Politecnico di Torino

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Department of Structural, Geotechnical and Building Engineering

SECED 2023 Conference

14-15 September 2023
Cambridge, UK

Influence of scour of foundations on the seismic performance of bridges

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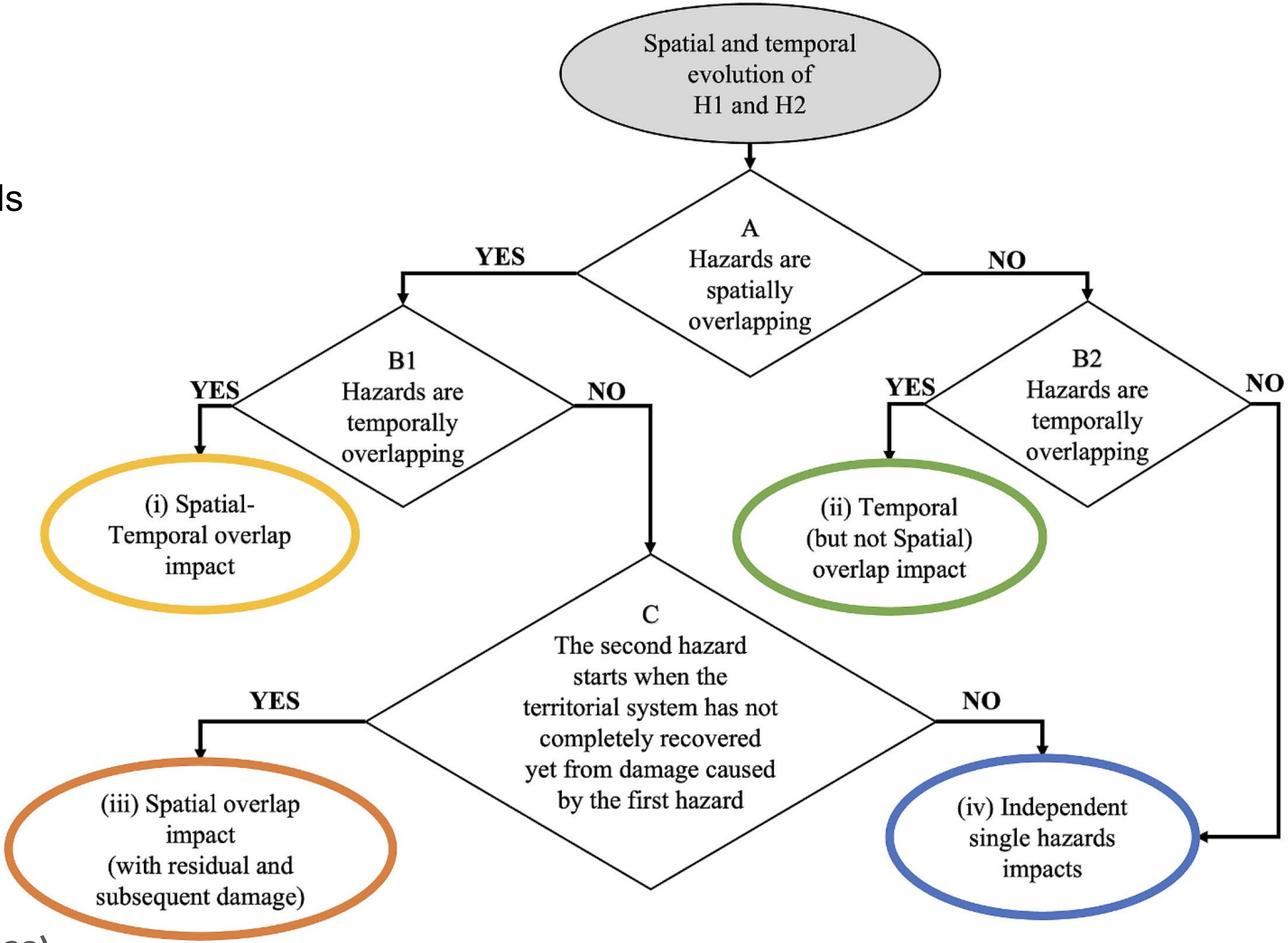
Outline

- Introduction & Motivation
- Simplified assessments of seismic behaviour of scoured bridge piers
- Advanced modelling of the foundation performance
  - Physical modelling
  - Calibration & Validation
  - Numerical modelling
- Future developments
  - Numerical simulation of the cyclic and dynamic response
  - In situ testing: dynamic characterization of scoured piers
  - ERIES SCOUR & SHAKE project
- Final Remarks

Introduction & Motivation

Multi-hazard analyses

Combined risk associated to the occurrence of two or more hazards which concurrently harm a given structure or system



e.g. damage scenario from an earthquake shock that weakens the levee system, and then combined with intense rain results in a levee collapse and flood

De Angeli et al. (2023)

Basic concepts

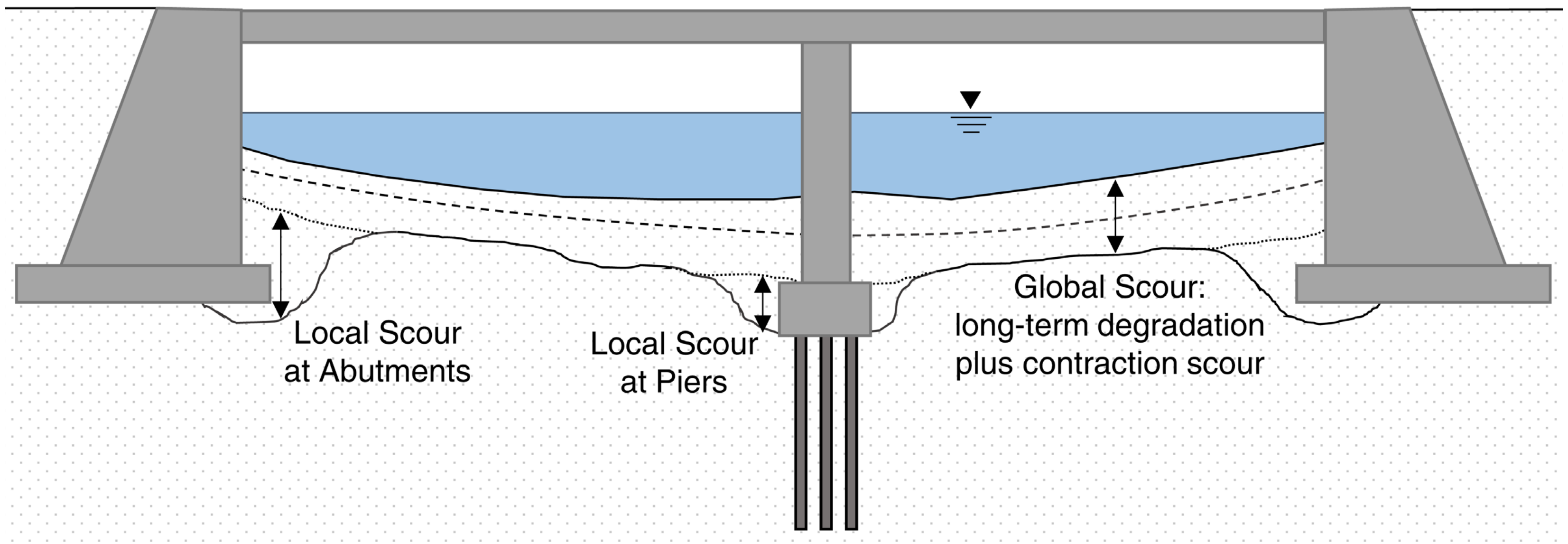
Bridge scour is the result of the **erosive action of flowing water**, which excavates and carries away material from the riverbed.

The total scour at bridge crossings is usually broken down into three components:

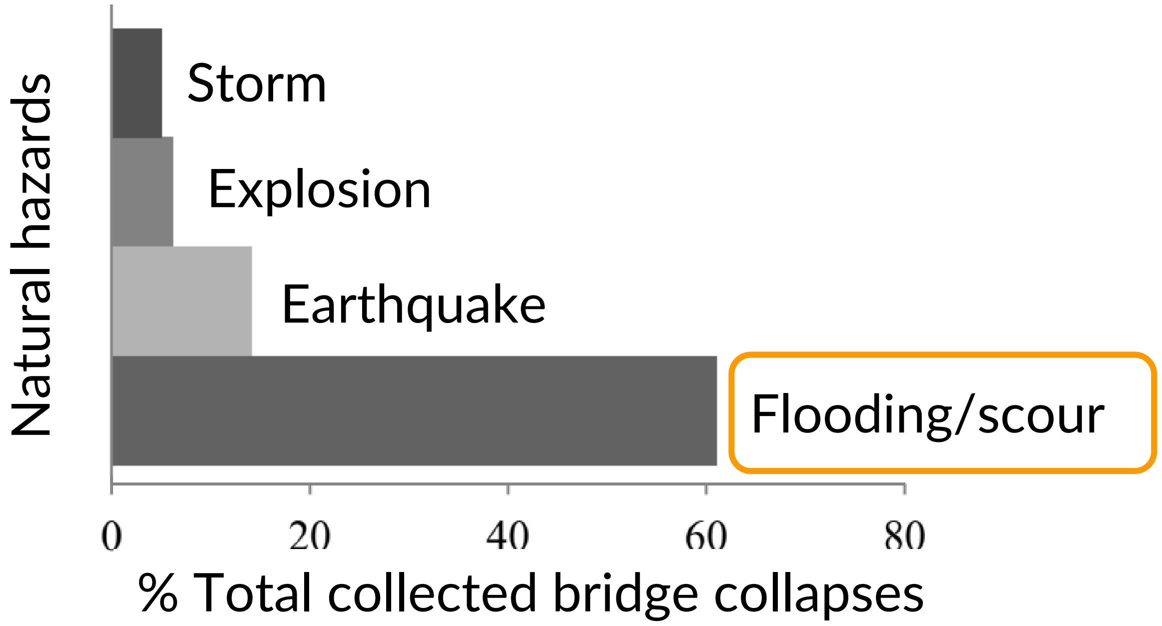
- Long-term degradation
- Contraction scour
- Local scour

→ *Uniform lowering of the riverbed: general scour* (Long-term degradation, Contraction scour)

→ *Localized erosion around bridge piers* (Local scour)



Relevance of foundation scour



IMHOF, 2004

- One main cause of bridge collapse worldwide
- **Dramatic consequences** in terms of fatalities, economic effort and disruption of the infrastructure network
- **Difficult detection** and **limited financial resources available** hinder immediate bridge retrofit interventions

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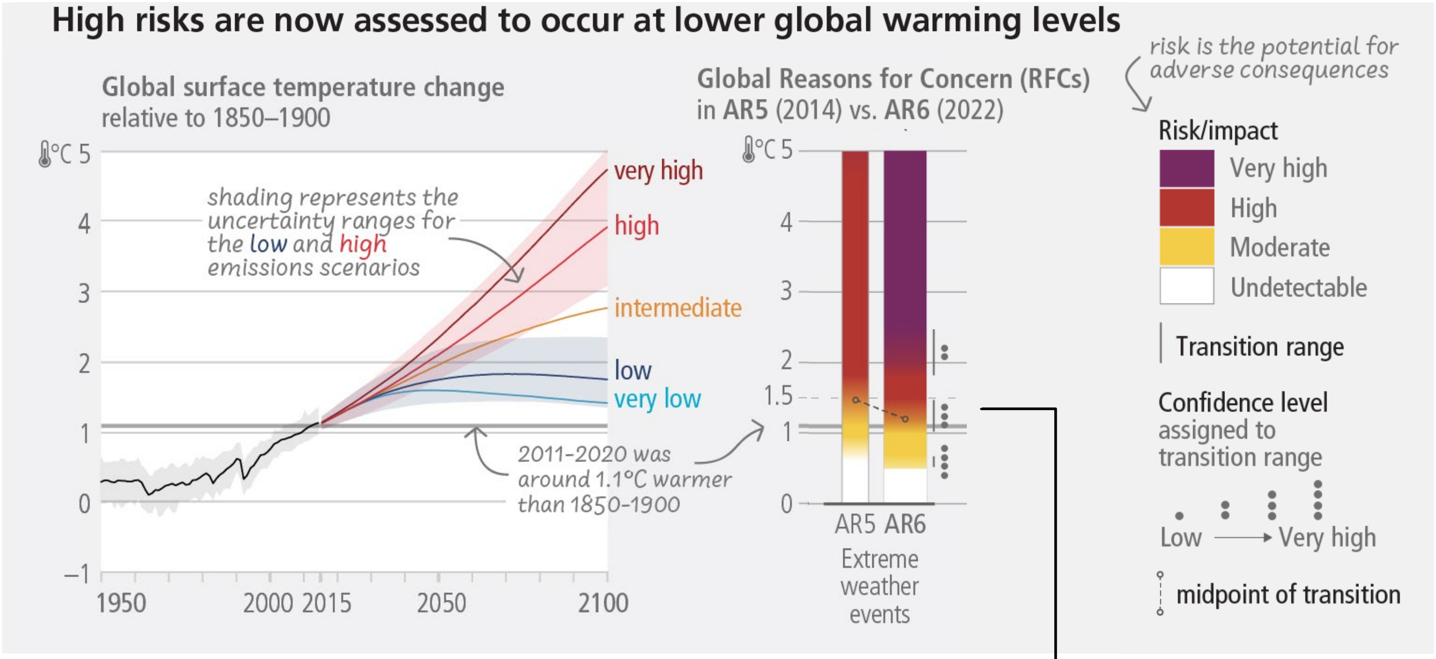
Detrimental on the seismic performance and on the long-term serviceability

Relevance of foundation scour



IPCC (2023)

The threshold moderate → high risk has shifted at lower warming levels

Summary of the IPCC report (2023)

- Temperature rise due to Climate Change
- High risk of extreme events, even at lower global warming scenarios

More frequent scour phenomena

SoA on seismic behaviour of scoured bridges

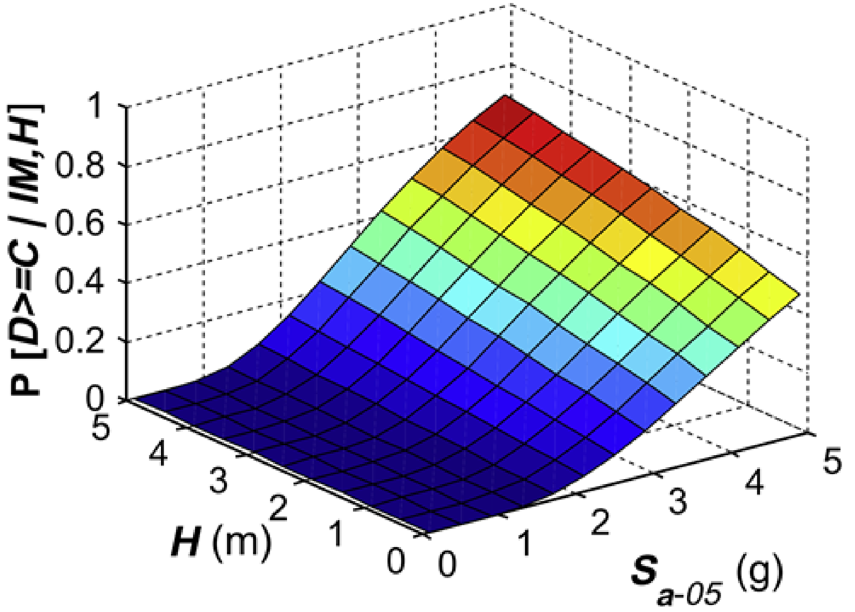
1. Predict of the expected scour depth for a given hydraulic scenario:

(i) *empirical methods* (ii) *numerical methods* (iii) *data-driven methods*

Monitor the evolution of the actual scour depth:

