

**5<sup>th</sup> International Bridge Seismic Workshop (5IBSW)**  
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# Seismic Protection of Bridges Through Geotechnical Seismic Isolation: From Soil–Structure Interaction to Innovative Structural Systems

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FUZHOU UNIVERSITY



Sustainable & Multi-Hazard Resilient Bridges and Structures Research Group

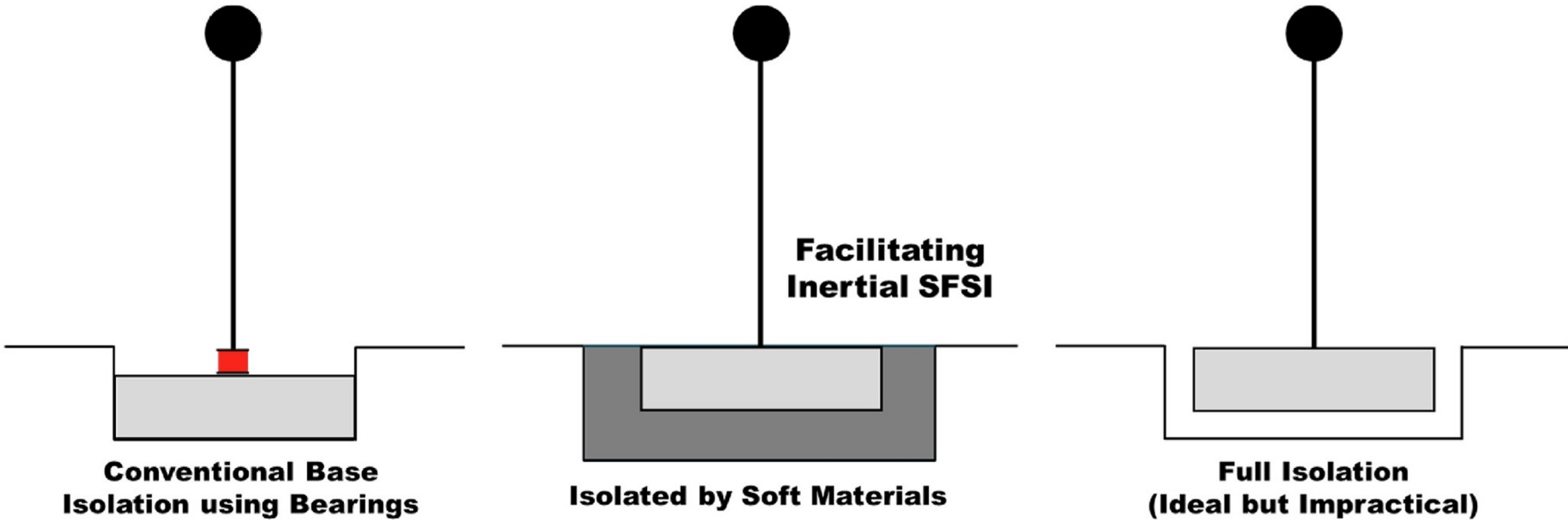
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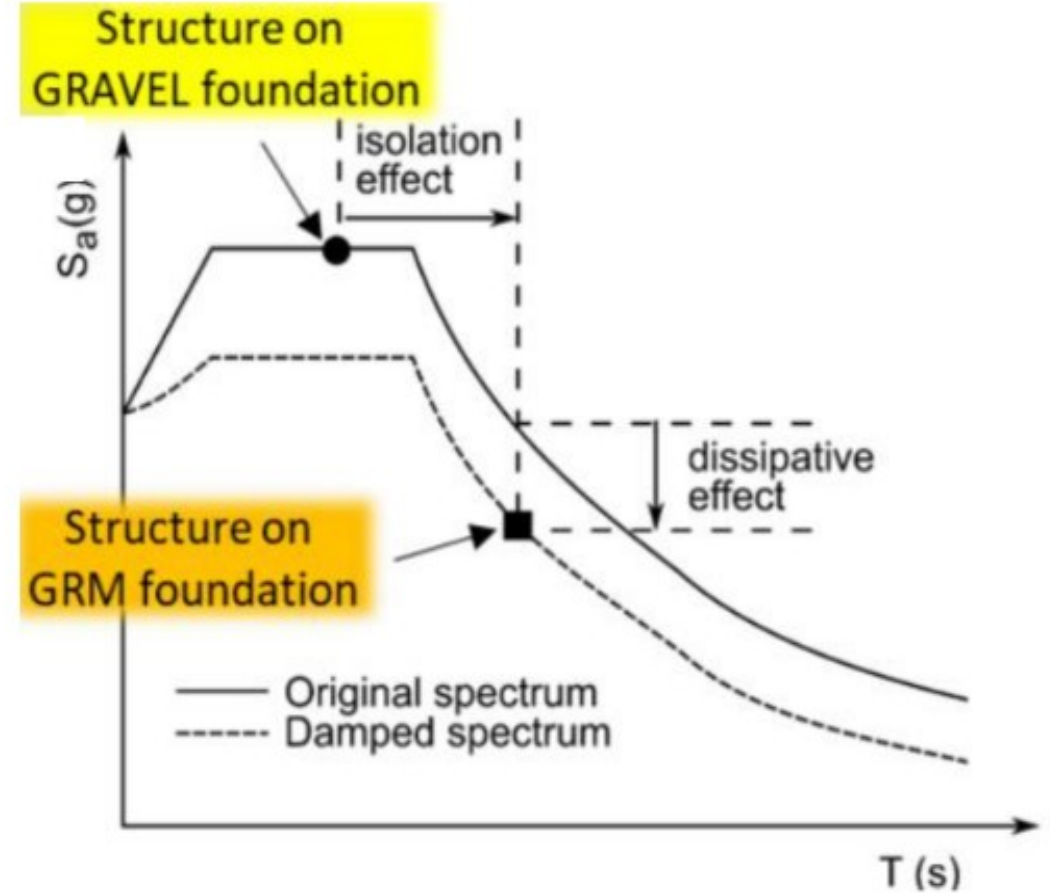
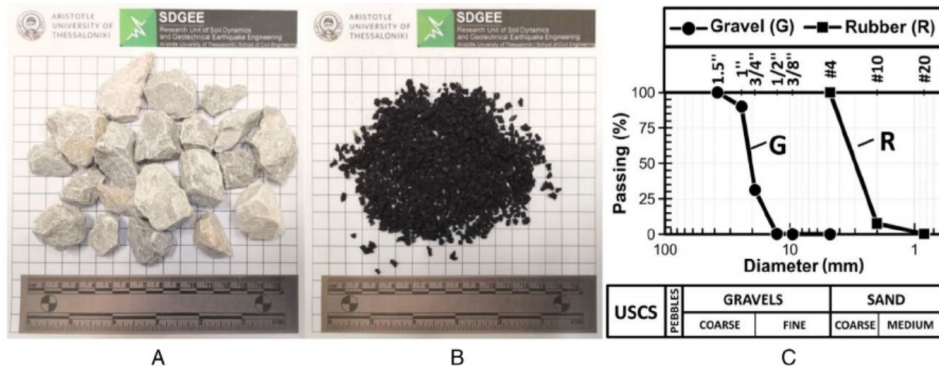
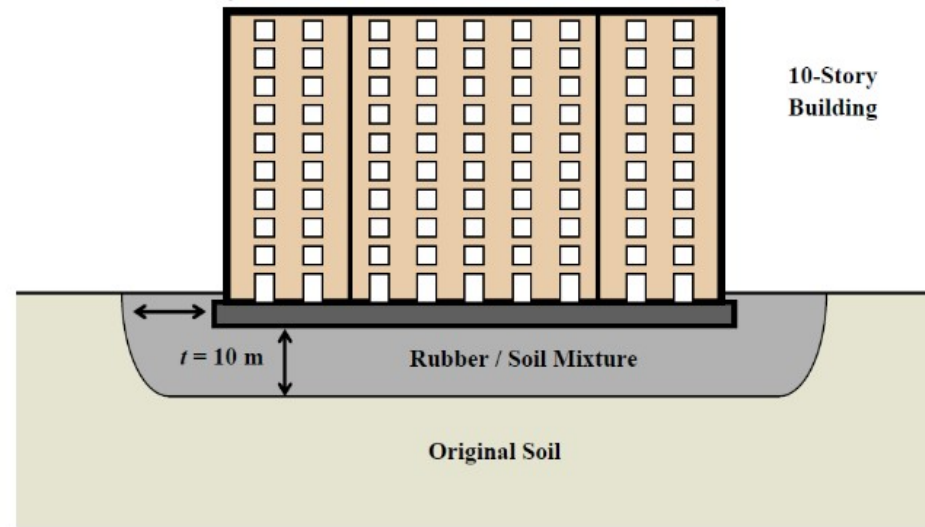
# 1. Introduction

