LABORATÓRIO NACIONAL
DE ENGENHARIA CIVIL

TERCENAS BRIDGE

A chloride induced corrosion case

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Location


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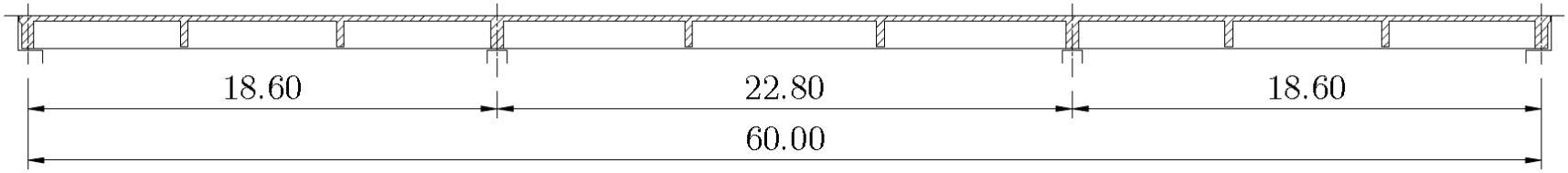
ATLANTIC OCEAN
SPAIN
Gulf of Cádiz
Lisbon
Porto
Coimbra
Aveiro
Viseu
Guarda
Castelo Branco
Évora
Beja
Faro
Portalegre
Santarém
Leiria
Setúbal
Braga
Bragança
Vila Real
PORTUGAL
National capital
District capital
City, town
Major airport
International boundary
Expressway
Main road
Railroad
0 25 50 75 100 km
0 25 50 mi