(i) *traditional techniques* (ii) *vibration-based techniques*

2. Evaluate the impact of foundation scour on the seismic performance of the structure



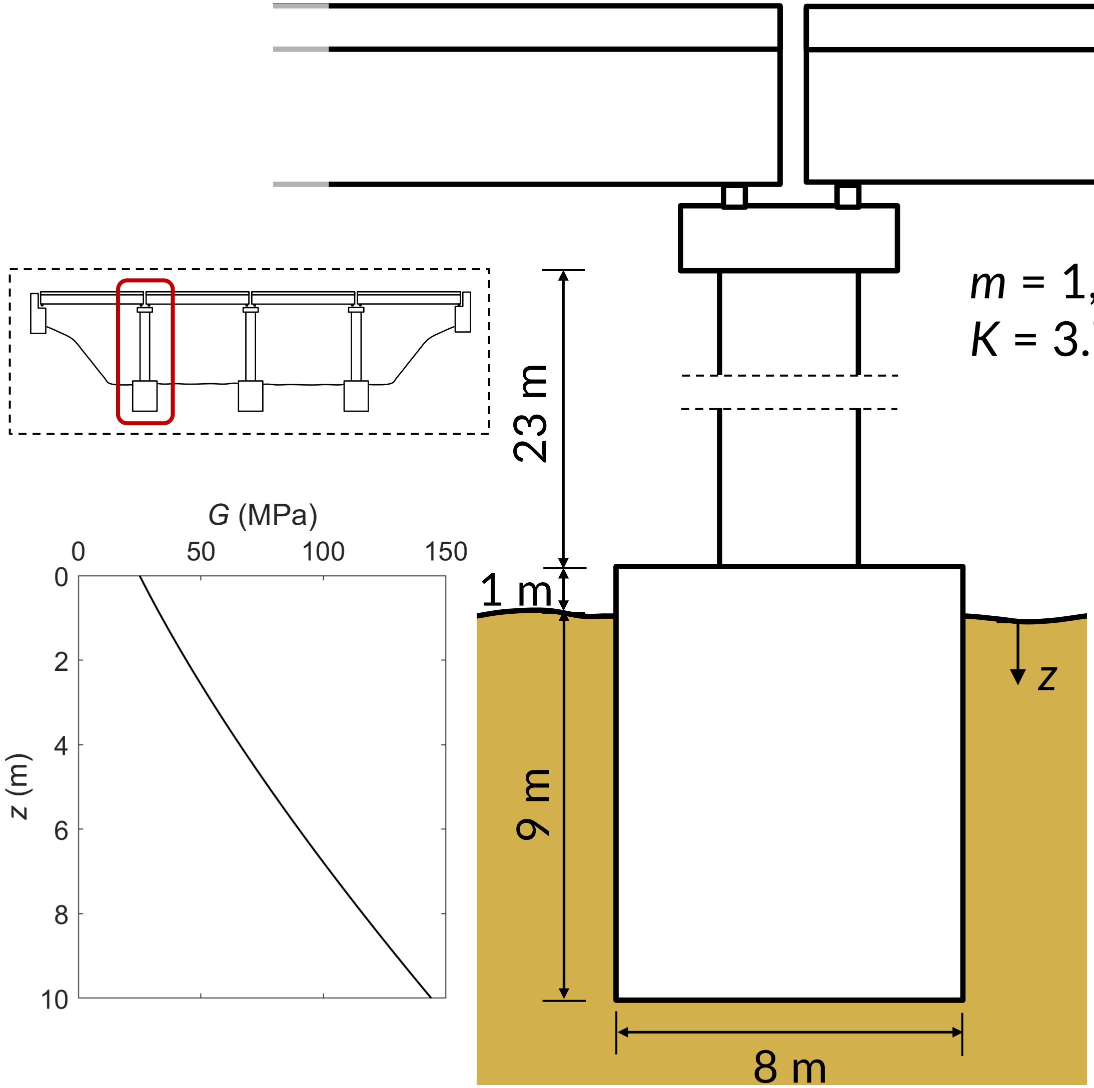
FRAGILITY SURFACE OF A SHORT-SPAN BRIDGE (WANG ET AL., 2014)

The different aspects of the problem are investigated independently:

- **no connection between the hydraulic phenomenon and its mechanical consequences**
- **SSI phenomena accounted through (over)simplified approaches**

Simplified assessments of seismic behaviour of scoured bridge piers

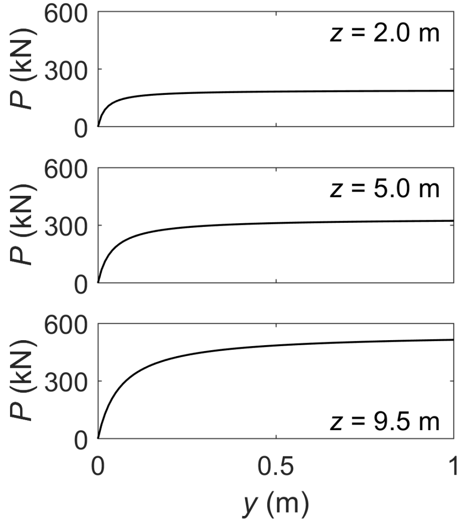
Case study



Target: circular, full RC pier founded on a cylindrical caisson

Superstructure: deck composed by simply supported, isostatic, RC beams

→ *Pier modeled as a SDOF system*



Soil: medium-loose homogeneous sand, characterized in terms of:

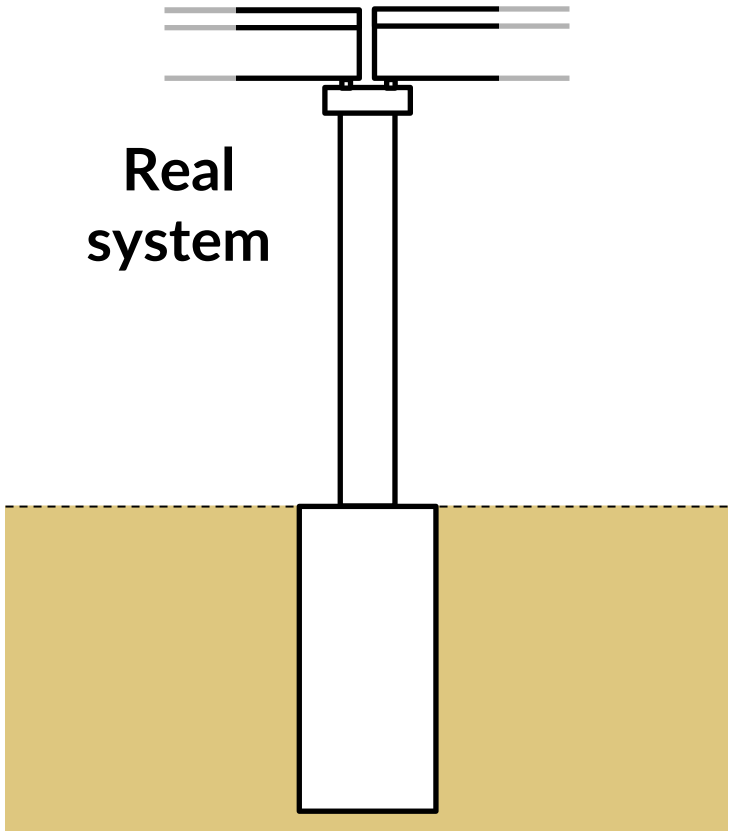
- *G*(*z*) profile (hyperbolic type)
- unit load transfer curves (*p*-*y* curves)

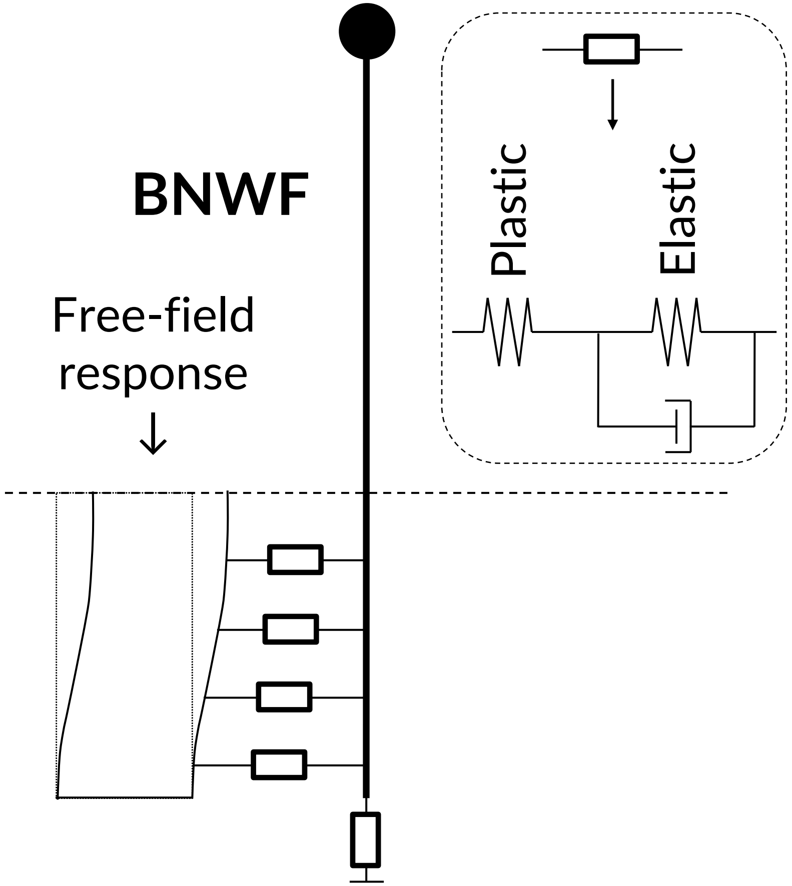
Conventional modeling schemes

Schematization of soil-structure interaction (SSI)

↓

Nonlinear Winkler Foundation (BNWF) model





«Elastic» part = linear spring + damper → elastic soil response + radiation damping

«Plastic» part → Soil nonlinear response (*p-y curves*)

Advantages:

- ✓ Recommended for short piers on deformable soils
- ✓ Insight on the foundation response
- ✓ Suitable to model scour

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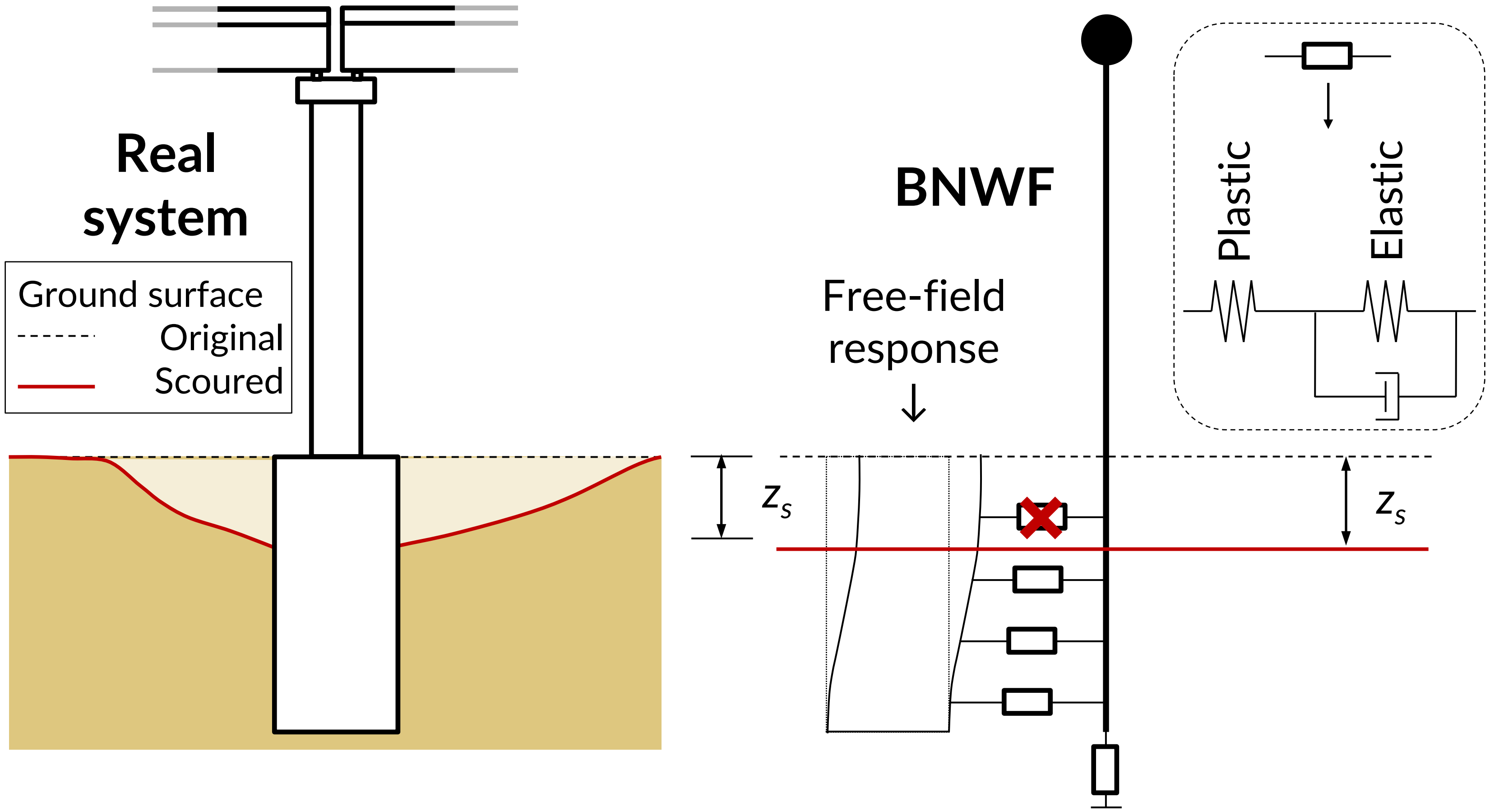

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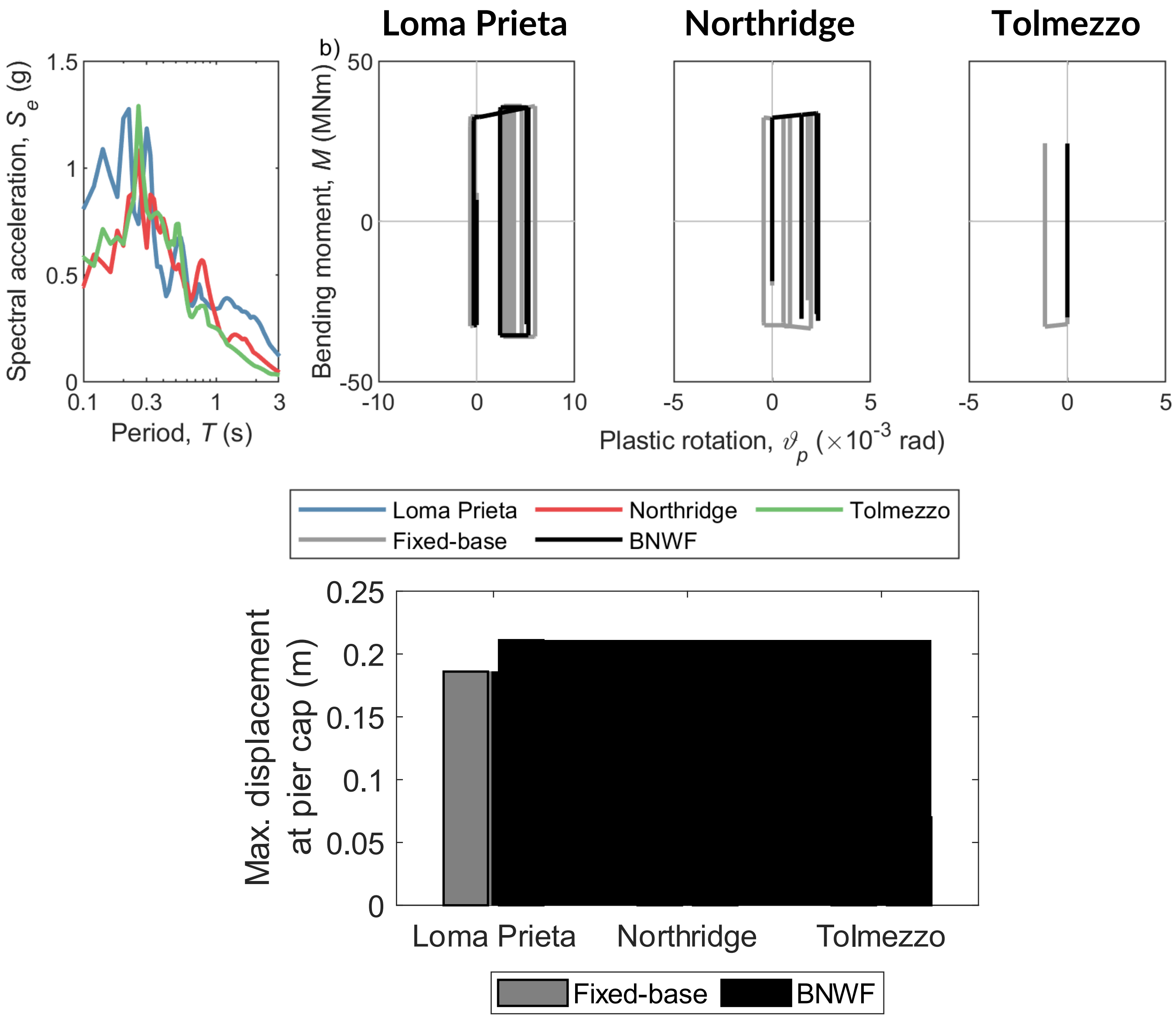


