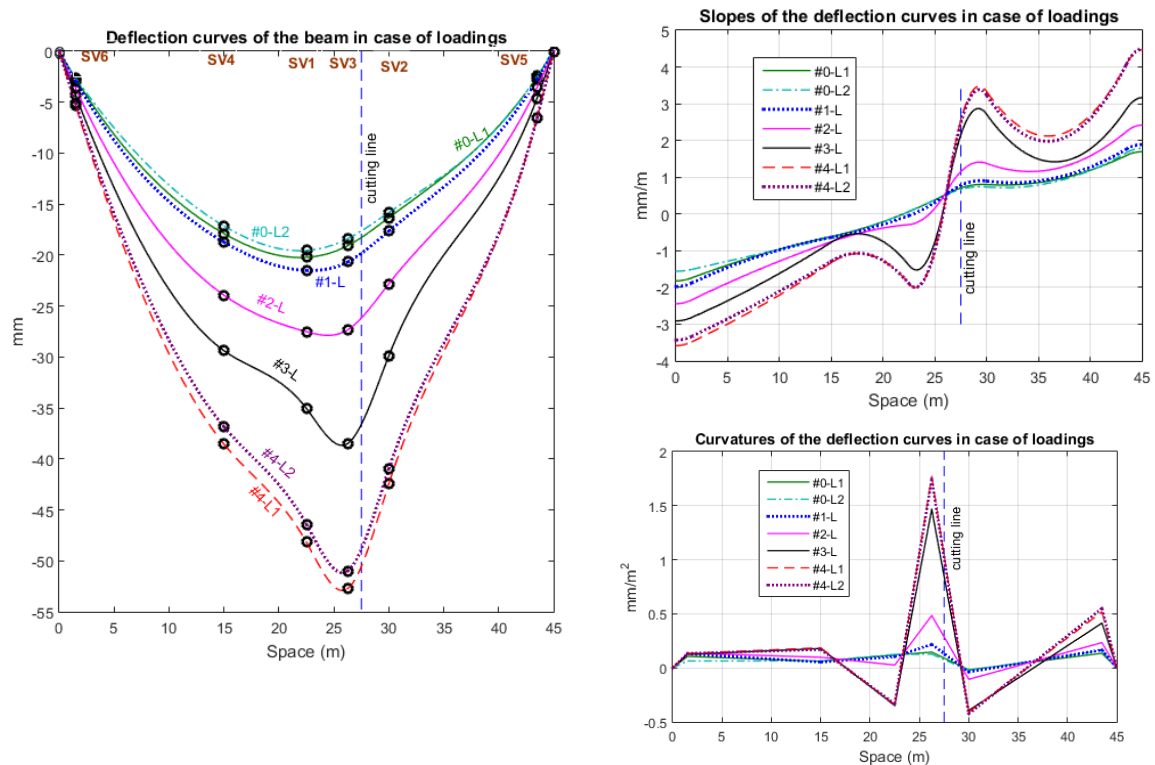
The beam was prestressed by 19 steel tendons along the longitudinal direction of the beam as illustrated in Fig. 6b for a half of the beam. Different damage scenarios were simulated by cutting the tendons at the cutting line indicated in Fig. 6. Static tests were carried out by loading and unloading the structure always with the two live loads, in total 7 times. Hence two principal situations have to be distinguished: loading (L) and unloading (UL). In total, 7 loadings are considered from #0 to #4 as #0-L1; #0-L2; #1-L; #2-L; #3-L; #4-L1 and #4-L2.

The aim here is to establish deflection lines of the beam, distinguished from zero position of reference configuration #0, UL1. Fig. 7 presents deflection lines of the beam for both unloading and loading states by connecting simply measured points SV1 to SV6. Two zero points are assigned according to the two border bearings. The data are picked up according to 8 unloading times and 7 loading times from scenario #0 to #4. Before the appearance of vertical cracks around the cutting line from scenario #0 to #2, the deflection curves are quite regular and smooth in an overall view. After that, the future breaking point became maximum deflection point and is clearly shown by the sensor SV3, which was close to the cutting line. The maximum deflection moved from SV1 (in the middle) to SV3, near the cutting line of the beam. This proves that the drawing of deflection curves from the initial state to all the damage states allows localizing damage.

For comparison purposes, the deflection lines were also smoothed by the cubic spline interpolation. To improve the visibility only the loaded states are presented in Fig. 8.



**Figure 7 :** Deflection of the beam in unloaded and loaded states



**Figure 8 :** Results from the cubic spline interpolation: Deflection lines, Slopes and Curvatures

While damage can be detected and localized already by the raw deflection lines in Fig. 7, it can also be localized by important change of shape of the curve and by the increase in displacement near the cutting line. The absolute values in Figs. 7-8 can already be used as damage indicator. Looking at only loaded or only unloaded state near the crack (position SV3), an increase of at least 30mm can be detected with respect to the healthy reference state. This very important change indicates as well the presence of damage.

Naturally, the derivatives of the deflection curve, namely the slope (1<sup>st</sup> derivative) and the curvature (2<sup>nd</sup> derivative) are also helpful for localization. Damage can be identified by strong variation of the slopes around the cutting line. These variations lead to high values of curvatures near the cutting line. Damages are accurately localized as the curvatures near the cutting line show dominant values compared to other positions. It shows that the damage localization is efficient and accurate from damage state #2.

#### 4 Conclusion

Several techniques from dynamic and static data for damage detection in bridges are presented in this paper. Dynamic methods are based on eigenfrequencies, mode shapes, flexibility, and Novelty Index. They showed different performance with respect to ambient and operational influences as for instance temperature variation and excitation level. Alternatively, the establishment of static deflection curves from load testing is an effective means to localize damage. Around breaking line, an increase of flexibility is observed and important changes of shape as well as amplitude of the deflection curves are revealed. Furthermore, their slopes and especially curvatures allow localizing damage by showing sudden changes along the structure.

The combination of dynamic and static methods provides an exact basis for the assessment of bridge health condition and may also be used for model updating techniques.

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## Qualitative performance indicators for bridge management in Italy

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**Abstract.** In this contribution, the activities related to the definition of performance indicators for bridge management, carried out at the University of Padova, Italy, are shown. In particular, a new procedure for evaluation of bridge conditions by means of visual inspections, aimed at general planning of maintenance in a Bridge Management System framework, is illustrated. This procedure was also coupled with a time-dependent algorithm with the aim of developing a statistically-based tool able to predict the time variation of bridges' maintenance state, according to visual survey outcomes. Since most of bridges are not designed for carrying seismic actions but can potentially be subjected to earthquake effects, a simplified seismic assessment procedure for large-scale bridge stocks was also proposed and integrated with the procedure for management of maintenance. Furthermore, an extensive cost analysis for maintenance and seismic retrofit of typical existing road bridges based on integrated procedures for the condition state and seismic vulnerability assessment is proposed. Some of the above procedures are currently applied on a real bridges' stock in the framework of an agreement between the Dept. of Civil, Environmental and Architectural Engineering of the University of Padova and an Authority managing a highway network and related infrastructures in the North-Eastern part of Italy.

**Keywords:** bridge management; deterioration; performance indicators; retrofit costs; service-life; visual inspections.

### 1 Introduction

Bridges are usually subject to deterioration depending on several factors e.g. environmental condition, natural aging, quality of the material, and planned maintenance. These structures are the most highly exposed to deterioration induced by harsh climatic conditions, ageing, and increased volumes and weights of traffic axle loads. Greater demand to improve the management of bridges is becoming increasingly evident. Many road and rail managing authorities have made significant efforts to develop bridge management systems (BMSs) (Zonta et al. 2007, Pellegrino et al. 2011), to obtain useful information when allocating resources and establishing management policies in bridge networks (Carturan et al. 2014). A BMS is a systematic method by means of which a public authority can manage all activities related to maintenance of its bridge assets, to optimize their life-cycle management and avoid any kind of damage or out-of-service situation, which could involve severe indirect losses to infrastructure users. Several BMSs have been developed over the years: examples can be found in Thoft-Christensen (1995), Markow (1995) and Kitada et al. (2000). During the last decade, several research projects focusing on management at network level of existing bridges have been financed by the European Commission and corresponding guidelines have been produced (BR.I.M.E. (2001), COST345 (2004), SA.MA.R.I.S. (2005) and Sustainable Bridges (2006)). In currently available BMSs, decision-making mainly depends on combined quantitative/qualitative information from in-situ investigations and visual inspections. The scientific community has studied these topics and contributed to the development of many BMSs currently in use worldwide. Questions regarding the seismic assessment of existing bridges are also examined here, since bridges are known to be the most vulnerable elements in transportation networks subjected to seismic events. Most of the existing bridges in the moderate earthquake regions of Italy are more than 50 years old, and the majority were designed without taking earthquake forces into consideration. Any moderate to major seismic event can cause severe damage to these structures, affecting public safety and interrupting vital lifelines (Shirole and Malik 1995; Kuprenas et al. 1998). Past experience has shown how, during their lifetime, bridges undergo structural problems due to environmental

conditions and natural disasters: concrete cover damage exposes bars to the atmosphere, steel may become corroded by icing cycles, and ageing of structural materials are some of the causes leading to degradation of the mechanical properties of reinforced concrete (Zanini et al. 2013; Biondini et al. 2014), thus amplifying the effects of earthquakes and increasing the risk of seismic damage (Franchin et al. 2006; Modena et al. 2014; Morbin et al. 2015). The optimal distribution of limited budgets is therefore a challenge connected with priority problems, if the service level of an infrastructural system is has to be maximized: maintenance operations against natural ageing and seismic retrofit interventions aimed at reducing local/global structural vulnerabilities (Zampieri et al. 2015) are interacting problems, important for proper bridge management by public authorities or private companies. In this contribution, procedures developed at the University of Padova for the evaluation of bridge conditions by means of visual inspections, aimed at general planning of maintenance in a Bridge Management System framework, are illustrated. Some of the above procedures are currently applied on a real bridges' stock in the framework of an agreement between the Dept. of Civil, Environmental and Architectural Engineering of the University of Padova and an Authority managing a highway network

## 2 Procedures for the deterioration and seismic vulnerability assessment for portfolios of bridges

Two specific procedures for the deterioration state evaluation and the seismic vulnerability assessment of bridge structures have been developed with the aim to enclose them in a BMS environment. The procedure for bridge qualitative deterioration assessment proposed by Pellegrino et al. (2011) was adopted here, with improvements taking into account the costs of maintenance operations. A brief description of the method, improved with the part related to costs, is given below. The inspection system used is the visual survey method, according to the standards adopted by countries (BR.I.M.E. 2001, Italian Ministry of Infrastructures 2008). Visual inspections can be carried out on main structural and non-structural elements of bridges, to assess their condition without the need for special equipment or restrictions on traffic flow. The method defines the Total Sufficiency Rating (TSR) parameter, a global qualitative indicator of the "state of health" of each bridge. Figure 1 shows a general overview of the TSR assessment framework.

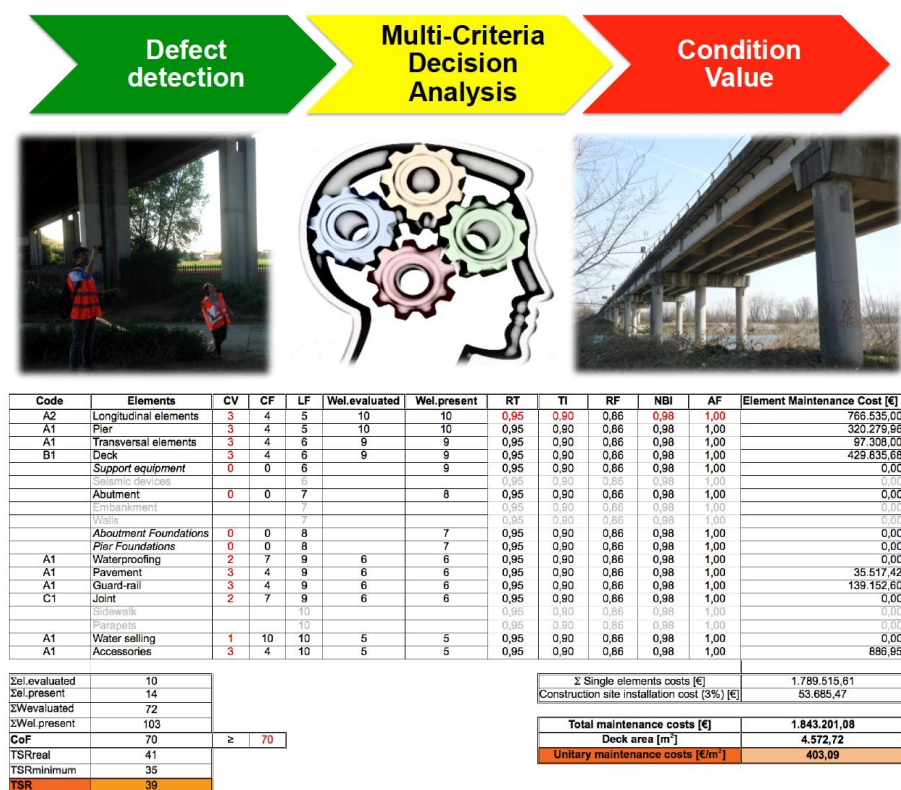


Fig. 1. General overview of the TSR assessment framework for a bridge case study.

Calculation of TSR involves a specific algorithm, based on the definition of the Condition Value (CV) of each element composing the bridge under analysis. The CV is a qualitative variable, representing a condition related to a precise group of defects of the element for which it is estimated. A CV value ranging from 1 to 5 can be defined

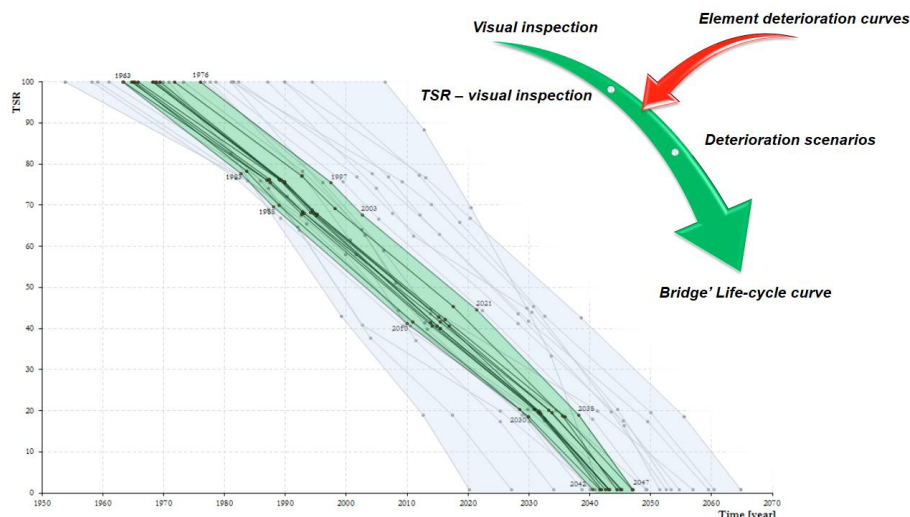


for every element of a bridge; if no evaluation can be expressed, CV is assumed to be zero. CV is defined through a multi-criteria decision analysis based on the assessment of the set of defects detected on each element. Once a CV for each visible element has been defined, specific Condition Factor (CF), Location Factor (LF) and Weight (W) are examined, to assign a different significance to each bridge element, in relation to its importance in defining the TSR. All such parameters are summarized in the TSR index, which takes into account deterioration on each element and at the same time its relative importance on a bridge.

Regarding seismic vulnerability assessment, the procedure adopted is described in Pellegrino et al. (2014) but is integrated here with a section concerning seismic retrofit intervention protocols and related costs. The particular vulnerabilities of the structural elements constituting masonry/stone arch bridges - arches, spandrel walls, piers, abutments and foundations - were studied in depth. For each masonry or RC/PRC bridge, the minimum safety factor value  $FC_{i,min}$  (of those calculated) was assumed to represent the main seismic vulnerability indicator for each structure, since it is related to the governing failure mode in the case of a seismic event.

### 3 Remaining service-life prediction framework

It is possible to define a time-dependent qualitative service-life relationship, when many visual inspections are carried out on a single bridge in different time instants, obtaining for each one a TSR index. Although, the problem of deterioration forecasting seems still unsolved. Here, a procedure was proposed and validated on two bridge stocks with the aim to try to solve such question. The procedure is schematically shown in Figure 2: firstly, visual inspections are performed; then, the bridge health state is evaluated; for each structural and non-structural element, deterioration curves are calibrated, taking into account visual inspection report data, statistically processed through Bayesian inference. Bayesian techniques provide powerful tools for integrating in a rigorous manner, epistemic and aleatory uncertainties (Igusa et al. 2002). Bayesian inference, in particular, was proven to be suitable in evaluating the expectation of a function of interest, providing a satisfactory way of explicitly introducing assumptions on prior knowledge, or conversely, ignorance. Additionally, the need for model updating can be easily solved using Bayesian approach, as observed in several works of interest about structural engineering applications (Beck and Au, 2002).



**Fig. 2.** Service-life prediction for a portfolio of existing bridges.

In this study, condition state forecasting is based on visual inspection data, and Bayesian updating is considered for the prediction of the number of years  $\theta$  asked by a generic bridge component, for moving from a specific  $CV_i$  to the next worse one  $CV_{i+1}$ . This allows formulating a deterioration prediction, based on a set of available visual inspection data, and progressively updated with new information collected during visual surveys on homogeneous bridge clusters (in terms of environmental conditions, ages of construction, materials and structural schemes).



Lastly, deterioration scenarios are run and bridges' life-cycle curves are derived. The greater number of visual inspections available for each bridge, the more accurate will be the prediction of the structure service-life curve.

#### 4 Costs vs TSR models

A subsequent step of the activities was the calibration of cost models, based on results derived by the assessment of maintenance state, seismic vulnerability for existing road bridges. Figure 3 shows a general overview of the key points of the cost model analysis calibrated from a stock of bridges in the district of Vicenza, North-East Italy. In this work, the datasheets implemented by Pellegrino et al. (2011) to evaluate the CV for each bridge component were upgraded by associating a maintenance intervention protocol, characterized for each bridge by a specific cost value. Costs partly derive from estimations for seismic retrofit projects by structural engineers (about 35% of cases) and the real costs of operations by contractors (45%), if available. As these data were not available for all the bridges in the stock analyzed here, estimations were made by the authors (20%) according to official prices given by the managing authorities (the usual approach of practicing engineers). Seismic retrofit costs were estimated for each bridge, characterized by a  $FCi.min$  value lower than 1, as the sum of the seismic retrofit costs of each component specifically calculated for each bridge.

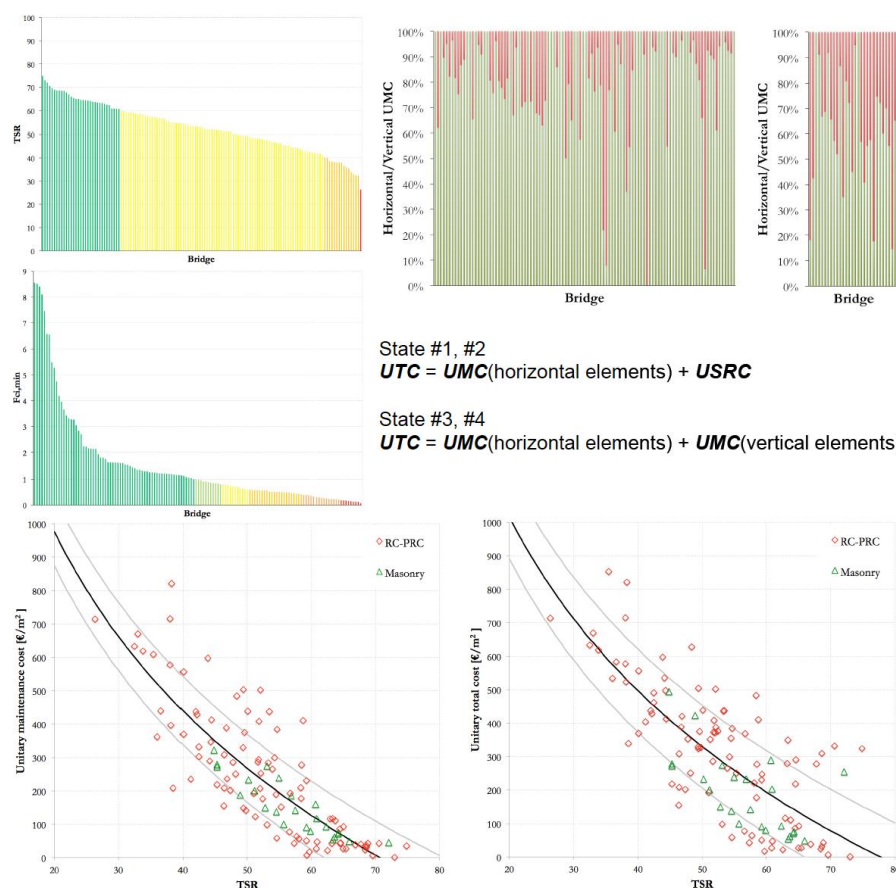


Fig. 3. Cost analysis performed on a bridge stock in the province of Vicenza.