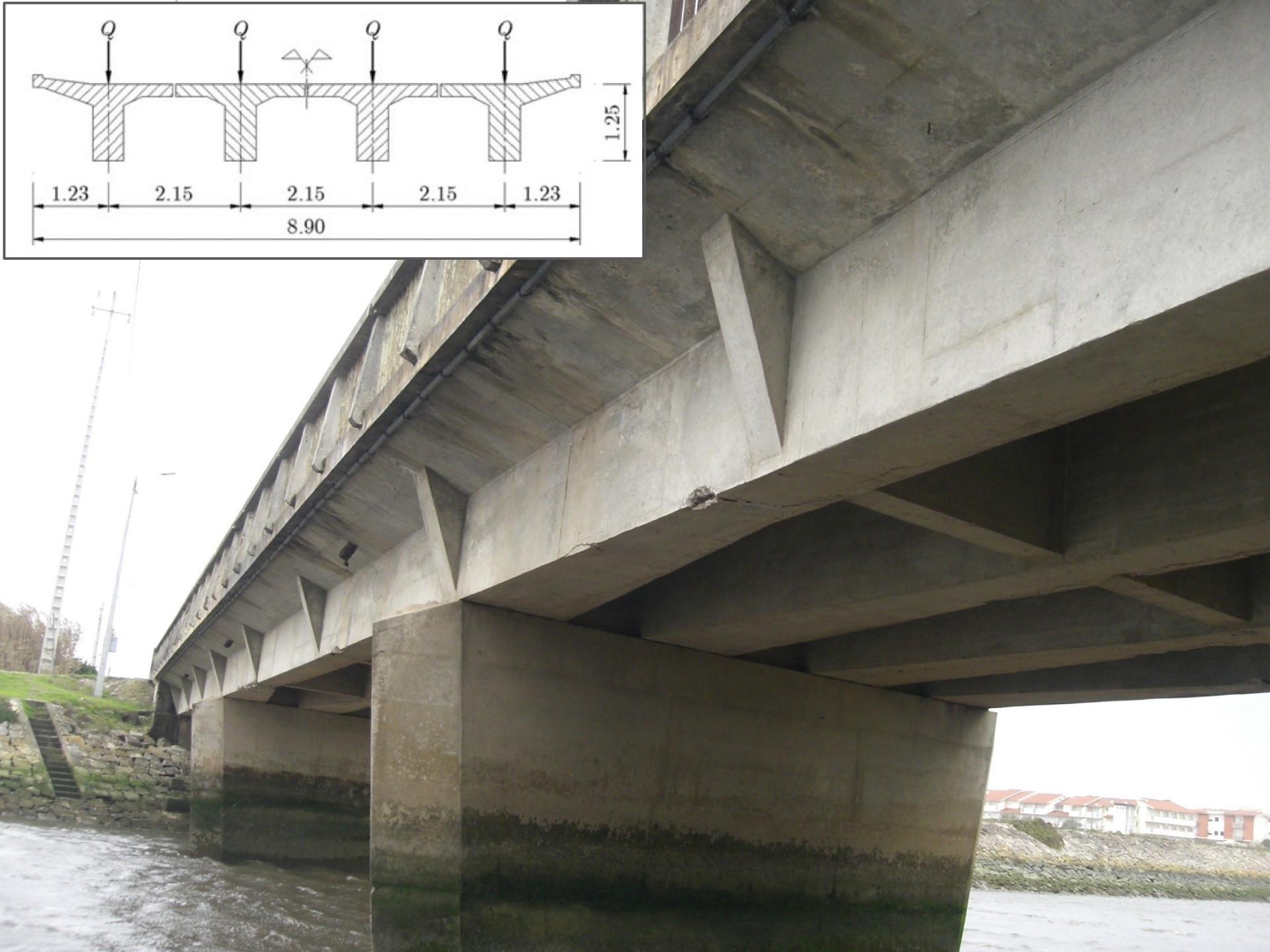
Location


500 m
Bairro da PSP
Praia da Vieira
Estrada Florestal
Rua das Tercenas
Rua da Lagoa
Rua do Mar
N349

Tercenas Bridge

Owner.....Office of Water Services
Construction……..…1970

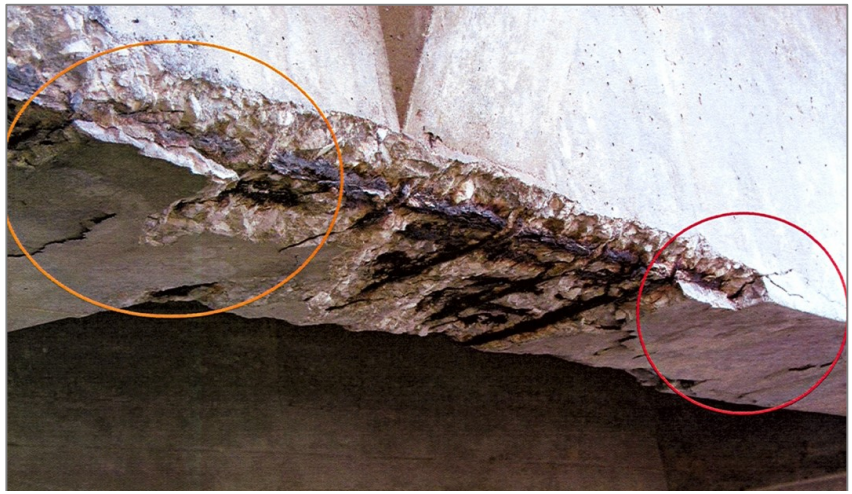



Q
Q
Q
Q
1.25
1.23
2.15
2.15
2.15
1.23
8.90

Visual inspection
Structural damages

Sep. 2004

- Cracking
- Concrete delamination
- Corrosion of reinforcement bars



Beam on the sea side (left beam)

Nov./Dec. 2004

On-site tests

In areas without apparent degradation of the concrete:

- Determination of concrete cover depth
- Measurement of carbonation depth
- Measurement of corrosion potential (ASTM C876:91)
- Measurement of corrosion rate (RILEM TC-154-EMC, 2002)
- Measurement of resistivity of concrete