Influence of soil structure interaction on the seismic response:

Fixed-base scheme → BNWF

- Reduction in maximum plastic rotation in the structure
- Increase of displacement magnitude

↓

✓ **Reduction of structural demand**

✓ Fixed-base scheme underestimates displacement, with potential **compatibility problems with deck and supports**

Seismic performance of scoured piers

Scour influence: 5 uniform scour scenarios, with scour depth ranging from 1 m to 5 m

Seismic performance: *fragility curves* referred to pier damage

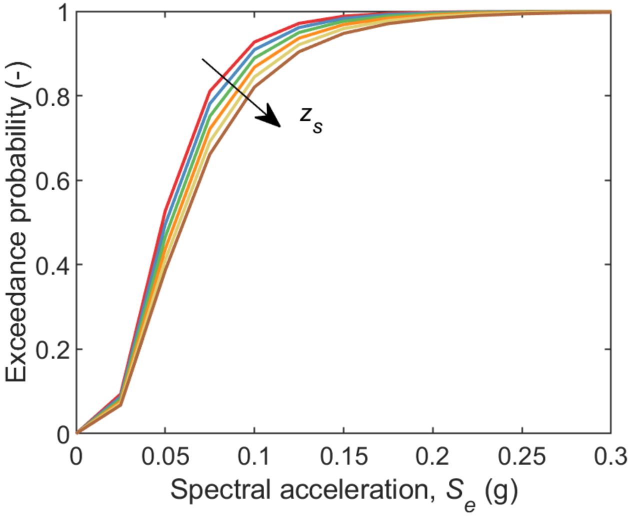
- **Damage parameter** = displacement ductility $$\mu_d = \frac{u_{max,pier}}{u_{y,pier}}$$ $u_{max,pier}$ → *Max. pier relative displacement*; $u_{y,pier}$ → *Pier relative displacement at yielding*

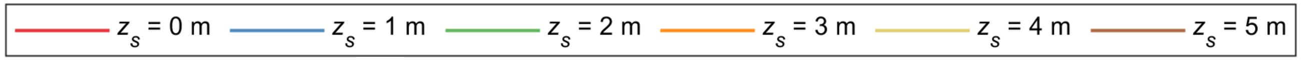
- **Seismic demand** = spectral acceleration at pier natural period of pier (close to 2 s – value representative of considered scour scenarios)

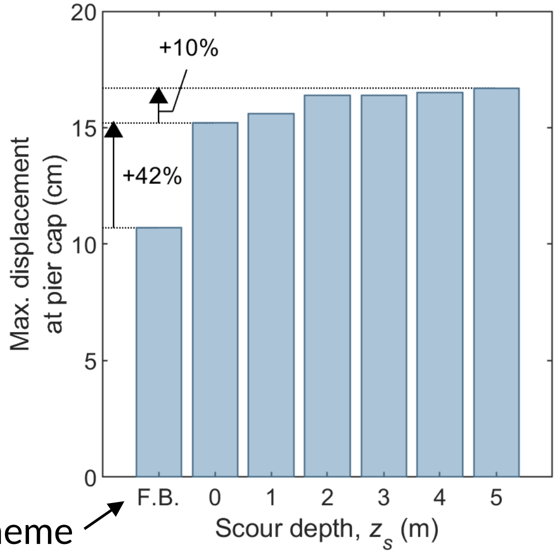
- **Analyses**: different ground motion scenarios with variable seismic action intensity were considered, to allow effective exploration of different damage scenarios → 252 nonlinear simulations

Seismic performance of scoured piers

Fragility curves: Moderate damage state





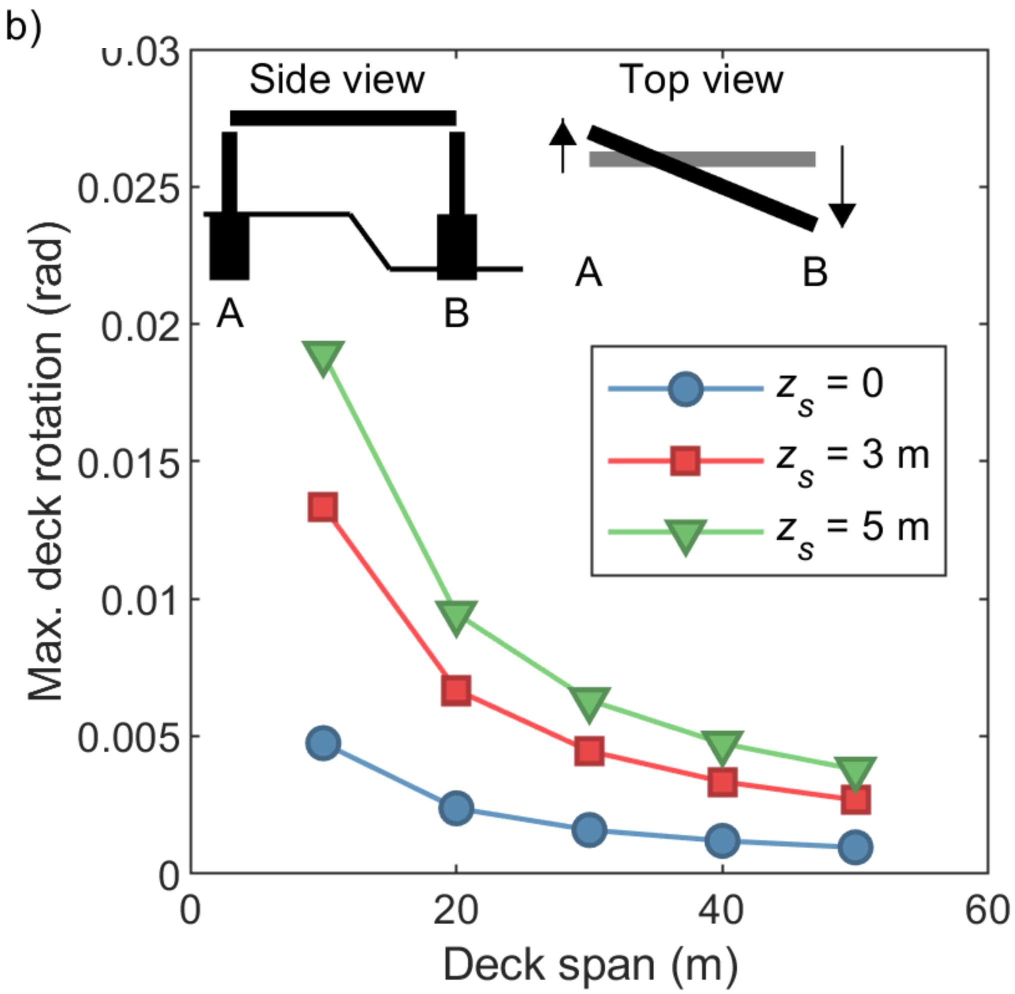


Fixed base scheme

- **Fragility curves**: Scour depth z_s > → Reduction of expected damage level at fixed seismic demand
- **Reason**: the increased deformability of the foundation system mitigates the entity of the seismic action carried by the structure
- However, there is a significant **increase of the total displacement** of the system due to the large rotations on the foundation (effect of soil deformability + scour).

Seismic performance of scoured piers

Hp: pier A unscoured, pier B scoured



Role of scouring in multi-span bridges

- In multi-span bridges, different piers can face various scouring conditions → motion variability between subsequent piers.
- This induces a **significant rotation of the deck** in the horizontal plane, especially at **span = 20-30 m** - usual span for simply supported decks.

Accounting for SSI and scour allows:

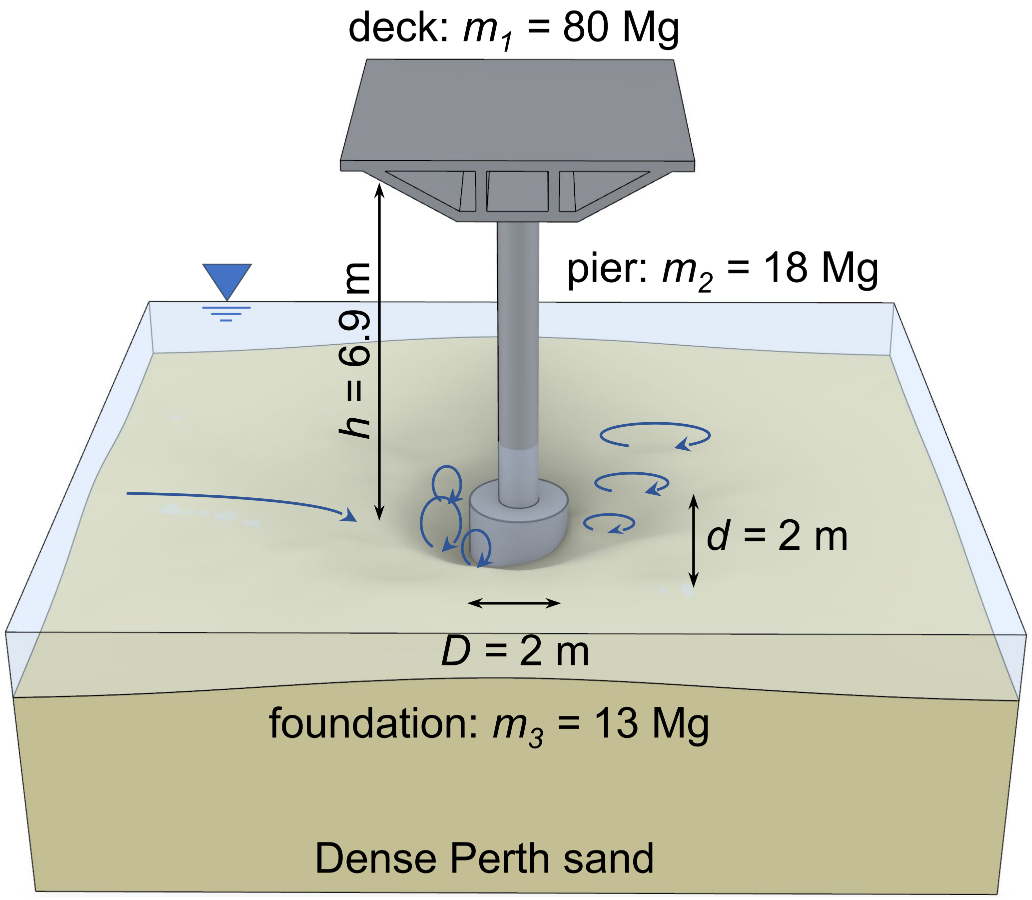
✓ **Reduction of structural demand**

✓ Reliable prediction of increased displacements and deck rotation → avoid **compatibility issues on the bearing devices** or even the **loss of support**.

Note: for a continuos deck (hyperstatic structure) the structural demand may instead be significantly increased

Advanced modelling of the foundation performance

Physical modelling: problem definition

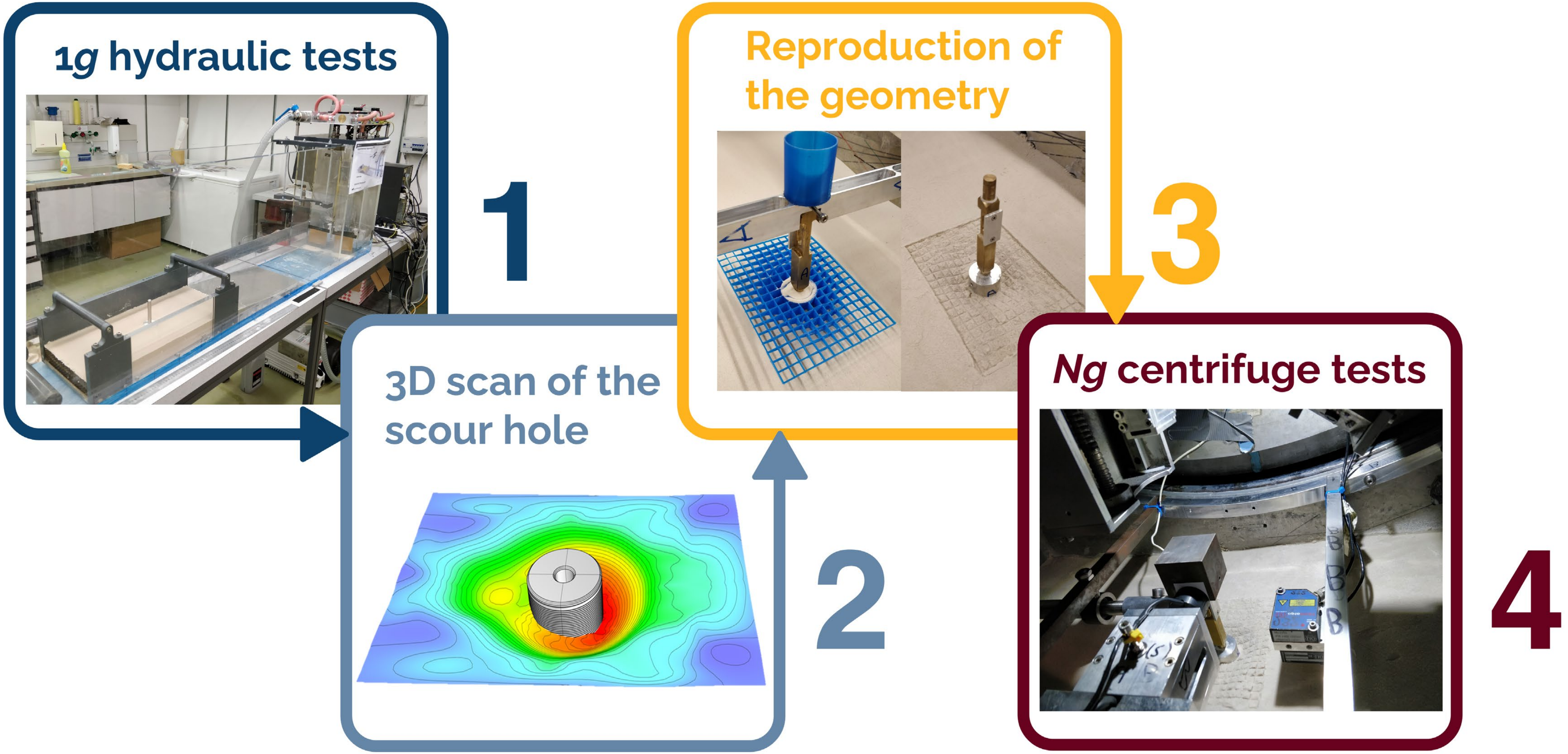


CIANCIMINO ET AL. (2022, A)

- **Slender prototype bridge pier** supported on a **cylindrical caisson** on a layer of **dense sand**
- Deck represented by a concentrated mass defined to achieve a $FS_V = 8$ (**moderately loaded structure**)
- **Practically rigid** bridge pier to focus on the foundation response

ETH zürich

Methodology: decoupled hybrid approach



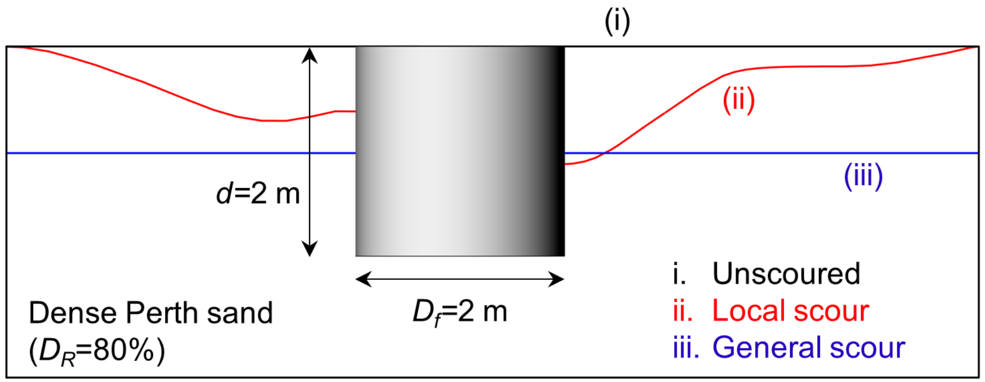
Geotechnical centrifuge modelling

The performance of the structure were analyzed considering three loading scenarios:

