ESCUELA DE INGENIERÍA EN CONSTRUCCIÓN
PONTIFICIA UNIVERSIDAD CATÓLICA DE VALPARAÍSO

Comité Desarrollo Productivo VALPARAÍSO por CORFO

Encuentro Internacional de Innovación e Infraestructuras Resiliente

Forensic Investigation Methods for Resilient Infrastructures

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SINGULARSTRUCTURES ENGINEERING

NORISK

IABSE International Association for Bridge and Structural Engineering

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Qualifications
Masters Module in Business Economics
Imperial College London Business School (London, UK)
Bespoke program with standards consistent MBA Programs - 2011
Master of Science
University of California at Berkeley UCB – (Berkeley, USA)
Major in Structural Engineering,
Mechanics and Materials with emphasis in dynamic analysis, and no-linear design of structures – 1998
Civil Engineering Degree
Swiss Federal Institute of Technology -EPFL – (Lausanne, Switzerland) - MEng
Emphasis in analysis and design of structures – 1995

Committees
Member of the **SEI Editorial Board** “Structural Engineering International” **Journal**
Vice-chair of IABSE´s Commission 5 “Existing Structures” / **Task Group 5.1 “Forensic Structural Engineering**”
Co-editor of **IABSE SED Bulleting** on "Cases studies on failure investigations in structural and geotechnical engineering"
IABSE Fellow
Bridge Expert for a Multilateral Institution on **“Cooperation and Development Projects” in Africa**

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ENGINEERING

0

PRELIMINARY STATEMENT

Examples of Structural "Collapse"

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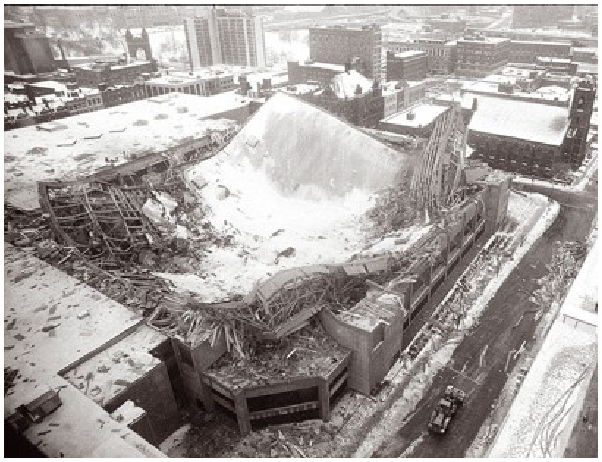

Hartfort Civic Center City (1978), Connecticut, USA

Hyatt Regency (1982), Kansas City, USA

Genoa Bridge (2021), Italy

Millenium Bridge (2000), London, UK

RC Bridge (2023), DRC

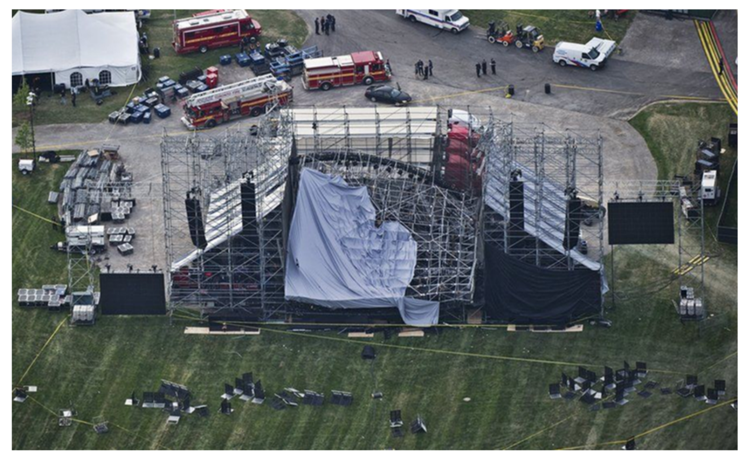

Image from Getty Images

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Investigation Methodology

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INTRODUCTION

1

Definitions

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Structure's Stage Approach (SS)

A type of forensic Engineering Study in which the engineer in charged of the investigation starts from the documentation available of the infrastructure project, from the **Planning stage, Design, Construction and Operation/Inspection & Maintenance stages**, and with the help of the ToolKit and Failure Analysis Report can investigate and narrow down the causes of a failure or pathology;