Bridges were characterized by the following parameters: (i) a TSR related to the state of maintenance of the structure; (ii) a unit maintenance cost (UMC); (iii) a  $FCi.min$ , describing the main critical situations detected in seismic assessment of bridges; (iv) a unit seismic retrofit cost (USRC); (v) a unit total costs (UTC) calculated, taking into account possible synergy effects due to common maintenance and seismic retrofit work. Regression formulas for predicting UMC, USRC and UTC for common RC-PRC and masonry bridges are proposed. In particular, significant correlations between TSR values and UMCs were found. In the case of USRCs, a slightly decreasing linear relationship with  $FCi.min$  was identified and compared with guidelines provided by the Italian OPCM 3362/04 (2004) model. Lastly, significant correlations were detected between TSR and UTCs. The

## 5 Procedures application to the Concessioni Autostradali Venete S.p.A. bridges' portfolio

**Fig. 4.** A portrait of the portfolio of structures managed by Concessioni Autostradali Venete S.p.A...

In this work, the activities related to the definition of performance indicators for bridge management, carried out at the University of Padova, Italy, were briefly presented. The application of the proposed frameworks in the real context of the Concessioni Autostradali Venete S.p.A. highway authority allowed to face the actual questions that roadway operators daily have to manage in the conservation of the existing built infrastructural asset and lead to an improvement of the original procedures. Summarizing, qualitative performance indicators seem to represent a feasible and cost-effective methodology for the management of huge stocks of bridges.

The authors would thank Concessioni Autostradali Venete S.p.A. who founded the development of part of the procedures described above.

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## Using an air permeability test to assess curing influence on concrete durability

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**Abstract.** This study investigated the differentiation capability of an onsite air permeability test (Torrent's method) when applied to concrete mixes subject to different curing. The statistical analysis of the experimental results concludes that the considered method is capable to detect significant differences in air permeability due to changes in the curing conditions.

**Keywords:** durability, reinforced concrete, curing, air permeability, assessment.

### 1 Introduction

Nowadays, air permeability - as measured by the Torrent method - is recognized as a suitable performance indicator of reinforced concrete durability (SIA, 2013; JCI, 2014) and has been used as control parameter in several structures (Torrent et al., 2013; Di Pace et al., 2008), more specifically in bridges (Li et al., 2015; Torrent, 1999). Moreover, it is covered by a standard that establishes limiting values, detailed sampling, moisture and temperature effects, testing and conformity procedures regarding concrete air permeability, tested on site on the structures (SIA, 2013). It is generally acknowledged that significant differences exist between concrete properties assessed on site and on laboratory cast specimens (Torrent et al., 2007). These differences may arise from different causes, curing being an important one of them. The impact of curing on concrete properties has been widely investigated (Fattuhi, 1986; Zhutovsky & Kovler, 2012). Despite all the research that has been carried out on this subject, it is still important to know whether a certain test method is capable of detecting the impact of different curing conditions on durability performance. This is so, because - contrary to compressive strength - durability relies on the performance of the surface layers that constitute the defense barrier against the penetration of aggressive species. This contribution aims at ascertaining the capability of the method described in Annex E of (SIA, 2013), applicable in the lab and on site, to differentiate the air permeability of concretes subjected to distinct curing.

### 2 Experimental Program

To attain the objective, two concrete mixes were subjected to five different curing and the resulting air-permeabilities measured in the laboratory. Details on the materials, mix proportions, specimen preparation and test method are provided in the following.

A limestone Portland cement, complying with EN 197-1 (CEN, 2001) requirements for II/A-L 42.5R cement, was used. Fly ash, complying with the requirements of EN 450-1 (CEN, 2005a) constituted 1/3 of the total binder weight in one of the mixes. Besides, two coarse aggregate fractions composed of crushed limestone rock, two siliceous natural sands and a commercial plasticizer were used.

Two mixes were designed, aimed at developing similar compressive strength and workability. Given the known sensitivity of concrete containing fly ash to curing conditions, in one of the mixes fly ash replaced 1/3 of the cement. The total binder content of each mix was set to 300 kg/m<sup>3</sup>, and the proportioning of the remaining constituents was defined aiming to achieve a slump value of 170 mm and a mean compressive strength at 28 days of 45 MPa. Workability and compressive strength were determined according to EN 12350-2 (CEN, 2009a) and EN 12390-3 (CEN, 2009b), respectively. Mix proportions, workability and 28-day compressive strength of the mixes are summarized in Table 1.

**Table 1.** Proportions and basic properties of concrete mixes.

Mix	PLC57	FA52	PLC57	FA52
Constituents	Properties			
Gravel 11/22, kg/m <sup>3</sup>	570	600	Slump, mm	170
Gravel 4/16, kg/m <sup>3</sup>	520	560	Compressive strength, MPa	50.0
Medium sand, kg/m <sup>3</sup>	510	480		43.1
Fine sand, kg/m <sup>3</sup>	290	270		
Cement, kg/m <sup>3</sup>	300	200		
Fly ash, kg/m <sup>3</sup>	-	100		
Water, l/m <sup>3</sup>	170	155		
Plasticizer, l/m <sup>3</sup>	3.0	2.4		

The concrete constituents were mixed in a revolving drum type mixer. Mixing was carried out until the concrete mixture was uniform (approximately 3-5 minutes). The concrete was placed in the molds in a single layer, which was consolidated by means of a poke vibrator, until the outflow of air bubbles to the surface was scarce. For each mix, 9 cubes (150 mm edge) were molded: 6 for air permeability testing and 3 for compressive strength testing. The specimens were demolded after 24 hours of casting. Afterwards, the specimens for compressive strength testing were immersed in water ( $20 \pm 2$  °C) until the age of testing (28 days). The procedures of curing and conditioning the specimens for air permeability testing were as follows. After demolding, one specimen of each mix was taken to a ventilated oven, set to a temperature of 35 °C and kept there for 3 days. The remaining specimens were immersed in water ( $20 \pm 2$  °C) during predefined periods of 2, 6, 13, 20 and 27 days, so that adding the 24 hours inside the molds, they had 1, 3, 7, 14, 21 and 28 days of curing. In the same way as for the first specimens, this was followed by staying 3 days in a ventilated oven at 35 °C to halt curing. After leaving the ventilated oven the specimens were kept in a climatic chamber set to a temperature of 20 °C and a relative humidity of 65% until the age of testing (42 days).

Air permeability was assessed using a test method developed by Torrent (1992) that is able to perform measurements on site and that is considered in Swiss standard SN 505 262/1 (SIA, 2013). A negative relative pressure was applied by a vacuum pump through a test chamber positioned over one of the flat surfaces of the specimen. After closing the connection between vacuum pump and the test chamber, the absolute pressure and the pressure variation inside the test chamber at the end of 12 min or the time elapsed until a pressure change of 20 mbar was reached, whichever occurred first, were recorded. Then an air permeability coefficient may be calculated using the following equation (Torrent, 2009):

$$kT = \left( \frac{V_c}{A} \right)^2 \times \frac{\mu}{2 \times \varepsilon \times p_a} \times \left( \frac{\ln \left( \frac{p_a + \Delta p}{p_a - \Delta p} \right)}{\sqrt{t_f} - \sqrt{t_i}} \right) \quad (1)$$

where  $kT$  - air permeability coefficient, m<sup>2</sup>;  $V_c$  - volume of the test chamber, m<sup>3</sup>;  $A$  - cross-section of the test chamber, m<sup>2</sup>;  $\mu$  - viscosity of air at 20 °C, N s/m<sup>2</sup>;  $\varepsilon$  - porosity of concrete, v/v;  $p_a$  - atmospheric pressure, N/m<sup>2</sup>;  $\Delta p$  - pressure increase in the test chamber, N/m<sup>2</sup>;  $t_i$  - time at start of the measurement, s;  $t_f$  - time at end of the measurement, s.

### 3 Results and Discussion

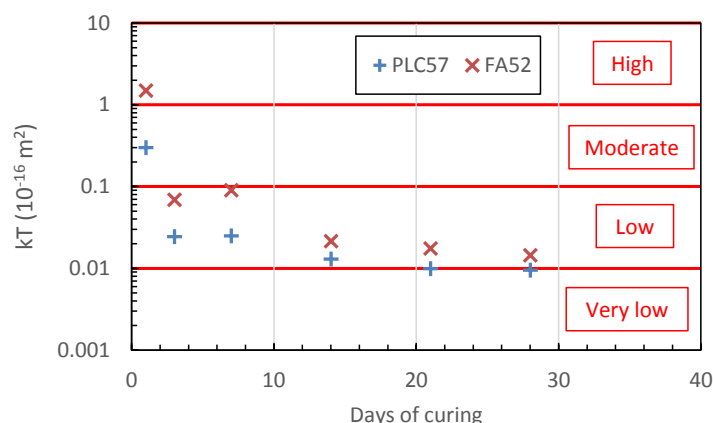
According to Neves et al. (2015) the air permeability of a concrete mix can be properly assessed through testing the molded faces of cubic specimens. Therefore, the air permeability of each set mix-curing was assessed by applying the cell on the five molded faces of a cubic specimen. As a single void or micro-crack that has meaningless influence on compressive strength, may increase air permeability by more than one order of magnitude, frequently, air permeability samples yield results that clearly fall outside the range of the rest. Following a quantitative approach, the definition of outliers proposed by Tukey (1977) may be applied: observations that differ more than one and a half times the interquartile range from the first or third quartile, percentile 25 and 75 of the sample, respectively. Following this definition, eight results, over 60 measurements, were classified as outliers.

Although disregarding outliers is questionable, in this particular case it is clear that the observed difference cannot be associated to the investigated variable: curing. Moreover, their presence in the analysis would definitely mislead the curing effect on permeability. Thus, the results classified as outliers will not be further considered.

As the median has been showing to be a suitable parameter to represent a sample from an air permeability population (Neves et al., 2012), the medians of each set mix-curing are reported in Table 2. Furthermore, a classification of concrete's permeability, based on a rating proposed by Torrent and Frenzer (1995), which comprises 5 levels ranging from 'very low' to 'very high' is also presented. The air permeability of both mixes for curing durations between 3 and 28 days is rated as low, while for curing duration of 1 day is either moderate (PLC57 mix) or high (FA52 mix). The variation of mixes' permeability with curing is depicted in Figure 1.

**Table 2.** Median values of  $kT$  and permeability rating.

Mix	Curing	$kT$ , $10^{-16}$ m <sup>2</sup>	Permeability	Mix	Curing	$kT$ , $10^{-16}$ m <sup>2</sup>	Permeability
PLC57	1 day	0.30	Moderate	FA52	1 day	1.5	High
	3 days	0.025	Low		3 days	0.069	Low
	7 days	0.025	Low		7 days	0.091	Low
	14 days	0.013	Low		14 days	0.022	Low
	21 days	0.010	Low		21 days	0.018	Low
	28 days	0.010	Low		28 days	0.015	Low



**Fig. 1.** Variation of  $kT$  with curing

Overall, the air permeability coefficient decreased with the increase of curing duration. For the shortest curing duration (1 day) the air permeability increased 23 times in comparison with the 28 day moist-curing, for the mix without fly ash, while it has increased two orders of magnitude for the mix containing fly ash. This marked effect of curing duration on the performance of fly ash mixes is well documented, as the pozzolanic reaction of fly ash with portlandite requires time and available water. Nevertheless for longer curing periods, the impact of curing duration on the air permeability of both mixes is quite similar. Another relevant aspect is the consistently higher air permeability of one mix over another, for all curing durations. Although there is a good correlation between water-cement ratio and air permeability, in which air permeability increases with water-cement ratio, there is also a good correlation between air permeability and compressive strength, in this case with decreasing air permeability for increasing compressive strength (Neves, 2012). In the present study the influence of the compressive strength prevailed over the water-binder ratio, as the air permeability coefficients of the mix with the lower compressive strength were the highest observed for each curing duration.

Although Figure 1 refers only to the median values, it is also important to take into account the scatter of the results inherent to the test method. Thus, in the following, the ability of the Torrent's method to differentiate the air permeability of concrete subject to different curing is assessed. Air permeability results for different curing



durations of each mix are compared by means of a hypothesis statistical test. Given the nature of the data – gas permeability results – a non-parametric test of hypothesis should be preferably used (Neves et al., 2012). However, the sets curtailed by the removal of outliers, constitute samples which are too small for the application of the suited Mann–Whitney–Wilcoxon test. Instead the Student’s test (Devore, 2011)), also used by the RILEM Committee TC 189-NEC to compare samples of air permeability populations (RILEM TC 189-NEC, 2005), is applied. The null hypothesis  $H_0$  is that both sets of results come from populations having the same mean air permeability coefficient. The alternative hypothesis  $H_1$  is that one set has a mean air permeability higher than the other, where, according to the accepted knowledge, the higher permeability is expected in the set with shorter curing duration. As in (RILEM TC 189-NEC, 2005), the outcome of the statistical test is evaluated as follows: If the result of the statistical test allows to reject the null hypothesis  $H_0$  at a level of significance  $< 1\%$ , the differentiation capability of Torrent’s method, for the particular sets compared, is considered “highly significant” (++) ; If the result of the statistical test allows to reject the null hypothesis  $H_0$  at a level of significance between  $1\%$  and  $5\%$ , the differentiation capability of Torrent’s method, for the particular sets compared, is considered “significant” (+) ; If the result of the statistical test does not allows to reject the null hypothesis  $H_0$  at a level of significance of  $5\%$ , the differentiation capability of Torrent’s method, for the particular sets compared, is considered “not significant” (O) ; If the results are in reverse order than expected, the response of Torrent’s method is considered “wrong” (X).

The input parameters for Student’s test are summarized in Table 3. The obtained differentiation capability of Torrent’s method for different curing durations for PLC57 mix is presented in Table 4, while the same analysis for FA52 mix is presented in Table 5, both with the Student’s test p-value between brackets.

**Table 3.** Input parameters for Student’s tests

Mix	Curing, day	Sample size	Mean $kT$ , $10^{-16} \text{ m}^2$	$kT$ variance, $10^{-36} \text{ m}^4$	Mix	Curing, day	Sample size	Mean $kT$ , $10^{-16} \text{ m}^2$	$kT$ variance, $10^{-36} \text{ m}^4$
PLC57	1	5	0.346	129.8	FA52	1	5	1.46	280
	3	4	0.0265	0.79		3	4	0.06925	2.02
	7	4	0.0245	0.229		7	4	0.0775	10.86
	14	5	0.0156	0.208		14	4	0.036	9.01
	21	4	0.01345	0.737		21	4	0.019375	1.32
	28	4	0.009675	0.336		28	4	0.013425	10.6

**Table 4.** Differentiation capability analyzed in PLC57 mix

Curing	1 day	3 days	7 days	14 days	21 days
3 days	++ (4.5E-4)	-	-	-	-
7 days	++ (4.3E-4)	O (0.37)	-	-	-
14 days	++ (1.0E-5)	+ (2.4E-2)	+ (1.1E-2)	-	-
21 days	++ (3.5E-4)	+ (4.0E-2)	+ (3.1E-2)	O (0.32)	-
28 days	++ (3.3E-4)	++ (9.6E-3)	++ (3.5E-3)	O (6.4E-2)	O (0.25)

**Table 5.** Differentiation capability analyzed in FA52 mix

Curing	1 day	3 days	7 days	14 days	21 days
3 days	++ (3.9E-7)	-	-	-	-
7 days	++ (4.4E-7)	X	-	-	-
14 days	++ (3.5E-7)	+ (4.6E-2)	O (5.6E-2)	-	-
21 days	++ (3.1E-7)	++ (7.9E-4)	++ (7.9E-3)	O (0.17)	-
28 days	++ (2.9E-7)	++ (1.3E-4)	++ (4.1E-3)	O (9.3E-2)	O (0.18)

According to the performed analysis, Torrent’s method was successful in differentiating the air permeability of different sets in 21 out of the 30 comparisons conducted, i.e. 70% of the situations. Moreover, it shall be noticed that following the model proposed by Bahador and Cahyadi (2009), after 7 days of wet curing 80% of OPC

hydration is achieved and their experiments shown also that after 7 days of wet curing the changes in pore size are negligible. Thus, small reductions in air permeability results should be expected for curing durations beyond 7 days. Actually, the results presented in Tables 8 and 9 indicate that there are at least significant differences in air permeability between 7 days moist curing mixes and longer moist curing durations (14, 21 and 28 days), whether fly ash is used or not. The reduction in air-permeability recorded from 14 days onwards is regarded as "not significant". Torrent's method failed to differentiate curing influence on the air permeability comparisons between 3 and 7 days of moist curing for both mixes. Definitely, these are unexpected results, even more when lower p-values were obtained comparing air permeability tested mixes with moist curing durations of 21 and 28 days. A survey on studies encompassing permeability and curing as variables, revealed lower differences between permeability in mixes cured for 7 and 28 days (Dhir et al., 1989; Quoc & Kishi, 2008). Thus, it is believed that there was a problem with the specimens that represent the 7 days moist curing, either in the manufacturing process, or (most likely) during the staying in the ventilated oven, that led to a higher air permeability than expected. This hypothesis also explains the shifting of the "threshold" curing duration from 7 days to 14 days, i.e. if the air permeability coefficient obtained in the specimens cured for 7 days were not so high, the null hypothesis would not be rejected in the respective test, therefore in agreement with "theory" (Bahador & Cahyadi, 2009).

#### 4 Concluding Remarks

The relevance of assessing concrete durability related properties on site was briefly discussed and Torrent's method ability to carry out such assessment was recalled. In order to ascertain Torrent's method, limitations and capabilities, the test sensitivity to different curing conditions was investigated.

It was confirmed that the Torrent method is sensitive to the length of initial water curing period, and suited to detect lack of curing in the laboratory. It is expected that, under the more severe natural exposure conditions of structural elements (solar radiation, wind), the effects of insufficient curing on air-permeability will be accentuated, particularly if microcracking occurs to which the kT values are very sensitive (Torrent, 1999). It was confirmed that air permeability tests frequently yield results (outliers) that clearly fall outside the range of the rest, which may be attributed to microcracking of the cubes during preconditioning.

Regardless of an eventual problem with the specimens that represented the curing duration of 7 days and despite the acknowledged gas permeability tests variability, it was found that Torrent's method can distinguish between air permeability of mixes subject to different curing in a statistically significant manner.

The outcome of this work is meaningful as it improves the knowledge on an onsite non-destructive method to characterize concrete air permeability, providing another step towards an effective compliance control to support the performance-based durability design of reinforced concrete structures, such as bridges.

However, further investigation, encompassing curing durations between 1 and 7 days, other than 3 days (already studied), is advised. In addition, conducting comparative tests on full-scale elements exposed outdoors, subjected to different curing treatments is also recommended.

#### Acknowledgements

The support of Betão Liz and of Mr. Alexandre Gamito in manufacturing the specimens and in the laboratory tests, respectively, is deeply acknowledged.

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## Consequence modelling for bridge failures

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**Abstract.** This paper presents a categorisation procedure through which consequences arising from potential bridge failures can be estimated. Failure consequences can manifest themselves in several forms which can be divided into human, economic, environmental and social categories. Consequence modelling depends on the system boundaries used, as well as the time frame considered. The paper provides an overview of consequence magnitudes and ranges arising from bridge failures and gives suggestions and guidance on how different consequence categories can be quantified. Associated models for quantifying their magnitude considering both spatial and temporal domains are highlighted. Finally, the predictive capability of the models is outlined through a case study.

**Keywords:** bridges, failure, consequences, models, case-study

### 1 Introduction

Bridges are critical components within transportation networks. The potential failure of a bridge structure will not only result in consequences associated with the structure itself but it may also lead to loss of, or reduction in, network functionality, which brings additional consequences. Moreover, consequences may also extend into environmental as well as societal impact. In this context, failure consequences can be seen as a good indicator of the importance of a bridge structure, and as such play an essential role in both qualitative and quantitative risk-based design and assessment and performance evaluation of bridges.

The consequences of failure vary significantly from structure to structure, and may depend on a range of factors which are related to the hazard itself, the structure and its function, as well as the surrounding environment. First, the source and nature of the hazard leading to the bridge collapse will affect considerably the consequences. It is expected that the greater the magnitude and duration of a hazard, the greater the consequences will be. The bridge type will also influence both its vulnerability and robustness, and, hence, the consequences, which are likely to be sensitive to factors such as the structural form, the material used, age and condition, as well as quality of construction.