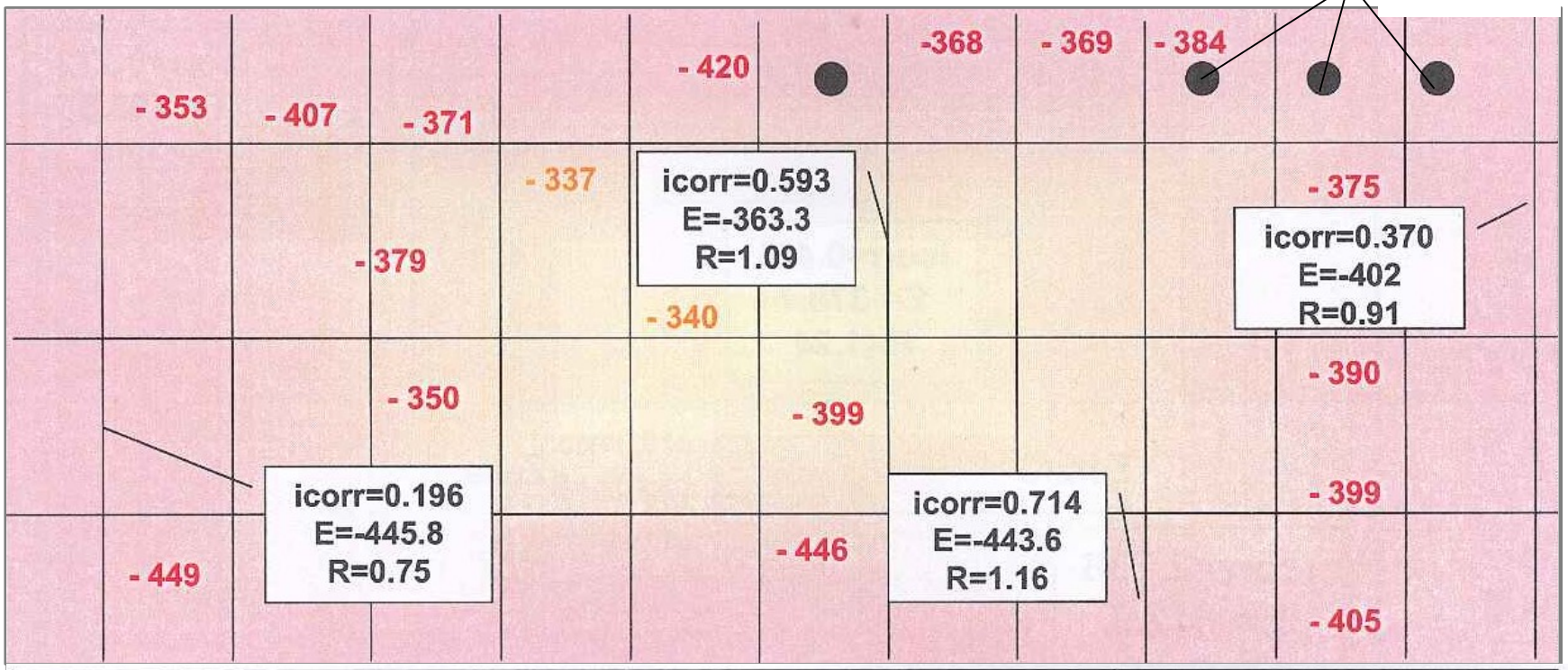
Measurements at Beams 1, 2 & 4; South pier; South Abutment

Manuel Salta *et al* . (2005).