Pathology Based Approach (PB)

A type of forensic Engineering Study in which the engineer in charged of the investigation starts from the **visible field data extracted from an inspection** and would trace-back the mechanism of failure identifying Shallow and Deep Causes; in other words, narrow down the causes that generated the observed pathology;

1 Terminology

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- **Failure :** A Failure is a non-conformity with design expectations, or unacceptable difference between intended and actual performance. Failure can be total or partial collapse, extensive damage (with no collapse), serious damage (still with no collapse), sign of distress, excessive deformations (serviceability issues), deterioration, soil settlements, …
- **Fault Tree Analysis :** Fault analysis approach where the Boolean combinations of different factors lead to a parent case that is likewise combined with others. The process can be extended ad-infinitum until reaching the higher parent case, which is the fault to study. Thus, the tree can be read deductively (Top-Down) from some causes to the eventual apparition of the pathology or inductively (Bottom-Up) from the pathology to its latest causes.
- **Analytic Hierarchy Process :** Multicriteria decision making approach, based on the comparison by pairs of the different possibilities, that results in the sorting of the possibilities according to their relevance.
- **Pathology :** Undesired phenomenon that produces a decrease in the comfort or the safety of a structure, deviating from its expected behaviour.
- **Shallow cause (1st Layer):** One of the situations that can lead to a pathology. Shallow causes are potentially visible and can be detected under inspection. Shallow causes are produced after a combination of flaws,
- **Deep cause (2nd, .. Layers):** One of the situations that can lead to a shallow cause of a pathology. Deep causes reside in the documentation of the project, or mechanical/chemical process underway, and are not necessarily visible following the inspection of the structure. In other words, this would lead to the root cause of the pathology.