Bridge location is one of the major factors expected to influence the magnitude of failure consequences. The type of road or rail route served by the bridge influences the traffic intensity and, hence, the number of people exposed to any given hazard, as well as the traffic delay costs. Moreover, the availability of emergency services and accessibility to treatment for injuries will most likely be best in urban areas, hence, the number of fatalities may be lower in such locations. Finally, the cost of repair or reconstruction of the bridge structure may be higher in rural areas due to increased labour, materials and transportation costs. On the other hand, access might be easier and inter-dependency issues might be less critical than in urban areas.

The time of the day that a bridge failure may take place will also have an effect on human consequences. Bridge structures will experience high levels of traffic during peak times and the potential for mass casualties is thus higher. Further temporal variations may occur daily, weekly, monthly, seasonally etc. and it is important to think of correlations between such variations and resulting consequences.

The time frame considered (days/weeks/years) in the consequence analysis will affect significantly its outcome. For example, in order to capture the influence of long-term effects of a bridge failure, consideration should be given to the full period until reconstruction is completed; even beyond that period there are likely to be residual influences that may take many more years before they are completely eradicated. In fact, the bridge failure and its resulting impact on the transportation network may be such that a new long-term equilibrium is reached, markedly different from what existed prior to the original failure.

## 2 Categorisation of consequences

The ‘cost of failure’ of major structures is widely recognised as being multi-faceted and highly variable. A systematic procedure to describe, and where possible quantify, consequences, bearing in mind the factors highlighted in the preceding section is required, starting with a representation of the considered system and its boundaries. In general, consequences resulting from bridge failures may be divided into four main categories: human, economic, environmental and social, as shown in Table 1. Each of these can be further sub-divided into a number of more specific areas, so that itemisation and appropriate modelling, where possible, may be undertaken. As it can be seen, there is a wide range of consequences that may arise from a bridge failure and the challenges in trying to compare them in a consistent framework are considerable. Consequences can be distinguished into direct and indirect depending on the system boundaries considered as well as the bridge’s function and considered importance. For example, traffic delay and management costs could also feature under direct consequences, as a result of repairs on damaged parts of a bridge structure.

It is evident from the above that the level and sophistication of the various analysis types increases considerably as the range and extent of considered consequences widens. Advanced structural analysis, considering a multitude of non-linear material and geometric effects, is required if a particular failure scenario needs to be taken beyond initial damage and member failure. Dispersion and CFD analysis may be required for the assessment of pollutant releases and their effects. Life Cycle Assessment methods form the basis for the estimation of CO<sub>2</sub> emissions and energy consumption associated with reconstruction and relocation/rerouting costs, and transport network and econometric analyses would provide estimates for business loss and regional economic effects.

**Table 1.** Categorisation of consequences

Type	Direct	Indirect
<b>Human</b>	Injuries Fatalities	Injuries Fatalities Psychological damage
<b>Economic</b>	Repair of initial damage Replacement/repair of contents Rescue costs Clean up costs	Replacement/repair of structure/contents Rescue costs Clean up costs Collateral damage to surroundings Loss of functionality/production/business Temporary relocation Traffic delay (detour)/management costs Regional economic effects Investigations/compensations Infrastructure inter-dependency costs
<b>Environmental</b>	CO <sub>2</sub> Emissions Energy use Pollutant releases Noise disruption	CO <sub>2</sub> emissions Energy use Pollutant releases Noise disruption Environmental clean-up/reversibility
<b>Social</b>		Loss of reputation Erosion of public confidence Undue changes in professional practice

### 3 Quantification of consequences

Consequences can be measured in terms of damaged, destroyed, expended or lost assets and utilities such as raw materials, goods, services and lives; they may also include intangibles, either from a practical or a theoretical standpoint, especially in the case of social consequences and long-term environmental influences. In general, they are represented through a vector, whose elements should be in appropriate units for the type of consequence considered. Where possible, consequences should be expressed in monetary units, though this is not easy to achieve, and may not be desirable or, indeed, universally acceptable. Consequences should be seen as random, so that the variability associated with, often complex, estimates can also be captured. Depending on the decision problem considered, it may be reasonable to consider only the mean value, though in this case an effort should be made to remain consistent in the modelling that is applied for different forms of consequences. In any case, it is prudent to consider and capture important statistical dependencies or correlations between the elements of the consequence vector (for example in considering models for rescue/clean up operations, pollutant release and environmental repair/reversibility).

Sources for the quantification of consequences from bridge failures can be found in natural hazard loss estimation manuals (e.g. FEMA, 2003), reports analysing past failures (e.g. Xie & Levinson (2009)), industry and regulatory authorities guidelines (e.g. Van Essen et al., 2004), insurance reviews and the general literature.

#### 3.1 Human consequences

Human consequences, considered as the most serious type, are highly variable between different events and subject to considerable uncertainty both in terms of predicting as well as valuing. An alternative in assigning monetary values to human consequences is to consider them separately, thus leading to multi-objective optimisation criteria in risk assessment.

A contentious issue in casualty modelling is the determination of an economic value for a human life, for which a range of methods can be found, including (i) willingness-to-pay and willingness-to-accept approach (ii) insured value statistics (iii) cost per (statistical) life saved approach (iv) dependents' lost earnings estimates and (vi) societal life saving cost estimates. As might be expected, there is considerable variation in the values that have been determined, reflecting different circumstances, varying social and economic contexts, as well as differences in the adopted methodology and the decision under consideration. Notwithstanding such differences in scope and context, it is worth noting that many estimates of the value of human life are within the €1.5 to €3 million range across Europe (Van Essen et al., 2004).

An important parameter in quantifying human consequences is to estimate the number of casualties and/or injuries resulting as a consequence of a bridge collapse. The HAZUS methodology (FEMA, 2003), employed within a regional loss estimation framework in the US, provides an empirical expression for the number of fatalities in a bridge collapse,  $K_s$ , related to the commuter population,  $N_c$ , and a 'usage' factor,  $F$ , which depends on the assumed time of the accident, namely

$$K_s = 0.07 \times F \times N_c \quad (1)$$

with suggested values for  $F$  being 0.02 during peak times and 0.01 otherwise. Suggestions for estimating the commuting population, based on census data, are also given in FEMA (2003).

In addition to fatalities, a bridge failure can also result in human injuries. Quantifying the consequences of injuries is an even more challenging task due to the wide range of different injuries that may result. Typical values suggested are ranging from €200000 for severe injuries to €15000 for light injuries. In a simpler classification, injury costs can be expressed as a fraction of the fatality cost, depending on the



injury severity, e.g. a critical injury being 70% of a fatality cost and moderate injury being 5% of a fatality cost.

### 3.2 Economic consequences

Economic consequence models are, on the whole, available for bridge structures, especially with respect to repair/reconstruction costs, typically linked to a damage severity index. An important distinction between structural and non-structural costs is often made, though data for the latter are more difficult to collect and categorise. A similar argument applies to rescue and clean up costs, for which published data are particularly sparse.

The cost associated with the reconstruction of a bridge will obviously depend on the type of the new bridge as well as its span and the duration of the project which is may be affected by a range of external factors. It has been suggested in the literature that the reconstruction cost of a bridge can be reasonably estimated as being equal to its original construction cost, adjusted from past to present values. On the other hand, a report by Atkins (2004) provides some example re-building costs for different bridge types and span lengths ranging between €3700 per m<sup>2</sup> for 10-20m spans to €1500 per m<sup>2</sup> for >50m spans.

As might be expected, models related to functional downtime/loss are more widely developed for the case of bridge failures, on account of their role in transport networks. Typical values which may be used in estimating traffic delay costs, due to detours, for both highway and railway networks are summarised in Table 2. Traffic management costs depend on the type of the road and volume of traffic and may vary from €700 up to €3000 per day (Wong et al. 2005). These can be used, together with site specific information regarding traffic and/or rail service levels, to produce estimates of economic losses as a result of bridge restrictions/unavailability. However, wider and long-term losses require the availability of econometric models, which analyse how detours and delays might affect supply and demand for goods and services in a region. Recent bridge failure events have also brought attention to crucial inter-dependencies that exist between critical infrastructures: for example, loss of a bridge may result not only in transport being disrupted but also in other utilities (electricity, water, gas) being adversely affected. Such losses are perhaps more difficult to quantify but should be borne in mind when a bridge's function provides a critical link within a multi-layered utility network.

**Table 2.** Average European value-of-time estimates, 1998 figures adjusted to 2015 prices (Van Essen et al. 2004)

Mode	Passenger Transport	Freight Transport
Car	Business: €37.70/person-hour	Light Goods Vehicle: €72.0/vehicle-hour
	Commuting/Private: €10.80/person-hour	Heavy Goods Vehicle: €77.0/vehicle-hour
	Leisure/Holiday: €7.20/person-hour	
Interurban Rail	Business: €37.70/person-hour	Full train (950 tonnes): €1300.0/tonne-hour
	Commuting/Private: €11.50/person-hour	Wagon (40 tonnes): €54.0/tonne-hour
	Leisure/Holiday: €5.70/person-hour	Average per tonne: €1.36/tonne-hour

### 3.3 Environmental consequences

Environmental consequences range from CO<sub>2</sub> emissions associated with clean up, reconstruction and traffic delays to the release of toxic or other pollutants that might affect water or air quality and human health. In terms of the former, life cycle assessment (LCA) analyses can be used to estimate typical CO<sub>2</sub> content per tonne of construction material used in repair/reconstruction, with typical values being equal to 1820 kg CO<sub>2</sub>/tonne for steel, 800 kg CO<sub>2</sub>/tonne for cement, 260-450 kg CO<sub>2</sub>/tonne for reinforced concrete and 46 kg CO<sub>2</sub>/tonne for asphalt. Similarly, emissions from traffic detours and delays can be estimated as a by-product of the economic analysis of such costs. Towards predicting the amount of emissions arising from traffic related sources, there are databases that provide characteristic greenhouse gas emission values for different types of vehicles, ranging between 0.12-0.30 kg CO<sub>2</sub>/km for passenger cars, 0.16-1.16 kg CO<sub>2</sub>/km for freight vehicles to 0.05340 kg CO<sub>2</sub>/km for passengers trains and 0.02850 kg CO<sub>2</sub>/tonne km for freight trains (Defra, 2010). Further hazardous substances which can be considered are PM<sub>10</sub> and NO<sub>x</sub>, especially as the detours around the bridge will increase pollution to surrounding

regions and households. The environmental damage caused by the latter two pollutants is usually expressed in terms of €/household/ $1\mu\text{g}/\text{m}^3$  for  $\text{PM}_{10}$  and €/tonne for  $\text{NO}_x$ .

A further environmental cost that may be considered is the increase in noise pollution to households along the detour routes. By using an estimate of the households disrupted, a cost factor can be applied based on the number of decibels imposed on the area.

If deemed appropriate, the above quantities can be expressed though monetary units, though, at present, there is a very wide range of values quoted for the economic cost of  $\text{CO}_2$  emissions. Environmental consequences may also be considered within a multi-criteria decision analysis, in conjunction with human economic and social consequences, without the need for monetization.

### 3.4 Social consequences

There have been bridge collapses in the past that have resulted in significant impact in terms of wider implications to the engineering profession and associated costs. A failure of a bridge due to an inherent lack of understanding in design may mean the strengthening or replacement of a whole class of structures, each designed according to the same criteria as the one which collapsed. Changes in codes of practice may also need to be introduced following a bridge collapse. A recent example is the I-35W bridge collapse, which prompted the US Department of Transportation to order the immediate inspection of all similar bridges in the country, followed by changes in maintenance practices, resulting in considerable additional costs incurred by the bridge stock as a whole.

## 4 Case study

In this section, the applicability of the consequence models is outlined through a case study assuming the potential collapse of the Vauxhall bridge in London, UK, over the river Thames. The bridge, which is 247m in length and 24m wide, has always been an integral part of London's transport infrastructure. This is still reflected today in the very high volume of traffic that flows over the bridge. Vauxhall bridge took 5 years to build with work being completed in 1906. The final cost for the structure was €572000 in the year of completion.

From census data, the commuter population on the bridge is assumed to be 124864 people crossing it per day with 15 boat movements under the bridge a day. By considering Eq (1) and assuming a peak time failure scenario ( $F=0.02$ ), the number of expected casualties is equal to 175. The casualty cost is assumed equal to €2.25 million.

The reconstruction cost of the bridge is assumed as equal to the original construction cost, translated in today's figure equal to €62 million. It is assumed that 2 years will be required for the reconstruction, required for the estimation of the economic and environmental consequences. Three possible detour routes around the bridge are identified, having lengths of 1.2, 2.9 and 7.2 miles. A split of 10%, 40% and 50%, respectively, for these three routes is assumed for the re-distribution of the traffic, although different scenarios should be considered to evaluate the sensitivity of the results to different assumptions. The total traffic mix is divided into motorcycles, cars, buses, light goods vehicles (LGV) and heavy goods vehicles (HGV) based on traffic statistics and data. The traffic management on the roads around the bridge area will require a full-contrafLOW across an 11-mile stretch, which equal to a cost of €35500 per day.

In terms of environmental costs, based on the detour lengths identified above, the additional  $\text{CO}_2$  emissions are quantified by assuming the same distribution of vehicle types as before and a typical price of €79/tonne of  $\text{CO}_2$  emitted. For  $\text{PM}_{10}$  pollution, it is assumed that the boroughs in the surrounding areas of the bridge will be affected, the ones being closer the bridge having more severe disruption. The number of affected households for each borough is estimated from census data and a typical value of €135/household/ $1\mu\text{g}/\text{m}^3$  is used for the  $\text{PM}_{10}$  cost. For noise pollution, similarly to the previous case, the affected households are estimated and a percentage breakdown of different noise level severities,

associated with different disruption costs, is assigned. Typical values for noise pollution costs that were used vary between €40/household for 50 decibels to €165/household for 75 decibels.

Table 3 provides an overall summary the estimated failure consequences for the Vauxhall bridge. It is evident that the traffic delay (detour) costs are dominating, partly due to the very busy traffic that the bridge is carrying and the unavailability of other bridge structures nearby the bridge to accommodate the traffic in a failure or closure event. Casualty costs are also significant due to the large number of estimated fatalities from the empirical model used. Environmental costs in terms of air quality are also not insignificant.

**Table 3.** Summary of the failure consequences of the case study Vauxhall Bridge

<b>Consequence type</b>	<b>Costs (€ millions)</b>	<b>Percentage (%)</b>
Fatality/Casualty costs	€393.8	28.7
Traffic delay/ Detour costs	€844.3	61.5
CO <sub>2</sub> emission costs	€7.2	0.52
Noise pollution costs	€5.4	0.39
Air quality costs	€59.8	4.36
Traffic management costs	€0.32	0.02
Reconstruction costs	€62.0	4.52
<b>Total Costs</b>	<b>€1372.8</b>	<b>100.0</b>

## 5 Concluding remarks

A categorisation of failure consequences and associated models for their quantification, applicable to bridge structures, has been presented. A thorough understanding and justification of the appropriate system boundaries, in relation to spatial and temporal domains, is fundamental in quantifying consequences, and in enabling a rational distinction between direct and indirect components.

Given the scarcity of information on structural failure consequences, investigating in detail selected past events should prove both instructive and valuable. Part of the challenge is to undertake such studies using a common framework so that meaningful comparisons can be undertaken, and it is hoped that this paper contributes towards this objective. Much work remains to be done in sifting through relevant sources and data, establishing commonly acceptable models and values for the various forms of consequences under consideration, and understanding the associated uncertainties and variabilities.

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## Data collection on Bridge Management Systems

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**Abstract:** The two main threats to bridges in future stem from deterioration processes and natural hazards. To adequately assess condition state of bridges thus enhance preparedness in face of future events, all available data from inventory, inspections and monitoring must be utilized. The collection of this data used with expert tools in analysis of engineering and economic factors, for making decisions regarding maintenance and repairs, comprise a Bridge Management System. Currently, there is only a few countries which Bridge Management Systems are being updated to take into account all the future threats with adequate approaches. The ongoing initiative, started by International Association for Bridge Management and Safety, with the questionnaire to collect data on bridge management practices around the world, has the goal to provide essential knowledge on the applied methodologies. Also underway, in Europe is the COST TU1406 project with the ultimate goal to elaborate and standardize quality specifications for roadway bridges, based on the bridge performance indicators. It is clear that the synergy of the results of these two approaches for data collection is going to provide engineers and authorities the clear insight in strategy for future development of Bridge Management Systems thus enable optimal allocation of resources for preservation of bridges. In this paper, the essential ideas for the update of the questionnaire are presented, which have aim to refine previously collected data and clarify country specific management practices.

**Keywords:** Bridge Management Systems, data collection, quality control plans, performance indicators

### 1 Data collection on bridge management practices

The mobility of goods and people in society is largely dependent on adequate maintenance of transportation infrastructure. Thus, it is an essential task for the civil engineers to provide optimal solutions in field of management, especially for bridges as an integral part of the infrastructure. Here, the focus is on aging bridges in road networks, particularly on those exposed to slow processes (i.e. deterioration) and/or those vulnerable to sudden processes (e.g. natural hazards).

In almost every country there are databanks where the inventory and inspection data on bridges in a network are collected. This information is used for assessment of condition state of bridges for purpose of elaboration of maintenance plans and optimal funding allocation. The practices for inspection and data collection differ depending on a country's awareness on certain threats, available funding and equipment at disposal. Approaches for data analysis, application of expert tools and software in decision making process are also country specific. Taking everything into consideration within different management practices, the two aspects may be outlined. The first is related to various methodologies in decision making process and the second is related to the data applied in these approaches.

In order to gather experiences in management of bridges worldwide, International Association for Bridge Management and Safety (IABMAS) Bridge Management Committee started in 2008 an initiative in a form of questionnaire, latest version given in the report of Mirzaei et al. (2014). The respondents of the survey are the national representatives who are affiliated with institutions which are responsible for maintenance/repairs scheduling and/or development of Bridge Management Systems. Recently, in order to elaborate standardized guidelines for quality control plans for road bridges on European level, COST TU1406 project started with screening of relevant national documents in pursue of crucial information on guidelines for assessment of bridge performance i.e. performance indicators. This screening procedure and the concept of performance indicator database has been briefly presented in Strauss et al., 2015.

Clearly, these two approaches (IABMAS and COST) are complementary, both aimed at gathering knowledge on management procedures which are conducted in various countries. Here, the update of the IABMAS questionnaire is discussed as the necessary task to clarify the data previously collected in two of its feedbacks and improve future respondents' experiences. This data is going to be used all at once with the COST's database of performance indicators, to aid in elaboration of guidelines for quality control plans for road bridges.

## 2 Update of the IABMAS Questionnaire

In 2008, the IABMAS Bridge Management Committee prepared the questionnaire to collect data on BMS in the world. Since then, there was one update of the questionnaire, two feedbacks and three reports. The latest report (Mirzaei et al., 2014) summarizes the information included in the filled questionnaires and provides basic comparisons among BMS. The total of 18 countries responded and the data on 25 BMS were collected which include more than one million objects of transportation infrastructure (65% bridges, 32% culverts, 3% tunnels and retaining structures). The findings of the report provide information which may prevent unduly efforts in the integration of new functionalities into management systems and encourages the development of ever better systems. The questionnaire comprises the groups of questions related to:

- General system information (owner, users, date implemented...)
- IT system information (architecture, platform, data collection capabilities...)
- Inventory information of the principal user (type of data stored...)
- Inspection information, including structure types, and numbers of structures per structure type
- Intervention information, including data collection level, information on the assessment on the element level, information on the assessment on the structure level,
- Prediction information, including the aspects being modeled,
- Use Information, and
- Operation information, with respect to data collection and quality assurance.

Although the existing questionnaire is well-structured and its questions are straightforward, the respondents' answers do not give clear insight on certain facts. For example, it is not explicit for every case what duties & tasks of Road Directorates/Authorities are supported by application of a BMS. Also, from the most of the collected answers only a vague notion of the procedures in decision making process may be deduced. Additionally, the information on BMS features and use of expert analysis tools/modules remains unclear.

Still, the collected data represents a solid basis for the update of the questionnaire, which goal is to improve respondents experience and enable extraction of more precise information. First and foremost is that the updated version of the questionnaire is structured in Google forms in order to enhance interactivity. The most of the questions are set as type: multiple choice, dropdown lists and checkbox instead of free input fields only. In the start of the survey, the general set of questions is introduced based on the respondents affiliation to one of the three groups of participants in process of management of transportation infrastructure: Owners of infrastructure (e.g. institutions such are Road Authorities, Road Directorates etc.), Consultant companies and University/Institutes. The rest of the survey is tailored accordingly to given answers at the start. The ultimate goal of the updated questionnaire is to clarify:

1. The decision making process in management of transportation infrastructure
  - a) The primary concerns & duties of owners of the infrastructure (maintenance/repairs scheduling, performance goals etc.)
  - b) The participants in the process and their relationships
2. The features of an existing Bridge Management System
  - a) Stage of development of a BMS (i.e. structure, IT platform)

- b) Ownership/use of a BMS and its development strategy
- c) Bridge database information, input of surveying/monitoring data and other databases
- d) Type, extent and mode of assessment of the infrastructure
- e) Specific Analysis and Expert tools/modules
- f) Possibilities for future development/update (both functionality and methodology)

The group of questions which refer to the first point in fact reveal general approach of a country in respect to procedures of collection & handling of data, elaboration of maintenance plans, funds planning and ultimate decisions making. If respondent is affiliated to a Consultant company or University/Institute, these starting questions are related to fields of expertise and role in the decision making process.

