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Study case: corrosion and structural monitoring of reinforced concrete wharves
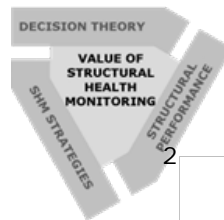
Nantes- France

Franck Schoefs & Yann Lecieux

suggested by the University of Nantes and supported by Nantes harbour

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Role of wharves and societal value

- 80% of the world overseas trade (99% in USA) passes through ports
- Key role in European defence
- 3 millions people are employed in the maritime transport sector in Europe

Stakes for maintenance

- In France: 106 km of wharves, among which 64 km are built with a reinforced concrete platform
- In a concrete platform: 350 m in length means 1,6 km of beams
- In France: €13 millions per year are spent for curative maintenance
- In USA: plan to spend $154.8 billion from 2016 to 2020

Source: [Boero et al, 2009] [2017 USA Infrastructure Report Card]

Presentation of study case

© Nantes Saint-Nazaire Port – Franck Badaire

What is a on-pile wharf?

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In plane view :

LOIRE

AMONT

T10

AVAL

T256

y

z

X

TMDC 4 - 2000

Anchoring plate

Tie-rod

Plate-forme

embankment

Backwharf wall

Cross-section

LOIRE

Pile network

gauges

piezometers
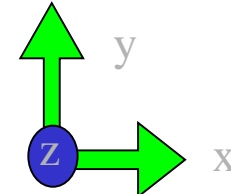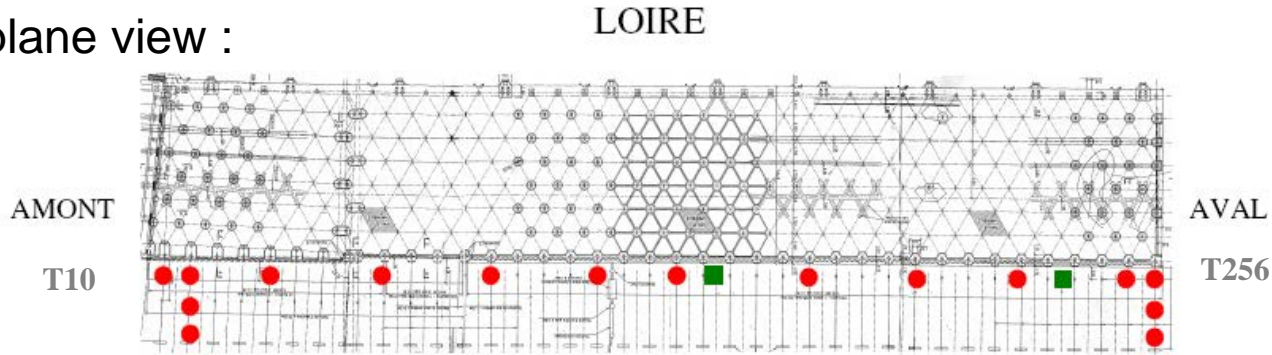
TMDC 4