## - Seismic Isolation Philosophy



# 1. Introduction

## - Concept of Geotechnical Seismic Isolation (GSI)

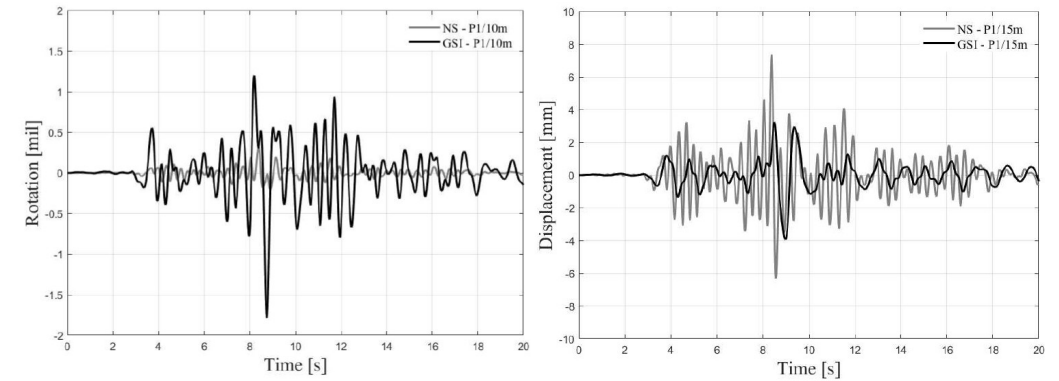
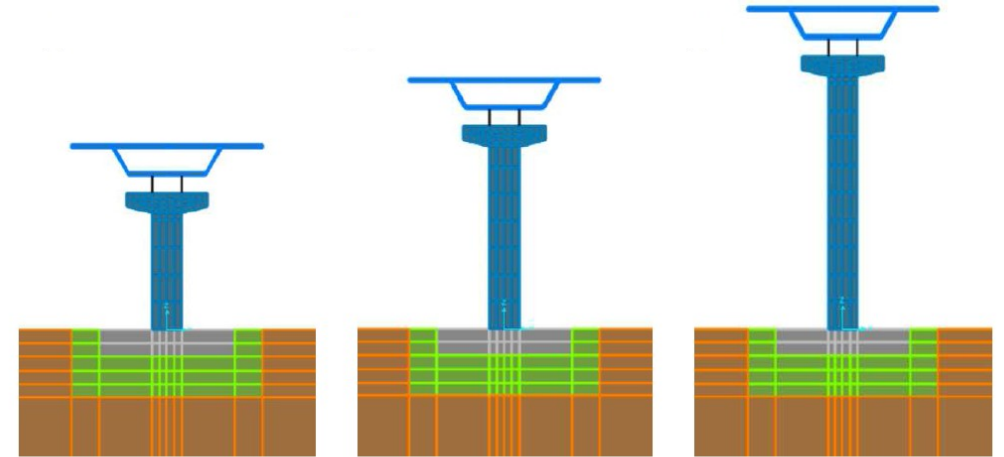
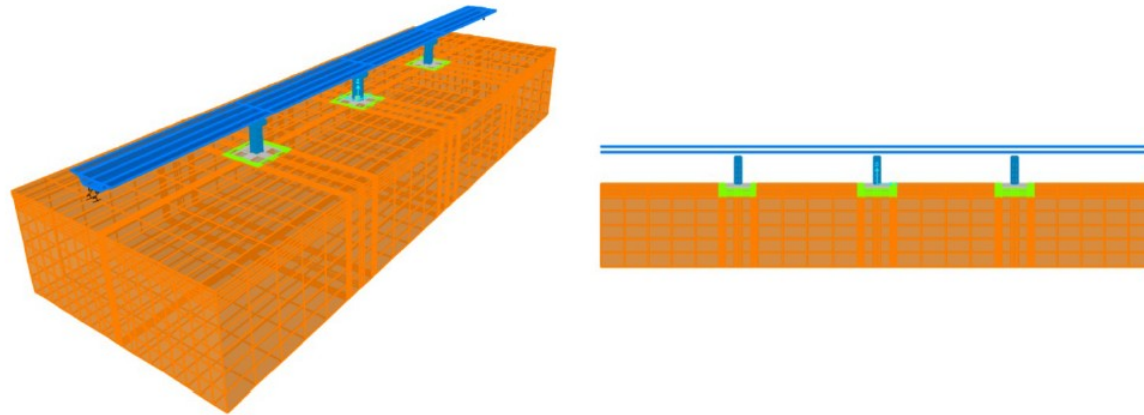
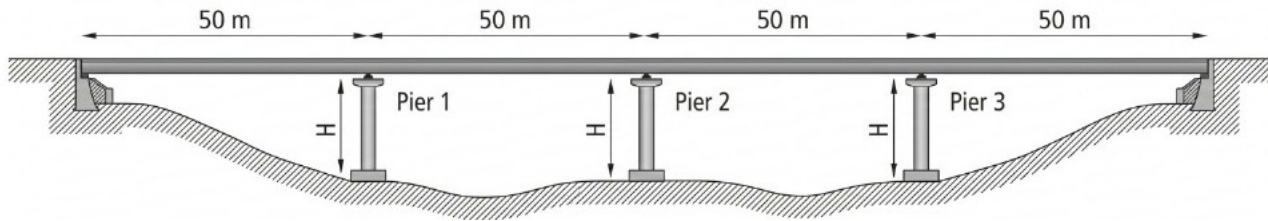


Seismic isolation by a layer of soil (e.g., gravel)-rubber mixture (SRM)      Effect on response spectrum

Tsang, HH. (2009). Geotechnical seismic isolation. Earthquake Engineering: New Research. Nova Science Publishers, Inc.: New York, U.S., pp. 55–87