INTRODUCTION

1 Analysis Methodology

Structure Stages

Governance stage

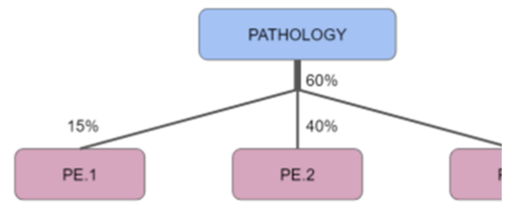
Planning stage

Design stage

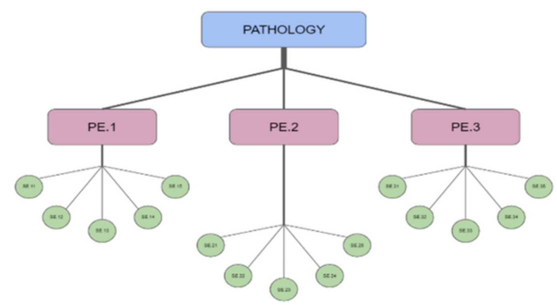
Construction stage

OI&M stage

Pathology Based Approach



Observed Pathology



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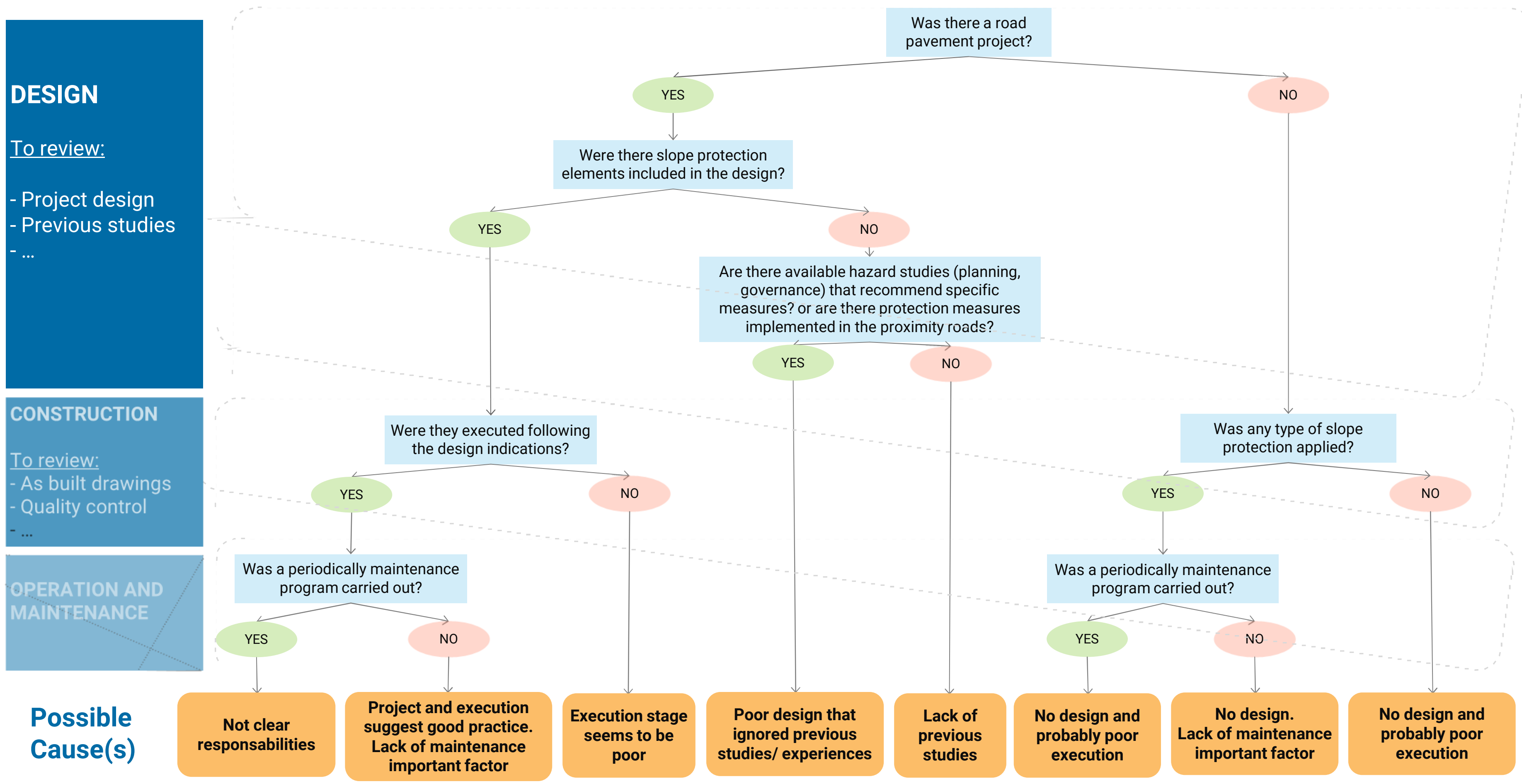
Investigation Methodology

2 FAULT TREE METHOD

The Fault Tree



FAULT TREE METHOD

2 Examples of Road Failure





FP1) **Surface Cracks** (Flexible Pavement);
FP2) **Lost of Pavement sections *(Potholes)***;
FP3) **Depression *(Rutting);***
RP1) **Surface Cracks** (Rigid Pavement)**;**
RP2) **Displacement of Prefabricated Concrete Blocks**;
RP3) **Lost of Concrete Sections / Rebar Exposure;**
EM1) **Scour / wash-out** of the embankment/base and/or sub-base materials below finishes;

=> Other pathology, not limited to:

- Drainage System;

FAULT TREE METHOD

2 Examples of Bridge Failure







SS1) **Lack of continuity** of the structural system;
SE1) **Concrete Spalling** / Rebar Exposure;
SE2) **Concrete Cracking**

SE3) **Concrete Deck Failure**;
ME1) **Scour**;
ME2) **Settlement** / **Tilting**;

ME3) **Total collapse of bridge** deck/pier;
MD1) **Bearings;**
MD2) **Movement Joints**; .....

Methodology Comparison

Failure Analysis Approach	Structure's Stage Approach	Pathology Based Approach
Overarching Methodology	Fault Tree Method (FTM)	
Methodology Description (Investigation Journey / Path / Roadmap)	The investigation process will follow chronologically the different **life-cycle stages of a civil engineering structure**, from Governance and Planning to the collapse time of the structure	The investigation process will be geared by the **identified structural pathology**, up to the potential originated causes of the pathology.
Analysis Technique	FTA Fault Tree Analysis	AHP Analytical-Hierarchical Process
Properties	Structured and systematic approach. Requires a certain **volume of data** to properly cover the life-cycle of a structure.	Quick approach as it starts from the observation and **requires a minimum of information for a preliminary assessment**.