5 monitored structures in Nantes: Cheviré4, TMDC4, Quai des darses, TC, TMDC5
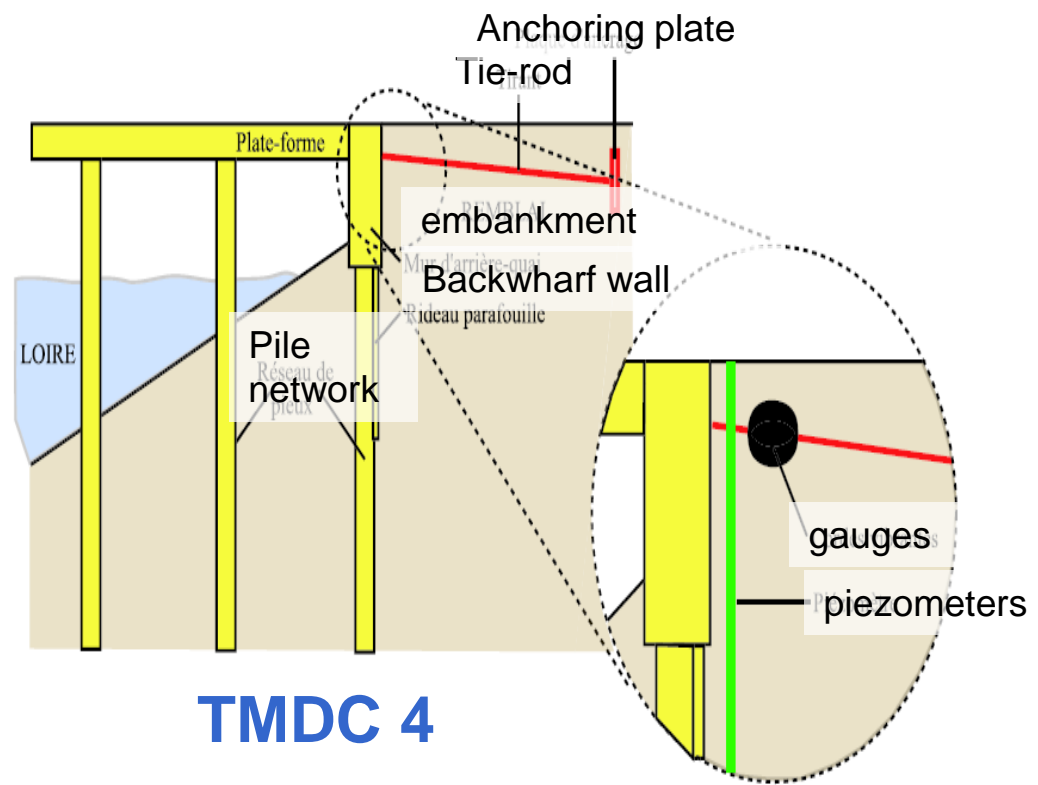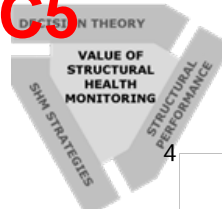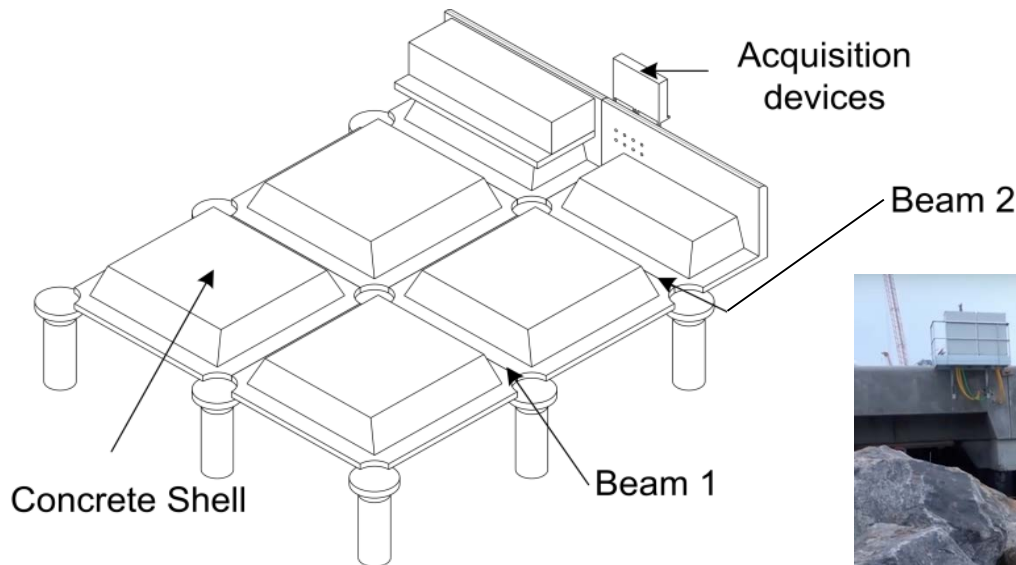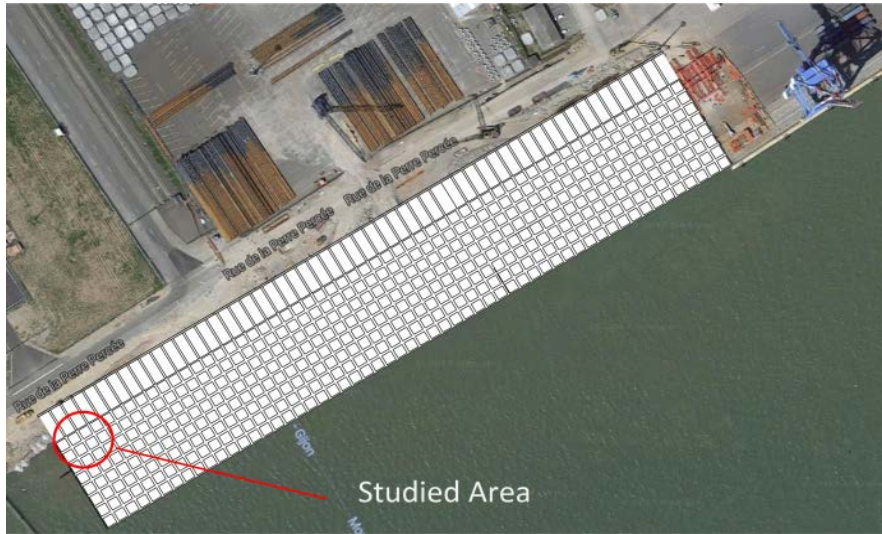
VALUE OF STRUCTURAL HEALTH MONITORING

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Optimize the maintenance, detect risk of structural failure, optimize conception

Studied Area

Acquisition devices

Beam 2

Concrete Shell

Beam 1

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Sensors in use (six months after instrumentation):

Sensors	Number	Number of sensors in use
FBG ε	20	17 (broken wire)
Resistivity	4	3 (water in connection)
RH%	6	5 (1 broken wire)
PT 100	6	6
Electrode Ag	6	6
Chloride	6	6
Optical fiber	2	No test
Thermocouples sensors	14	14

Decision context (infrastructure in Civil Engineering)

Usual quantification (VoI) based on total cost and preventive maintenance

Reference case (usual inspection practice) without SHM   Sub-study case 1

As-built mechanical behaviour for model updating and future retrofitting (change of use, new needs, …) / A= [SHM during construction; SHM after construction works]

Reference case (NDT and conservative models based on large uncertainties) (poor knowledge of behaviour) *retrofitting: collaborative work?*   Sub-study case 2