# 1. Introduction

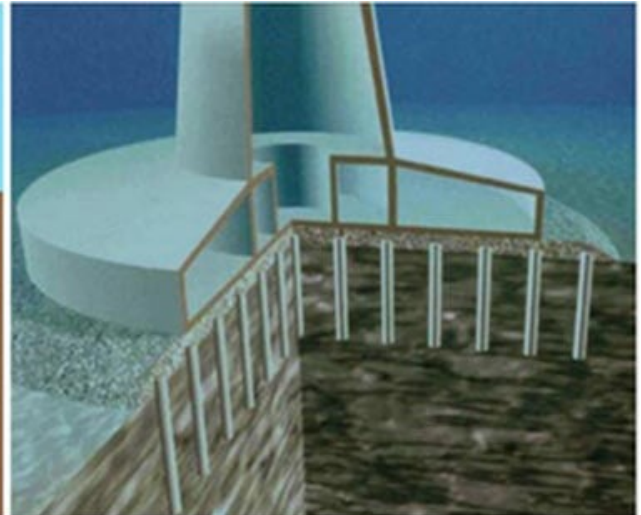
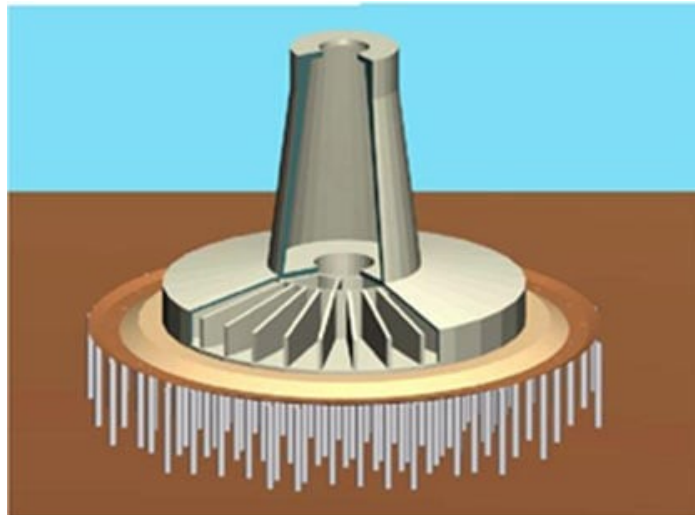
## - Short and Medium Span Bridges





# 1. Introduction

## - Long Span Bridges

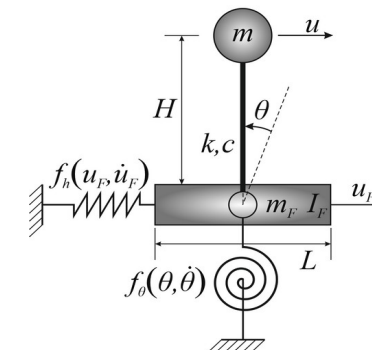
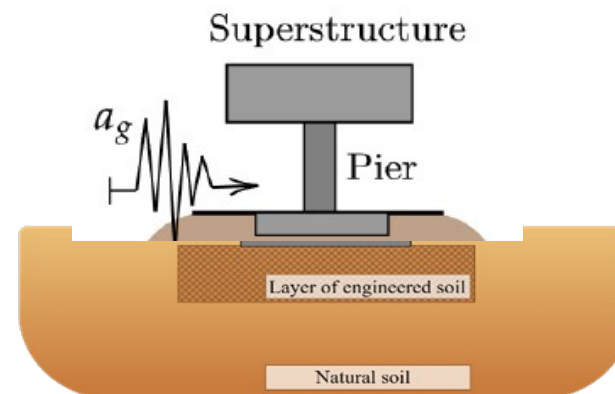
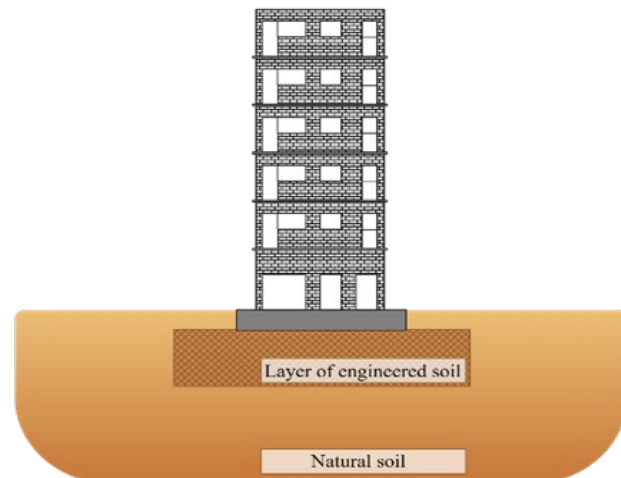


## 2. Nonlinear SSI of GSI-Protected Bridges

### - Two-stage approach for seismic nonlinear SSI of structures with GSI

Develop new procedures to model the nonlinear soil-structure interaction (SSI) of Geotechnical Seismic Isolation (GSI)-protected structures, aiming to:

- Improve computational efficiency.
- Account for system uncertainties.



## 2. Nonlinear SSI of GSI-Protected Bridges

### - Two-stage approach for seismic nonlinear SSI of structures with the GSI

A two-stage approach is proposed to study the seismic nonlinear SSI of structures protected by a GSI system based on a rubber–soil mixture layer (GSI-RSM).

1. First stage: Distinct Element Method (DEM) is used to determine the soil-foundation interaction mechanism accounting for soil variability.
2. Second Stage: Preisach formalism is adopted along with an energy balance approach. The amplitude dependent equivalent springs and dashpots, are then calibrated using the results from the DEM study.