Besides the structure of an applied BMS (e.g. a databank or an expert system), it is essential to reveal the respondent's involvement in development of the BMS software/tools. Here the difference between development of BMS functionality and development of BMS methodology must be outlined. Based on the answers to groups of questions referring to points 2. c), d) and e), the application of country specific performance indicators may be revealed (Figure 1.) as well as the essential details on current quality control plans.

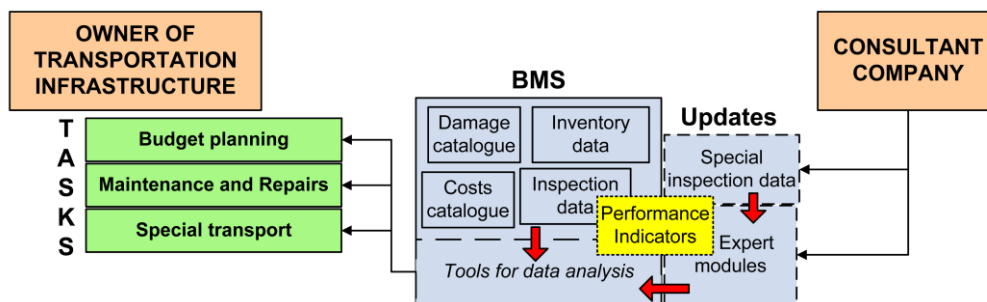


Fig. 1 Performance Indicators in Decision Making Process

The process of updating the questionnaire is currently underway and is due to be finished by the beginning of IABMAS meeting in Brazil, 2016.

### 3 Synergy of the IABMAS survey and the COST project

The performance indicators and procedures for their collection/evaluation found in national documents reflect the minimum set of data necessary for conducting quality control plans. However, the characteristics of methodology in which these indicators are used, govern the adequacy of these plans.

The IABMAS questionnaire collects information on BMS software/methodology, which is not entirely in the scope of the COST screening process. This is due to the fact that owners of the infrastructure (e.g. Road Authorities) are not by rule of thumb the developers of the applied software/methodology, and the screened documents often do not cover well this topic. On the other hand, the screening approach in the COST project relies on group of documents instead of sole experience of a respondent as in case of the IABMAS questionnaire. To conclude, the combination of results from these two approaches will give the complete information on a country's strategy for management of roadway bridges (Figure 1.) and thus provide solid background to elaborate guidelines for conducting adequate quality control plans.

The development of BMS is underway in many countries, and one of the main tasks is update of existing methodologies and establishing new ones, which allow risk based approaches i.e. consideration of the total consequences of inadequate bridge performance due to specific failure scenarios (excessive deterioration, natural hazards impact). Here, the information collected in the IABMAS survey and the



data on performance indicators collected in the COST project, particularly from research documents, give valuable standpoint on the possibilities for future updates in this direction.

#### **4 Conclusion**

The readiness of a country to cope up with future threats to transportation infrastructure reflects through the stage of development of its Bridge Management System (BMS). Owners of transportation infrastructure and developers of Bridge Management Systems can benefit from an up-to-date view of the capabilities of the most advanced system. Such knowledge may be used by countries to help determine future strategy in development of own BMS. The previously collected data with the existing IABMAS questionnaire give sufficient information to make the update, which will enhance respondent experience and provide essential information on BMS features and application. Here, the questions related to the decision making process, software features and applied methodologies are put forward.

The current actions of IABMAS and COST TU1406 are complementary providing both general and detailed approaches in data collection. Although still underway, these two processes are suggested to be merged in order to have a whole picture of bridge management practices for every country. This will reveal the possibilities to improve current methodologies and implement additional data comprising various social and technical performance indicators.

#### **Acknowledgment**

The author would like to thank the IABMAS Bridge Management Committee group, especially the colleagues which have prepared the questionnaire and the report.

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## **Scheduling bridge rehabilitations based on probabilistic life cycle condition information**

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**Abstract.** Being able to reliably assess and select among rehabilitation schedules for an aging bridge is a major issue in cost-effectively maintaining this in safe and operational condition. This task is seriously hindered by the high uncertainties that govern the deterioration rate over the lifetime of bridges. In the present work, data from a large-scale dataset of the US Federal Highway Administration are utilized, which include age and structural condition information for several thousands of bridges. In particular, the real sample utilized includes 57,056 steel bridges of various ages, which are exposed to deicing salts and humidity. The available information is appropriately processed and adjusted to calibrate Weibull distribution functions that provide structural condition probabilities over the lifetime of a steel bridge exposed to the aforementioned deterioration factors. Based on the calibrated distributions and the risk attitude of the decision maker, the time-to-rehabilitation can be probabilistically estimated and a respective rehabilitation schedule can be specified. In the framework of life cycle management of a bridge, various rehabilitation schedules are comparatively assessed with respect to the expected total rehabilitation cost induced, as well as the expected cost due to the possible need for bridge replacement.

**Keywords:** Life cycle management; Risk; Risk attitude; Deterioration; Corrosion; Repair; Bridge replacement

### **1 Introduction**

Aging bridges need continuous interventions either in the form of maintenance or major rehabilitation demanding vast budgets. Estimating the deterioration rate and the lifetime of bridges are essential aspects in determining optimal schedules regarding maintenance and/or rehabilitation. Such information can greatly assist decision makers in both elongating the useful life of bridges and controlling their structural safety in a cost-effective manner. However, the structural performance of bridges in time is governed by high uncertainties, which need to be quantitatively treated, in order to be able to make rational predictions and decisions regarding any intervention. In this respect, various reliability- and risk-based approaches have been developed to effectively handle the process of deciding under uncertainty when to maintain/rehabilitate individual bridges or bridge components, bridge stocks/networks and infrastructure assets in general (e.g. Kleiner, 2001; Liu & Frangopol, 2006; Lounis & Daigle, 2008; Orcesi & Cremona, 2010; Frangopol & Bocchini, 2012).

In the present work, a method recently presented by Alogdianakis et al. (2015) is employed to estimate the future structural condition of a bridge taking into account uncertainty in its deterioration with time. Hence, using real data maintained by the Federal Highway Administration (FHWA) for USA bridges, probabilistic information for the structural performance of an aging steel bridge exposed to deicing salts and elevated humidity is calibrated. This information is then exploited in the framework of life cycle management of the bridge. In particular, the required rehabilitations of the bridge within a span of 150 years are scheduled based on various attitudes of the decision maker toward risk. Moreover, risk-based cost estimations of the specified rehabilitation schedules are determined, which allow for objective comparative assessments.

### **2 Probabilistic information for life cycle structural condition of bridges**

The real data exploited in this work are extracted from the National Bridge Inventory (NBI) of FHWA, which is updated annually and contains a considerable amount of information, including the description of the structural condition for over 500,000 bridges (FHWA, 1995). In particular, bridge condition ratings are recorded on a scale of 0-9, with 9 representing 'excellent' and 0 'failed' conditions (Table 1).

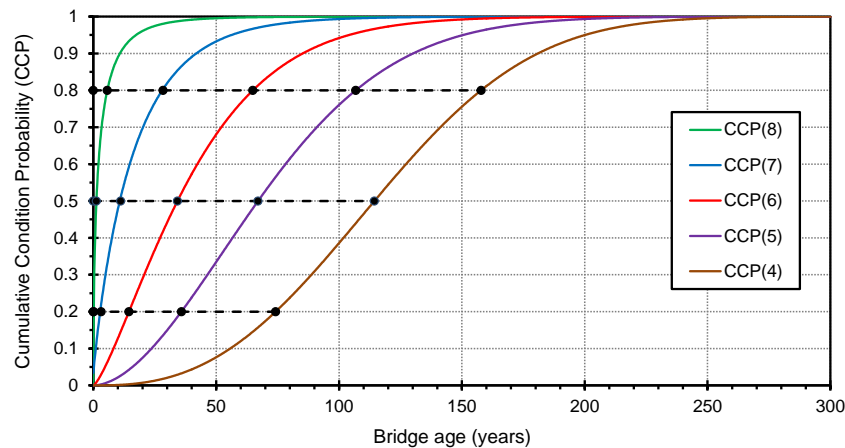
**Table 1.** Condition ratings for NBI bridges (FHWA, 1995).

Rating	9	8	7	6	5
Condition	Excellent	Very good	Good	Satisfactory	Fair
Rating	4	3	2	1	0
Condition	Poor	Serious	Critical	'Imminent' failure	Failed

The focus herein is on steel bridges deteriorating with age, e.g. due to corrosion. Deicing salts are known to accelerate deterioration, especially in combination with humidity (Alogdianakis et al., 2014). To locate bridges exposed to chlorides, information from FHWA on the areas of USA using deicing salts have been exploited. To ensure the presence of humidity, only bridges with water passing underneath the structure were considered. Moreover, to limit the structural and material effect on deterioration, information only for simply supported steel bridges was extracted from the NBI database. Finally, several cases, which correspond to deterioration of a bridge regardless of age (e.g. due to earthquakes, accidental actions, etc.), have been excluded from the analysis under study. Rehabilitated bridges have also been ruled out, as there was not enough data on their deterioration rate from initial construction. Thus, a sample containing 57,056 steel bridges was established, which included age and structural condition information for all bridges at a particular year.

The method of Alogdianakis et al. (2015) uses NBI data of a single year to calibrate a probabilistic model for predicting the structural condition of a bridge over time. Thus, all bridges in the data-stock processed are used, based on their ages, to represent the condition of a single bridge during its lifetime. Hence, the portion of bridges being in a certain age and condition represent the probability of the bridge under study to be in the same condition at that age. This way, curves relating bridge age with cumulative probability for each structural condition can be assembled. Certain time-shifts and scalings are then applied to achieve predictions for bridge ages not covered by available data. By fitting Weibull distribution functions to the original and shifted data and specifying some criteria for deciding bridge rehabilitation, the time left for a bridge until it reaches a structural condition, that induces a need for rehabilitation, can be probabilistically evaluated.

The application of this method to the above described sample of 57,056 steel bridges yields the probabilistic information of Fig. 1. In this figure, Weibull curves relating bridge age with Cumulative Condition Probability (CCP) are provided. CCP is the probability of a bridge of a certain age to be equal or below a certain structural condition. Hence,  $CCP(i)$  denotes the CCP-curve that refers to a bridge of structural condition  $\leq i$  ( $i=8,7,6,5,4$ ). As an example of using the probabilistic information of Fig. 1, the age of a bridge with probability  $P(\text{Condition} \leq 4) = 0.2$  can be estimated from  $CCP(4)$  as 74.2 years.



**Fig. 1.** Probabilistic information for life cycle structural condition of steel bridges exposed to deicing salts and elevated humidity: Cumulative Condition Probability (CCP) versus bridge age for structural conditions  $\leq i$ ,  $i=8,7,6,5,4$ .

### 3 Life cycle management: scheduling bridge rehabilitations based on risk attitude

The CCP-curves of Fig. 1 reveal the probabilistic deterioration rate of a bridge, as they provide the probability and the corresponding duration needed to reach each structural condition  $\leq 8$  to  $\leq 4$ . This probability is a measure of uncertainty that can be taken into account when scheduling bridge rehabilitations. An example is given in this section to illustrate the exploitation of the CCP-curves in life cycle management of bridges under uncertainty.

In this regard, certain assumptions are made. The initial structural condition of a bridge, from which it starts to deteriorate with time, is a crucial input information for a life cycle analysis. Bridges of the same age or era delivered may have a very different life cycle cost due to different initial structural conditions. To facilitate the demonstration of this section, an initial condition 9 ('excellent') is assumed for a hypothetical steel bridge considered as an example. Moreover, a rehabilitation is assumed to fully restore the bridge in its initial state, i.e. condition 9 is reestablished. Hence, contractors and constructors perform any construction/rehabilitation phase with no flaws, while the duration of bridge construction/rehabilitation is ignored. Once the bridge is constructed/rehabilitated, successive condition drops occur as time passes: condition 8 succeeds 9, 7 succeeds 8, etc.

Three different CCP-levels (20%, 50% and 80%) are considered, which represent the attitudes of 3 different decision makers toward risk (Hillson & Murray-Webster, 2005): from a risk-averse (CCP-level of 20%) to a risk-seeking (or risk-loving) attitude (CCP-level of 80%). Table 2 presents 6 different rehabilitation schedules based on these risk attitudes. The time-to-rehabilitation reported is the duration for a bridge starting from condition 9 to reach structural conditions  $\leq 5$  or  $\leq 4$  for the 3 aforementioned CCP-levels and is easily determined from the Weibull curves of Fig. 1. Hence, revisiting the example of the previous section for Fig. 1, a bridge needs to be rehabilitated at the age of 74.2 years for a CCP-level of 20%.

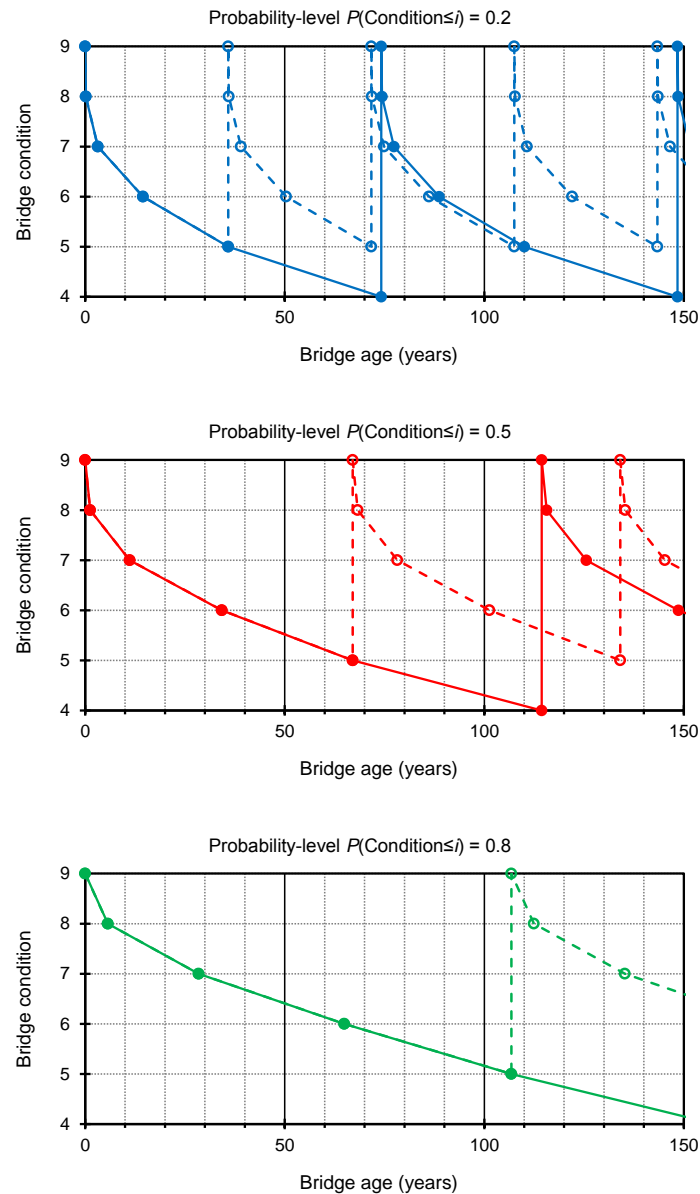
**Table 2.** Time-to-rehabilitation and number of required rehabilitations within a span of 150 years for 6 different rehabilitation schedules corresponding to various probability (CCP) levels.

Rehabilitation schedule	Probability-level	Time-to-rehabilitation (years)	Required rehabilitations
1	$P(\text{Condition} \leq 4) = 0.2$	74.2	2
2	$P(\text{Condition} \leq 5) = 0.2$	35.8	4
3	$P(\text{Condition} \leq 4) = 0.5$	114.4	1
4	$P(\text{Condition} \leq 5) = 0.5$	67.1	2
5	$P(\text{Condition} \leq 4) = 0.8$	157.8	0
6	$P(\text{Condition} \leq 5) = 0.8$	106.8	1

Table 2 provides probabilistic information regarding bridge deterioration with time, which is very valuable for a decision maker. Hence, assuming that condition  $\leq 5$  (i.e. bridge condition is 'fair' or worse) signifies the need for rehabilitation, a risk averter would schedule an early intervention, at about 36 years after the construction of the bridge (although the probability that the bridge will actually reach condition  $\leq 5$  is only 20%). A risk seeker, on the other hand, would schedule a late upgrade, at about 107 years after construction, when the probability that the bridge will actually reach condition  $\leq 5$  is 80% and also the probability to reach condition  $\leq 4$  is relatively high ( $>40\%$ ). A decision maker with a more balanced attitude toward risk (CCP-level of 50%) would schedule an upgrade at about 67 years after bridge construction. If it is assumed that condition  $\leq 4$  (i.e. bridge condition is 'poor' or worse) induces the need for rehabilitation, longer times can be tolerated before any intervention takes place. Thus, rehabilitation would be scheduled at the bridge age of about 74 years by a risk averter, 158 years by a risk seeker and 114 years by a decision maker exhibiting an intermediate risk tolerance.

Figure 2 illustrates the effect of the 3 risk attitudes in the context of life cycle management for maintaining a bridge in good and operational condition by scheduling regular interventions. In this figure, we consider a newly constructed bridge that is delivered at age 0 in excellent condition (code 9) and starts deteriorating. Depending on the CCP-level adopted, successive condition drops are predicted at certain bridge ages determined through the CCP-curves of Fig. 1. A rehabilitation is scheduled at the age the bridge is predicted to reach condition  $\leq 5$  or  $\leq 4$  for the particular CCP-level (Table 2). It is assumed that a rehabilitation fully restores the bridge condition to code 9. Then, deterioration starts again, which causes once more successive condition drops that may lead to a new rehabilitation according to the respective time of Table 2 and so on. The same attitude of the decision maker toward risk is presumed for the life cycle of the bridge, i.e. the adopted CCP-level remains unaltered.

According to the life cycle setting specified above, a series of bridge rehabilitations need to be scheduled within a certain time frame (indicatively taken herein as 150 years), depending on the CCP-level adopted. This results in the 6 aforementioned schedules with required rehabilitations that are evident in Fig. 2 and summed up in Table 2.



**Fig. 2.** Life cycle management for a bridge considering 3 different risk attitudes corresponding to probability-levels  $P(\text{Condition} \leq i) = 20\%$ ,  $50\%$  and  $80\%$  ( $i=8,7,6,5$  or  $4$ ). Rehabilitation takes place when the bridge is expected to reach condition  $\leq 4$  (solid lines) or  $\leq 5$  (dashed lines) for each probability-level considered.

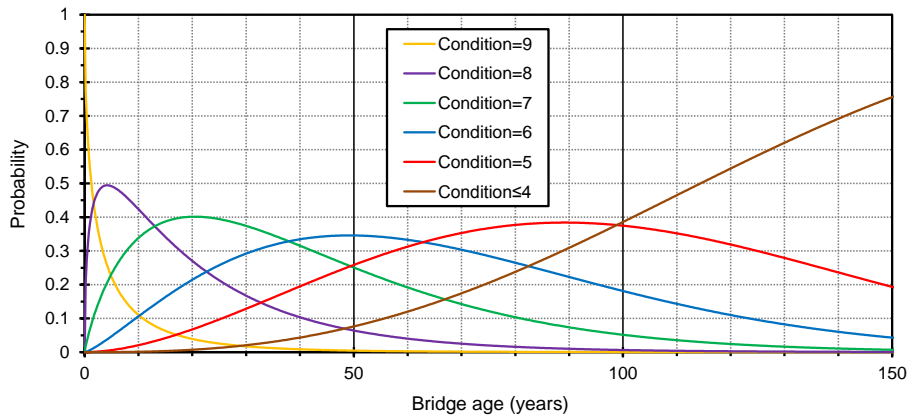
Hence, assuming that any interventions are decided by monitoring the event of the bridge condition being  $\leq 5$ , a risk averter (CCP-level of  $20\%$ ) would schedule 4 rehabilitations within 150 years, because a rehabilitation is required every about 36 years. Accordingly, a risk seeker (CCP-level of  $80\%$ ) would schedule just one rehabilitation at the age of about 107 years, while an intermediate risk attitude (CCP-level of  $50\%$ ) induces the need for 2 rehabilitations within 150 years (every about 67 years). If the event of the bridge condition being  $\leq 4$  would shape the decision for rehabilitation, a risk seeker would not schedule any intervention within 150 years. A risk averter, however, would still schedule 2 rehabilitations within this time frame (every about 74 years), while an intermediate risk attitude would lead to a single rehabilitation at the age of about 114 years.