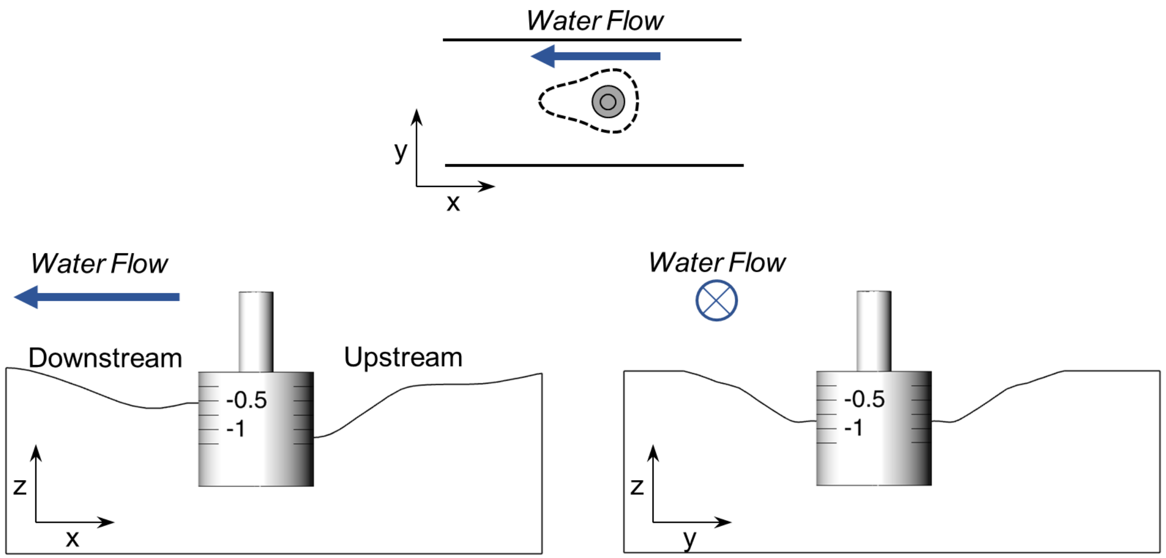
- **Vertical loading**
- **Lateral pushover loading**
- Slow-cyclic lateral loading

and three hydraulic scenarios:

- **Unscoured**
- **General scour**
- **Local scour**

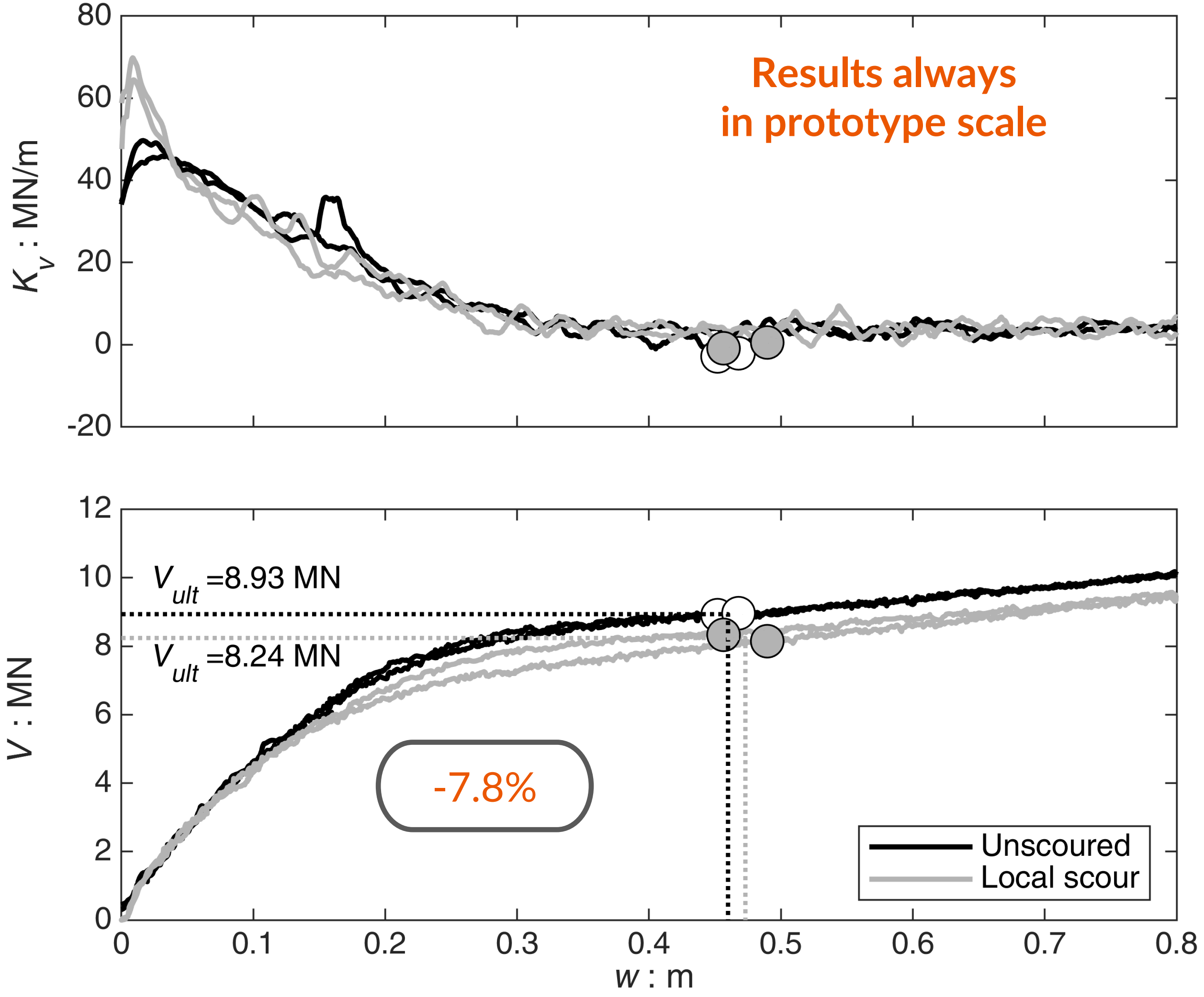


HYDRAULIC SCENARIOS



CROSS-SECTIONS OF THE SCOUR HOLE

Vertical tests

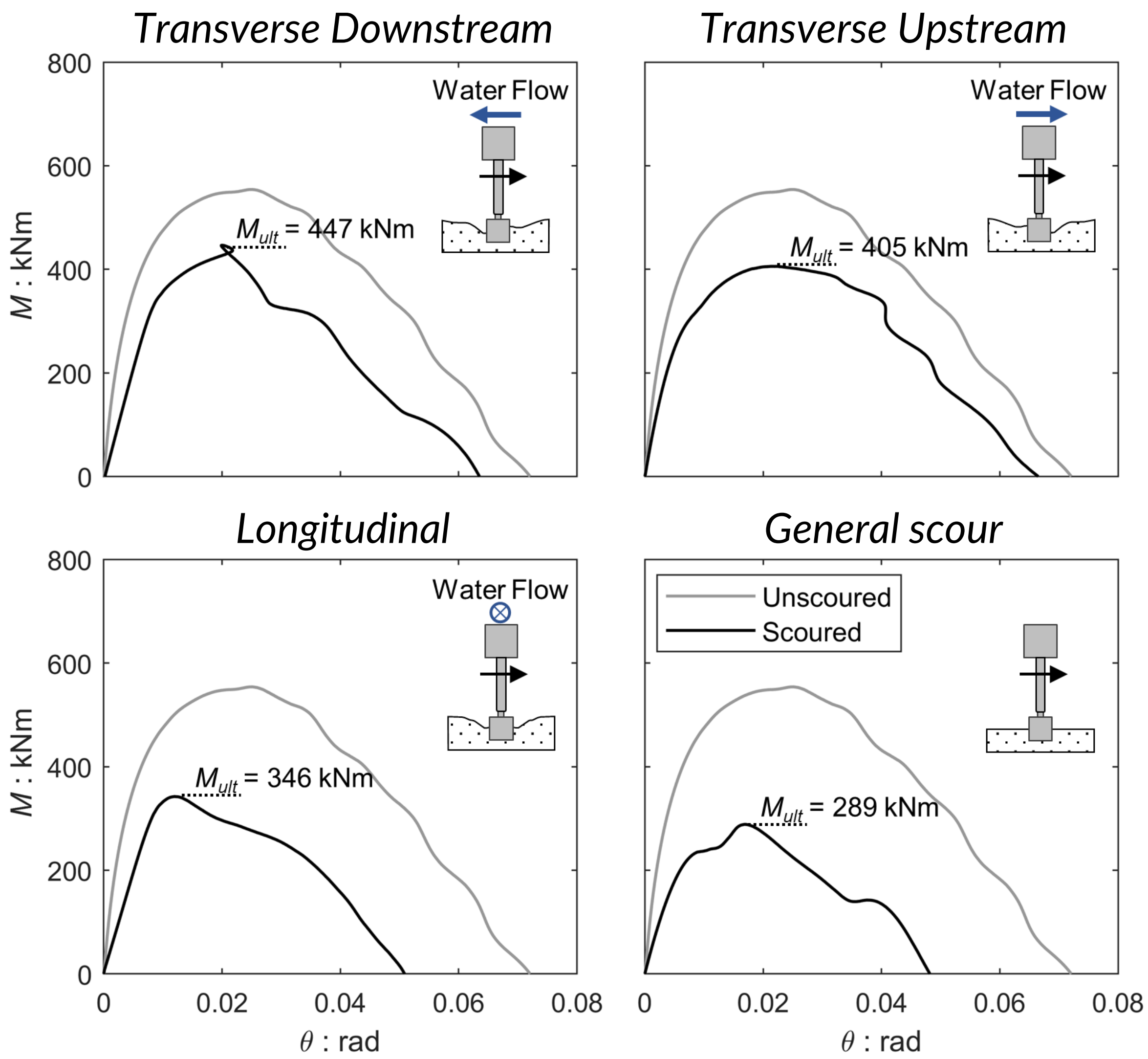


A **local shear mechanism** is observed: The curves exhibit an almost linear **hardening response**

The **vertical bearing capacity** is defined as the load at the initiation of the hardening regime

Local scour produces a limited **reduction of V_{ult}** : the size of the local scour hole does not intersect the failure surface

Pushover curves



Foundation scour always leads to a **substantial decrease of M_{ult} and θ_{ult}**

Local scour has a strong impact on the lateral response of the structure, with M_{ult} **reduced by 19% to 38%** depending on the **direction of loading**

General scour has a more pronounced effect, leading to a **reduction of 48%**

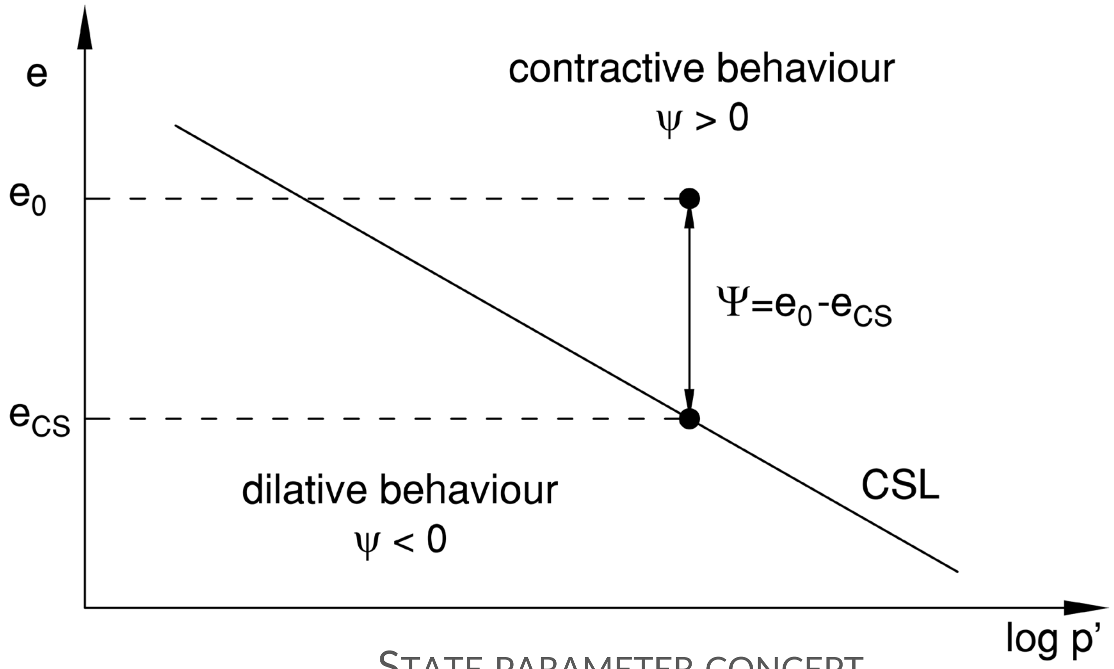
The SevernTrent sand model

The constitutive model is based on the framework of the **classical kinematic-hardening plasticity** and it adopts a **hyperelastic formulation** and a **hyperbolic degradation of plastic stiffness**.

The model accounts for both pressure and density dependency through the **state parameter ψ** (Been and Jefferies, 1985):

$$\Psi = v_0 - v_\lambda + \lambda \ln p'$$

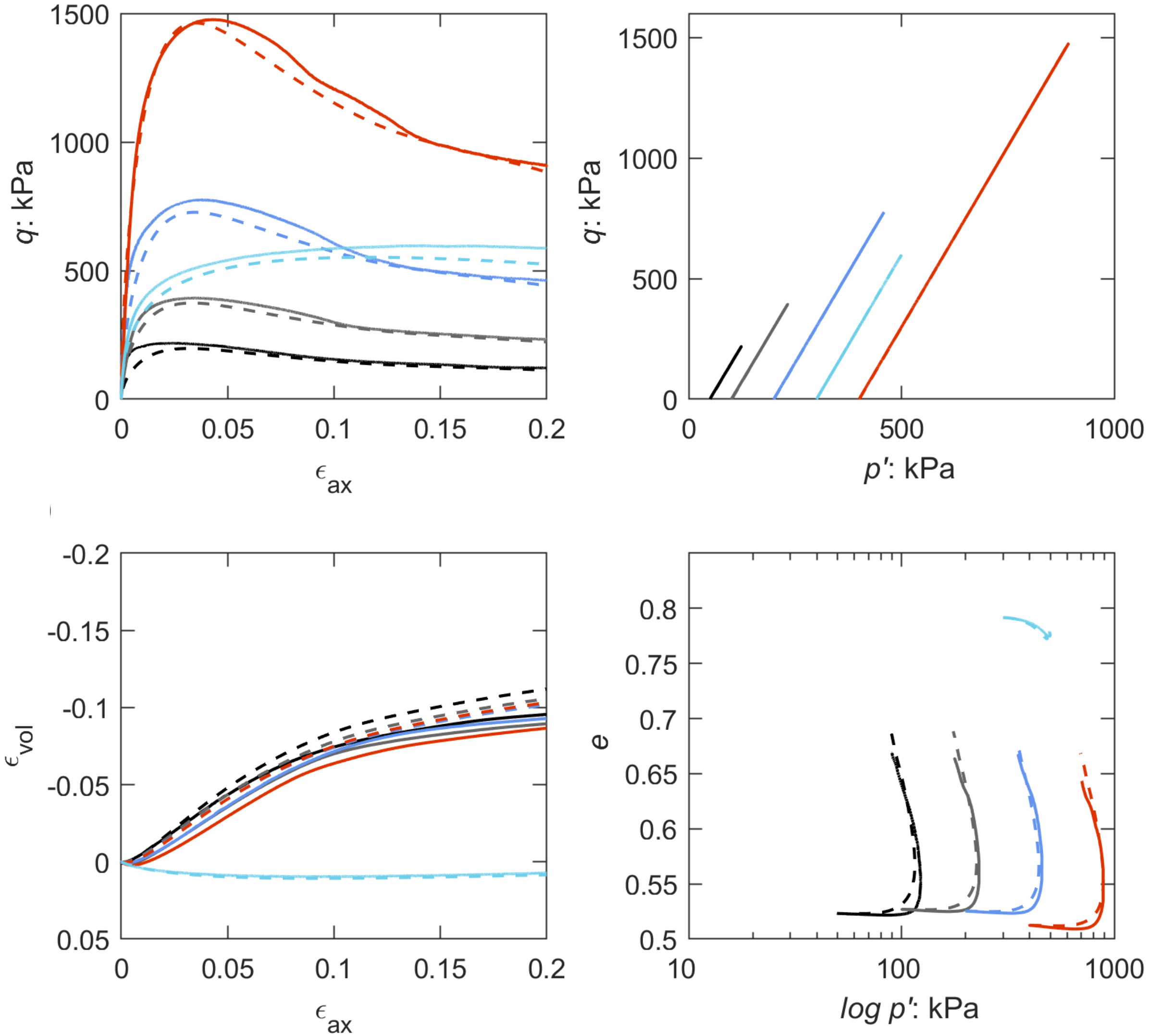
GAJO & MUIR WOOD (1999), GAJO (2010)