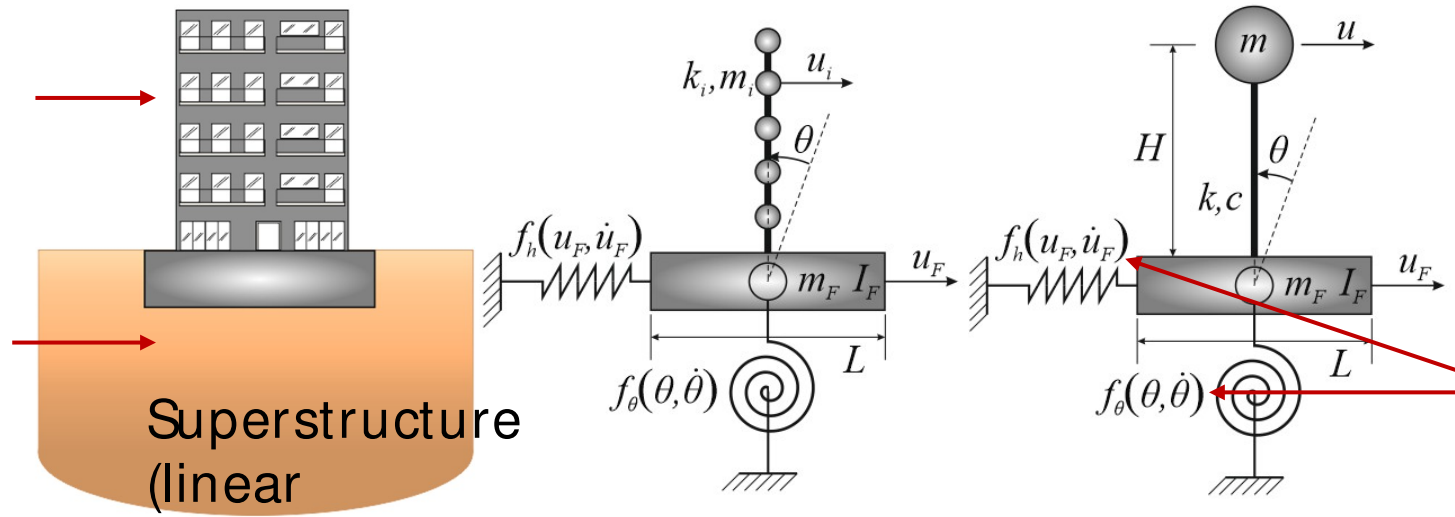
Maksimov, F., Contento, A., Briseghella, B., Cacciola, P. (2026). Nonlinear Soil-Structure Interaction in Geotechnical Seismic Isolation: A Two-Stage DEM-Preisach Formalism Framework. *Computers & Structures*, 323, 108159

# 2. Nonlinear SSI of GSI-Protected Bridges

## - Mechanical Model

- Multi-degree-of-freedom system

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) + \mathbf{h}(t) = \mathbf{p}(t)$$



$m$  superstructure mass  
 $m_F$  foundation mass  
 $I_F$  foundation moment of inertia  
 $k$  superstructure lateral stiffness  
 $H$  height of the superstructure

- 3-DoF lumped mass model

$$\mathbf{M} = \begin{bmatrix} m & 0 & 0 \\ 0 & m_F & 0 \\ 0 & 0 & I_F \end{bmatrix} \quad \mathbf{C} = \begin{bmatrix} c & -c & 0 \\ c & c & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \mathbf{K} = \begin{bmatrix} k & -k & -kH \\ -k & k & kH \\ -kH & kH & kH^2 \end{bmatrix} \quad \mathbf{h}(t) = \begin{bmatrix} 0 & f_h(u, \dot{u}) & f_\theta(\theta, \dot{\theta}) \end{bmatrix}^T$$

$\mathbf{h}(t)$  is the nonlinear hysteretic vector including the nonlinear forces generated by the SSI modelled as nonlinear springs (i.e., the horizontal force  $f_h$  and the moment  $f_\theta$ )

## 2. Nonlinear SSI of GSI-Protected Bridges

### - Mechanical Model

- Equivalent damping ( $\mathbf{C}_e$ ) and stiffness ( $\mathbf{K}_e$ )

$$\mathbf{p}(t) = \mathbf{p}_0 \cos(\omega t) \quad u_F(t) = a_h(t) \cos(\omega t + \phi(t)) \quad \theta(t) = a_\theta(t) \cos(\omega t + \phi(t))$$

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) + \mathbf{h}(t) = \mathbf{p}(t)$$

$$\mathbf{C}_e = \begin{bmatrix} 0 & 0 & 0 \\ 0 & c_{e,h}(a_h) & 0 \\ 0 & 0 & c_{e,\theta}(a_\theta) \end{bmatrix} \quad \mathbf{K}_e = \begin{bmatrix} 0 & 0 & 0 \\ 0 & k_{e,h}(a_h) & 0 \\ 0 & 0 & k_{e,\theta}(a_\theta) \end{bmatrix}$$

- Steady state response


$$\mathbf{U}(a_h, a_\theta; \omega) = \left[ \mathbf{K} + \mathbf{K}_e(a_h, a_\theta) + i\omega(\mathbf{C} + \mathbf{C}_e(a_h, a_\theta)) - \omega^2 \mathbf{M} \right]^{-1} \mathbf{p}_0$$