A small number of upgrades over the life cycle of the bridge translates to a low overall anticipated rehabilitation cost, but also to a high risk associated with the bridge condition reaching code 5 or 4 earlier than expected or even dropping below it. This could induce additional, non-scheduled direct and indirect costs, compromise the safety and operational availability of the bridge and possibly force decision makers to partially or even fully replace it. Such issues are further investigated in the next section.

#### 4 Expected life cycle cost estimation and comparative assessment of rehabilitation schedules

In order to be able to make a rational decision regarding the rehabilitation schedule of a bridge, the expected total cost over the time frame of study needs to be estimated for every choice identified. Thus, an overall rehabilitation cost is calculated for each schedule specified in Table 2 by taking into account the number of interventions planned and the bridge ages, at which they are intended to take place (Fig. 2). Moreover, an overall expected cost for bridge replacement is determined, which refers to the risk of the bridge dropping to such a condition that rehabilitation is not a suitable choice anymore. Replacement of the bridge may be dictated by extensive failure that renders uneconomical the repairs required, partial/full collapse, dropping of the safety level provided below an acceptable/tolerable threshold, etc.

The initial cost to construct at time  $t=0$  the hypothetical steel bridge studied in the present work is designated as  $C_0$ . All costs given in this section are expressed with respect to the initial cost  $C_0$ . Hence, the cost of rehabilitation (i.e. of restoring condition 9) from condition 8 is taken as  $C_{R8}=0.005C_0$ . Accordingly, the rehabilitation costs from conditions 7, 6, 5,  $\leq 4$  are set to  $C_{R7}=0.01C_0$ ,  $C_{R6}=0.03C_0$ ,  $C_{R5}=0.1C_0$ ,  $C_{R4}=0.4C_0$ , respectively. It is assumed that a rehabilitation from conditions 5 and  $\leq 4$  is also associated with user costs (due to delays, increased travel expenses, increased accident rates, inconvenience, etc.) because of works needing the bridge to be closed for 0.1 and 0.5 months, respectively. User costs during rehabilitation are taken as  $3C_0$  per month of bridge closure. Thus, the costs for rehabilitation from conditions 5 and  $\leq 4$  are increased to  $C_{R5}=0.4C_0$  and  $C_{R4}=1.9C_0$ , respectively. The expected rehabilitation cost of the bridge at time  $t$  is then given by  $C_{Reh}(t)=\sum_i [P(\text{Condition}=i) \times C_{Ri}] + P(\text{Condition} \leq 4) \times C_{R4}$ ,  $i=8,7,6,5$ . The probabilities  $P(\text{Condition}=i)$  with time are given in Fig. 3. These are easily calculated from the probabilities  $P(\text{Condition} \leq i)$  of Fig. 1, e.g.  $P(\text{Condition}=7)=P(\text{Condition} \leq 7)-P(\text{Condition} \leq 6)$  at any age  $t$ .



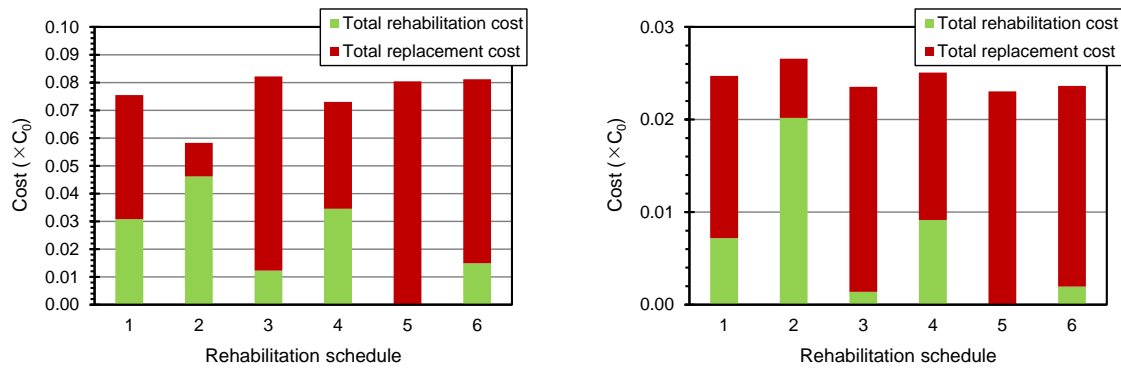
**Fig. 3.** Probabilities  $P(\text{Condition}=i)$ ,  $i=9,8,7,6,5$ , and  $P(\text{Condition} \leq 4)$  versus bridge age.

The bridge replacement cost at any time  $t$  is taken as  $1.2C_0$ . This includes the amount of  $0.2C_0$  for the removal of the old bridge, as well as the amount of  $C_0$  for the construction of the new one. It is assumed that all replacement actions (removal of old bridge, establishment of detour, design/bidding/construction of new bridge, etc.) are carried out within 12 months, during which the bridge is closed. User costs during replacement works are taken as  $5C_0$  per month of bridge closure. This results in a total replacement cost at time  $t$  of  $61.2C_0$ . Due to lack of data, it is simply assumed that the replacement probability at any time  $t$  is  $P_{rep}=0.2 \times P(\text{Condition} \leq 4)$ . Then, the expected replacement cost of the bridge at time  $t$  is given by  $C_{Rep}(t)=P_{rep} \times 61.2C_0$ .

The above mentioned costs  $C_{Reh}(t)$  and  $C_{Rep}(t)$  refer to Future Values (FV), since these are costs to be paid at various instances  $t$  within the period of study (150 years). Any FV at time  $t$  can be transferred to time  $t=0$  by discounting it to the corresponding Present Value (PV) according to the formula:  $PV=FV/(1+r)^t$ , where  $r$  is the discount rate adopted (assumed to remain constant over the period of study).

Assuming 2 different discount rates, Fig. 4 presents the total expected cost of each of the 6 rehabilitation schedules for the period of 150 years. This cost includes the total expected rehabilitation cost of each schedule, which is calculated as  $PV[C_{Reh}(t_1)]+PV[C_{Reh}(t_2)]+\dots$  for the planned rehabilitations at bridge ages  $t_1, t_2, \dots$  according to this schedule. The total expected cost includes also the expected replacement cost, which is set as the average over all years  $0 \leq t \leq 150$  of the costs  $PV[C_{Rep}(t)]$ .





**Fig. 4.** Total expected cost and its allocation to expected rehabilitation and replacement costs for the 6 bridge rehabilitation schedules, considering a discount rate of  $r=4\%$  (left) and  $r=6\%$  (right).

Figure 4 demonstrates the interplay between the contributions of the rehabilitation and replacement costs in the total life cycle cost. The overall cost resulting from a schedule with frequent rehabilitations (e.g. schedule 2) is governed by rehabilitation costs, while expected replacement costs are the major concern in case of infrequent or no rehabilitations (e.g. schedules 5, 6). The discount rate considered decisively influences the cost-effectiveness and the comparative assessment of the rehabilitation schedules and actually dictates the choice to make.

## 5 Conclusions

Scheduling rehabilitations for an aging bridge within a highly uncertain deterioration setting in a cost-effective manner is a great challenge. Rational decisions can be made by, first of all, acquiring probabilistic information regarding the deterioration rate of the bridge. Then, any rehabilitation schedule can be quantitatively assessed with respect to the expected life cycle cost it induces. The gathering and estimation of reliable data (mainly including rehabilitation, replacement and user costs, as well as the discount rate) and the risk attitude of the decision maker are crucial aspects in the process of life cycle cost assessment and management of a deteriorating bridge.

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## Environmental effects on bridge durability based on existing inspection data

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**Abstract.** Published bridge inspection data are analysed to assess the durability of bridge components (deck, superstructure and substructure) with respect to time from construction. The data are also used to estimate the resistance of common construction types/materials (steel, reinforced/prestressed concrete) to various deterioration factors (water, sea/deicing salt, etc.).

**Keywords:** Bridge; Corrosion; Deterioration; Durability; Environment.

### 1 Introduction

The durability of existing bridge stocks is one of the biggest problems governments around the globe have to face. Vast budgets are spent annually to keep bridges in serviceable condition. Bridge durability depends on the type of structure, the material as well as the environmental exposure. This study identifies the conditions, under which bridges deteriorate rapidly. For this purpose, inspection data from the USA bridge stock are used, in which recordings for more than half a million bridges are included. The results of this work may help authorities to optimally allocate funding for bridge construction and maintenance.

### 2 Bridge inspection database

USA's Federal Highway Administration, in order to assist the maintenance and rehabilitation of the built infrastructure, preserves an up to date inventory of bridges, tunnels and culverts. This inventory is known as NBI (National Bridge Inventory) and contains a vast amount of information in coded form (116 items) concerning: location, structural condition, age, materials, traffic etc. (FHWA, 1995).

**Table 1.** Condition scale used to assess bridges in USA (FHWA, 1995).

Rating	Description
9	<b>EXCELLENT CONDITION</b>
8	<b>VERY GOOD CONDITION</b> - no problems noted.
7	<b>GOOD CONDITION</b> - some minor problems.
6	<b>SATISFACTORY CONDITION</b> - structural elements show some minor deterioration.
5	<b>FAIR CONDITION</b> - all primary structural elements are sound but may have minor section loss, cracking, spalling or scour.
4	<b>POOR CONDITION</b> - advanced section loss, deterioration, spalling or scour.
3	<b>SERIOUS CONDITION</b> - loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	<b>CRITICAL CONDITION</b> - advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored, it may be necessary to close the bridge until corrective action is taken.
1	<b>'IMMINENT' FAILURE CONDITION</b> - major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.
0	<b>FAILED CONDITION</b> - out of service - beyond corrective action.

To keep the inventory up to date, biennial inspections are conducted from specially qualified personnel, whose responsibility is to evaluate the condition of different structural parts of each bridge. Condition ratings use a scale 0-9 (Table 1); 9 for excellent and 0 for failed condition, respectively. From these ratings the evaluated infrastructure is prioritized for further inspection, repair work or replacement.

The database refers to data from 608,533 structures; 470,417 of these met certain requirements to be included in the processed sample. In particular, 131,980 non-bridge elements (e.g. culverts) were excluded from the analysis. Also, 545 bridges built before 1900 and 2685 bridges last inspected before 2000 were also excluded. The database includes data from prestressed concrete bridges built before 1950, most of which are rebuilt. To avoid misleading interpretation of results, those bridges were excepted (332 bridges). Finally, taking into account limitations posed by NBI standards on bridge length, a number of bridges were excluded, in order to obtain certain uniformity of the processed data, in regards to inspection standards.

The bridge parts which are rated include the: substructure (i.e. columns), superstructure (i.e. beams) and deck. Structural deficiency is defined in this work as a condition rating of either superstructure, substructure or deck evaluation of 5 or less.

### 3 The effect of distance from sea coast

This section examines the influence of sea salt on bridge deterioration. Near the coastline the environmental conditions are normally more aggressive in comparison to inland due to the sea salt existence, which enhances the atmosphere's chloride concentration. The NBI database is used to evaluate the effect of the distance from the sea coastline on bridge durability.

To study this effect, the state of Florida was chosen, so that uniformity could be achieved on repair policies (Dunker & Rabbat, 1995). Florida also has a great coastline length and a large sample of bridges, which increased the probability of locating bridges near the coast. Additionally, the area's low earthquake hazard and the non-deicing policy within the coastline region provided a good analysis sample.

The bridge coordinates, which are included in the NBI database, can be used to locate the bridges. Fig. 1 shows the coastline of east USA and Fig. 2 highlights the bridge locations at a certain part of the state of Florida.



Figure 1. Map of USA with areas under study.

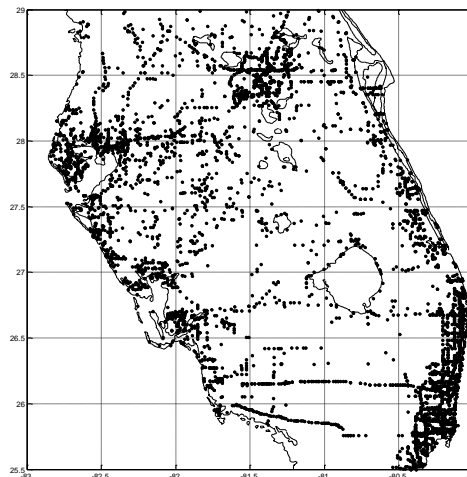
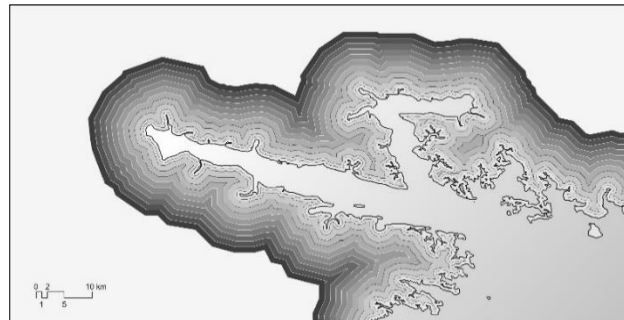


Figure 2. Bridge locations at a certain part of the state of Florida (see also Fig. 1).

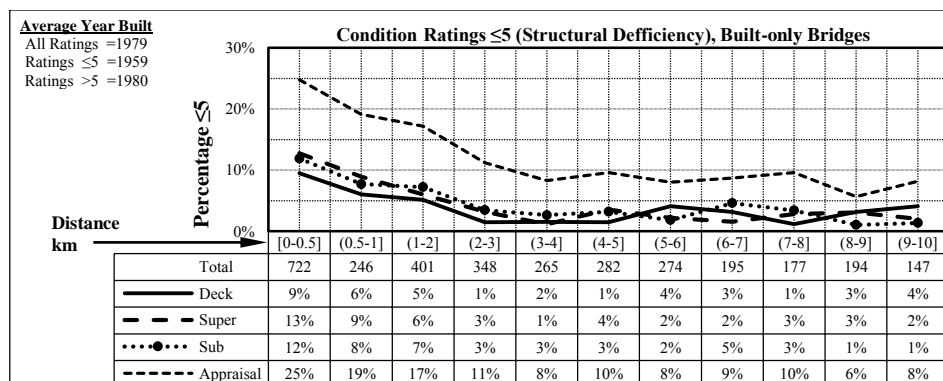
Coastline coordinates were obtained from the National Geophysical Data Centre. Equal coastline distance polylines were drawn at various inland distances forming bridge-area-zones near the coastline (see example of Fig. 3 from other area). The bridges in each area were captured and their conditions were determined and compared to bridges located to other formed areas.



**Figure 3.** Formed zones near and parallel to North Carolina's coastline (see also Fig. 1).

Florida's climate can be categorized mostly as humid subtropical and tropical in regions located south from Lake Okeechobee. The geographical terrain has low rises and the existence of high intensity winds can lead to greater transfer distances of airborne chlorides.

Fig. 4 gives condition probabilities on built-only bridges (i.e. excluding rebuilt bridges) at zones up to 10km from the coastline for substructures, superstructures and decks. The 'appraisal' line refers to minimum rating between substructure and superstructure. The analysis was performed on the entire Florida's coastline, along which 3934 bridges are located (3251 built-only and 683 rebuilt) within 10km from the coastline.



**Figure 4.** Condition probabilities for bridges in Florida at various distances from the coastline.

The results of Fig. 4 and others show that the coastline affects bridge durability at distances up to 3km. Bridge condition probabilities remain practically flat at coastline distances >3km; the probability of structurally deficient bridges within 3km from the coastline is significantly higher. In other studies, the coastline-affected zone is reported to be around 1-2 km wide (Meira et al., 2003; Meira et al., 2007; Pontes et al., 2009).

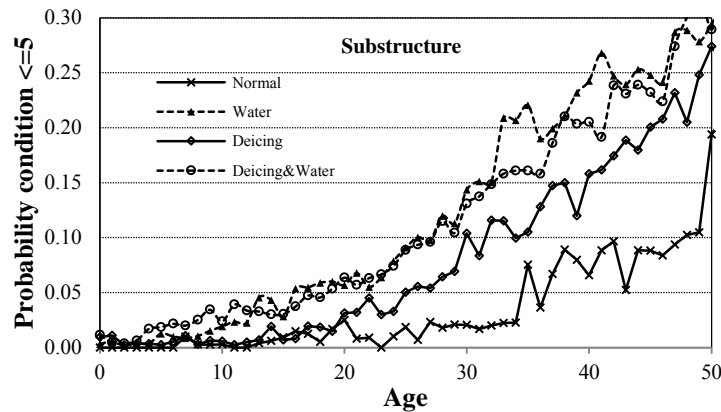
#### 4 The effect of water and deicing salts

To evaluate bridge durability under other environmental conditions, four different environments are examined:

- 'water': bridges with water underneath;
- 'deicing': bridges exposed to deicing salts;
- 'deicing & water': bridges with water underneath and exposed to deicing salts;
- 'normal': bridges without water underneath and deicing salts.

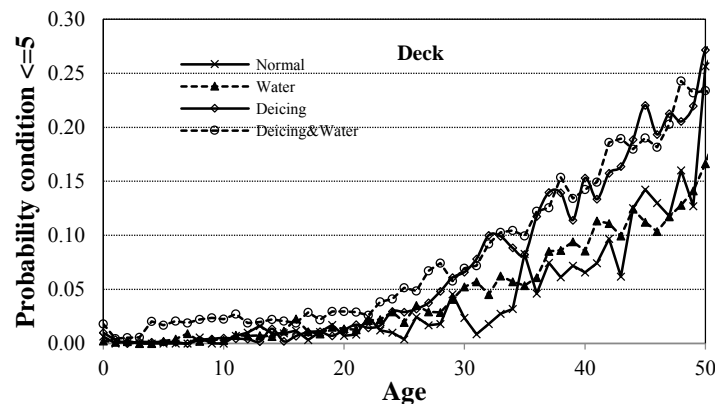
Note that bridges located near the sea coastline are excluded from this analysis.

Fig. 5 shows corrosion probabilities (condition  $\leq 5$ ) for bridge substructures. The presence of water increases corrosion probabilities to more than double in comparison to bridges located in 'normal' environments. Corrosion probabilities for bridges exposed to deicing salts for the first 20 years are similar to 'normal', but for older bridges the corrosion probabilities are increased to values between 'normal' and 'water' environments. This is attributed to the time needed for chlorides to diffuse through the concrete cover and initiate corrosion.

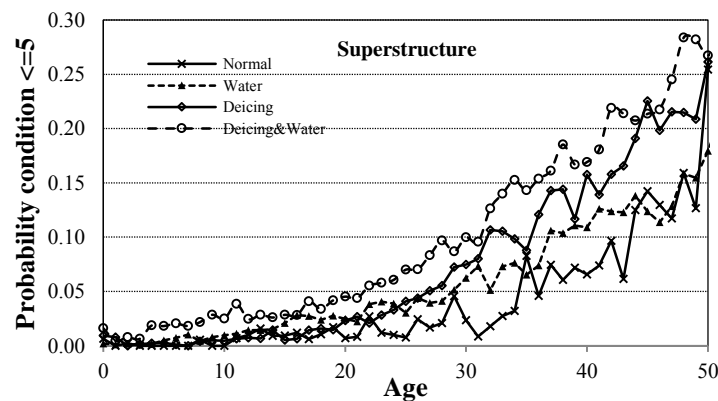


**Figure 5.** Condition probabilities with age for bridge substructures.

The evolution of corrosion probabilities with age for bridge decks (Fig. 6) shows that deicing salts fuel corrosion, while water presence does not seem to affect corrosion. This is an expected outcome, because water runs underneath the bridge, hence it is not in direct contact with the bridge deck. However, water increases the environmental humidity. This enhances chloride convection and reduces the time-to-corrosion-initiation. This effect is evident in Fig. 6 in the rise of the 'deicing & water' condition probability curve at young ages in comparison to the 'deicing' curve.



**Figure 6.** Condition probabilities with age for bridge decks.



**Figure 7.** Condition probabilities with age for bridge superstructures.

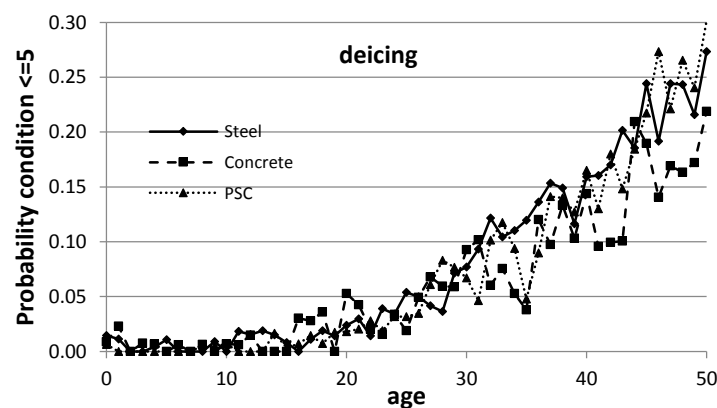
The above is more pronounced in superstructures shown in Fig. 7. It can be observed that, up to the bridge age of 20 years, the environments that contain water possess higher threats for corrosion. At later age, corrosion initiates and the curve of bridges exposed to chlorides without water rises to give similar corrosion probabilities to those with water present.