STATE PARAMETER CONCEPT (AFTER BEEN AND JEFFERIES, 1985)

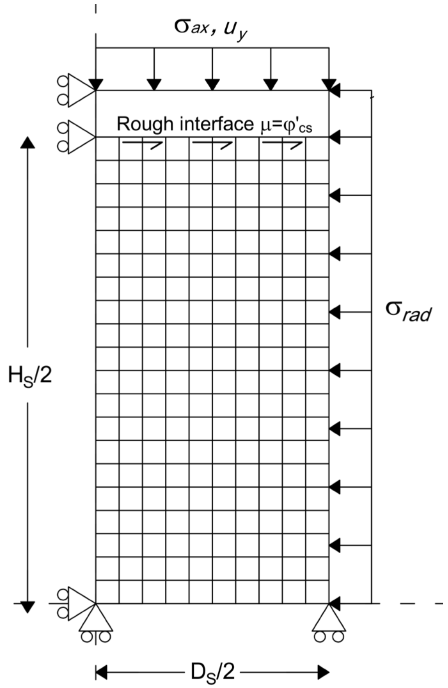
Calibration of the constitutive model

v_λ = 1.89
λ = 0.019
φ'_{CS} = 30°
G = G_0
ν = 0.2
B_0 = I
m = 0.8
R = 0.01
k = 2.6
A = 0.65
k_d = 1.8
B = 0.007
α = 1.2



EXPERIMENTAL DATA (SOLID LINES) AND SAMPLE BEHAVIOUR (DASHED LINES)

Sample behaviour



CIANCIMINO ET AL. (2022, B)

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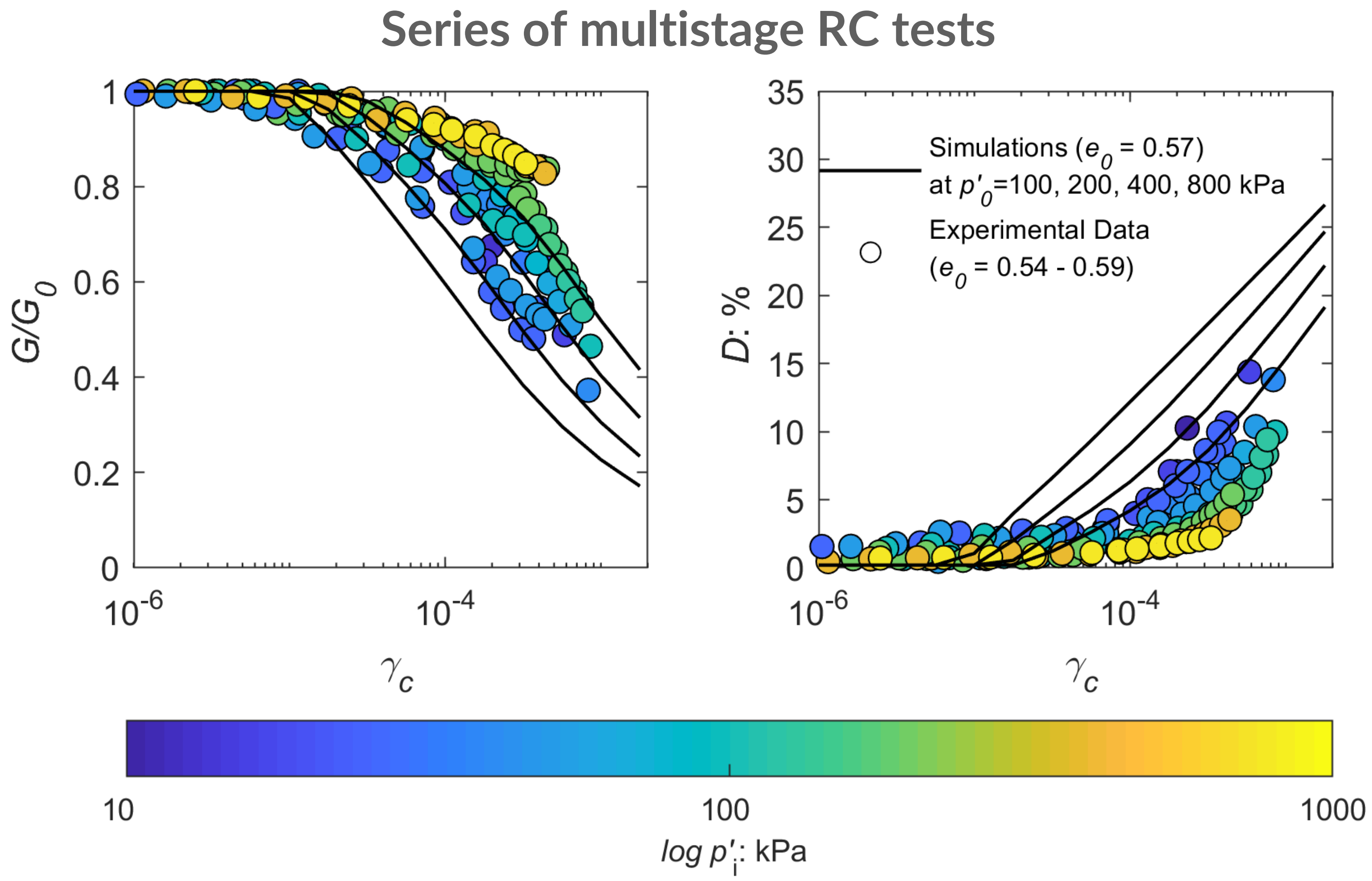
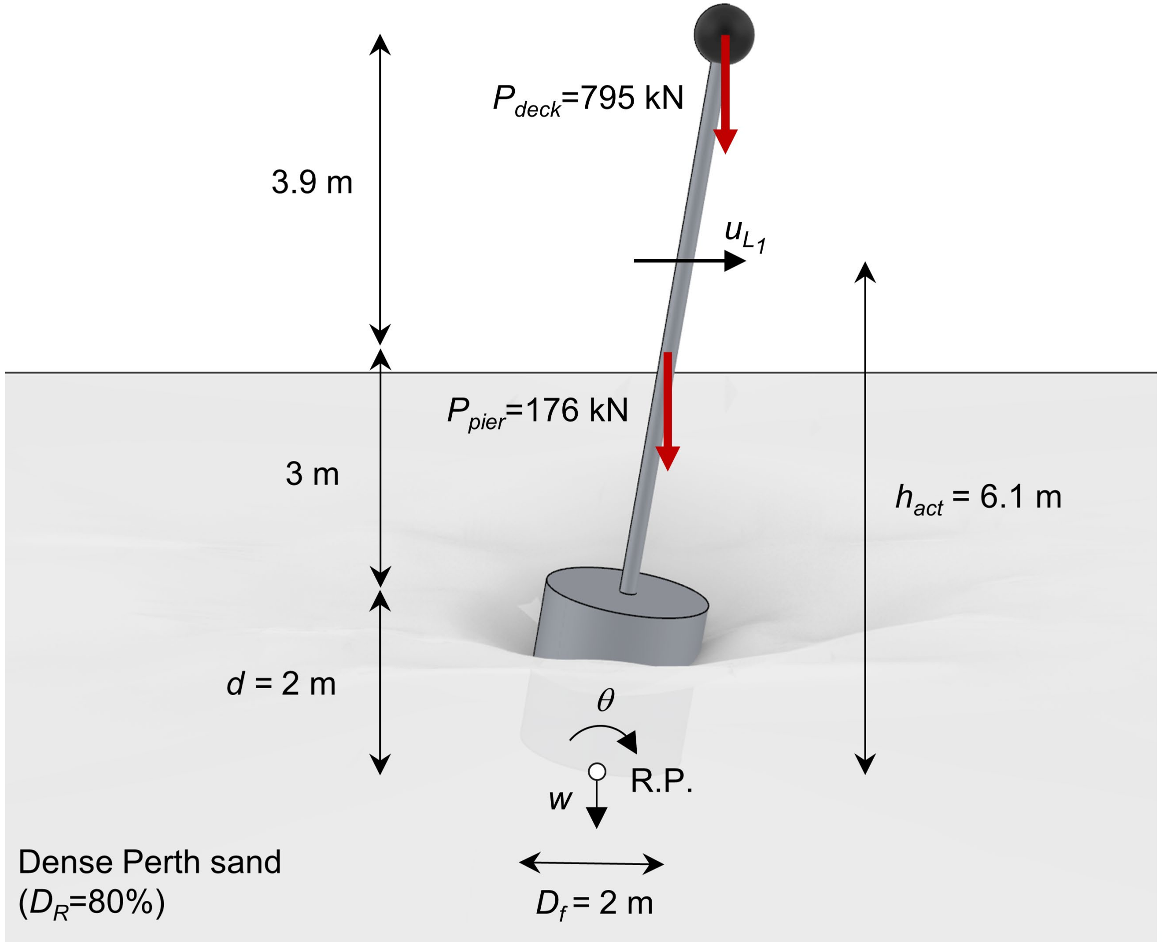
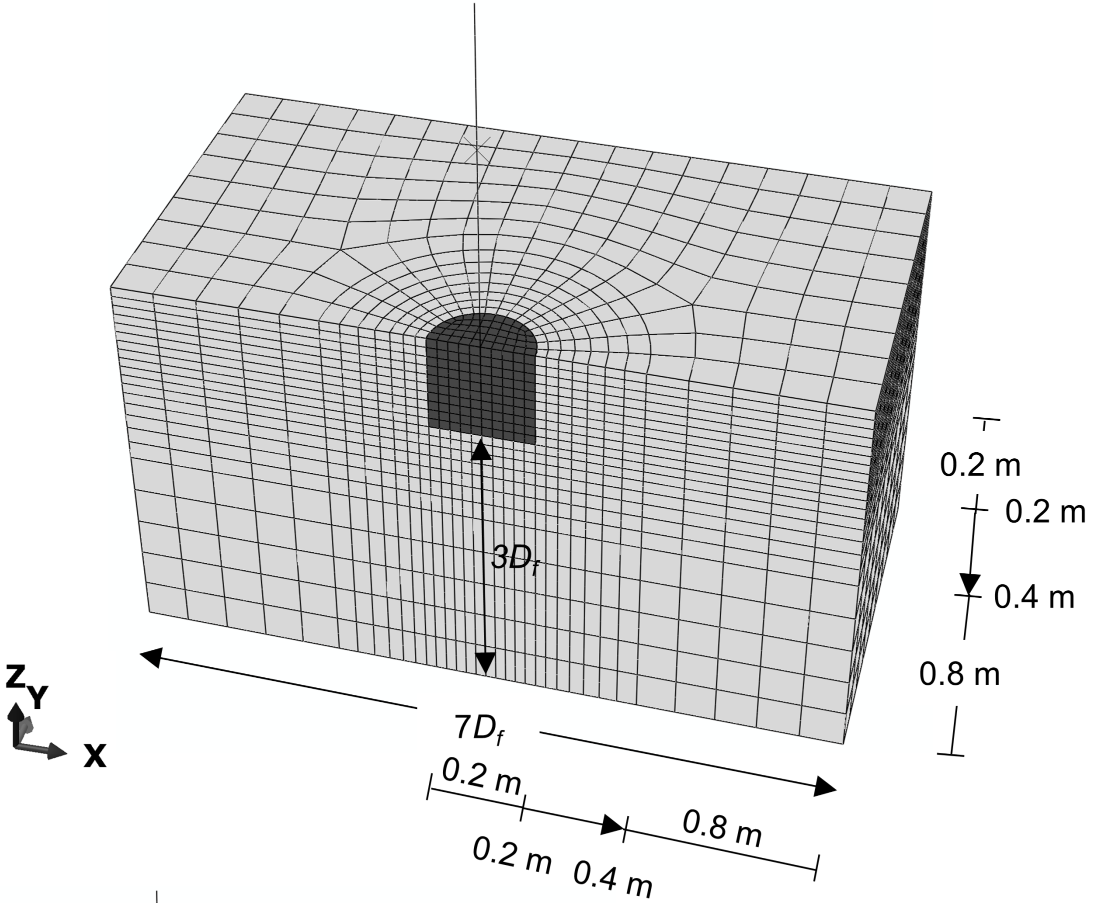


CIANCIMINO ET AL. (2022, B)

Validation against centrifuge tests



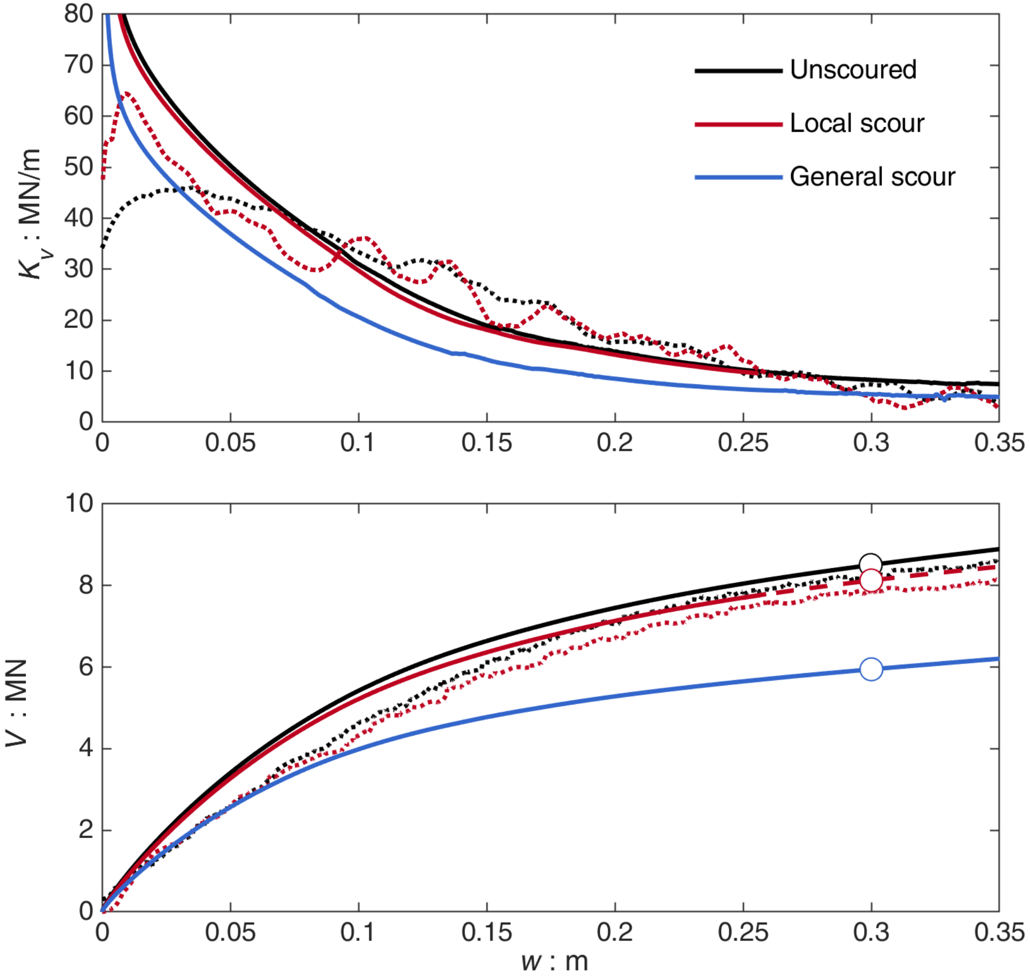
SDOF BRIDGE PIER ADOPTED TO MODEL THE LATERAL TESTS