## 2. Nonlinear SSI of GSI-Protected Bridges

### - First stage: Distinct Element Method (DEM) Approach

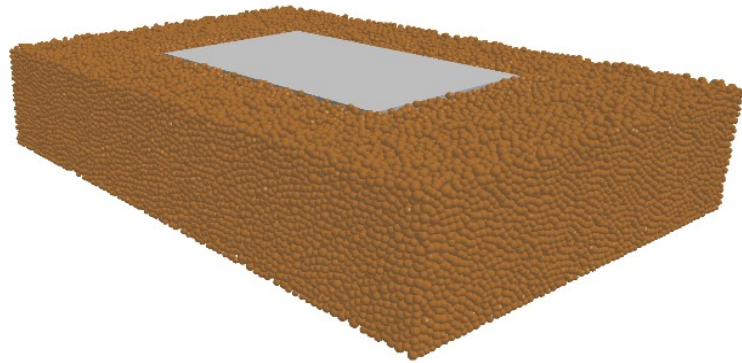
- Granular medium modelled as assembly of discrete particles interacting through contact forces - spring-dashpot systems
- Capacity to account for heterogeneity and dilative behaviour at the particle scale
- Solution of the equations of motion of each particle  $\hat{\mathbf{F}}_i(t)$

$$m_i \ddot{\mathbf{x}}_i(t) = \hat{\mathbf{F}}_i(t) = I_i \dot{\omega}(t) \quad \hat{\mathbf{M}}_i(t) \quad \hat{\mathbf{M}}_i(t)$$

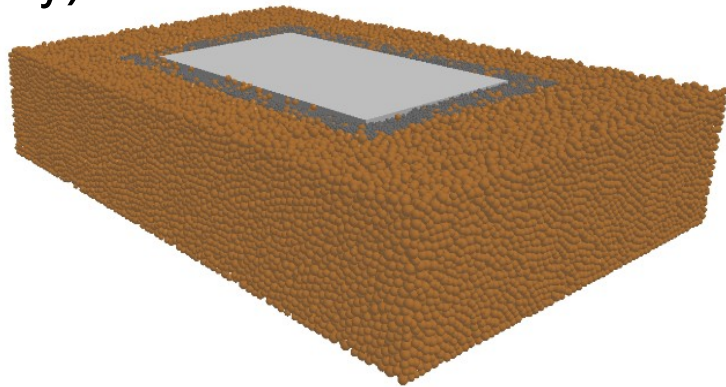
- Contact forces from the Hertz-Mindlin no-slip formulation
- Simulations performed with the open-source framework YADE

## 2. Nonlinear SSI of GSI-Protected Bridges

### - First stage: Distinct Element Method (DEM) Approach

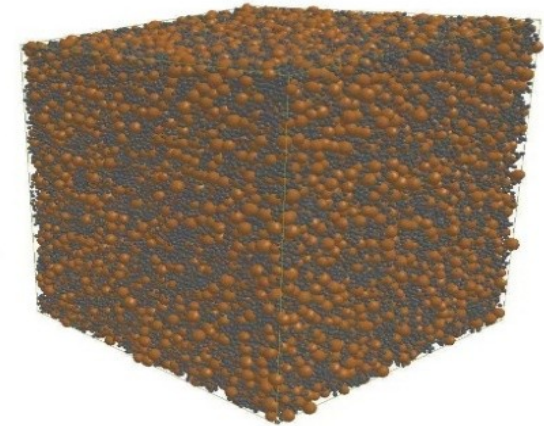
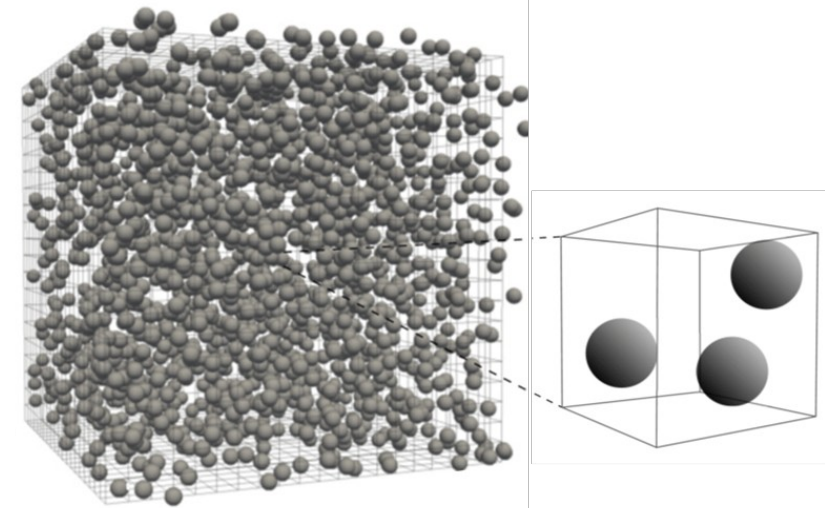


Foundation assembly (gravel-only)



Foundation assembly (RSM)

The particle distribution for each pack was determined using a Monte Carlo approach based on four independent random variables: the three spatial coordinates (uniformly distributed) and the particle radius, sampled according to the specified particle size distribution.