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Investigation Methodology

3 STRUCTURE'S STAGE APPROACH

Investigation "Journey" Overview

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PHASES

- **Planning**
- **Design**
- **Construction**
- **Operation, Inspection and Maintenance**

Recommendations: Avoid Misleads & Mistakes

POTENTIAL PATHOLOGIES*

- Rutting
- Potholes
- Cracking
- And on…

Lesson Learnt

*Please refer to Annex A to view the full list of identified pathologies

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STRUCTURE'S STAGE APPROACH

Investigation Journey: Planning Phase

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Pre-feasibility Studies

Stage 1
Business Case

Stage 2
Preliminary Technical Studies

- Public Utility Plan
- Property Plan
- Region/District Limit Plan
- Topographical Study
- Road Alignment Study
- Environmental Impact Assessment
- Geotechnical Investigation Campaign
- Regional and River Flow Hydrology
- and so on

Stage 3
Natural Hazard Studies

3 STRUCTURE'S STAGE APPROACH

Investigation: Planning Phase

Stage 1 Business Case | **Stage 2** Preliminary Technical Studies | **Stage 3** Natural Hazard Studies

A business case provides **justification** for undertaking a project, **estimated program** and **cost**. It evaluates the benefit of several alternative routes, sets the risks and becomes a record of the recommended option with rationale and evidence to support the decision.

Strategic Context

Technical Alternatives

Economic Analysis

Financial Approach

Management Approach

Recommendations:

- Being capable of **determining the impact** (socioeconomic, environmental…) the infrastructure is going to have in medium-long term.
- The **alternatives** should **evaluate alignments** that can reduce cost, damage, time or combinations of them in comparison to the actual infrastructure. The document tends to lead to the definition of a preferred option.
- In the **economic analysis**, use **standardized prices** and also foresee the inflation of the construction prices.
- The **Business Case** shall **cover the whole life** cycle of the infrastructure.

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STRUCTURE'S STAGE APPROACH

Investigation: Planning Phase

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Stage 1 Business Case	**Stage 2** Preliminary Technical Studies	Stage 3 Natural Hazard Studies

The Preliminary Design Technical Documents develop the information the designer has to consider when calculating and designing the road/concrete structure.

Land-use Planning + **Site Study Planning** + **Hazard Study Planning**

Land-use Planning
- Public Utility Plan
- Property Plan
- Region/District Limit Plan
- …

Site Study Planning
- Topographical Study
- Road Alignment Study
- Environmental Impact Assessment
- …

Hazard Study Planning
- Geotechnical Investigation Campaign
- Regional and River Flow Hydrology
- …

Recommendations:

- All **Preliminary Technical Studies** shall be **sufficiently extensive** to retrieve relevant information for the project.
- **Extensive data gathering** (Analysis, site testing, representativity…) and **ownership** (corresponding Authority) regarding hydrological or geotechnical data are going to avoid design flaws later on

Potential Pathology Generation: ***

Most Relevant Pathologies among Shared: EM1 SD4 MD3

3

STRUCTURE'S STAGE APPROACH

Investigation: Planning Phase

Stage 1 Business Case | **Stage 2** Preliminary Technical Studies | **Stage 3** Natural Hazard Studies

The region of Valparaiso is exposed to multiple natural hazards due to its geographical position within Chile, its physio-topographic and climatic profile.

Earthquake	High
Landslide	High
Tsunami	High
Water scarcity	High
Wildfire	High
Urban flood	Low
Coastal flood	Low
Extreme heat	Low
River flood	Very low

Recommendations:

- The most important hazards are earthquake, landslides, tsunami, water scarcity and wildfire.
- **Extensive data gathering** (Analysis, site testing, representativity…) and **ownership** (corresponding Authority) hazard data are going to avoid design flaws later on

Source: https://thinkhazard.org/en/

*** Potential Pathology Generation

MD3 Most Relevant Pathology among Shared

3

STRUCTURE'S STAGE APPROACH

Investigation: Planning Recommendations

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Strategic Context

Compelling case for infrastructure development.

Technical Alternatives

Scenarios of infrastructure technical solutions, both land use and structural typologies.

Economic Analysis

Return on investment based on investment options (Publically funded, or Private-Public Partnership -PPP-.

Financial Approach

Derived from state/region sourcing strategy and/or design/construction procurement process strategy for a given time frame.