## 5 The effect of structural material

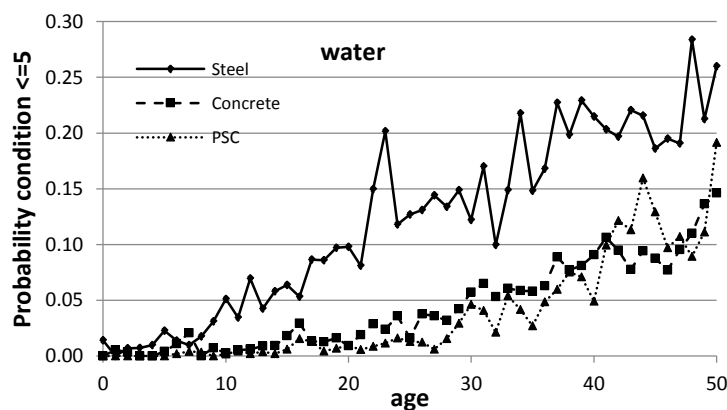
The corrosion resistance of bridges made of steel and reinforced/prestressed concrete and exposed to various environments are examined in this section. The results in Figs. 8, 9 and 10 show that steel structures are prone to corrosion at humid environments. At the same time, they give similar corrosion probabilities as reinforced/prestressed concrete bridges at low humidity conditions. Fig. 8 shows such conditions when deicing salts are used. All lines follow a similar corrosion probability path with age. Similar results are found at low humidity environments and warm environments, hence without deicing salt used.

An early jump is observed on steel structure's corrosion propagation curve at humid locations exposed to chlorides (Fig. 10). This is not seen at similar environments not exposed to chlorides (Fig. 9). Chloride exposure causes rapid corrosion initiation at early ages and, in humid locations exposed to chlorides, building a steel bridge should be considered with caution.

Reinforced and prestressed concrete bridges appear to be similarly influenced irrespective of the environmental conditions. In humid environments, such bridges exhibit lower deterioration rates than steel bridges.

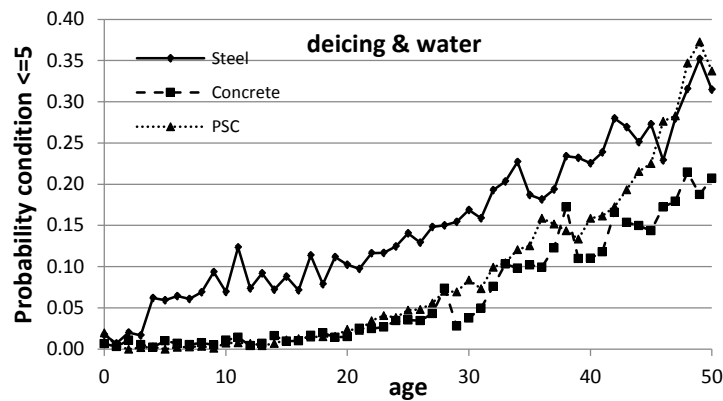


**Figure 8.** Condition probabilities for steel, reinforced and prestressed concrete bridges exposed to deicing salts at low humidity environments.



**Figure 9.** Condition probabilities for steel, reinforced and prestressed concrete bridges located at humid environments.





**Figure 10.** Condition probabilities for steel, reinforced and prestressed concrete bridges located at humid environments exposed to chlorides.

## 6 Conclusions

Data from bridge inspections are used to study the durability of bridges under various environmental conditions and materials. The results show that durability is threatened for:

- bridges located within the first 3km from the sea coastline;
- substructures at humid locations, because they are often in direct contact with water;
- decks and superstructures exposed to deicing salts;
- steel structures at humid locations, especially when exposed to chlorides.

Finally, reinforced and prestressed bridges gave similar corrosion probabilities at all environmental exposures.

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## Development of the bridge management system under the project Bridge<sup>SMS</sup>

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**Abstract.** Bridge inspection and management systems must have a knowledge and appreciation of structural engineering, geotechnics, hydraulics, hydrology, materials and transport management. This paper will provide a reader with general information of Bridge SMS tool which will couple state-of-the-art scientific knowledge in hydrology, river and structural engineering with industrial knowledge in infrastructure management and web based bridge management systems to develop an open source cloud based intelligent decision support system for the assessment and management bridges structural and hydraulic vulnerability of bridges over water, and also vulnerability for other effects. Bridge SMS aims to deliver standards for complete bridge inspections (scour and structural) and to develop decision support system which would manage bridge failure risks on efficient and multidisciplinary approach.

**Keywords:** bridge inspection, monitoring, bridge management system, structural risk assessment, scour risk assessment, software development

## 1 Background

Bridge SMS (“Intelligent Bridge Assessment Maintenance and Management System”) will build on an existing industry-academia collaboration between University College Cork (UCC), Faculty of Civil Engineering University of Zagreb (UNIZAG), Cork County Council (CCC), Infraestruturas de Portugal (INFPO) and NIVAS. Researchers from UCC have also established strong collaboration with National Roads Authority (NRA), University of Minho (UNIMIN), South Dublin City Council (SDCC) and Dublin City Council (DCC), all of which have pledged their support for this project. Collaboration between UCC and UNIZAG evolved as a result of a major railway bridge collapse at Malahide on the main Dublin to Belfast line in August 2009 as a passenger service passed over the Malahide Viaduct (McKeogh & Bekic, 2010abc). Also, UCC carried out inspections and assessments of more than 100 railway bridges in Ireland (Bekic et al., 2012) and have carried out inspection, testing and assessments for around 250 road bridges in Ireland working closely with the National Roads Authority and the County Councils. A recent study by UCC and UNIZAG on 100 bridges in Ireland (Bekic et al., 2012) utilised the US (U.S. DO Agriculture, 1998) and UK (The Highway Agency, 2006) standards for the assessment of scour risk at bridges. The study showed that the resulting scour ranking obtained by the two assessment methods differs for 20% of bridges and that a significant difference occurs in approximately 10% of cases. A study of 57 bridges showed that improvements of the assessment methodology are required and could significantly improve resulted scour rankings (Johnson, 2005). A similar conclusion was

obtained after a scour risk assessment in the US and Turkey where a new algorithm was applied (Yanmaz et al., 2007).

## 2 Introduction

Government agencies, the public and private sectors and professional engineering sectors across Europe need to come together and proactively meet the challenge of creating a climate resilient infrastructure system (Engineering the Future, 2011). The continual inspection, assessment and maintenance of bridges requires a multidisciplinary approach (structural engineering, geotechnics, hydraulics, hydrology, materials and transport management). Bridge SMS will couple state-of-the art scientific knowledge in hydrology, river and structural engineering with industrial knowledge in infrastructure management and web based bridge management systems to develop an open source cloud based intelligent decision support system for the assessment and management bridges structural and hydraulic vulnerability of bridges over water, and also vulnerability for other effects (Bekic et al., 2012; Weninger-Vycudil et al., 2015; Znidaric et al., 2011; Pakrashi et al., 2011).

In 2010 the IABMAS Bridge Management Committee prepared an overview of the existing bridge management systems (Klatter et al., 2010). This report assessed a total of 18 bridge management systems, in operation across 15 countries being used to manage 900,000 objects. The systems all show a strong focus on the structural health monitoring of bridge structures, managing this facet of bridge stability to varying degrees. IABMAS found that while the systems are strikingly similar in their overall approach and operation, there was a lack of standardisation, which meant systems could not be easily adopted by other agencies. The IABMAS report concluded “that a certain level of standardisation could potentially enhance the exchange of knowledge and experience between managing agents, and improve the usefulness of management systems.” The majority of bridge management software systems also do not place adequate emphasis on the risk of hydraulic failure due to scour (Katell & Eriksson, 1988), focusing instead on structural issues. Only the upcoming version of Pontis considers scour as a factor in the management of its bridges (Marshall et al., 1999). Marshall (1999) stated that the current Pontis Bridge Management System can provide an agency with recommendations for bridge maintenance and capital improvement projects. Recommendations are generated using bridge inventory and inspection data.

The current standards and policies for the assessment and the management of bridge scour have been mainly developed in the US and UK. In the US three documents on bridge scour risk assessment and management have been published, based on experiences from bridge analysis and the Technical Advisory section (U.S. DOT, 1988). The US Department of Agriculture, Forest Service (1998) has also developed its own programme for the assessment of bridge scour risk. In the UK, two standards for the assessment and management of bridge scour have been used. The first Railtrack method was introduced for British Rail and was published as handbook (British Railway Board, 1993), and the second method was developed by the UK Highway Agency and was published as Design Manual BA 74/06 (The Highways Agency, 2006). In May 2012, BA 74/06 “Assessment of Scour at Highway Structures” has been replaced by BD 97/12 (The Highways Agency, 2012). Other standards, manuals and publications of EU countries mainly consider the analysis of scour process the stability of structures in the water and the scour protection measures.

## 3 Methodology and Approach

Bridge SMS is a software application that empowers engineers and key personnel to predict, identify and prepare for potentially destructive flood events. It is robust and efficient tool designed to lower maintenance/planning costs and to provide more secured bridge management/operation. The proposed system should provide infrastructure management and staff all appropriate information for management, decision making, maintenance and mitigation in one place and at any time: updated multi-level prioritization list of all structures (bridges) with descriptive statistics; general information about the single structure (name and ID, road / railway line, location, structure type, year of construction, directions how to get to the structure location, etc.); priority and current status (recommendations and in case of installed monitoring systems real time data from monitoring equipment); proposed short and midterm works and maintenance; easy access to all documents about the structure history and future plans (bridge inspections, comments, reports, pictures, maintenance, construction works, etc.).

Bridge SMS key goals:

1. To develop standardised methods for bridge scour inspection.
2. To develop standards for bridge assessment and management.
3. To calculate the risk of and manages the potential effects of flood events.
4. To develop a database framework which is designed for intuitive use, encouraging participation by personnel at all levels within management authorities.

5. To develop a system that
  - a. collects integrates and processes real-time data at regular intervals from weather and hydrologic sources, meters and gauges, and other sensing devices.
  - b. will rapidly notify based on in-built intelligence and decision-making processes, relevant personnel of possible maintenance and failure issues.
  - c. will advise in relation to current Scour Risk at bridge structures and prompt an appropriate Plan of Action (POA) which may involve various levels of maintenance and repair.
  - d. which will prioritize and optimize the operational and maintenance budget spend for infrastructure companies.
6. Maximum use of new Information and Communications Technology (ICT) hardware such as tablets and cloud-based systems for on-site rapid communications, etc.

### **3.1 Develop standards for bridge assessment and management which can be applied to various transport networks**

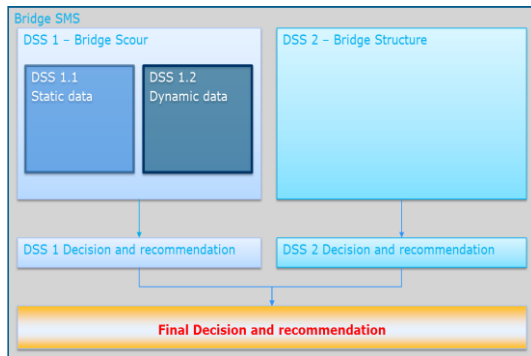
This will involve extensive research into existing standards worldwide, such as (US DOT, 2001a; US DOT 2001b, US DOT 2009, US DOT, 1988; US DOA, 1998; British Railway Board, 1993, The Highway Agency, 2012). Other proposed scour risk assessment methods which are not part of a standard will be also considered. Such methods include (a) assessment based on stability for a stable reference reach and then the departure from stable conditions on an unstable reach of the same stream type (Rogsen, 2001), (b) a diagnostic approach in which the system and system variables are defined, and an evaluation is made to assess the causal mechanisms producing the current condition (Montgomery & MacDonald, 2002), or (c) a simple and brief stability assessment based on sound indicators, supported by photographs and by walking a distance well upstream and downstream of the project reach (Johnson, 1999). As standards are provisionally prepared they will be tested on several networks in collaboration with field personnel, to ensure they are relevant and practical. The pilot cases for testing will include streams in different geographic regions: (1) region with a history of scour problems based on information from on-site engineers (CCC and INFPO) and a (2) region where the waterways are stable and scour issues rare but they might have structural problems.

### **3.2 Incorporate a system that calculates the risk of and manages the potential effects of hydraulic events**

A bridge's vulnerability to failure is generally influenced by two basic factors, the degree of stress or degradation that a bridge can safely withstand and the corresponding severity of the hazardous event required to induce this degree of stress or degradation. Components of the risk determination will involve the product of the estimated probability of failure (which includes hydrological, hydraulic and geomorphological factors) and the total cost of failure (bridge replacement, workarounds, loss of life). The continuous feedback nature of the BRIDGE-SMS system will allow the optimisation of risk indices based on the catalogued data on assets and events. The current EU practices on the selection of scour risk management measures include deterministic and probabilistic approaches. Deterministic approaches are developed around the risk matrix (Federal Office for Water Management, Switzerland) or the fault tree method (Hoffmans & Verheij, 1997; Pilarczyk, 1995; Pilarczyk, 1998). In the probabilistic approaches the risk is evaluated by the probability of bridge failure due an extreme flood event. Risk Analysis methods will form an integral part of the system. The risk of failure will be evaluated through a probabilistic approach, and will involve correlating historic rates of failure with the potential for a given hazard at a site, in addition to indicators of a bridge's vulnerability to failure. Develop a database framework which is designed for intuitive use, encouraging participation by personnel at all levels within management authorities

Researchers will focus on preparing a robust system, designed to be open source and cloud-based. Bridge SMS consists of two Decision Support System modules (Structural DSS and hydraulics/bridge scour DSS). Each module operates independently giving as an output: risk of failure, decision and recommendation. Final decision and recommendation considers output from both modules (Fig. 1). By removing subjectivity through optimal inspection standards, exploring the application of technology to accelerate inspections, and using an intelligent database system to prioritise maintenance tasks, Bridge SMS aims to more effectively risk-assess, and direct personnel in a more efficient manner. An intuitive, accessible database for cataloguing all available bridge data from multiple experts and sources will make all pertinent information easy to retrieve as appropriate Bridge SMS will provide an automated way of assessing the individual and cumulative risks to the

bridge structure. This will result in more timely interventions at vulnerable structures and an increase in bridge safety and reliability.



**Fig. 1.** Bridge SMS Decision Support System



**Fig. 2.** Bridge SMS software interface

The system will allow the integration of external data, allowing more informed decision-making and adding value to existing data collection services, such as meteorological stations and water level gauges. UCC and UNIZAG began working with commercial and associate partners and data providers in Ireland such as Office of Public Works (OPW), Met Éireann, EPA, Waterways Ireland and the local authorities, to begin the incorporation of external data including meteorological data and water level gauges. This relationship will be crucial, and will bring added value to the external agencies, as these new applications for the data they are gathering are presented.

### 3.3 The system will rapidly notify relevant personnel of possible maintenance and failure issues

The system will be tested in the field with simulated events, reviewing how it reacts to events in a pilot; how it notifies personnel and how that improves the management of hydraulic issues at bridge sites. Considered pilot catchments were Bandon, Blackwater, Bride, Ilen, Lee and Owenacurra, of which the selected catchment for pilot study is the river Bandon catchment. The flexible framework is more desirable as this will allow rapid adaption of the Bridge SMS software for other uses. Developing a flexible, Open-Source (OS) software based bridge management system which is not rooted in the requirements and standards of one user will reduce the initial capital costs to users. The OS common platform will encourage knowledge sharing between agencies, and foster research beyond the specific functionality of a bridge management system (Fig. 2.). Developing the system as a cloud-based application reduces platform limitations frequently associated with engineering software. It will also allow the software to run on the majority of computer and mobile devices. The interface would provide GIS data on the bridges in the Bridge SMS database, it would indicate if the bridge is at any risk, it would provide additional information decision and recommendation together with a real time data (recorded and forecasted water levels and scour depth) which would be plotted for the individual bridge.

### 3.4 Social networking and website of the project

- **Website** <http://www.bridgesms.eu/>
- **Twitter** @BRIDGESMS\_MaREI [https://twitter.com/BRIDGESMS\\_MaREI](https://twitter.com/BRIDGESMS_MaREI)
- **Facebook** <https://www.facebook.com/Bridge-SMS-1603198356632504/timeline/?ref=hl>
- **Linkedin** [https://www.linkedin.com/grp/home?gid=8337384&trk=my\\_groups-tile-grp](https://www.linkedin.com/grp/home?gid=8337384&trk=my_groups-tile-grp)
- **Youtube** <https://www.youtube.com/channel/UCPAMvdlzSwQrPBfPQXcqVTA>

## 4 Conclusions

One of the key issues highlighted by the IABMAS report in 2010 (Klatter et al., 2010) was the lack of communication and collaboration in BMS in Europe and worldwide, which is partially due to the absence of a standard for many aspects of bridge inspections and maintenance. To maximise the uptake potential of Bridge SMS, a standard format which works to the satisfaction of the majority of transport agencies, or else a flexible framework which can be customised, needs to be developed.

## Acknowledgements

Bridge SMS is an EU Marie Curie FP7 Project funded under the IAPP call. **Grant No. 612517.**

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## The assessment method of Hungarian documents on bridge inspection

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**Abstract.** In Hungary 4 levels of bridge inspection are implemented. The existing documents focus on annual bridge inspection and 10 yearly performed main supervision. For the annual bridge inspection, the PONTIS system is used which provides a detailed inspection guide.

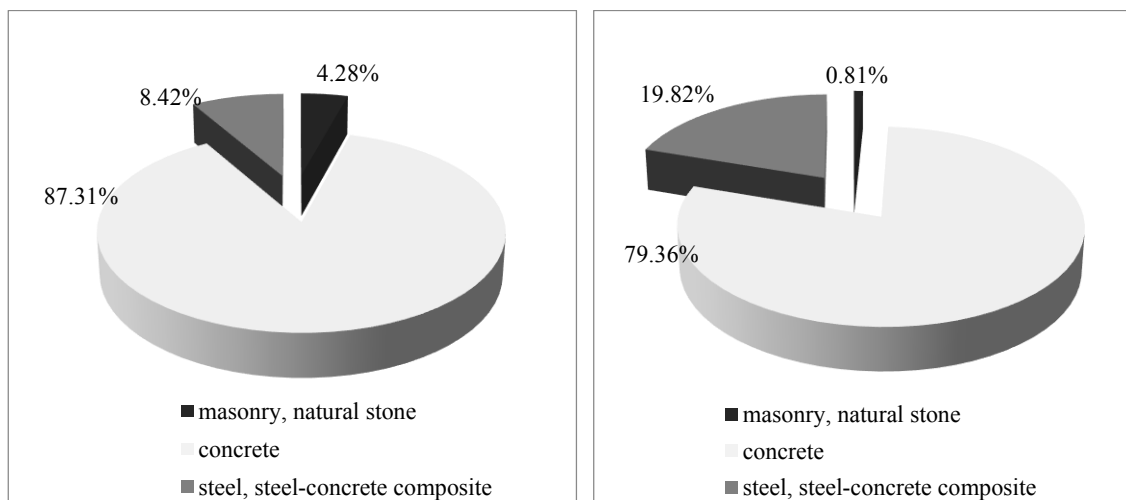
**Keywords:** Technical Specification of Roads, annual bridge inspection, bridge supervision, PONTIS

### 1 Road bridges in Hungary

In Hungary, 7 528 road bridges exist, more than half of them are located on the minor road network. Majority of these bridges are 2-5 m span concrete bridges. Table 1 presents the categorization and main data of road bridges.

Road category	Number	Area ( $\times 1000 \text{ m}^2$ )	Length (m)
Motorway	1 586	1 350,25	95 731,57
Main road	1 799	583,92	44 802,61
Minor road	4 143	524,55	54 417,02
<b>Together</b>	<b>7 528</b>	<b>2 458,72</b>	<b>194 951,20</b>

Most of the bridges are made of concrete, approximately the quarter of them are made of steel and other materials as shown in Figure 1.



**Fig. 1.** Percentage ratio of bridge material according to  
a –number; b – area

## 2 Bridge inspection types

In Hungary 4 levels of bridge inspection are implemented in the relevant maintenance system which are summarized in Table 2.