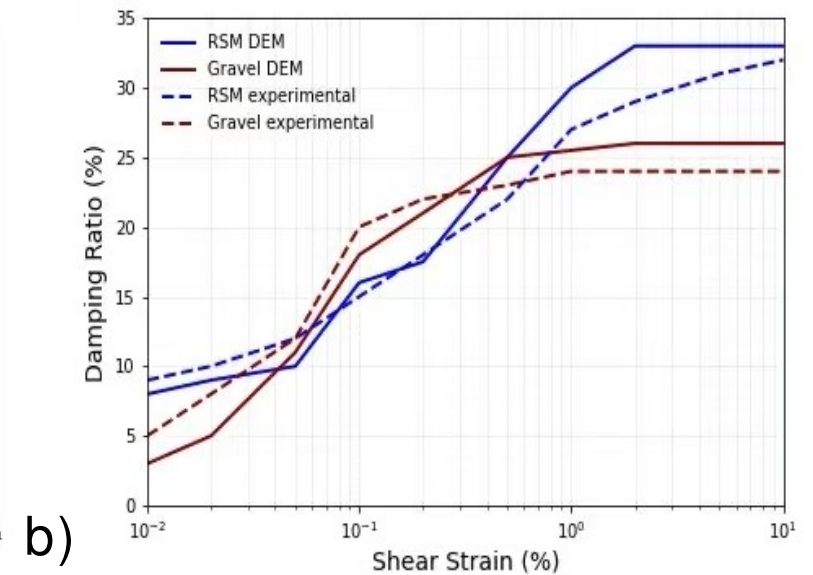
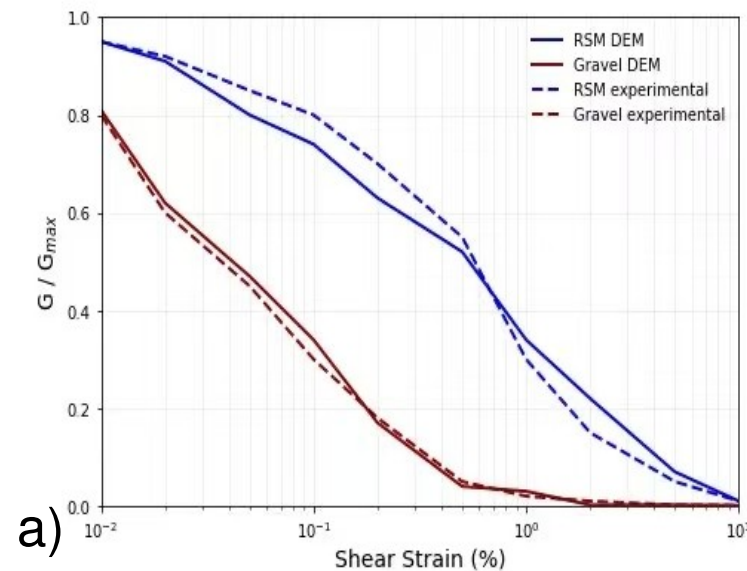
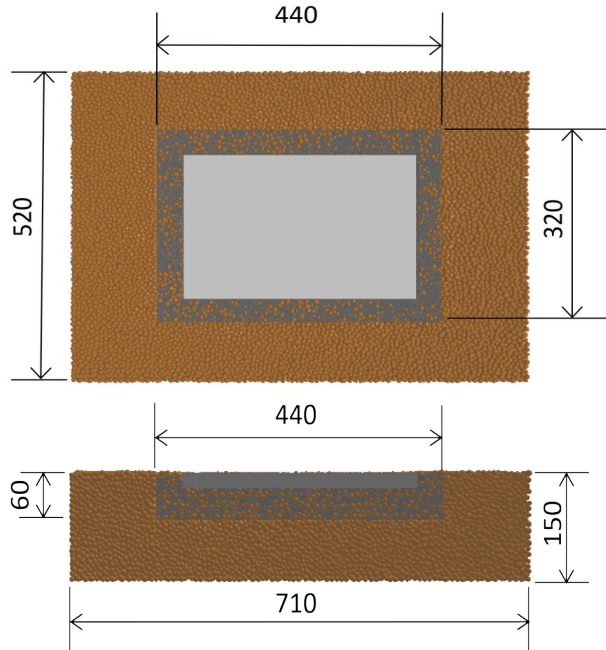


Settled RSM layer assembly

## 2. Nonlinear SSI of GSI-Protected Bridges

### - Pseudo centrifuge tests with DEM

The proposed methodology was validated through comparisons with benchmark centrifuge experiments by Tsang et al. (2021). Numerical (DEM) results for both shear modulus reduction ( $G/G_{\max}$ ) and damping curves versus shear strain agreed well with experimental values from cyclic tests.