Management Approach

Project stages, Procurement Process, Roles and Responsibilities (Governances Structure), life cycle choice, Concession periods, Payment mechanisms, etc.

Lesson learnt

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Investigation Methodology

Potential Pathologies List

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Road Structures Pathologies

FPx Flexible Pavement
- FP1 Surface Cracking
- FP2 Potholes
- FP3 Rutting

EMx Embankment
- EM 1 Scour and Washout
- EM 2 Excessive Deformations

Concrete Structures Pathologies

MDx Mechanical Decay
- MD 1 Cracking
- MD 2 Deformations
- MD 3 Structural Failure

SBx Structural Components Behavior
- SB 1 Bearing Malfunctioning
- SB 2 Movement Joint Malfunctioning
- SB 3 Lack of Continuity

SD x Surface Decay
- SD 1 Spalling
- SD 2 Corrosion
- SD 3 Honeycombs
- SD 4 Scour and Erosion

*** Shared Source among all categories

Flow Chart Pathology Based Approach

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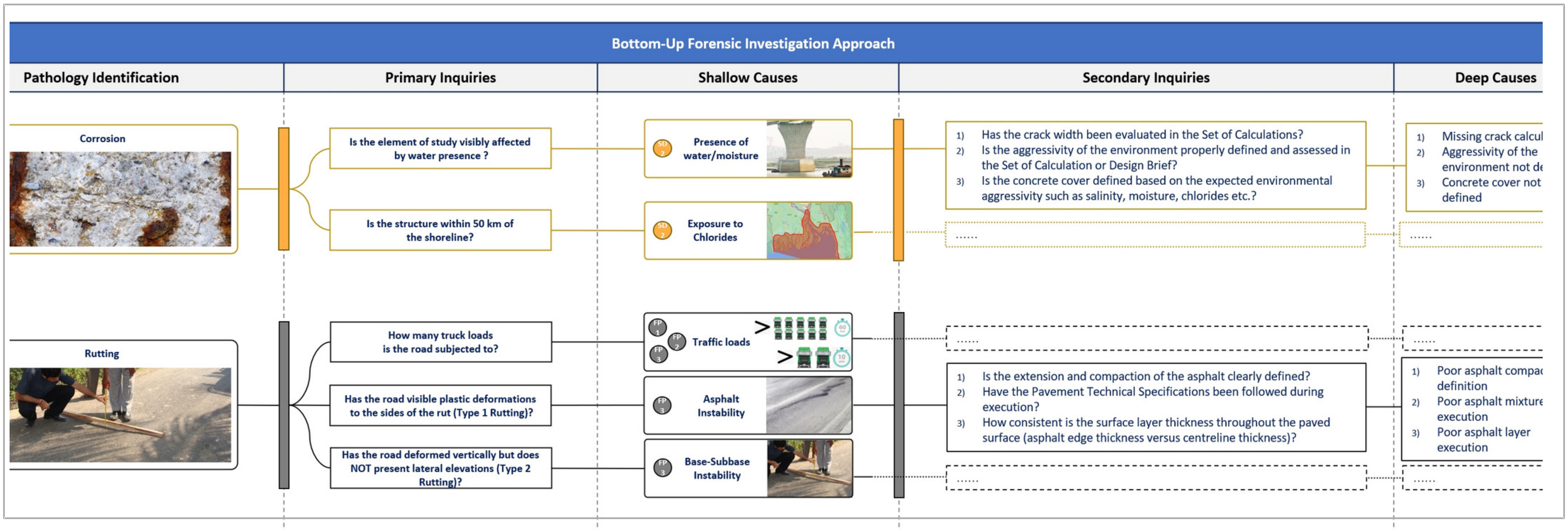

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PATHOLOGY BASED APPROACH

Potential Pathologies

Concrete Structures Pathologies

SDx Surface Decay

- SD2 Steel Reinforcement Corrosion
- SD4 Scour and Erosion

PATHOLOGY BASED APPROACH

4

Surface Decay

SDx

SD2 Steel Reinforcement Corrosion

Corrosion of reinforcement is one of the most frequent types of damage to reinforced concrete structures. It is manifested by the detachment of the concrete in a punctual or longitudinal way, leaving the reinforcement close to the surface without protection, so that over time they are covered by a film of rust that is manifested by the appearance of stains in the affected area.