On-site tests

Nov./Dec. 2004

Corrosion potential, corrosion current & resistivity of concrete

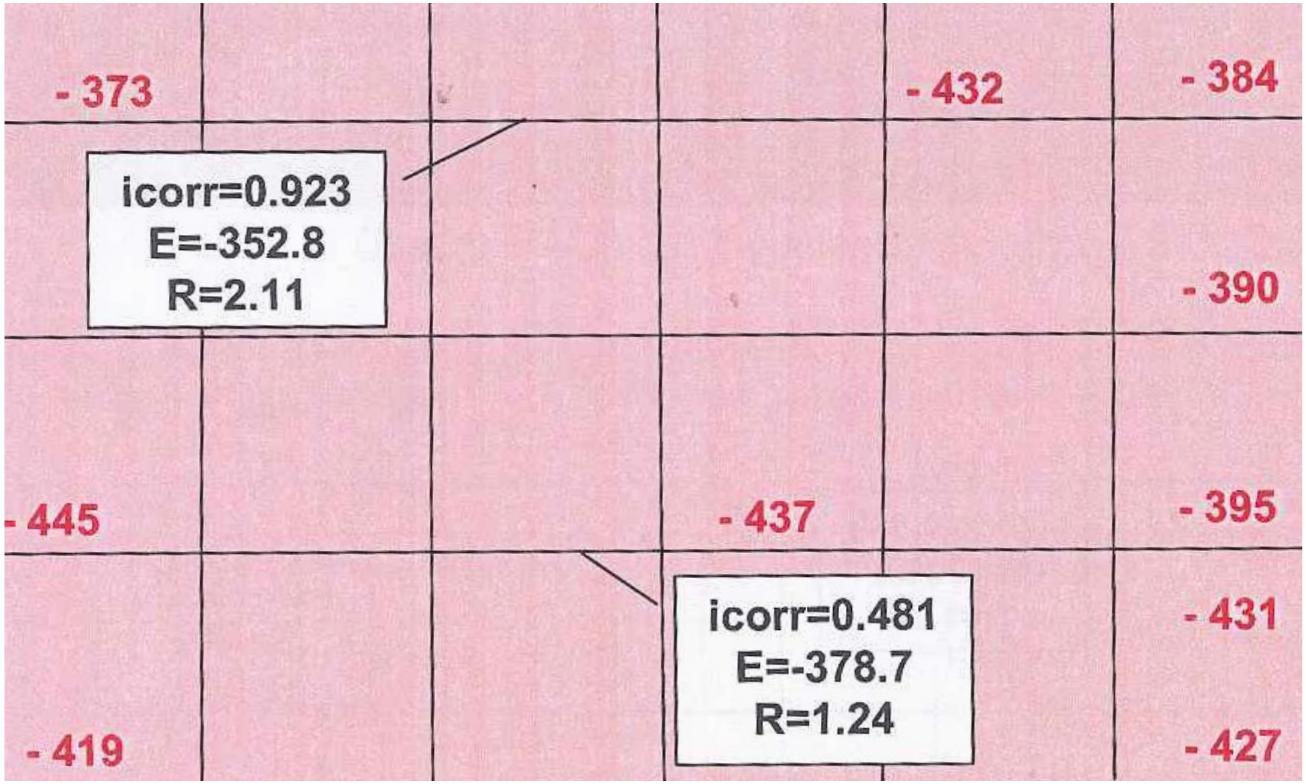


Icorr - Corrosion current ($\mu A\ cm^{-2}$)	Probability of corrosion	Symbology
E - Corrosion potential (mV)	90 %	
R - Resistivity of concrete ($k\Omega$)	10-90%	
Manuel Salta et al . (2005).	10%	

On-site tests

Nov./Dec. 2004

Corrosion potential, corrosion current & resistivity of concrete



Corrosion potential limits (ASTM C 876:91)	Probability of corrosion	Symbology
E<-350 mV	90 %	
-350 mV < E < -200 mV	10-90%	
E > -200 mV	10%	