Change of paradigm: from means-based contract towards performance based contract during works: concrete performance as built (mechanical, durability)
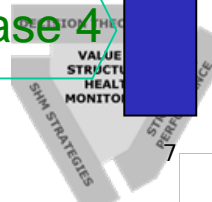
Reference case: means-based samples with poor conservation tested at 7 and 28 days (various temperature): *benchmark of practice/contracts ?*   Sub-study case 3
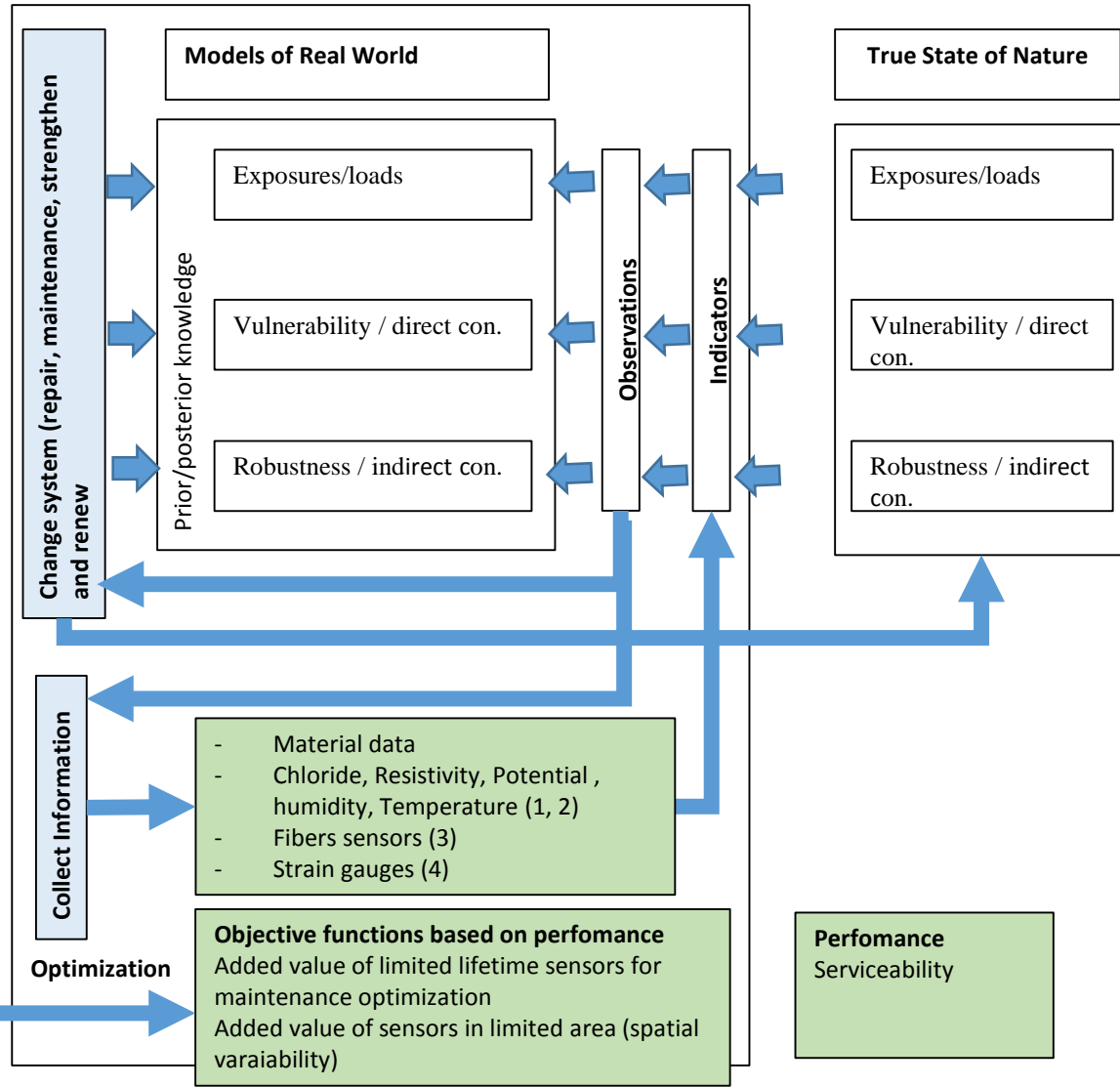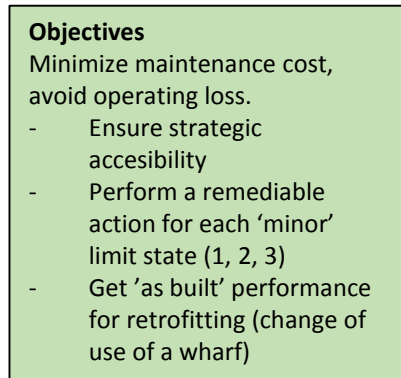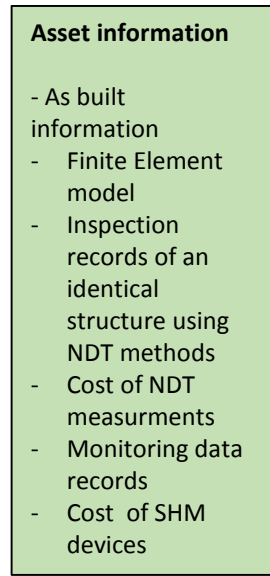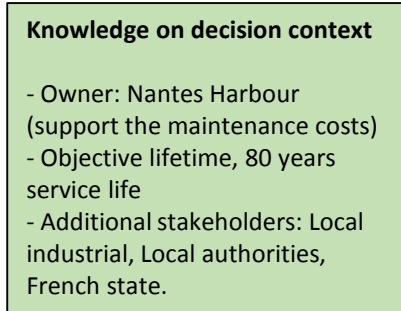
Detection of initial cracking during construction for long term   Sub-study case 4

durability assessment

Availability

Remedial actions

- Concrete repair (three techniques –MAREO)
- -Armature and concrete repair
- Destruction of the structure

Events of interest

- Concrete contamination (1)
- Corrosion initiation (2)
- Crack and spaling of concrete (3)
- Ultimate failure (4)

Indicators

Crack
Chloride content
Resistivity

study case 1

Knowledge on decision context

- Owner: Nantes Harbour (support the maintenance costs)
- Objective lifetime, 80 years service life
- Additional stakeholders: Local industrial, Local authorities, French state.

Asset information

- As built information
- Finite Element model
- Inspection records of an identical structure using NDT methods
- Cost of NDT measurments
- Monitoring data records
- Cost of SHM devices

Change system (repair, maintenance, strengthen and renew)

Prior/posterior knowledge

Models of Real World

Exposures/loads

Vulnerability / direct con.

Robustness / indirect con.

Observations

Indicators

True State of Nature

Exposures/loads

Vulnerability / direct con.

Robustness / indirect con.

Objectives

Minimize maintenance cost, avoid operating loss.