**Table 2.** Inspection levels in Hungary

	Regular checks		Annual inspection	Main supervision
Bridge type	all bridge	all bridge	all bridge	span length is more than 20 m; length of superstructure is more than 40 m; railway overpass of irrelevant length
Frequency	weekly	every half year	yearly	every 10 years
Type of inspection	visual inspection	visual inspection	visual inspection (measurement if necessary)	visual inspection and measurement
Focus	traffic safety, suitability for operation, presence of serious damage	traffic safety, suitability for operation, presence of damage, cleanness	all structural and non-structural parts	all structural and non-structural parts

## 3 Technical Specification of Roads

The “Technical Specification for Roads” is a complex collection of standards being the basic regulation for roads in Hungary.

It includes 9 main topics:

- 1) General
- 2) Traffic planning
- 3) Design of roads
- 4) Traffic control
- 5) Construction materials
- 6) Construction of roads
- 7) Bridges and other load-carrying structures
- 8) Maintenance and operation of roads
- 9) Measurements and testing

The last three chapters deal with bridges.

The “Bridges and other load-carrying structures” part provides rules on design of bridges: general rules, structural analysis, design of steel, concrete, composite and timber bridges. It also contains a standard that focuses on the assessment and restoration of existing bridges. The second chapter of this part deals with the construction aspects of different bridge types (steel, concrete, composite and timber). The third and fifth chapters focus on bridge equipment such as bearings, dilatations, waterproofing, restraining system etc. The fourth chapter deals with protection against corrosion.

The “Maintenance and operation of road” part contains rules on the register and technical supervision of bridges:

The “Measurements and testing” part includes a whole chapter on bridges: testing methods of concrete corrosion and waterproofing; non-destructive testing methods for concrete pavements, surface hardness measurement of asphalt pavements.

From the point of view of the Action TU1406, the two most relevant standards of the “Technical Specification of Roads” are: *Register and Technical Supervision of Highway Bridges* and *Register and Technical Supervision of Highway Bridges. Additional Dates and Examination Points of View*.

## 4 The selected documents

### 4.1 Register and Technical Supervision of Highway Bridges

This document expounds the different types of bridge inspection. It contains aspects, but does not give assessment methods.

## 4.2 Register and Technical Supervision of Highway Bridges. Additional Dates and Examination Points of View

This document gives information on the annual bridge inspection and the main supervision of bridges.

In the case of the *annual bridge inspection*, the document refers to the “PONTIS bridge inspection guide”.

The main structural elements and the sub-elements are rated and then classified into condition classes as follows:

- 1: as if it were new (no significant deterioration has been observed)
- 2: initial defect (only minor surface defects)
- 3: average defect (more than surface defect)
- 4: serious defects (well-developed defect)
- 5: very serious defect (a defect that has influence on the load-bearing capacity of the structure and incorporates accident hazard)

If an element is classified into class 4 or 5, its repair is required.

Regarding the *main supervision of bridges*, this document contains supervision aspects and detection methods for

- the main structural elements of steel, concrete and natural stone bridges,
- the parts of bridges that are most sensitive to defects: foundation, bearings, deck slab and equipment.

## 4.3 PONTIS-H bridge inspection guide

The original PONTIS bridge system has been a complex bridge management system used in the USA. The Hungarian version of this system is called as PONTIS-H. The bridge management module of the program is not applied in Hungary, however the bridge inspection module is widely used.

The “PONTIS-H bridge inspection guide” is a 100 pages long document that gives aspects for inspection and condition evaluation for every bridge element.

As a first step, the document defines the bridge elements of every bridge types. Each bridge is divided into five main structural parts and then further subparts (elements). Each element has a numerical code and, for the sake of exact identification, several photos are stored. As an example, Fig. 2 shows how a concrete girder bridge is stored in the system.

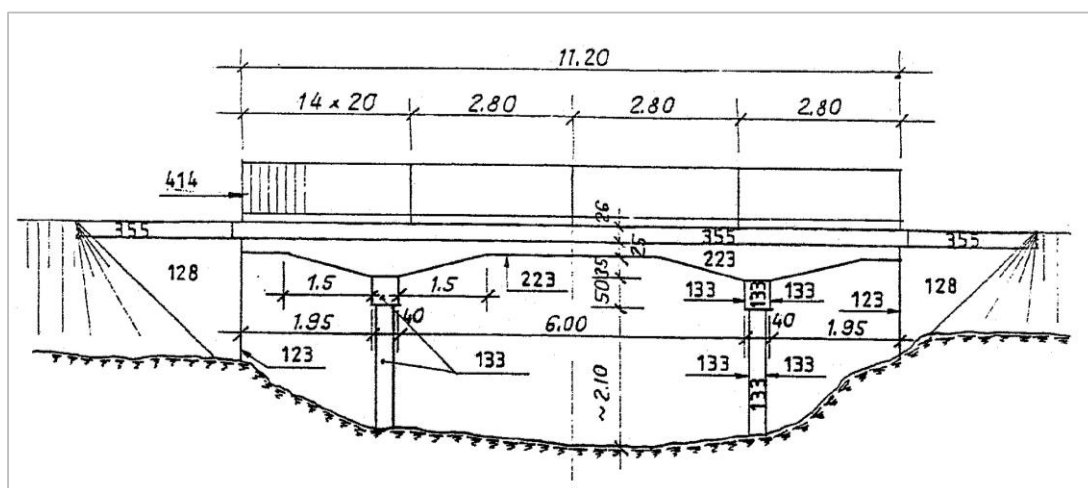


Fig. 2. Concrete girder bridge, side view

In Fig. 2 and 3, the following elements are distinguished:

- 123: reinforced concrete abutment (front wall)
- 128 reinforced concrete wing wall,

- 133 reinforced concrete pier,
- 223 monolithic concrete girders,
- 325 asphalt pavement
- 344 gully
- 355 any kind of pavement on footways
- 414 galvanized steel pedestrian guardrail
- 525 rainwater collecting pipe system

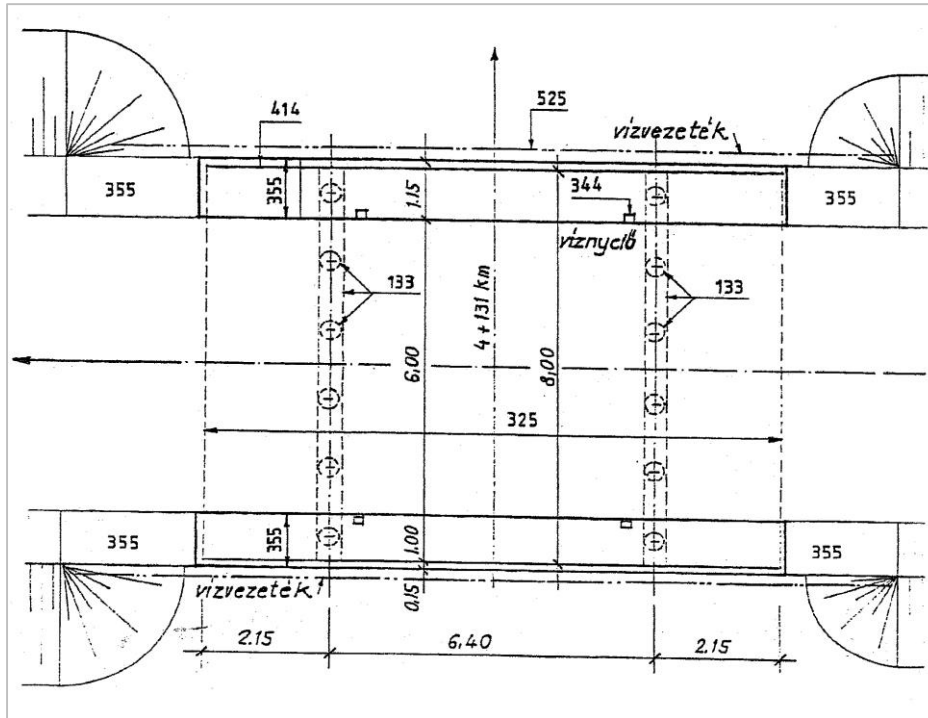


Fig. 3. Concrete girder bridge, plan view of the deck

As second step, the document gives methods for calculating the (surface?) area of the elements.

As third step, the inspection guide defines the typical damage and deterioration types belonging to the five condition classes for each element.

Finally, the inspector fills the bridge inspection sheet (Fig. 4 shows a sample) denoting the condition class of each element.

## 5 Summary

From the point of view of the Action TU1406, the two most relevant standards are: *Register and Technical Supervision of Highway Bridges* and *Register and Technical Supervision of Highway Bridges. Additional Dates and Examination Points of View*. For the regular checks of road bridges only the “Register and Technical Supervision of Highway Bridges” standard contains information. For the annual bridge inspection the most useful document is the “PONTIS-H bridge inspection guide”. In the case of the main supervision of bridges, the “Register and Technical Supervision of Highway Bridges. Additional Dates and Examination Points of View” standard is helpful. Table 3 summarizes the inspection levels and the relevant documents used in Hungary.

Table 3. Summary of the Hungarian documents

Specification	Regular checks	Annual inspection	Main supervision
Register and Technical Supervision of Highway Bridges (e-UT 08.00.11.)	☺	☺	☺
Register and Technical Supervision of Highway Bridges. Additional Dates and Examination Points of View (e-UT 08.01.25.)		☺	☺ ☺
PONTIS-H bridge inspection guide		☺ ☺ ☺	☺

Figure 4. Bridge inspection sheet

Prime No.: .....		Road No.: .....									
Section: .....		Year of inspection: 2008									
Inspector's name:		Date of inspection:									
Bridge name: .....		Road No., section: .....									
Superstructure material: .....											
Operator of bridge: .....		OMC: .....									
Spans: ... db	Max span: ... cm	Struct. Length: ... cm	Salt spreading: ...								
Bridge width: ... cm	Year of last encroachment: ...										
Surface: ... m2	Stand. load b. cap: ...	Limitation 1: ...									
ADT: 0 E/nap	Load b. cap.: ...	Limitation 2: ...									
Main grades: Superstruct.: ... Substruct.: ...											
Br.accessories: ... Pavement: ... Br.environment: ...											
Note/Megjegyzés:											
Cod e Kód	Element name	Quant/ mennyiség	1+2	%	3	%	4	%	5	%	VT
113	Reinforced steel concrete foundation	m2									
123	Reinforced steel abutment	m2									
128	Reinforced steel wing wall	m2									
133	Reinforced steel concrete pier	m2									
248	Reinforced steel beam	m2									
320	Plastic and other kind of insulation	m2									
325	Asphalt and other pavement surface	m2									
335	Asphalt expansion structures	m									
344	Steel gully, drainage, dewatering sys	db									
353	Material of reinforced steel supplementary lanes	m2									
355	Any kind of supplementary lane pavement	m2									
365	Backfill	m2									
419	Zinc layer steel barrier	m2									
422	Concrete (and other material) stairs	m2									
432	Concrete slope pavements	m2									

## Development of a Quality Management Plan for Timber Bridges

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**Abstract.** The Swiss State Secretariat for Education Research and Innovation SERI in conjunction with the European Cooperation in Science and Technology COST allows applying for research projects dealing with scientific problems in relation to a COST Action. Therefore a research project application was submitted within this framework. The background, content, objectives and relation to the COST Action TU 1406 will be given in this paper. The presentation of the project already during its application phase will ensure a direct link and most effective knowledge exchange for both, the project and the COST Action. The results will also directly be exchanged.

**Keywords:** timber, bridge, quality specification, quality plan, performance indicators, NDT methods

### 1 Introduction

The Swiss State Secretariat for Education Research and Innovation SERI in conjunction with the European Cooperation in Science and Technology COST allows applying for research projects dealing with scientific problems in relation to a COST Action. Therefore a research project application was submitted within this framework. The research project is closely related to the COST Action TU 1406. The main objective is to provide the knowledge and methods necessary to provide new developments in the area of timber construction mainly to timber bridges. Therefore, the research project specifically cooperates with the objectives of working groups (WG) 1, 2, and 3 of the COST Action TU 1406. The research results directly support WG 1 - Performance Indicators, WG 2 - Identification of existing performance goals and WG 3 - Establishment of a QC plan.

The project is in very good agreement with the defined aims of the ongoing COST Action TU 1406. The project will be integrated into the Action due to the active participation. On the one hand, it will benefit from the outcome of the networking platform of recently obtained results from different countries around the world and on the other hand, it will support the objectives of the COST Action by the development of the first Q-Plan for Timber bridges. The research results will be published and presented during working group meetings and conferences. The intense discussion within the COST Action will result in direct feedback and input for the project with regard to the definition of assessment methods, time intervals and parameters and limits observed.

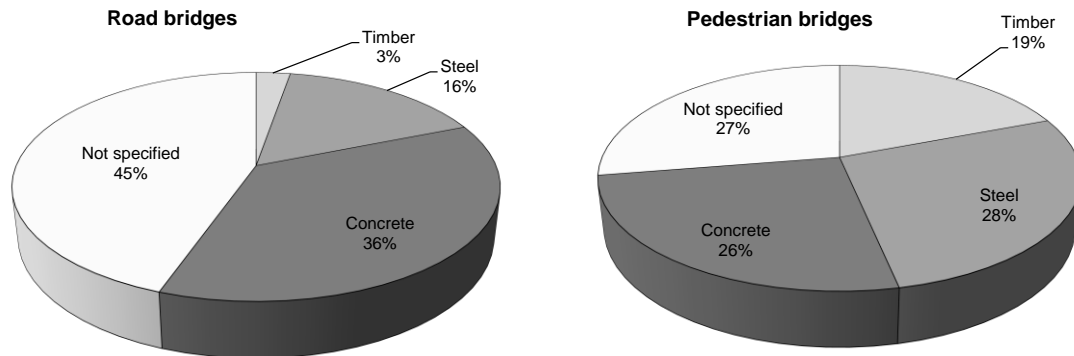
### 2 Research project

#### 2.1 Background and current State of Knowledge

In Switzerland, pedestrian and road bridges made of timber have historically and consistently been built. For example, the “Kapellbrücke” in Lucerne was built in 1333 and is still used by pedestrians every day (Gerold 2005) or the “Ennigerbrücke” in Malters which is relatively new, being erected in 2010. The “Ennigerbrücke” is a timber road bridge with a load carrying capacity of 28 tons and a span of 42 meters. Wiederkehr (2008) shows that road bridges of timber are high performing, simple and smart. However, the statistical analysis of building applications for new bridges and renovations of bridges shows that timber is a minority material for road bridges in Switzerland, as shown in Fig. 1. On the other hand, there is a quite homogenous distribution for pedestrian bridges. One reason could be that the durability of timber bridges remains a high barrier on the market for building bridges. But timber shows potential for pedestrian and cycle bridges as well as for road and wildlife bridges. The available construction cross sections of glued laminated timber, and block glued glulam or timber concrete composite provide sufficient load resistance for all applications. Timber members can be supported, connected and protected at a high quality level. This capability of high quality must be used in order to further



increase the acceptance and to promote timber bridges to be built by authorities. Furthermore, the long-term performance of timber bridges must be ensured to avoid constraints and to successfully promote timber bridges when compared with concrete and steel bridges.



**Fig. 1.** Analysis of the building applications for new bridges and renovation of bridges from 2010-2014, Source: University of Applied Sciences, Berne, Institute for Timber Construction, Structures and Architectures

In order to calculate the significant cost potential, as well as the safety risk, which can occur through damage to bridges, regular examination of the structure is required. Minor damage can thereby be prematurely detected and repaired to impede subsequent larger repair measures. Here, the time intervals and scopes of inspection are essential. Furthermore, standardized testing methods as well as guaranteeing the comparability of results of studies that are conducted at different times can considerably reduce the associated amount of effort. As a result, changes in the properties of the bridge, for example, can give indications of lesser or greater examination intervals or more in-depth studies.

Therefore, to ensure the high quality and long-term performance of constructions, quality management plans are essential and are successfully used in other areas like steel constructions especially for welds (see section 2.2). The Q-plan is an instrument for quality assurance and defines the mandatory controls and audits from the perspective of the client or project author. It defines the type, scope, performance and timing of the systematic control of execution, including specifying quality requirements and admissible deviations as well as the regulations regarding responsibilities and flow of information. However, there are no specific regulations, performance indicators and quality control plans for the inspection of timber bridges in Switzerland. The Swiss Federal Office for Highways (FEDRO) requires a standard inspection every five years for all bridges within the national road network. In general, the same regulation will be applied for bridges on a regional level. This inspection is independent of the main construction material. However, to ensure the high quality and long-term performance of timber bridges, minor inspections in between could be beneficial, but no guidance is available. On the other hand, the RI-EBW-Prüf in Germany has required annual inspections of timber bridges near bodies of water (e.g. rivers) or similar situations since 2013. But compared to a 5-year rule, this represents a very rudimentary and strict regulation which leads to disadvantages and higher maintenance cost compared to bridges of concrete or steel which only have to be inspected every 5 years. This disadvantage could be reduced and even lead to better quality management (compared to employing the 5-year rule) by introducing methods and control parameters which allow a hierarchical structuring of inspection and especially an adaptive adjustment of the inspection intervals. This could be supported by characterizing and defining missing performance indicators and development of a quality plan for the entire life cycle of timber bridges. These documents would support the planning architects and engineers during the design process and later the public organization in the maintenance of timber bridges.

For efficient inspections and maintenance, later inspections should be considered in the design and planning of new bridges. They could provide useful information for comparisons with later inspections even during the production but mainly during erection and could be used as the first set of performance parameters before the bridge is commissioned. They offer information during the life time and operation of the bridges, but also information on the break off with regards to the reasons of the break off and possible failures and defects that occurred, which can be used for future bridges. On the construction site, inspection must initially focus on the neuralgic points of bridges but must also respect the continuous flow of traffic, for example, during the assessment procedure.

The project will focus on the definition of assessment methods and performance indicators which can efficiently be used gradually for the high quality control of timber structures. The objective is to define cost-efficient methods to easily assess timber bridges (e.g. with dynamic methods as shown by Li et al 2007, Crews et al. 2004

and to avoid high conservation costs. Therefore, non-destructive testing methods (NDT methods), which are common for timber assessment, are preferred but also new methods, which are used for steel bridges, will be adapted if applicable. In addition to the assessment methods, parameters and limits of the monitoring and control of the performance of timber bridges must also be defined. According to the assessment methods and parameters defined, the time interval of the inspection shall be derived adaptively. It is not the aim to define fixed time periods but rather individual time targets according to the performance of the timber bridges, which lead to high-quality and safe timber bridges in a cost-efficient manner.

Timber bridges are present in all categories, from road bridges, pedestrian and cycle path bridges, to wild animal cross overs, on the national and international road network level. In Switzerland, the general requirements for bridges are regulated in an hierarchic order through national laws, the standards and regulation by the Federal Roads Office (FEDRO), the SIA standards, and the VSS – Research and standardization in the field of road and transportation. For the design of the structural safety and serviceability of timber bridges the SIA 260:2002, SIA 261:2014, and SIA 265:2012 are applied for the load assumption and design in Switzerland. Furthermore, the European standards EN 1990, EN 1991:2003, EN 1995-1-1:2004, EN 1995-1-2:2004, and EN 1998-2:2005 can be applied under consideration of the national annex for Switzerland. For the preservation of bridges, the principles are regulated in the guideline Astra 308.314 (2005). The main objectives of the preservation of structures are maintaining the basis structure, guaranteeing sufficient security, ensuring or re-establishing serviceability, economic optimization of maintenance necessities, detecting new potential risks, and reducing immediate action to a minimum. The obligatory guidelines of the FEDRO are valid for all construction materials. The guidelines require monitoring and maintenance of bridges (Astra 308.314, Astra 308.103) as well as a quality security (Astra 308.070). There are no specific regulations available for timber bridges. However, for the other construction materials like steel and concrete, initial additional guidelines and Q-plans for the preservation of bridges are available, which provide explicit support to planning engineers (e.g. DIN 1076).

Fig. 2 summarises the relevant topics for the development of a Q-Plan/Guideline for quality and safe timber bridges. The Q-Plan should comprise all steps of a bridge starting from the planning process to the break off of the structure. These include the definition of responsibilities and plans for maintenance, clarification of neuralgic points for assessment as well as parameters and limits which shall be met. For cost-efficient quality management, clear recommendations and methods are necessary. Currently, mainly only single-assessment methods are specified for timber structures. The combination, time dependency, and cost estimation as required in a Q-Plan is not specifically given for timber bridges.