Laboratory tests

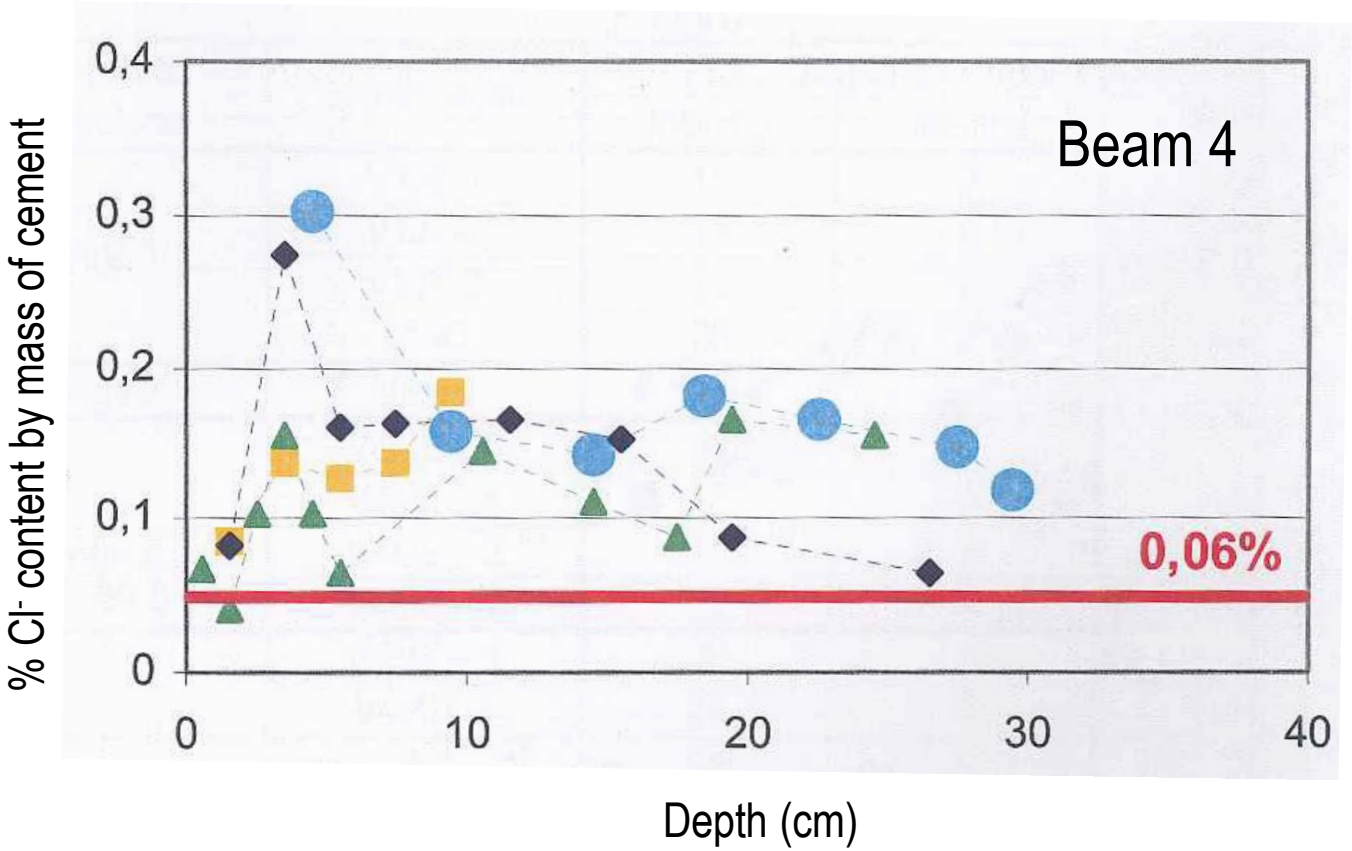
Taking cores for testing:

- Chloride content of concrete
- Carbonation of concrete
- Compressive strength of concrete
- Microscopic analysis

Laboratory tests

Nov./Dec. 2004

Chloride penetration profile



Conclusions and recommendations from the tests

Taking into account:

- The advanced state of degradation of the bridge
- The very depth contamination of concrete with chlorides.

Bridge replacement was recommended.

Bridge visual inspection
Structural damages

Jan. 2008

Bridge visual inspection
Structural damages

April 2009

Safety until replacement ?

- Traffic restrictions
  - Speed limit
  - Maximum weight
  - Avoid traffic over the left beam

- Frequent visual inspections

Traffic restrictions

Safety until replacement ?