- Ensure strategic accesibility
- Perform a remediable action for each 'minor' limit state (1, 2, 3)
- Get 'as built' performance for retrofitting (change of use of a wharf)

Collect Information

- Material data
- Chloride, Resistivity, Potential , humidity, Temperature (1, 2)
- Fibers sensors (3)
- Strain gauges (4)

Optimization

Objective functions based on perfomance

Added value of limited lifetime sensors for maintenance optimization
Added value of sensors in limited area (spatial varaiability)

Perfomance

Serviceability

Decision context (infrastructure in Civil Engineering)

Usual quantification (VoI) based on total cost and preventive maintenance

Reference case (usual inspection practice) without SHM

Sub-study case 1

As-built mechanical behaviour for model updating and future retrofitting (change of use, new needs, …) / A= [SHM during construction; SHM after construction works]

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Sub-study case 2

Change of paradigm: from means-based contract towards performance based contract during works: concrete performance as built (mechanical, durability)

Reference case: means-based samples with poor conservation tested at 7 and 28 days (various temperature): *benchmark of practice/contracts ?*
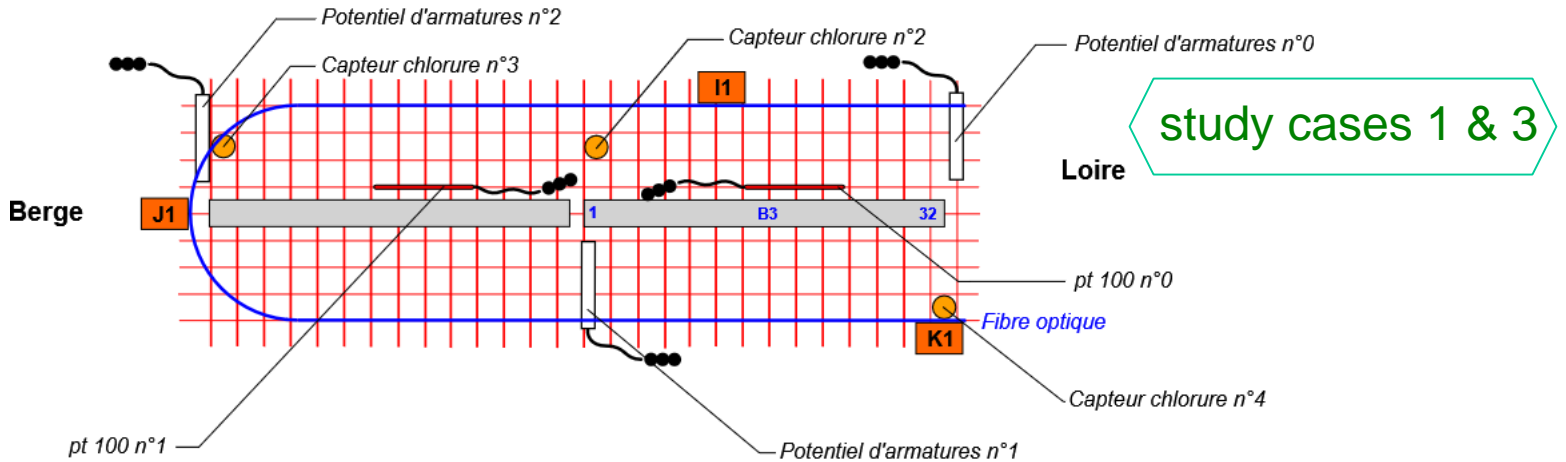
Sub-study case 3

Detection of initial cracking during construction for long term durability assessment

Sub-study case 4

Availability

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Corrosion monitoring :

- ➢ Temperature, RH%, **Resistivity, Armature potential, Chloride**, Porosity (laboratory test)
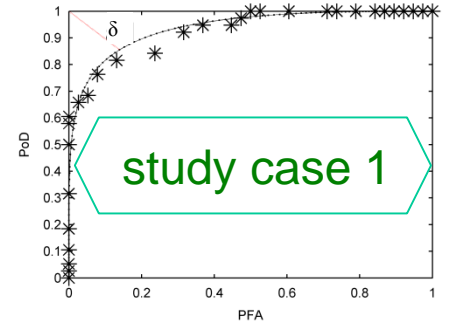- ➢ Possibility to perform accelerated tests in laboratory including the same instrumentation
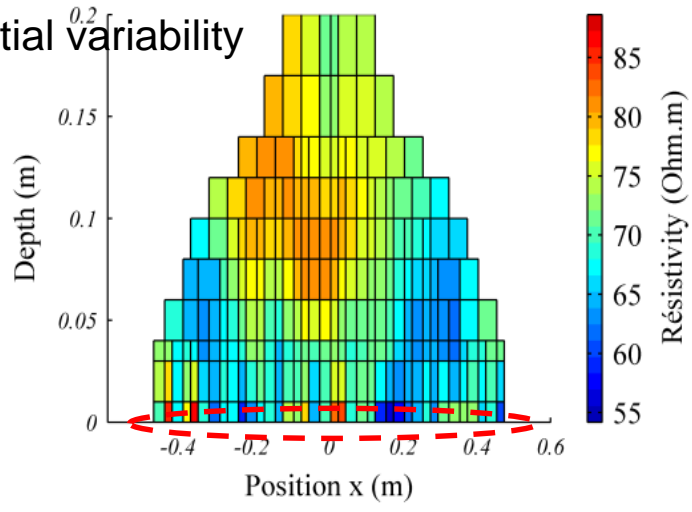
Sample of results :