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PATHOLOGY BASED APPROACH

Surface Decay

SDx

Shallow Causes – Corrosion -

1	**Presence of water/moisture** Water leakage is the main cause of early onset of corrosion and concrete deterioration as water acts as electrolyte.
2	**Exposure to Chlorides** The sea water contains high concentrations of chlorides. The moisture will enter into the concrete from the porous surface and corrode the reinforcement rapidly.
3	**Fire exposure** Fire reduces concrete and steel resistance when high temperatures are extended in time. Thermal gradients produce cracking and corrosion.

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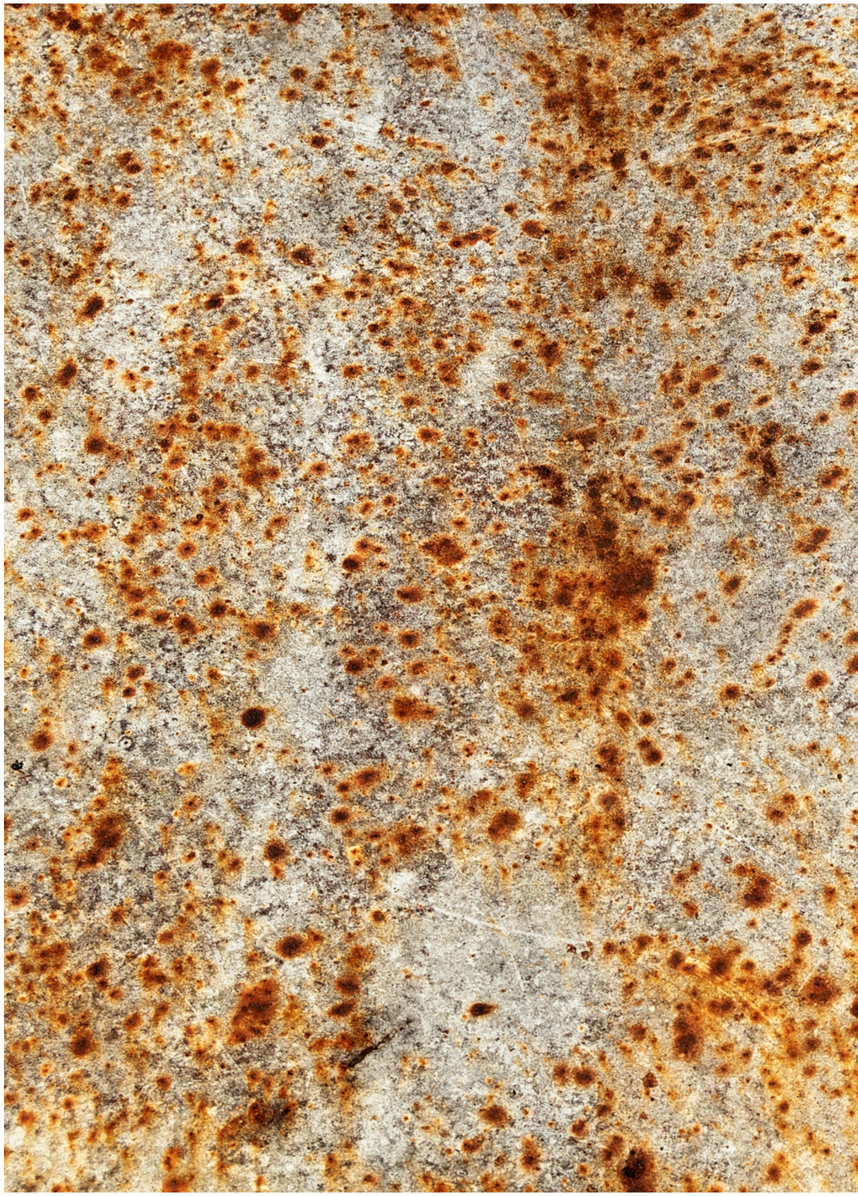

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1 Presence of water / moisture

Evaluation of Potential Shallow Cause

S.NV. Is the element of study visibly affected by water presence?	
0	There is no sign of water/moisture in the concrete nor in the rebars
25	-
50	Oxide marks are visible from the outside of the concrete cracks
75	-
100	The rebars are visible and moist to the touch
NO DATA	There are no signs of oxide marks nor seepage
NON APPLICABLE	The element has no rebars

Note: Please refer to 'Image Clarification' section to assist in the evaluation of the above rating