- Critical limit state: bending at mid-span of the central span of left beam
- According to the Portuguese national code: Unsafe.
- Target reliability index, β_T=3,8
- Reliability analysis based on prior information

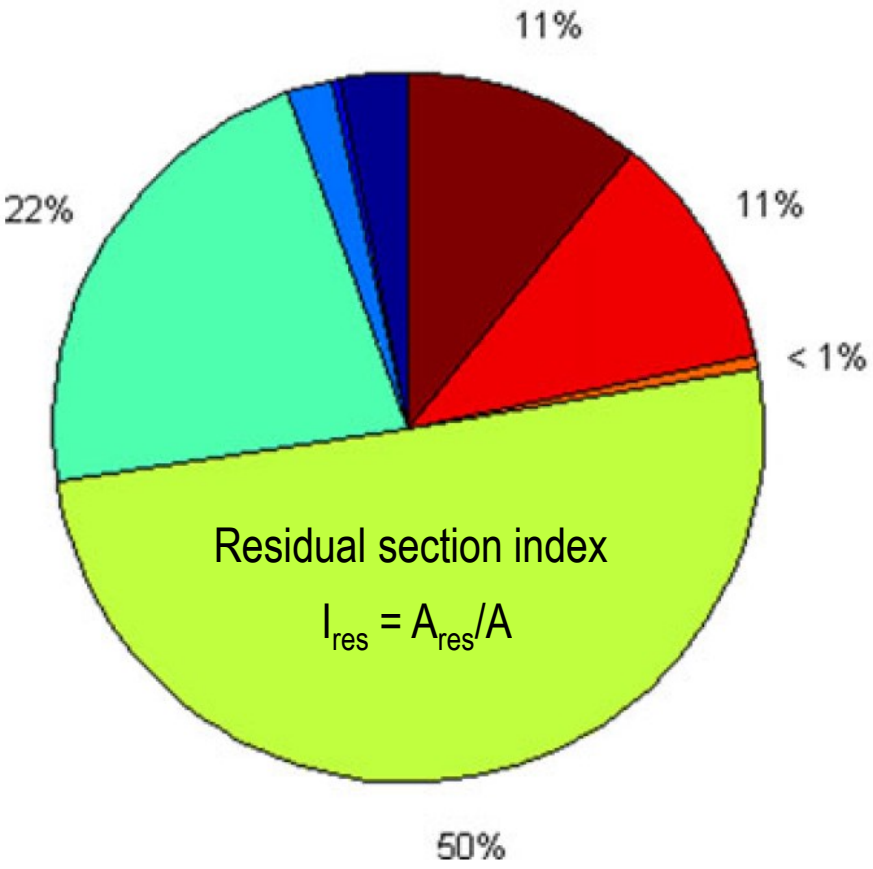
Basic variables and transformation models

Variable	Distribution	Parameters	
Bending moment due to self-weight	Normal	$\mu = 608.2$	$\sigma = 30.2$
Bending moment due to additional dead load	Normal	$\mu = 108.4$	$\sigma = 10.8$
Weight introduced by a vehicle wheel	Gumbel	$u = 38.0$	$\alpha = 0.56$
Concrete strength	Lognormal	$a = 10.81$	$b = 0.25$
Reinforcing steel strength	Normal	μ =460E3	σ =30E3
Residual section index	Beta	variable	variable
Bottom distribution of the 1st layer of reinforcing steel	Uniform	$a = 0.04$	$b = 0.06$
Bottom distribution of the 2nd layer of reinforcing steel	Uniform	$a = 0.09$	$b = 0.13$
Structural model uncertainty	Lognormal	$\mu = 1.0$	$V = 0.05$
Resistance model uncertainty	Lognormal	$\mu = 1.0$	$V = 0.05$