➢ **Probability of Cl⁻ threshold detection:**

  ✓ Map of resistivity for a cross section

  ✓ Inversion analysis

  ✓ ROC curves

  ✓ Spatial variability
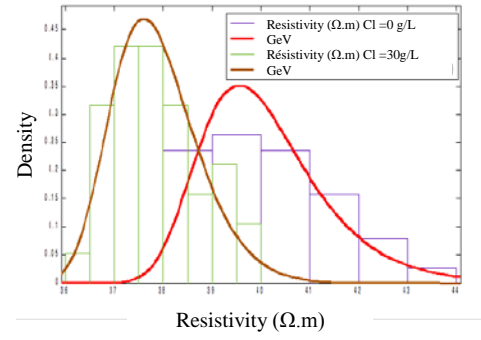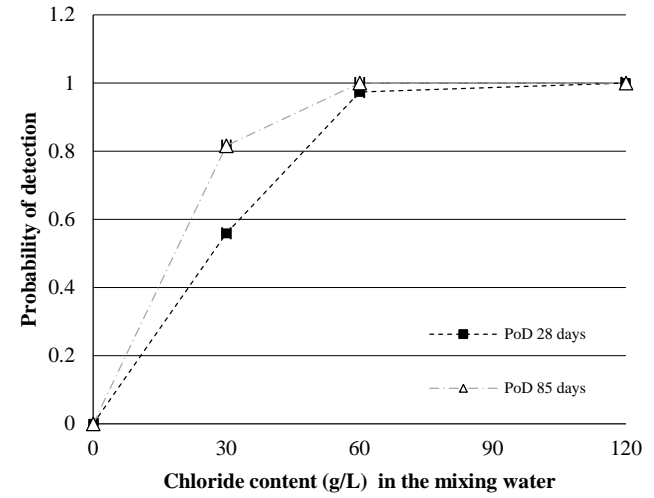

a) Experimental and fitted distributions of resistivity at 28 days

study case 1

b) ROC curves for the detection of 30g/l of NaCl at 28 days.

Data

Chloride threshold detection

[Lecieux]: Yann Lecieux, Franck Schoefs, Stéphanie Bonnet, Trystan Lecieux and Sergio Palma Lopes, Quantification and uncertainty analysis of a structural monitoring device: detection of chloride in concrete using DC electrical resistivity measurement, (2015) Nondestructive Testing and Evaluation

Decision context (infrastructure in Civil Engineering)

Usual quantification (VoI) based on total cost and preventive maintenance

Reference case (usual inspection practice) without SHM study case 1

SLS durability due to chloride ingress induced corrosion
Inspection
- SDTcl: Cores (large uncertainties – *Medachs EU project, Bonnet et al, 2017*)
- DTa: Autopsy (large uncertainties on corrosion initiation threshold – a_{crit} - *MAREO project*)
- Rws, Rds, Rfc, Repair efficiency (*MAREO project- Bastidas et al. 2015*)

Actions
A = [SDTcl; SDTcl + DTa; Rc]
A_{SHM} = [SHMd,cl; SHMcl; SHMd,cl + SHMcorr; + SHMcl accelerated in lab]
aopt = agmin E(U(ai, x),x) / U= E(Ctot) and sustainability *(Bastidas et al., 2015)*
Pf=Pcorr,ini *(no rebar replacement)*
x= [Cl(x_{rb}); a_{crit}]

Rws

Beam after hydrodemolition

Wet/(dry) shotcrete

Rfc

Formed concrete

Manual rena

SHMd,cl: distributed sensors
SHMcl: standard probe
SHMcorr: corrosion initiation

Fact Sheet WP3

Uncertain performance OK

Uncertain performance ?

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Decision context (infrastructure in Civil Engineering)

Usual quantification (VoI) based on total cost and preventive maintenance
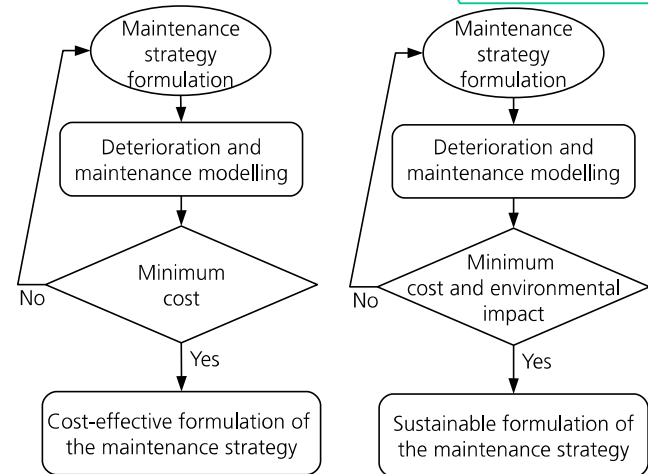
Reference case (usual inspection practice) without SHM

study case 1

SLS durability due to chloride induced corrosion
Inspection
- SDTcl: Cores (large uncertainties – *Medachs EU project, Bonnet et al, 2017)* nb of samples *(Tran et al., 2016)*
- DTa: Autopsy (large uncertainties on corrosion initiation threshold – a_{crit} - *MAREO project*)
- Rws, Rds, Rfc, Repair efficiency (*MAREO project- Bastidas et al. 2015*)

Fact Sheet WP3

Maintenance strategy formulation → Deterioration and maintenance modelling → Minimum cost — No / Yes → Cost-effective formulation of the maintenance strategy

Maintenance strategy formulation → Deterioration and maintenance modelling → Minimum cost and environmental impact — No / Yes → Sustainable formulation of the maintenance strategy

Actions
A = [SDTcl; SDTcl + DTa; Rc]
A_{SHM} = [SHMd,cl; SHMcl; SHMd,cl + SHMcorr]

aopt = agmin E(U(ai, x),x) / U= E(Ctot) and

sustainability *(Bastidas et al., 2015)*
x= [Cl(x_{rb}); a_{crit}]

Fact Sheet WP3

DECISION THEORY
VALUE OF STRUCTURAL HEALTH MONITORING

1: component approach
2: Structural approach (SV): UoN NTNU TCD

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Decision context (infrastructure in Civil Engineering)