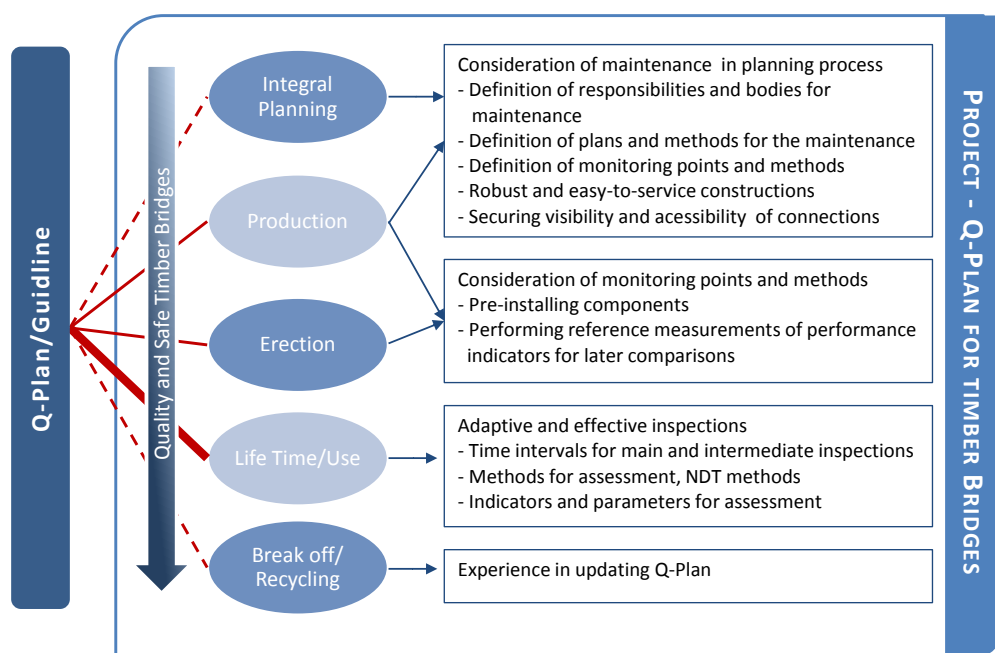


Fig. 2. Relevant topics for the development of Q-Plan

For the derivation of the neuralgic points on the structure of timber bridges, the failure analysis e.g., by Frese & Blass (2011), Fink & Kohler (2011, 2013), and Dietsch (2012) will be used. Available assessment methods for timber structures are summarized in e.g., Dietsch & Köhler (2010), Kasal & Tannert (2010), Kohler et al. (2011), and Franke et al. (2014). The methods are here mainly described with regards to their function and the specific results observed. The connection to the entire performance of timber bridges, however, is missing. Case studies and the application of single-assessment methods on timber bridges are summarised in e.g., Emerson et al. (1999), Brashaw et al (2005, 2014), Sonnenberg (2014), and Franke et al. (2014).

## 2.2 Objectives and Methods

The overall objective and deliverable is a Q-Plan for timber bridges. This involves:

- Development of a template or catalogue of neuralgic points in combination with efficient NDT methods and performance indicators
- Definition and production of reference standards, testing and inspection bodies for the particular NDT methods for wood application and indication of effectiveness
- Development of an failure catalogue in order to ensure reproducibility and reliability in test performance
- Development of a Q-Plan
- Knowledge transfer

A basis is provided by known NDT methods for timber and steel constructions and their application and distributed approaches for inspections or guidelines as provided by DIN 1076, for example. Furthermore, an existing inspection plan and the corresponding results of a timber bridge at “Olten” by one of the team members can be accessed. Relevant information will be summarized, proofed and used for further investigations and development. Methods and approaches from other areas such as steel constructions (e.g. guidelines for inspection intervals, inspection methods and indicators for weldings) will be adapted and proofed for timber constructions and unknown reference samples will be developed and used for timber. On-site applications will be performed in order to proof the applicable methods and the developed Q-plan.

## 2.3 Work plan

In order to reach the objectives, the project will be divided into 5 working packages (WP's).

In WP 1, the damage statistic of timber structures will be analyzed in order to derive neuralgic/priority points for the maintenance of timber bridges. Relevant bridge elements according to the damage statistic and the loss chain will be defined and classified and furthermore analyzed regarding there consequences of the loss. Finally a template plan for monitoring and inspection points of timber bridges will be developed.

WP 2 deals with the evaluation of assessment methods for timber as well as from steel bridges for the characterization of neuralgic/priority points on timber bridges. Standard assessment methods and their parameters and limits shall be defined and calibration methods for the verification of the measurement and/or reference values shall be evaluated. Therefore, reference standards may be defined and produced. Furthermore, a failure catalogue shall be developed in order to ensure reproducibility and reliability.

The physical Q-plan will be developed in WP 3 which comprises defining time intervals for inspections and methods to be applied, classification of order of reactions according to the assessment results.

The developed Q-plan will be tested, evaluated and proofed in practical applications during WP 4 and knowledge transfer to practitioners and official institutions as well as working group meetings of Cost Action TU1406 will be in WP 5.

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## Guide for the Assessment of Masonry Bridges – Technical Parameters

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**Abstract.** In order to support the inspection and assessment of masonry bridges, aiding the detection of defects, understanding their origins and possible consequences, a Guide for the Assessment of Masonry Bridges was developed by the University of Aveiro in close collaboration with IP and LNEC. This Guide presents a systematized approach to common defects, related with structural stability, durability and functionality. For each, several technical parameters and reference values were suggested, aiding the definition of a condition rating for the component where they were observed.

**Keywords:** Masonry bridges, visual inspections, defects, condition ratings, technical parameters

### 1 Introduction

Infraestruturas de Portugal (IP) is the state owned Portuguese general concessionaire for roadways and railways, managing over 5300 roadway bridges. The company Bridge Management System (SGOA) is a decision support tool based on the assessments made by highly qualified engineers through visual inspections, with the main objective of setting intervention priorities among this large group of assets.

In order to aid a comprehensive assessment of bridges, and also to guarantee a uniform use of the condition rating scale defined in IP's BMS, IP promoted the development of six different studies related with the inspection and diagnosis of the different types of bridge structures. These manuals are being developed in partnership with universities, consultants and the National Laboratory of Civil Engineering - LNEC.

This paper presents the Guide for the Assessment of Masonry Bridges, developed by University of Aveiro in close collaboration with IP and LNEC. It was intended to develop something more than a defect catalogue, including important topics that might contribute to a correct diagnosis, such as historic considerations related with construction techniques and codes, types of structures, materials, and causes of defects. Bridge tests, monitoring possibilities and rehabilitation techniques are also briefly described in order to aid the definition of subsequent actions.

In this paper, after a brief presentation of the main themes developed in the guide, will be made a summary of technical parameters suggested in the evaluation of the most common defects observed in masonry bridges.

### 2 Historical Background

Historical background is important to understand the behavior of structures and materials, therefore, the evolution of building techniques, characteristics and used codes were summarized in the initial chapters of the guide.

#### 2.1 Building techniques

Masonry construction begun with the first civilizations, around 10.000 and 8.000 B.C. Most ancient known arch bridge is dated 1.300 B.C., located in Kazarma, Greece, and build by Mycenaean civilization.

In Portugal the Roman era was a period of great importance in expanding the construction of masonry arched bridges. Several bridges remained to the present day and some still in the service of road traffic. Symmetry and aesthetic harmony, slight slope, identical arches, mostly semi-circular arches, are common characteristics of Roman bridges, as shown in the examples in Figure 1.

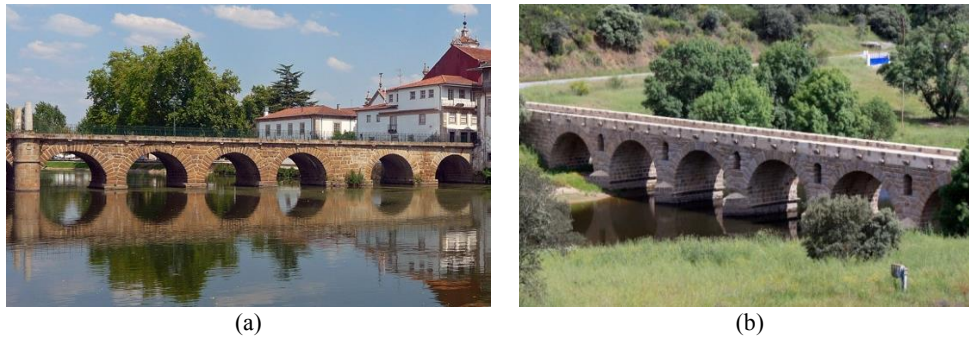


Fig. 1. Roman bridges in Portugal: a - Ponte Trajano; b - Ponte de Vila Formosa

Pointed arches, with bigger central arch, steep slope and lack of mortar between masonry stones typically define a medieval bridge, built after the Roman Empire. Renaissance brought arches of bigger span and small arrow, with taller piers located in steep valleys. In turn, the Industrial Revolution marked the advent of iron and railways, and the construction of large viaducts in masonry. The rapid expansion dictated the replacement of arches by metallic decks, still with masonry piers and abutments, until the surge of concrete.

## 2.2 Evolution of codes for masonry bridges

Bridge construction evolved in ancient times due to trial and error. The knowledge was compiled in treatises, being the first known the Vitruvius' *De Architectura libri decem* dated I B.C. Only with the 17th century mathematics knowledge was possible to establish design rules based on scientific studies of the arch behavior. Since that time several concepts were studied, being the most important shown in the timeline in Figure 2.

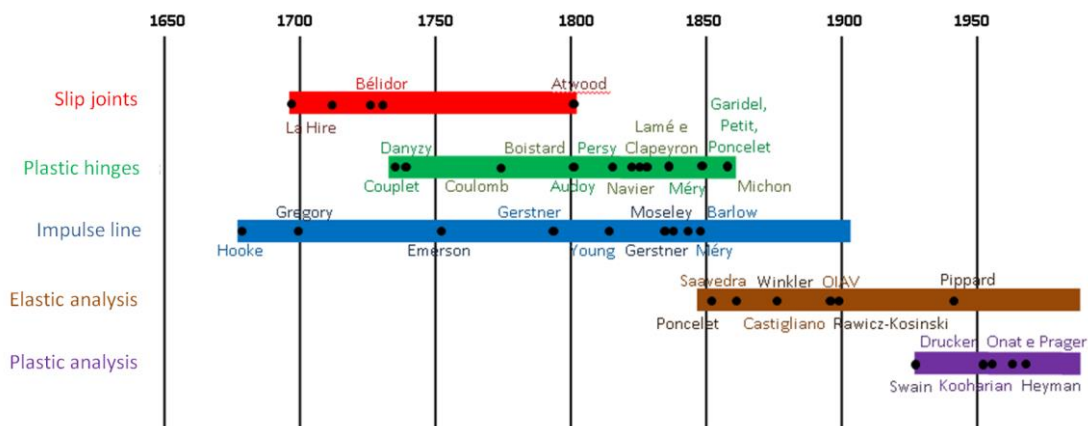


Fig. 2. Evolution of concepts in masonry bridges analysis (adapted from Costa, 2009).

## 3 Materials and structural systems

The characterization of masonry bridges is determined by the behavior of its structural materials and the interaction of its constituent elements. It is therefore important to know the main concepts of the materials used in masonry bridges as well as the behavior of elements and structural systems.

### 3.1 Masonry types and constitutive elements




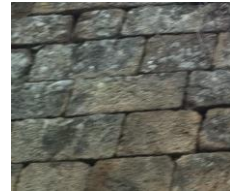




Masonry is a technique that consists in associating blocks, brought by joints with or without mortar, in order to form a composite material. Masonry blocks can be of natural stone or artificial bricks. The most common natural stone blocks in Portugal are limestone, granite and schist. All present a good compressive strength and reasonable tensile strength.

Traditional mortars are constituted by calcareous binders, aggregates and water. Additives and adjuvants can be found in repair mortars; however, the use of cement should be banned and considered as a defect once it prejudices masonry behavior. Above the arches and inside large elements such as piers and abutments is commonly found a backfill material, usually a low quality fill of granular material.

According to the bricks shape and the use of mortar, several types of masonry can be defined, as shown in table 1.

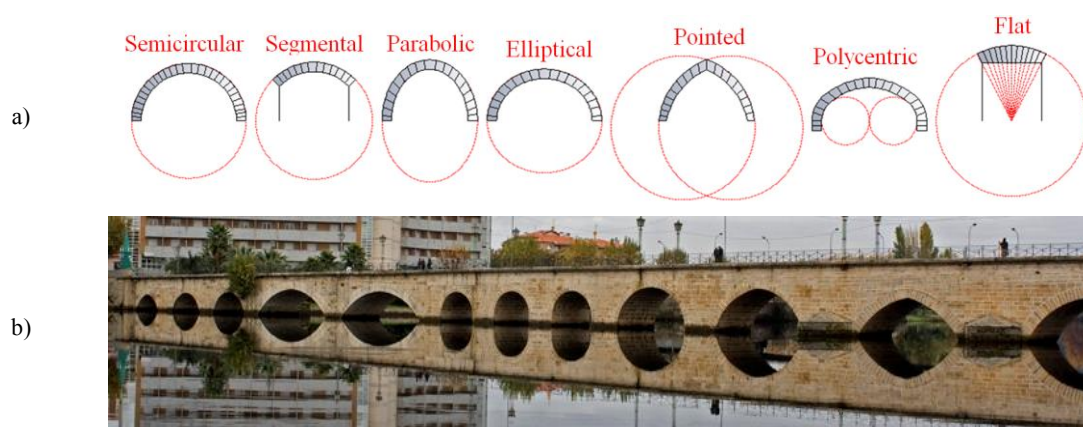


**Table 1.** Types of masonry according to joints and bricks shape.

	Joints with mortar		Joints without mortar	
Regular masonry				
Irregular masonry				

### 3.2 Types of arches

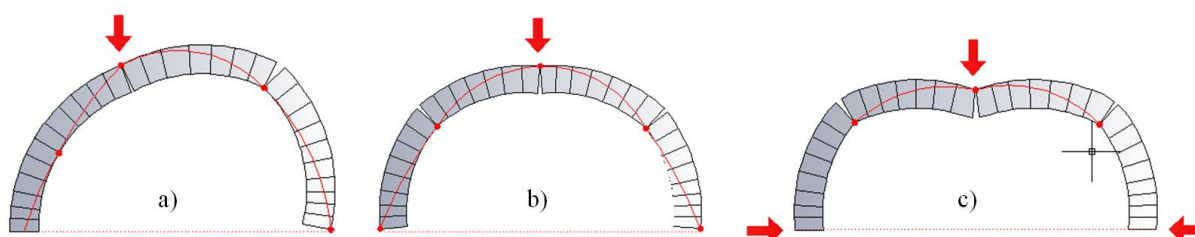
The structural system of the masonry arch bridges has distinct characteristics depending on their time of construction. Due to the similarity between techniques and the fact that the original bridges were rebuilt over the centuries not always their unique identification is simple or even possible. In Figure 3 are shown different types of arches and a bridge where several types of arches were used due to reconstructions.



**Fig. 3.** Masonry arches: a - Types of arches; b - Mirandela Bridge in Portugal

### 3.3 Failure modes

Generally masonry has a good compressive behavior and poor behavior to traction. The failure modes of these structures are associated with the strength of the material and structural equilibrium, with different behavior in the longitudinal and transverse direction. Figure 4 exemplifies the longitudinal failure modes of an arch.



**Fig. 4.** Longitudinal failure modes mechanisms: a- 4hinges; b- 5hinges; c- 3hinges snap-through (adapted from Costa, 2009).

Failure can occur in the different elements of an arch bridge conditioned by resistance, structural equilibrium or combination of these factors, as systematized in Table 2.

**Table 2.** Structural failure modes in masonry arch bridges: a – longitudinal; b – transversal direction. (adapted from Costa, 2009)

	Elements	Failure modes	Conditioning factors
(a)	Arch	4 plastic hinges mechanism	Resistance, equilibrium
		5 plastic hinges mechanism	Resistance, equilibrium
		3 plastic hinges snap-through	Equilibrium
		Crush	Resistance
		Slip	Resistance
	Spandrel walls	Crush	Resistance
(b)	Bridge	Global plastic hinges mechanism	Resistance, equilibrium
	Backfill, spandrels and arch	Longitudinal cracks in the vault	Resistance, equilibrium
		Bending and punching shear of the arc	Resistance

## 4 Defects, origins and condition assessment

### 4.1 Causes of defects

Understanding the causes of defects is essential for a proper asset management policy, so that repair actions are focused in the elimination of these causes.

Defects arise from actions which generate stresses, deformations or alteration of material properties. A systematization of these actions is presented in Table 3.

**Table 3.** Actions on structures and their materials (adapted from ICOMOS)

Actions acting on the structure (Mechanical)	Static actions	Direct	Applied loads (e.g. permanent load, equipment, intrusive vegetation, etc.)
		Indirect	Applied strains (e.g. imposed deformations due to settlements, mortar shrinkage, etc.)
	Dynamic actions		Imposed accelerations (e.g. seismic action, wind, traffic, etc.)
Actions acting on the materials	Physical		Decay of material properties due to ambient factors (e.g. water, temperature gradient, moisture, pollution, etc.)
	Chemical		
	Biological actions		

Design misconception, building mistakes and insufficient maintenance are also common causes of defects. Although not specified in the examples above were considered in the text.

### 4.2 Common defects

Defects represent situations that cause a deviation from the normal behavior of structures, resulting in damages that can affect its safety, durability and functionality. In this study were considered the defects that can be observed in a visual inspection and grouped as: structural defects, those that may threaten the structural safety of the structure; durability defects, usually do not endanger bridge safety in the short-term but can lead to serious long-term damages; functionality defects, which jeopardize the safe operation of the bridge such as deficient drainage or damages in guard-rails. Structural and durability defects will be further analyzed in section 4.3.

### 4.3 Technical parameters for the assessment of defects in masonry bridges

The main purpose of this guide is to provide guidelines for the assessment through the condition rating scale defined in IP's BMS. This goal was achieved through the systematization of the most common defects, definition of the parameters to be evaluated in each defect, and finally a suggestion of Condition Ratings for certain ranges

of values or a combination of observed parameters. Table 4 presents the systemization of structural defects and the technical parameters to be analyzed in each case.

**Table 4.** Technical parameters for the assessment of structural defects in masonry bridges

General Defect	Specific Defects	Technical parameters to be analyzed
Localized defects in blocks	Localized cracks in blocks	Number of affected blocks
	Fractured blocks	Aperture of cracks
	Crushed parts	Displacement between fractured parts
		Possible formation of plastic hinges
Longitudinal cracks		Number and length of the cracks
		Width variation along the length
		Extending to adjacent elements
		Backfill out through the opening
Transversal cracks		Number and length of the cracks
		Width variation along the length
		Extending to adjacent elements
		Backfill out through the opening
Oblique cracks		Localized defects in blocks
		Number and length of the cracks
		Width variation along the length
		Extending to adjacent elements
Vertical cracks		Backfill out through the opening
		Number and length of the cracks
		Width variation along the length
		Extending to adjacent elements
Loss of blocks or mortar		Partial or total loss
		Affected area
		Depth of the hollow
Geometric deviations outside the masonry plane	Buckling	Local or generalized (Affected area)
	Leaning or tipping	Deviation from original position
	Displacement along a transversal plane	Condition of joints and blocks
Geometric deviations in masonry plane	Flattening	Deviation from original position
	“Slipping” of a single row of blocks	Condition of joints and blocks
		Condition of the backfill
Settlement of piers / abutments		Partial or uniform settlement
		Deviation from original position
		Presence of undermining
Ruin		Partial or total ruin of the element
		Extending to adjacent elements

Similarly, Table 5 shows the same approach to the durability defects.

**Table 5.** Technical parameters for the assessment of durability defects in masonry bridges

General Defect	Specific Defects	Technical parameters to be analyzed
Water ingress		Affected area
		Presence of undermining
Intrusive vegetation	Moss and grass	Affected area
	Vegetation	Trees supported against the bridge
Efflorescence		Affected area
		Presence of stalactites
Soot deposits		Affected area
Cement based mortars		Affected area
Visual dissonance		Affected area
Blocks deterioration	Erosion	Affected area
	Dissolution	Depth of the affected area
	Disintegration	Weather exposure
Degraded / Loss of mortar		Affected area
		Weather exposure

#### 4.4 Diagnosis and condition assessment

Each of the defined defects was thoroughly described and illustrated, analyzed for possible causes, aggravating factors, evolving potential and consequences, possible testing or monitoring, mitigation measures and possible repair techniques.

Durability defects were considered regardless of the elements in which they occur. Structural defects were analyzed according to the bridge component where they were observed, importance of the component to the structure stability, location of the defect in each component, stable or evolutionary state, presence of water, proximity to the stream, and possible conjugation with other defects.

The analysis of the factors described above is considered to allow bridge inspectors to understand the causes of the observed defects in masonry bridges, determine possible consequences, and therefore aid a more documented and uniform assessment of the bridges condition. This condition will be summarized as a Condition Rating according to the scale defined in IP's BMS (from 0 – optimal, to 5 – critical), which will allow the prioritization of major repairs.

## 5 Conclusion

This article describes the methodology used to aid the definition of a Condition Rating according to the scale used by IP's BMS. Despite this specific orientation it is believed that the systematization used in this study, i.e., the identification of the most common defects and technical parameters to evaluate them, may be used for a wider methodology, such as the definition of performance indicators and goals, as desired the COST Action TU1406.

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