Evaluation of Potential Deep Causes

- *[D.DE]* Has the crack width been evaluated in the Set of Calculations?
- *[D.DE]* Is the aggressivity of the environment properly defined and assessed in the Set of Calculation or Design Brief?
- *[D.DE]* Is the concrete cover defined based on the expected environmental aggressivity such as salinity, moisture, chlorides etc.?
- *[D.DE]* Is the concrete water/cement ratio well defined for the expected environment?
- *[D.DE]* Are drainage systems or minimum surface slope implemented to prevent water accumulation over the structure?
- *[D.EX]* Has the design concrete water/cement ratio maintained during the execution according to the Concrete Technical Specifications?
- *[D.MA]* Has water infiltration been observed during the lifespan of the bridge?

0	25	50	75	100	NO DATA	NON APPLICABLE
All of the time	Often	Some of the time	Rarely	None of the time	No collected data	Nonexistent information to apply

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2 Exposure to Chlorides

Evaluation of Potential Shallow Cause

S.NV. Is the structure within 50km of the shoreline?	
0	The structure is inland far from the coast (50+ km)
25	-
50	The structure is near the coast (20-50km)
75	-
100	The structure is over the sea (20- km)
NO DATA	-
NON APPLICABLE	-

Note: Please refer to 'Image Clarification' section to assist in the evaluation of the above rating

Evaluation of Potential Deep Causes

- *[D.DE.XX] Is the concrete exposure category properly defined?*
- *[D.DE.XX] Is the concrete cover designed for the expected chloride intrusion?*
- *[D.DE.XX] Is the concrete water/cement ratio well defined for the expected exposure?*

0	25	50	75	100	NO DATA	NON APPLICABLE
All of the time	Often	Some of the time	Rarely	None of the time	No collected data	Nonexistent information to apply

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2 Fire Exposure

Evaluation of Potential Shallow Cause

S.NV.05 Has the element suffered severe fire exposure resulting in temperature grading, leading to concrete spalling and ultimately to rebar corrosion?	
0	No signs nor reports of fire.
25	-
50	Signs or reports of mild and local fires, extinguished briefly after.
75	-
100	Signs or reports of strong and generalised fires near the structure
NO DATA	The element cannot be inspected.
NON APPLICABLE	The element is underwater.

SD4 Scour and Erosion

Scour is the result of the erosive action of the flow of water over rivers, which uproots and carries material from the bottom of the bed and lateral banks. The greatest damage due to scour occurs during floods, periods in which the speed of the water current is at its maximum, causing the greatest damage to the foundations of piles and abutments.

PATHOLOGY BASED APPROACH

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Shallow Causes Scour and Erosion

1

Water Erosion

Water is the most common and principal component of the origin and aggravation of the scour-erosion process.

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PATHOLOGY BASED APPROACH

Shallow Causes Scour and Erosion

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1

Water Erosion

Evaluation of Potential Shallow Cause

S.NV. Has the water eroded the soil material under the foundations/abutment/piers?	
0	There is no sign of material transportation near the foundations and the protections remain intact
25	-
50	The pier/abutment stability needs maintenance duties, as the foundation is starting to lose contact with the soil.
75	-
100	The pier/abutment stability is heavily compromised, landslides occur in the embankment's slopes near the abutment and/or the piers are unsubmerged.
NO DATA	The piers/abutment foundations cannot be inspected
NON-APPLICABLE	There is no pier or abutment

Note: Please refer to 'Image Clarification' section to assist in the evaluation of the above rating

0

50

100

Evaluation of Potential Deep Causes

- [D.PL.xx] Was there any hydraulic study done before the Design Stage and taken into account into the design?
- [D.DE.xx] Are the pier/piles protections defined in the design?
- [D.EX.xx] Are the pier/piles protections executed as per the design?
- [D.DE.xx] Is the abutment protection defined in the design?
- [D.EX.xx] Is the abutment protection executed as per the design?
- [D.MN.xx] Has the last inspection of the pier/piles/abutment been taken in less than two (2) years?