Usual quantification (VoI) based on total cost and preventive maintenance

Reference case (usual inspection practice) without SHM   Sub-study case 1

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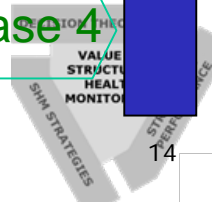
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Detection of initial cracking during construction for long term   Sub-study case 4
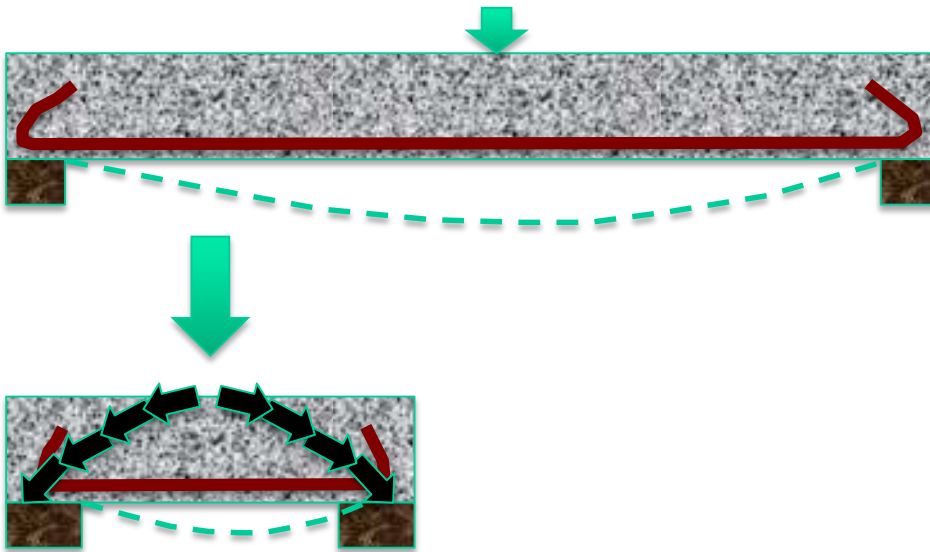
durability assessment

Availability

Optimize the maintenance and optimize the conception of structure

➢ **Monitoring of structural element behaviour** (optical fibber for strain and temperature measurement associated with optical strain gages for strain measurement)
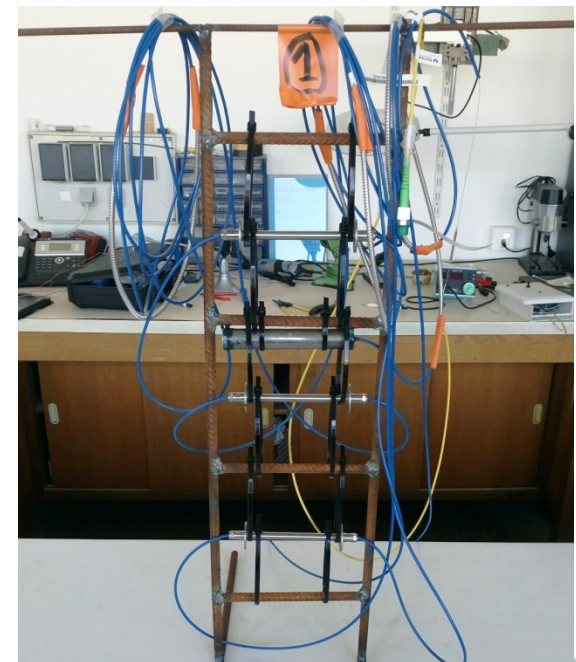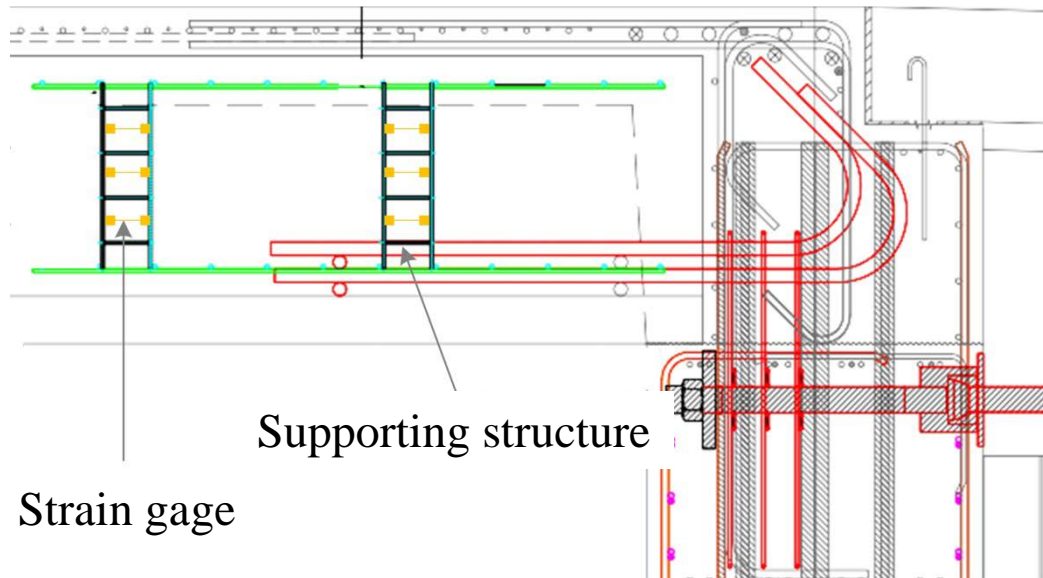
study case 2

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Strain measurement, mechanical behavior, crack detection

➢ Temperature, FBG for strain measurement, Rayleigh-Brillouin diffusion for strain measurement, mechanical tests performed on concrete specimen

study cases 2 & 3 & 4

Supporting structure

Strain gage

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Decision context (infrastructure in Civil Engineering)

As-built mechanical behaviour for model updating and future retrofitting
Reference case: NDT

study case 2

SLS
Retrofitting
- SDTc (cores): mechanical behavior
- NDTcorr and DTa autopsy: corrosion assessment with large uncertainties

SHM
- Sensors for behavior of beams
- Sensors for behavior of tie rods (Schoefs et al. 2011, 2013)

Data available:
Cost,
Corrosion assessment
SDT tests

SHM data for tie rods on two wharfs.