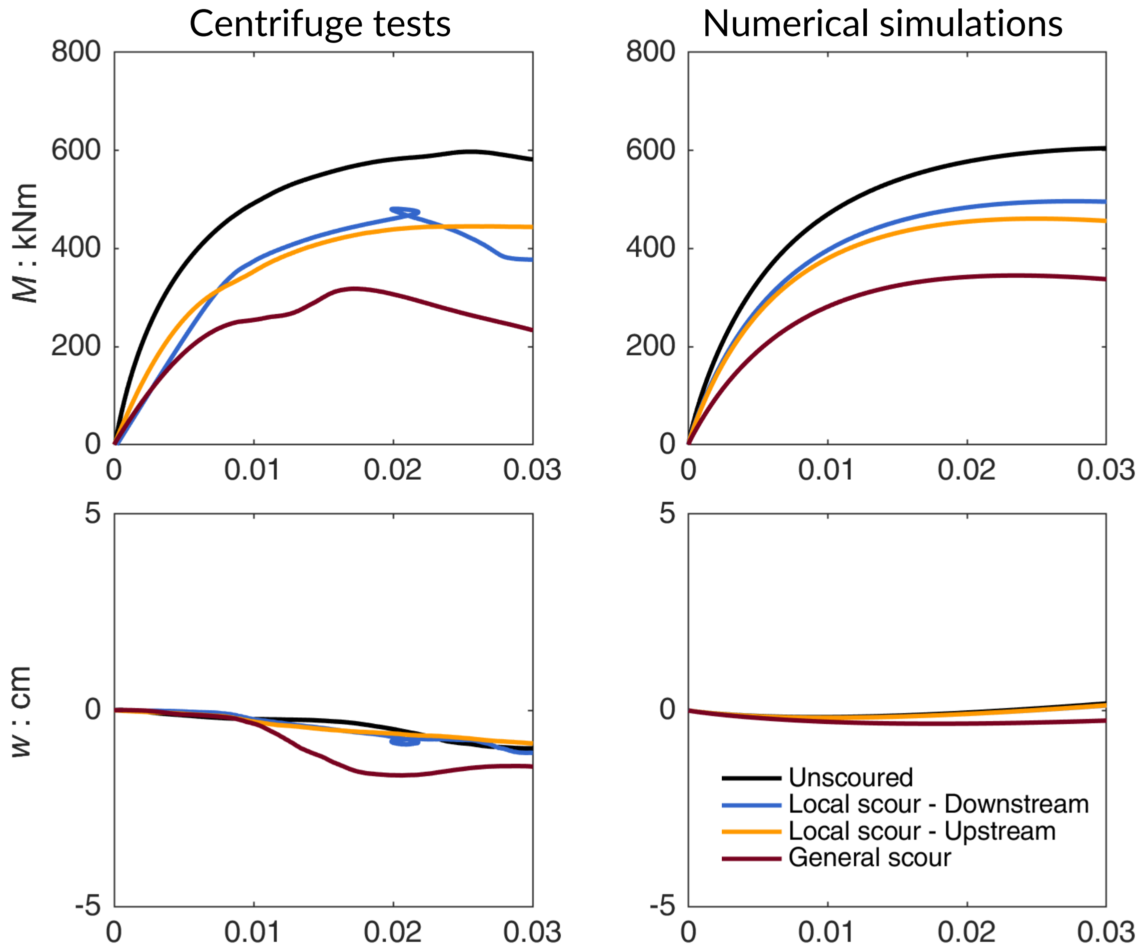
3D FINITE ELEMENT DISCRETIZATION

Validation against centrifuge tests

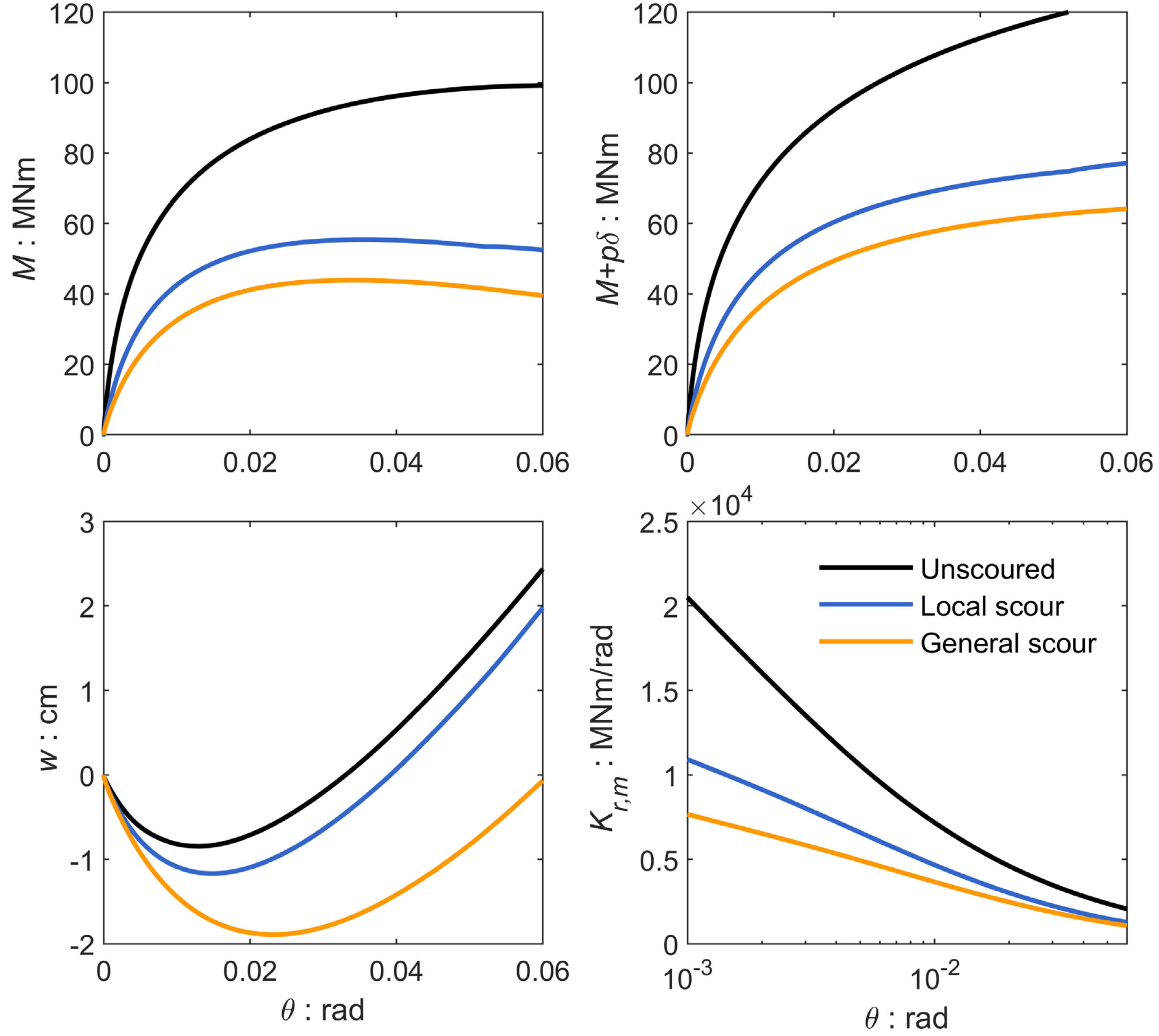
VERTICAL TESTS



PUSHOVER CURVES



Numerical modelling of the case study



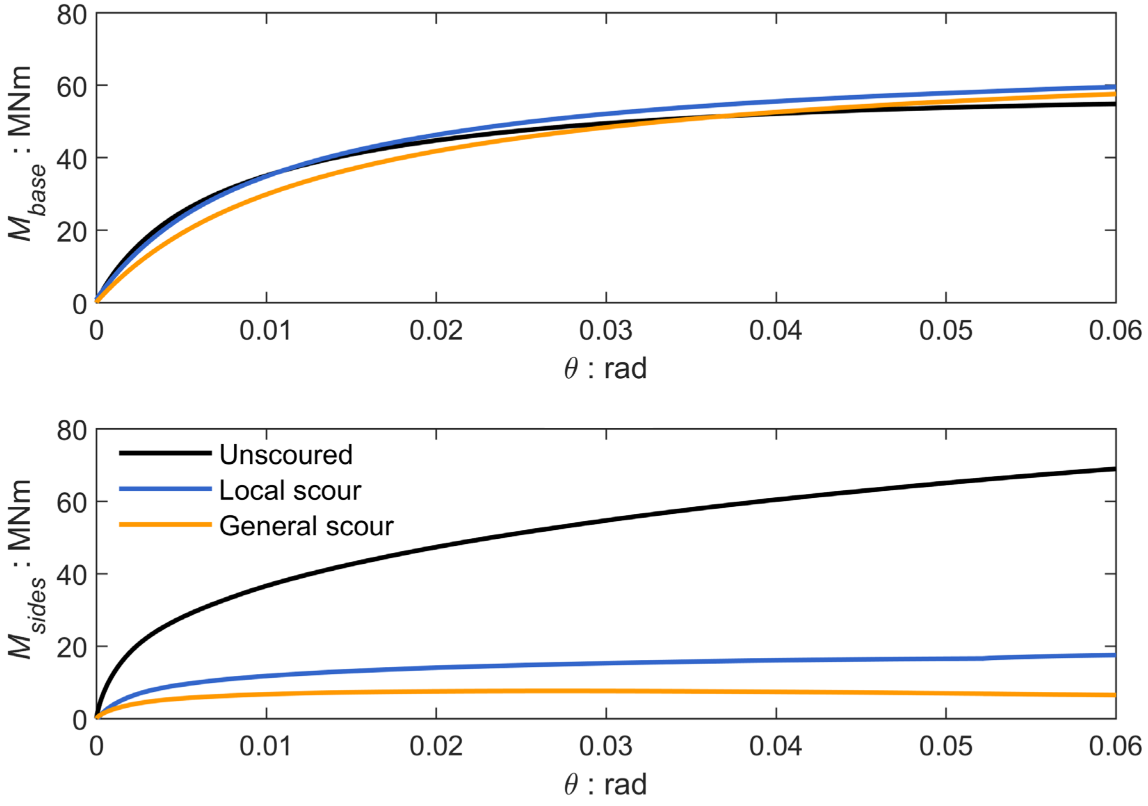
Localized erosion **reduces M_{ult}** of 45%, increasing up to 55% when generalized erosion takes place

General scour increases ***w***, but the regime is still uplifting-dominated. Increased settlement can be **relevant under cyclic loadings**.

Relevance of second-order (***P* - δ**) additional moment, often neglected in simplified models

K_r at small strains reduces of 50% and 62% due to local and general scour. This is consistent with monitoring data collected from real bridges.

Numerical modelling of the case study



Local scour does not affect significantly the bearing capacity of the caisson foundation. General scour leads to a slight reduction of FS_v, affecting to some extent also M_{base}.

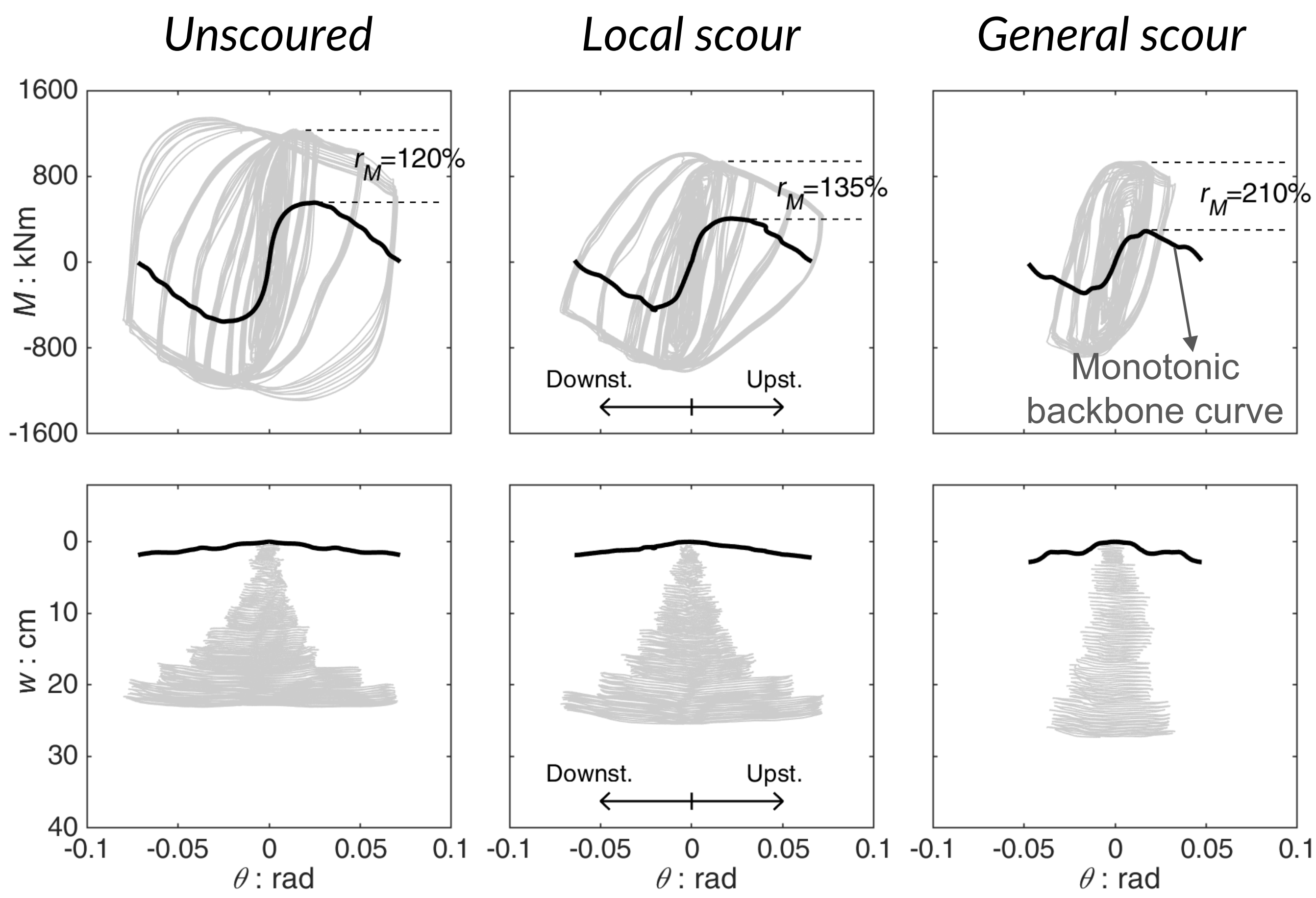
The influence of scouring is such as practically nullify the contribution of the soil along the sides of the caisson to the capacity of the foundation system.

The detrimental impact of foundations scour, combined to P-δ effects, leads to a fragile response of the footing. Under extreme conditions, this may cause a sudden failure of the pier and, in turn, of the entire structure.