Reliability analysis based on prior information (MCM): β=3,04 < β_T

Sensitivity analysis

FORM Sensitivity coefficients



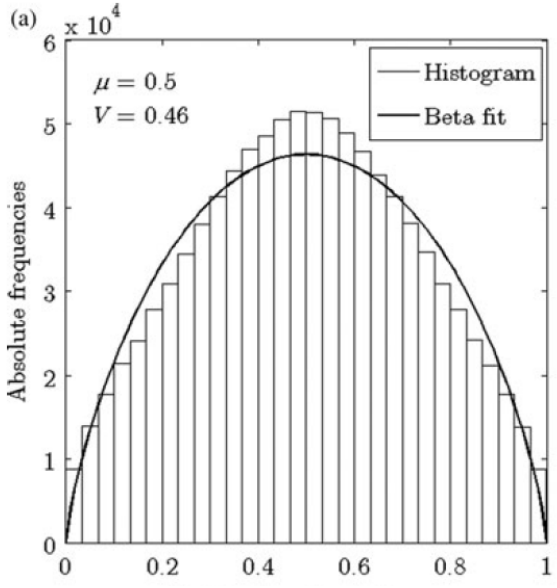
- Bending moment due to self-weight
- Bending moment due to additional dead load
- Weight introduce by a vehicle wheel
- Concrete strength
- Reinforcing steel strength
- Residual section index
- Bottom distribution of the 1st layer of reinforcing bar
- Bottom distribution of the 2nd layer of reinforcing bar
- Structural model uncertainty
- Resistance model uncertainty

Bayesian updating of the residual section index

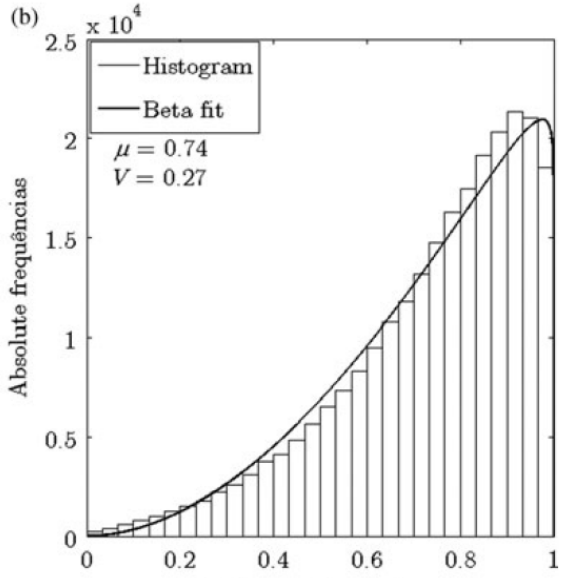
- Collection of information on residual areas of reinforcement