Actions
A = [SDTc; NDTcorr; NDTcorr + DTa; NDTcorr + Dta + SDTc]
A_{SHM} = [SHM_{FOS}; SHM_{Vw}]

aopt = agmin E(U(a_i, x),x) / U= E(Ctot) incl retrofitting cost

Review of sensors for tie-rods available

SHM_{FOS}: Fiber Optical Sensors
SHM_{vw}: Vibrating wire strain gauge

DECISION THEORY
VALUE OF STRUCTURAL HEALTH MONITORING
STRUCTURAL PERFORMANCE
SHM STRATEGIES

Decision context (infrastructure in Civil Engineering)

As-built mechanical behaviour for model updating and future retrofitting
Reference case: NDT

SLS
Retrofitting
- SDTc (cores): mechanical behavior
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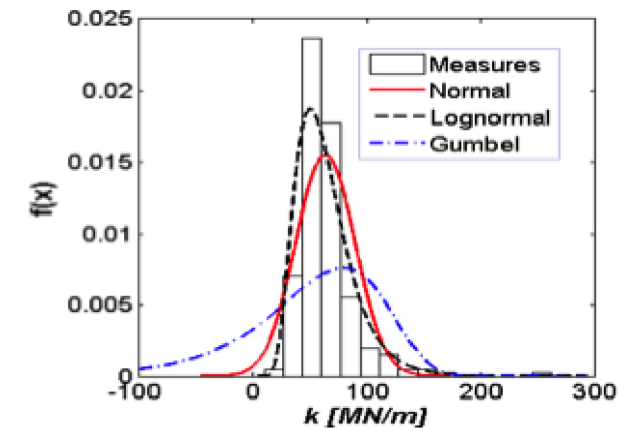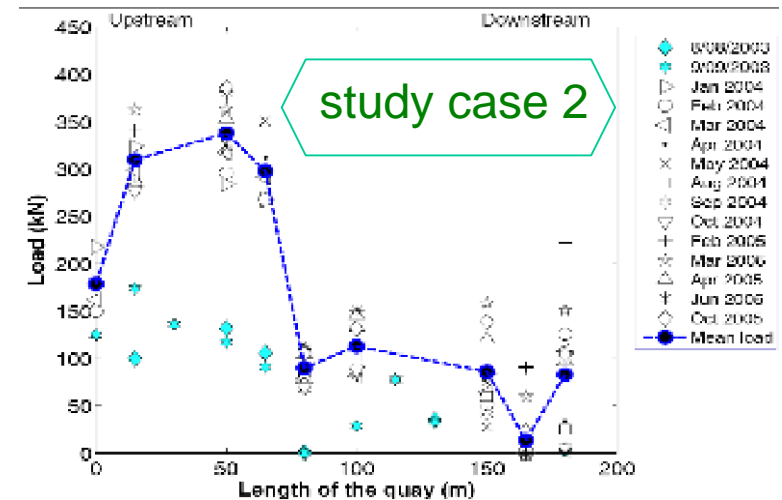
SHM
- Sensors for behavior of beams
- Sensors for behavior of tie rods (Schoefs et al. 2011, 2013)

Actions
A = [SDTc; NDTcorr; NDTcorr + DTa; NDTcorr + Dta + SDTc]
A_{SHM} = [SHM_{FOS}; SHM_{Vw}]

aopt = agmin E(U(ai, x),x) / U= E(Ctot) incl retrofitting cost

study case 2

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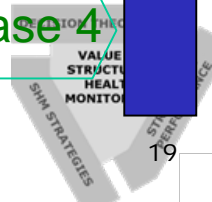
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Detection of initial cracking during construction for long term   〈 Sub-study case 4 〉

durability assessment

Availability

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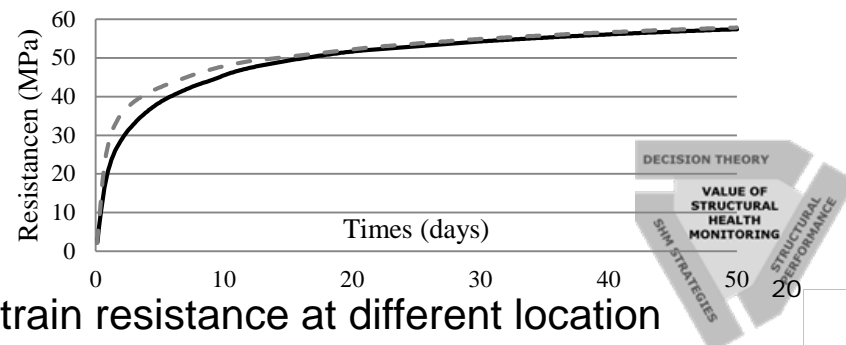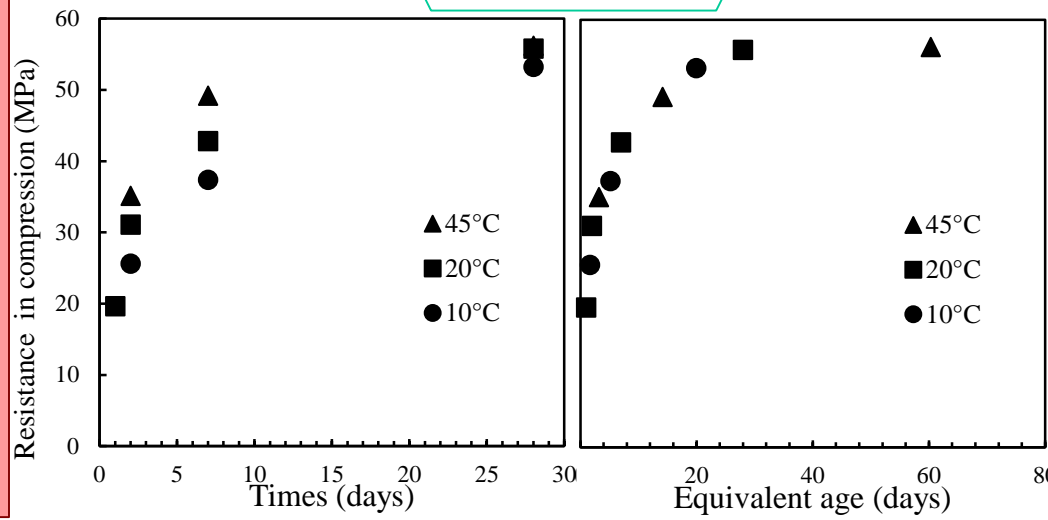mer et littoral
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Decision context (infrastructure in Civil Engineering)