Future developments

Cyclic response of scoured foudations

Slow-cyclic lateral tests



$r_M = \Delta M / M_{ult}$
moment overstrength ratio

The r_M is equal to 120% for the unscoured foundation, increasing in the case of local scour, and going to 210% under general scour conditions

According to Kokkali et al. (2015), the cyclic overstrength is due to:

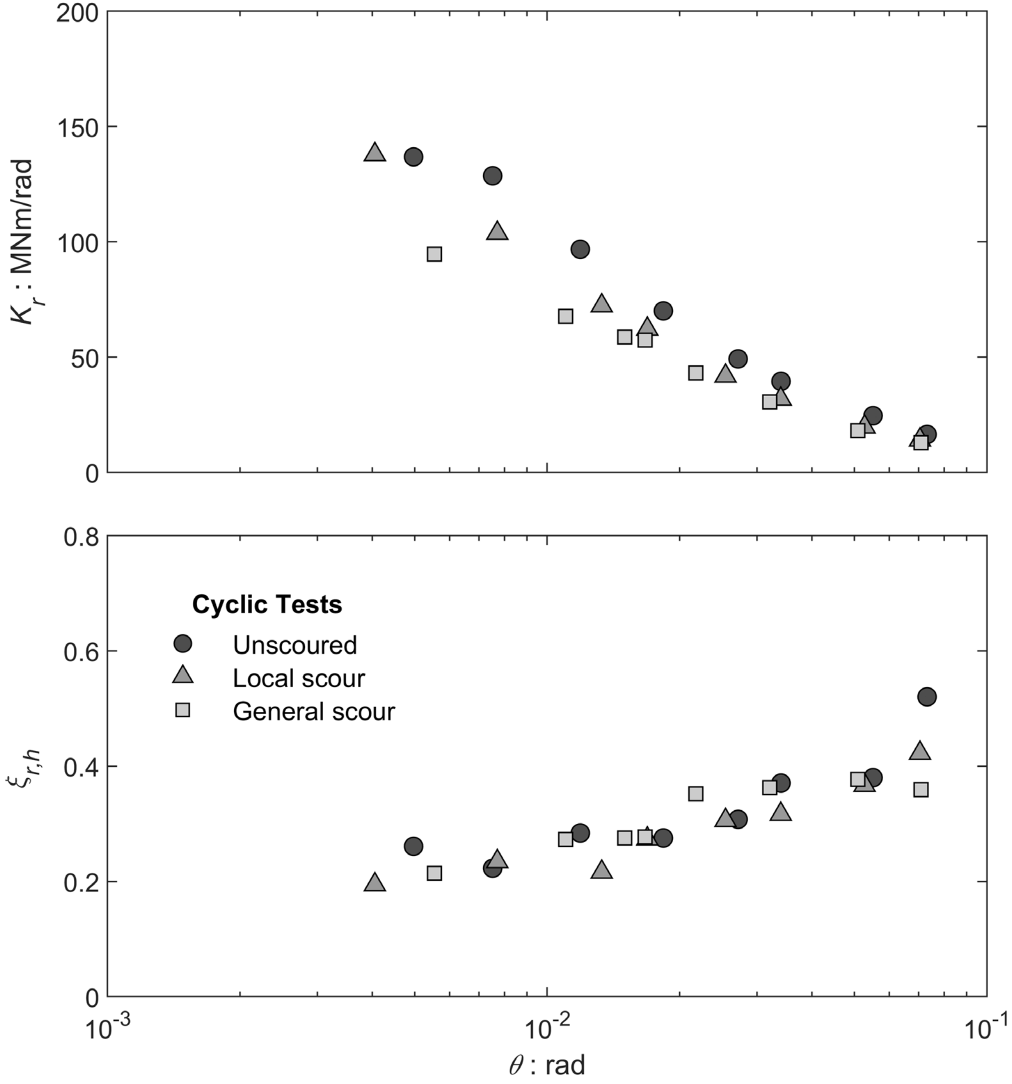
- sand “*densification*”
- increase of embedment depth

Cyclic response of scoured foudations

Slow-cyclic lateral tests: $K_{r,c}$ and $\xi_{r,h}$ curves

$K_{r,c}$ and $\xi_{r,h}$ offer a convenient way to quantify **nonlinear rocking foundation response** (Gazetas et al., 2013):

- Nonlinearity strongly affects the foundation response
- Both **general and local scour reduce the $K_{r,c}$** of the structure
- $\xi_{r,h}$ **increases with θ** up to 0.4-0.5 but is slightly **sensitive to scouring**

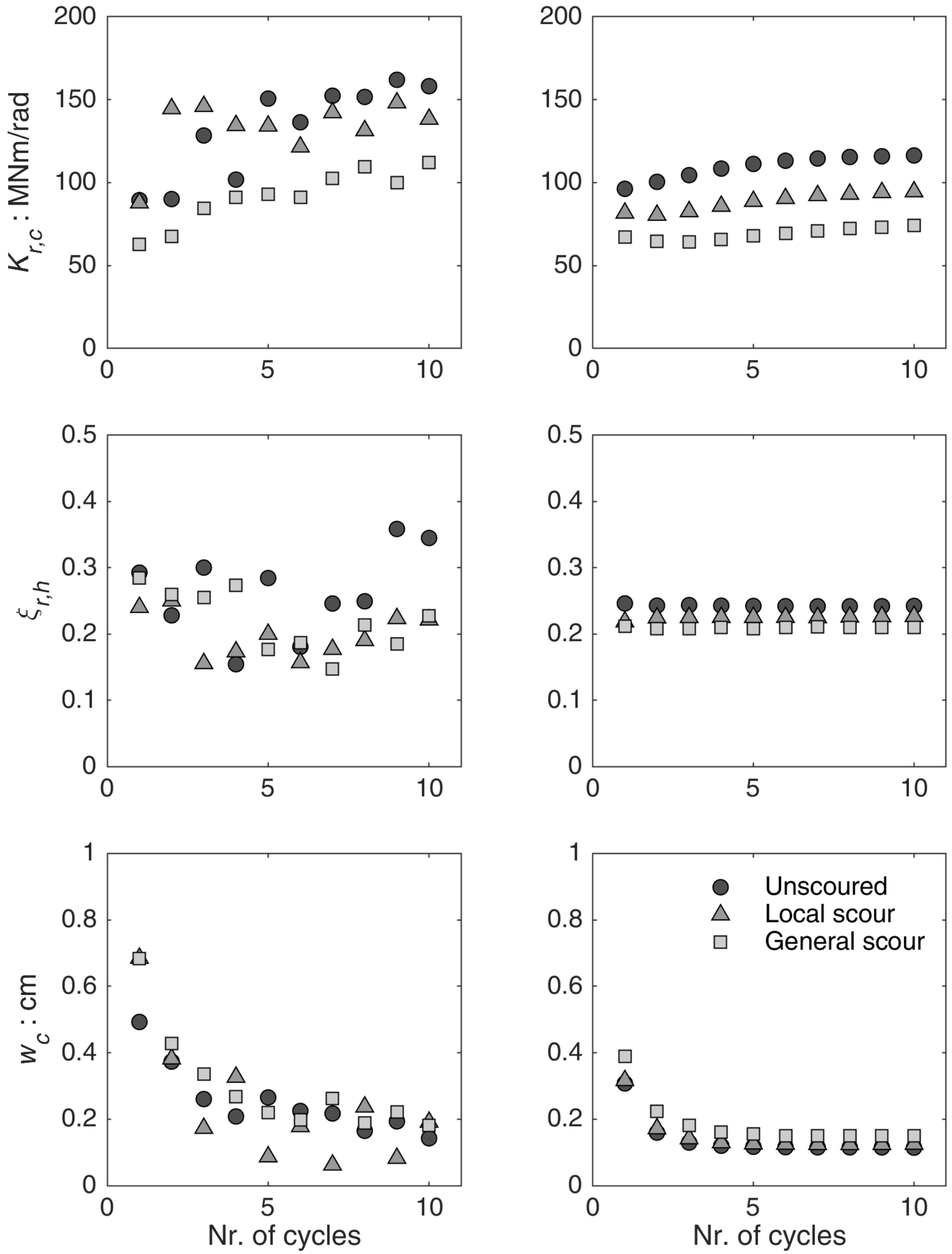


Numerical simulations vs centrifuge tests

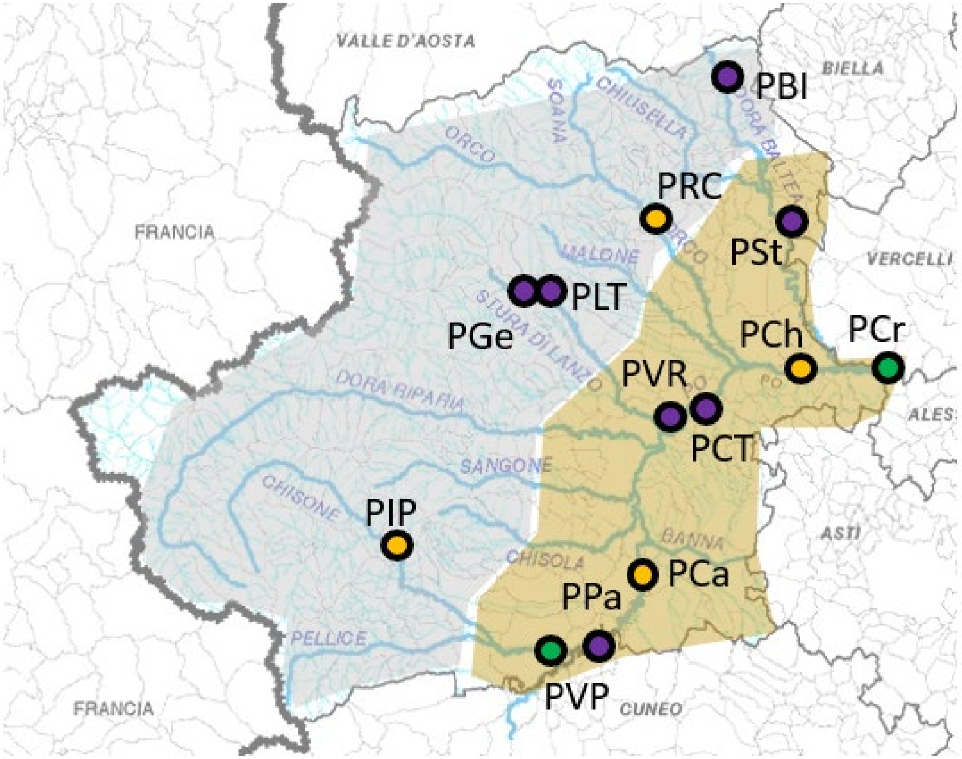
The **initial $K_{r,c}$ values are consistent** with the experimental values

The **progressive hardening** of the foundation is just partially captured (differences attributed to *fabric* effects)

The comparison is very **satisfying** in terms of **cyclic settlement** and **hysteretic damping ratio**



In situ testing: dynamic characterization of scoured piers



- Simply supported beam bridge
- Continuous bridge
- Arch bridge

- Coarse gravel and cobbles
- Sands and gravels

Target: road bridges in the Metropolitan City of Turin, representative of different hydraulic, geotechnical and structural conditions

Monitoring:

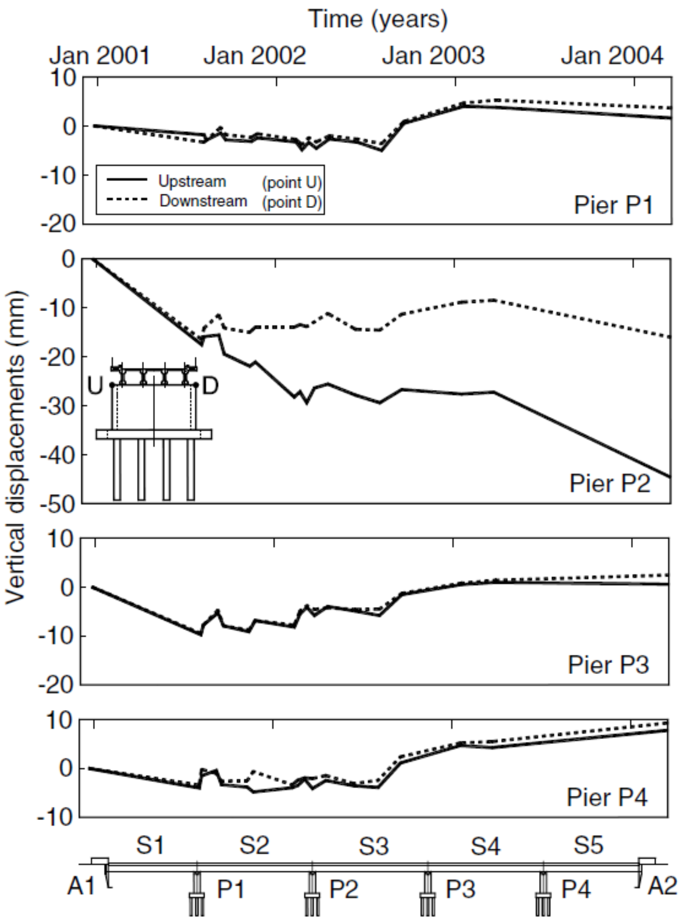
- Static measurements (e.g., inclinometers)
- Dynamic measurements (e.g., accelerometers) on piers and deck
- Hydraulic surveys → hydrologic conditions
- Geophysical surveys → riverbed conditions

In situ testing: dynamic characterization of scoured piers

Example of possible monitoring scheme: Strambino bridge (Foti and Sabia, 2011)

Before

P2



Topographic measurements

- Evidence of significant rotations at Pier P2

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P2 retrofit

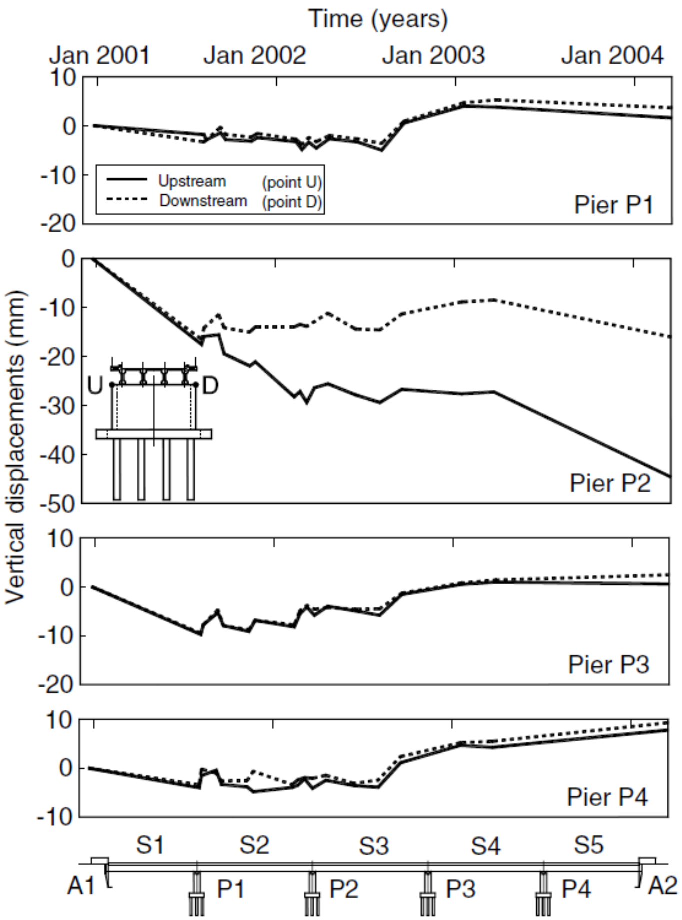
In situ testing: dynamic characterization of scoured piers

Example of possible monitoring scheme: Strambino bridge (Foti and Sabia, 2011)