Bayesian updating of the residual section index

- Updating the residual section index predictive model



Residual section index
Prior histogram



Residual section index
Posterior histogram

Reliability analysis using this updated probabilistic model : β=3,9 > β_T

Bridge demolition

2012

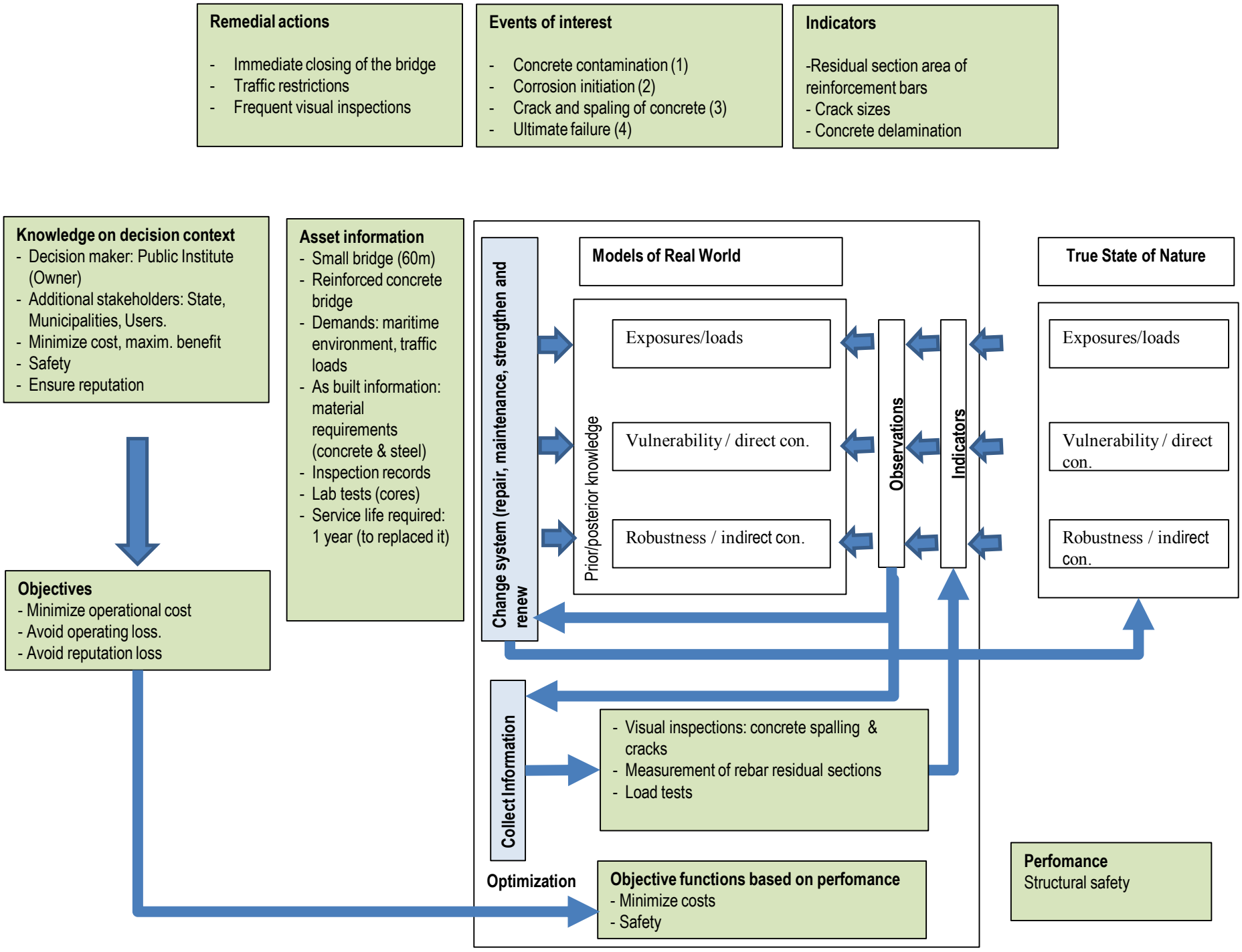
New Tercenas Bridge

Tercenas Bridge: the problem

- Bridge inspection → High level of degradation (corrosion)
- Lab tests (cores) → Chloride induced corrosion
- Decision: bridge replacement
- Question: is the bridge safe until replacement ?
- Code-based safety assessment: Not safe
  (Critical limit state: bending at mid-span of the central span)
- Reliability analysis based on prior information: Not safe

Tercenas Bridge: the solution

- Sensitivity analysis to identify the random variables more significant to structural safety → Residual section index ($i_{res} = A_{res} / A$)
- Collect information on key variable (i_{res})
- Updating the residual section index predictive model → Bridge safe


Remedial actions
- Immediate closing of the bridge
- Traffic restrictions
- Frequent visual inspections
Events of interest
- Concrete contamination (1)
- Corrosion initiation (2)
- Crack and spaling of concrete (3)
- Ultimate failure (4)
Indicators
-Residual section area of reinforcement bars
- Crack sizes
- Concrete delamination
Knowledge on decision context
- Decision maker: Public Institute (Owner)
- Additional stakeholders: State, Municipalities, Users.
- Minimize cost, maxim. benefit
- Safety
- Ensure reputation
Asset information
- Small bridge (60m)
- Reinforced concrete bridge
- Demands: maritime environment, traffic loads
- As built information: material requirements (concrete & steel)
- Inspection records
- Lab tests (cores)
- Service life required: 1 year (to replaced it)
Objectives
- Minimize operational cost
- Avoid operating loss.
- Avoid reputation loss
Change system (repair, maintenance, strengthen and renew
Models of Real World
Prior/posterior knowledge
Exposures/loads
Vulnerability / direct con.
Robustness / indirect con.
Observations
Indicators
True State of Nature
Exposures/loads
Vulnerability / direct con.
Robustness / indirect con.
Collect Information
- Visual inspections: concrete spalling & cracks
- Measurement of rebar residual sections
- Load tests
Optimization
Objective functions based on perfomance
- Minimize costs
- Safety
Perfomance
Structural safety