0	25	50	75	100	NO DATA	NON APPLICABLE
All of the time	Often	Some of the time	Rarely	None of the time	No collected data	Nonexistent information to apply

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Investigation Methodology

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FORENSIC STRUCTURAL INVESTIGATION REPORTING

Closure Report

To include:

- **Primary cause** of the failure
- **Contributing factors** to the failure
- **Trigger** and evolution of the failure
- **Responsibilities**

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Investigation Methodology

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1. Introduction
2. Fault Tree Method (FTM)
3. Structure's Stage Approach
4. Pathology Based Approach
5. Forensic Structural Investigation Reporting
6. **Lessons Learnt**

6 LESSONS LEARNT

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International Master in Risk Assessment and Management of Civil Infrastructures

1. Introduction to risk assessment and management of infrastructures
2. Reliability and risk analysis of infrastructures
3. Infrastructures management and decision supporting tools
4. Monitoring and digitalization of infrastructures
5. Assessment and intervention techniques on infrastructures
6. Integrated Project within the scope of Risk Analysis and Management of Infrastructures
7. Dissertation

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Università degli Studi di Padova

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LESSONS LEARNT

Reference Documents (Not limited to)

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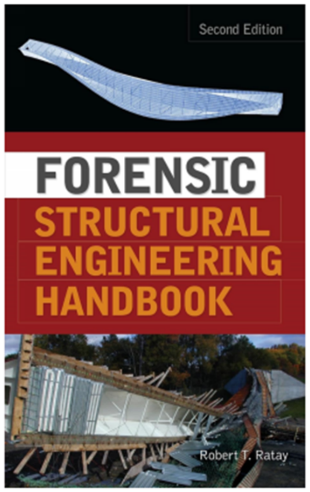
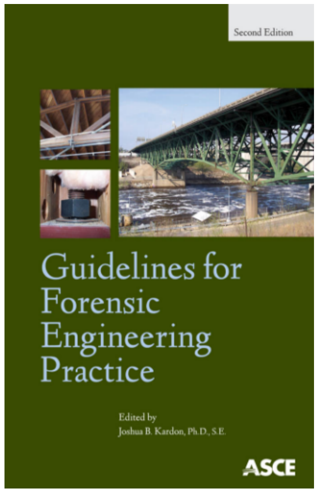
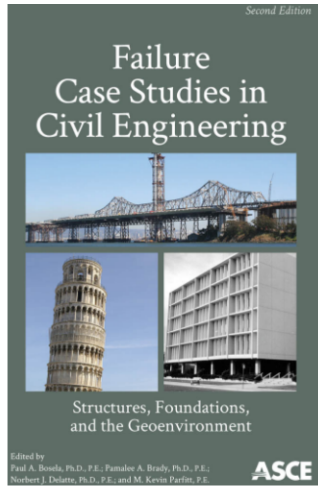


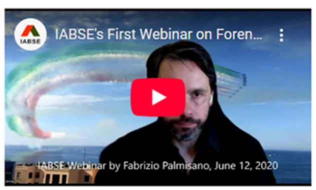




IABSE BST Lecture: Bridge Failure Analysis: Shallow and Deep Causes
by
Laurent Rus
https://www.iabse.org/eLearning/Lecture series

IABSE New Delhi Congress 2023

IABSE Webinar
The Chirajara Bridge Collapse
West Gate Collapse Report
Merrison Report
27 May 2021



IABSE Webinar
Forensic Structural Engineering:
A field of practice and research
by
Fabrizio Palmisano

IABSE Webinar
Without even touching it: the story of the Leaning Tower of Pisa
7 October 2022

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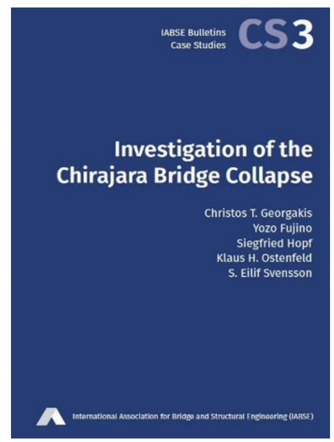

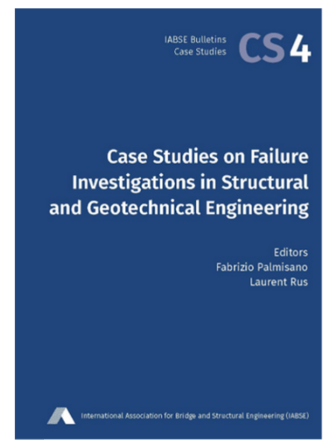

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MUCHAS GRACIAS POR SU ATENCIÓN!

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