Before

P2

After



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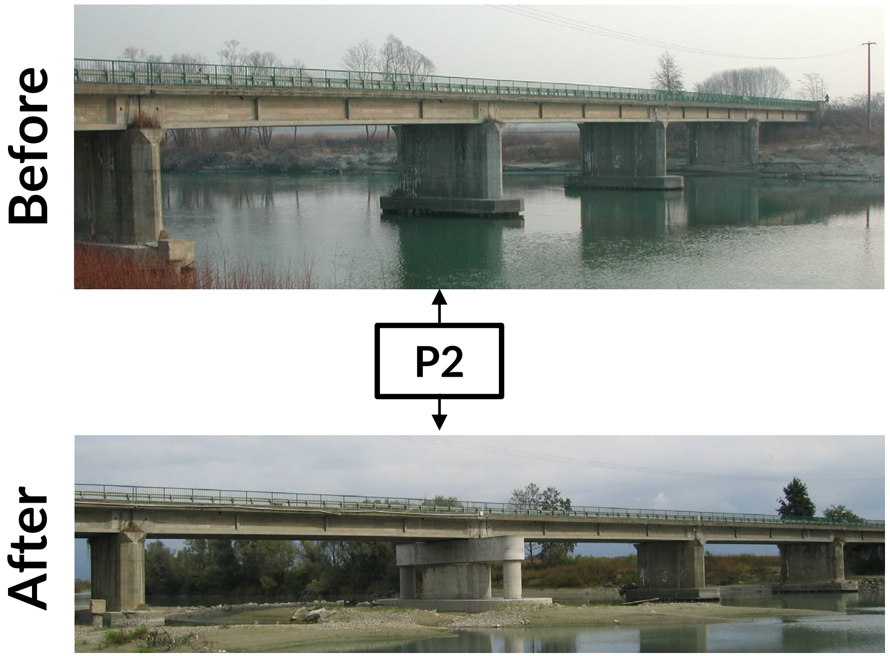
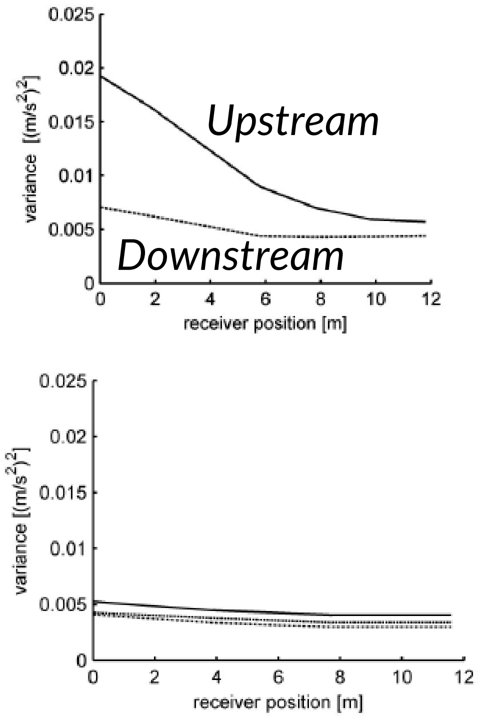
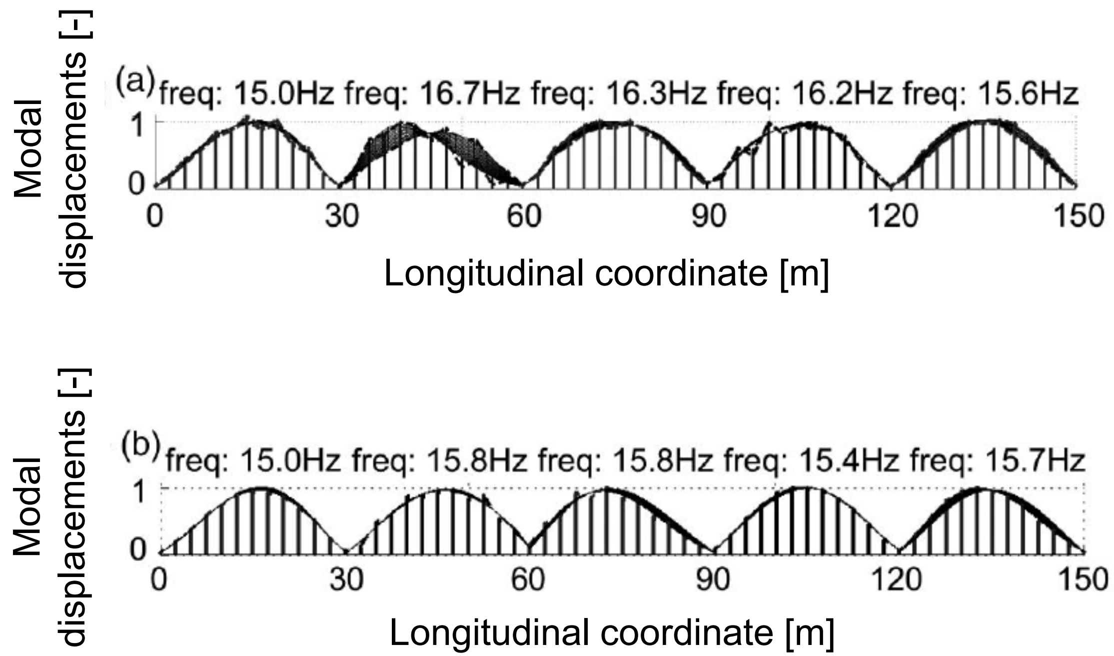


Dynamic measurements on pier P2
→ reduced asymmetry in the response

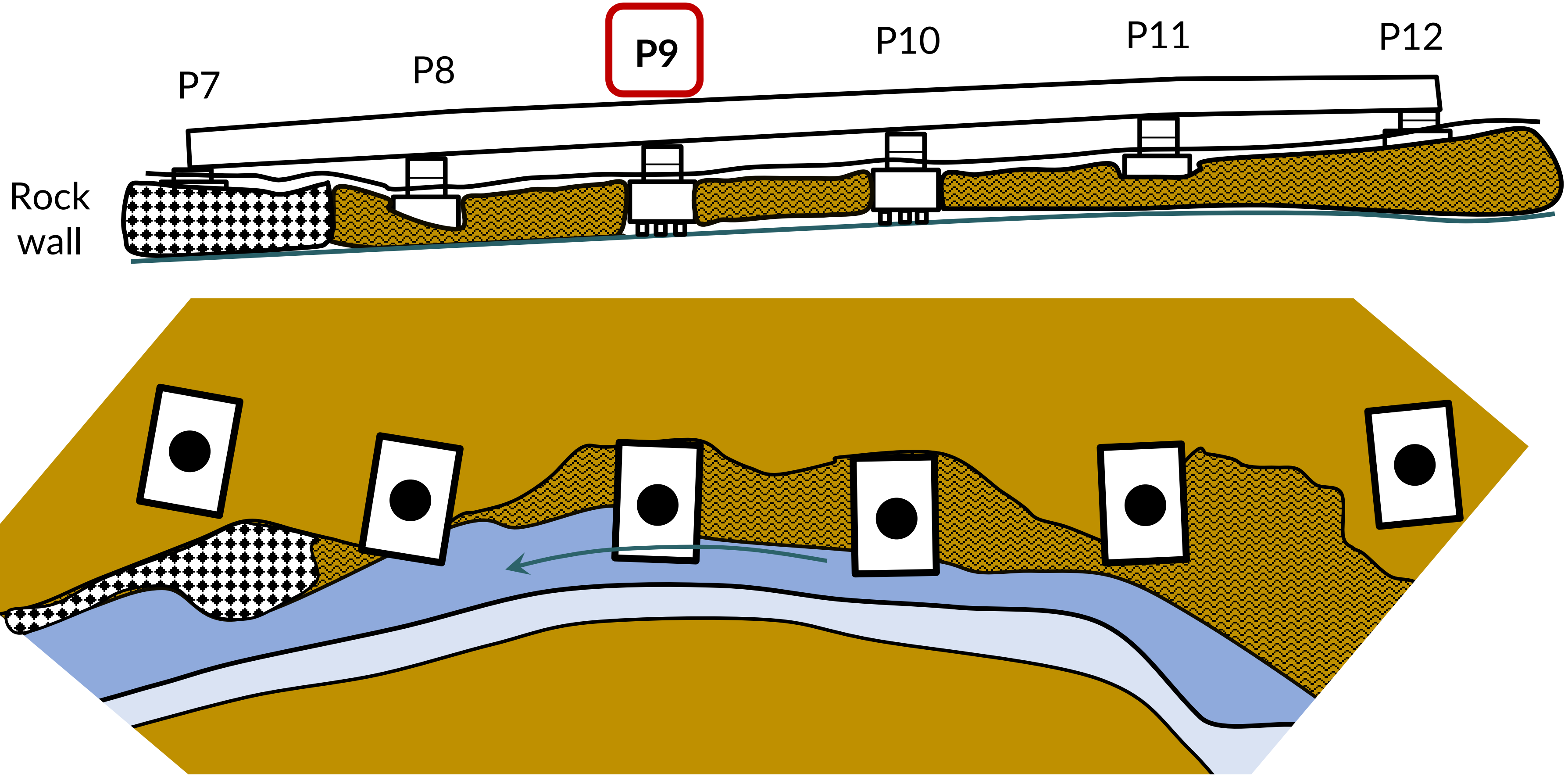


Dynamic measurements on the deck
(modal shapes)



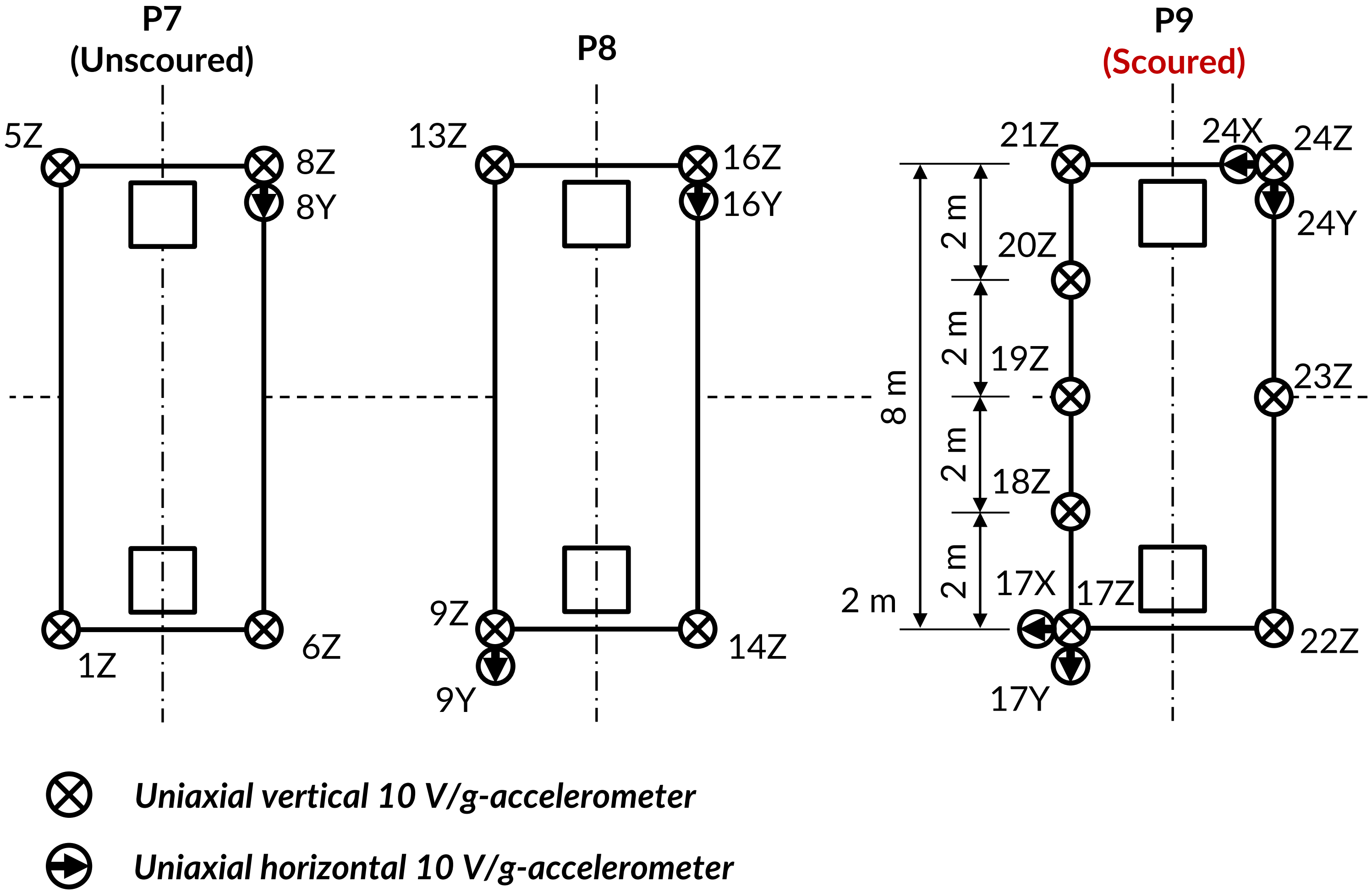
In situ testing: dynamic characterization of scoured piers

Example of possible monitoring scheme: Inverso Pinasca bridge



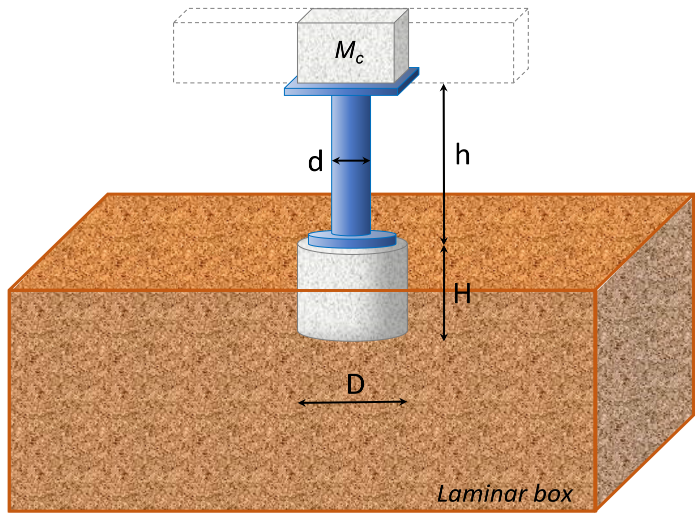
In situ testing: dynamic characterization of scoured piers

Example of possible monitoring scheme: Inverso Pinasca bridge



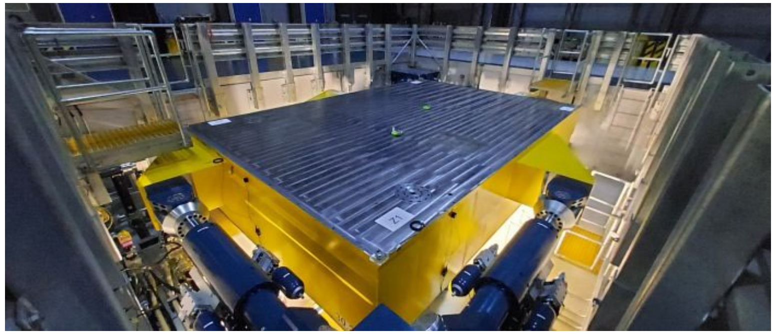
- **Measurement target**: deck and piers, both on the scoured part and the unscoured part
- **Goal**: identify differences and asymmetries in the response due to scour

Physical modelling: ERIES_SCOUR&SHAKE PROJECT



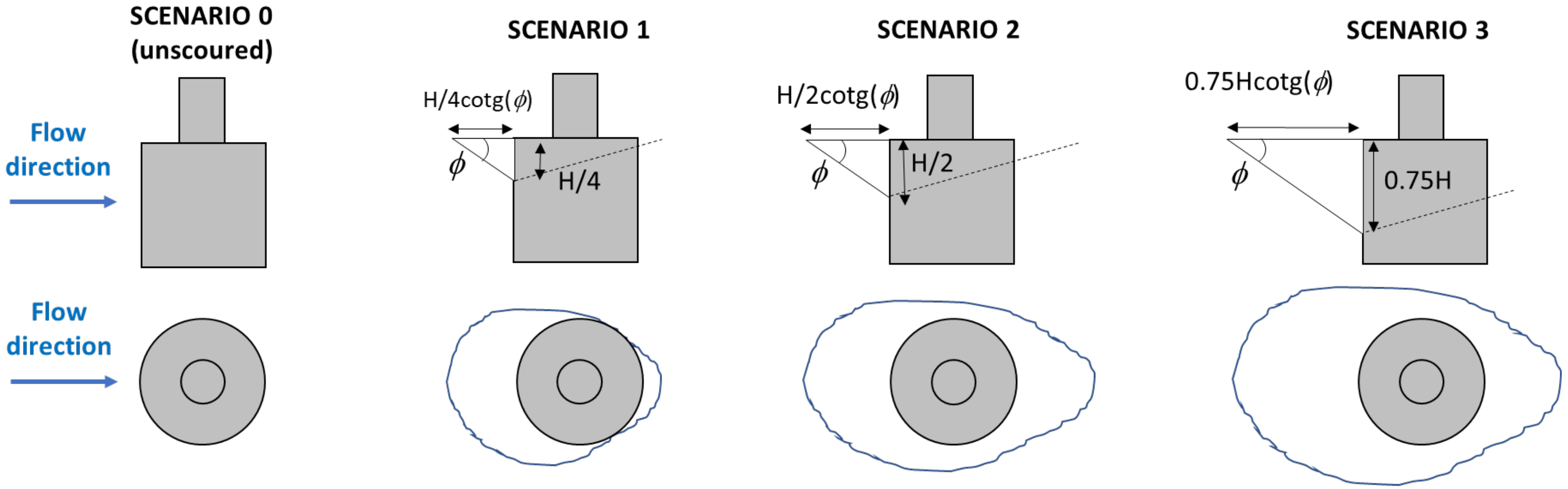
ERIES ENGINEERING RESEARCH INFRASTRUCTURES FOR EUROPEAN SYNERGIES

Shaking table @University of Bristol



Structural Performance monitoring and evaluation of scoured bridges under dynamic actions

- Physical investigation of the pier response with foundation local scour, through shaking table tests
- Investigation of multiple local scour scenarios, in terms of scour depth
- Assessment of the effectiveness of remedial measures (e.g., riprap)



Final remarks

Final Remarks

- The increasing number of extreme flood events leads to concerns regarding the long term static performance and seismic response of existing bridges with foundations in the river bed
- Budget limitations and sustainability concerns on heavy retrofitting call for a careful assessment of multi-hazard exposure
- Simplified methods may lead to either unconservative estimates or to unnecessary retrofitting
- Dynamic tests can provide useful information for monitoring the evolution of bridge scouring and for the calibration of advanced numerical models for the assessment of static and seismic performance of existing bridges affected by scour of foundations

Politecnico di Torino
Department of Structural, Geotechnical and Building Engineering

SECED 2023 Conference

14-15 September 2023
Cambridge, UK

Thank you for your kind attention!

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