Change of paradigm: from means-based contract towards performance based contract during works: concrete performance as built (mechanical, durability)

ULS
Checking during works
- Position of rebars
- Quality of concrete (Abrams cone slumping, DT_{ys} yield stress at 7, 28 days without temperature control 20°C)

SHM (mixted)
- Temperature
- DT_{ys} yield stress at 7, 28 days with temperature control 20°C

Actions
$A = [n \times DT_{ys}]$
$A_{SHM} = [SHM_T + n/3 \times DT_{ys}]$

aopt = agmin E(U(ai, x),x) / U= E(Ctot) retrofitting cost

study case 3

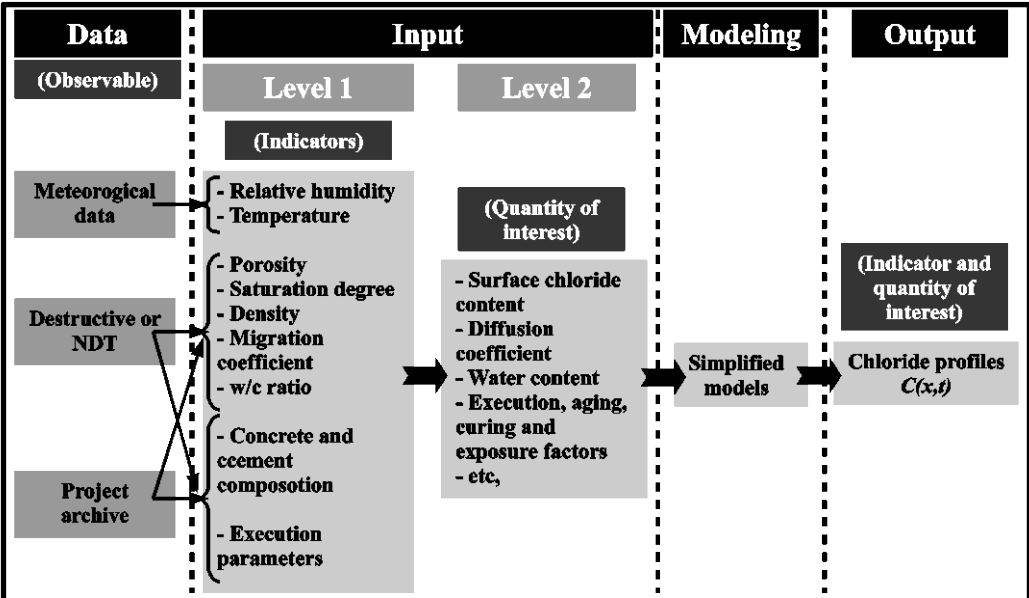In situ strain resistance at different location

DECISION THEORY

VALUE OF STRUCTURAL HEALTH MONITORING

SHM STRATEGIES

STRUCTURAL PERFORMANCE

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About the modelling of a virtual reality and model updating

Modelling uncertain reality: 1. with simplified models

Figure 1 General structure and required data for simplified chloride ingress models.

Parameters

1st Drawback: Correlation after calibration comes from the model itself (ex: Fick function)

Use in a probabilistic framework: to be avoided (model updating > bad prediction) (Evadeos project, PhD Decatoire)

2. with FE/DF models for simulation (complexity of updating: lot of correlated parameters) + Gama process for updating (El Hajj, 2016, SI3M project) with uncertain measurement (behaviour of sensor\chloride: Lecieux et al., 2016)

DECISION THEORY

Annex
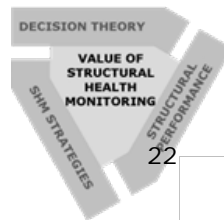
Contribution to COST action

Knowledge on decision context

- Decision maker ✓
- Time/space boundary conditions: exploitation conditions and predicted evolution of traffic level and type (retroffiting): ✓
- Budget constraints: annual available founds ✓
- Values/preferences: actual praticle with NDE and related costs of curative maintenance ✓
- Legal/regulatory boundary conditions: multiusages area ✗

Objectives

- Life-cycle optimal design of structure(s): **tie-rods** (retroffiting and better future design with a global and non-sequential modelling): ✓
- Cost optimal assets integrity management of existing structure(s): multi-sensor measurement of risk of corrosion **concrete beams** in partially satured environment: ✓
- Service life extension of existing structure(s): **short beams** (better knowledge of arch behavior: future proposal for JCSS/Eucrocodes): decrease steel/concrete ratio: ✗

Monitoring/inspection strategies (NDE are very expensive: access and conditions)

Value of the contribution of NDE: **on going study** ✓ (TC and DécofRé projects)

Spatial sensor placement optimisation: **on going study** (chlorides, resistvity, electrical potential) ✗

Knowledge on structure context

- Existing FEM model: ✓
- Existing stochastic modelling of chloride ingress in partially saturated concrete: environment: ✓
- Contribution of accelerated tests (added value): ✓

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Summary of knowledge