## 2. Nonlinear SSI of GSI-Protected Bridges

### - Second stage: Lumped parameter model based on Preisach formalism

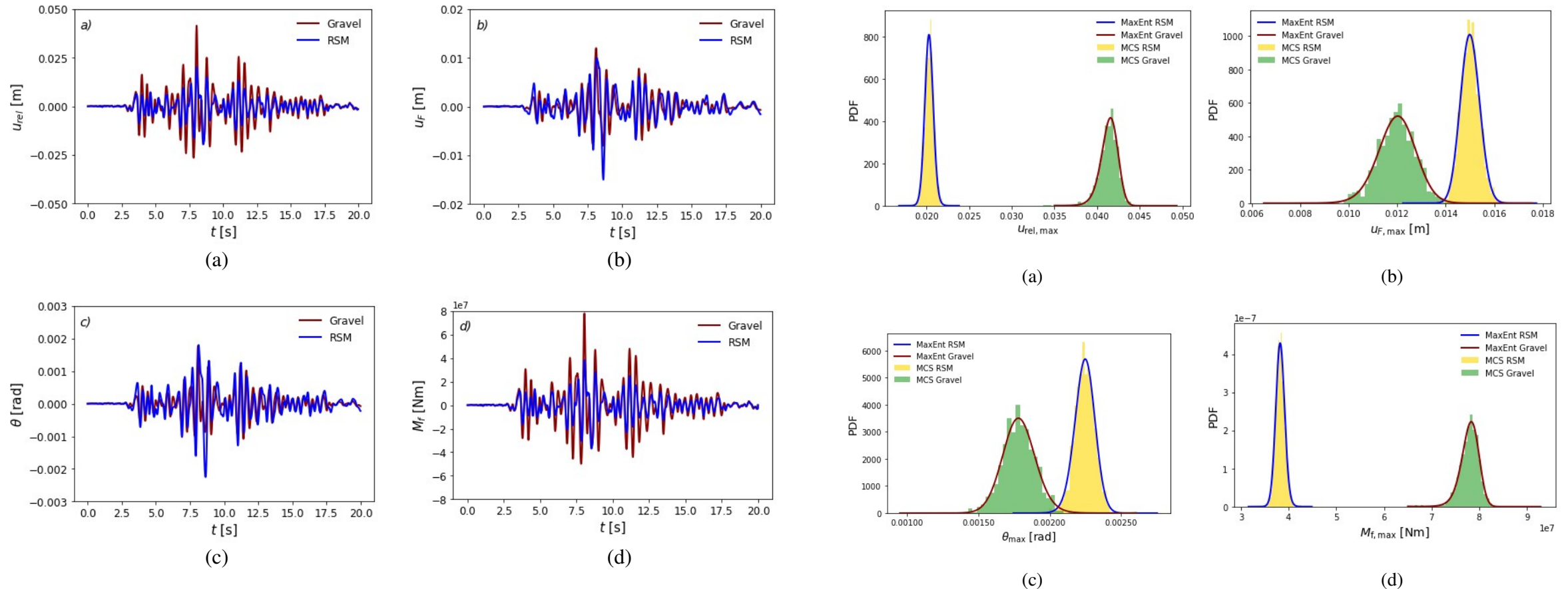
- A surrogate SSI system has been adopted to reduce both the complexity and computational costs associated with a full DEM/FEM analysis.
- The lumped parameter model developed by Cacciola and Tombari (2021) is adopted, with its parameters calibrated using the DEM analyses performed in Stage 1.
- The hysteresis is the result of the superposition of an infinite set of elementary hysteresis operators (hysterons or relay operators)  $f_{\alpha,\beta}$ , having local memory, that is:

$$f_{i,H}(x, \dot{x}) = \iint_{\alpha \geq \beta} \mu(\alpha, \beta) f_{\alpha,\beta}(x, \dot{x}) d\alpha d\beta, \quad i = h, \theta \text{ and } x = u_F, \theta$$



# 2. Nonlinear SSI of GSI-Protected Bridges

## - Second stage: Lumped parameter model based on Preisach



(a) relative displacement, (b) base displacement, (c) base rotation and (d) base moment.

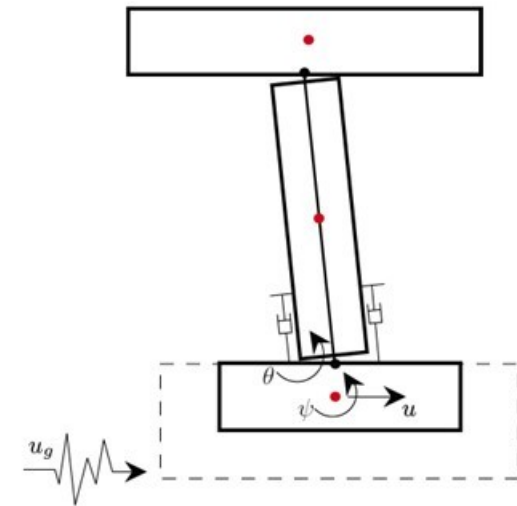
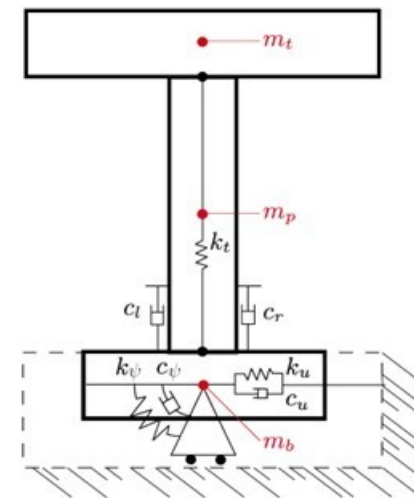
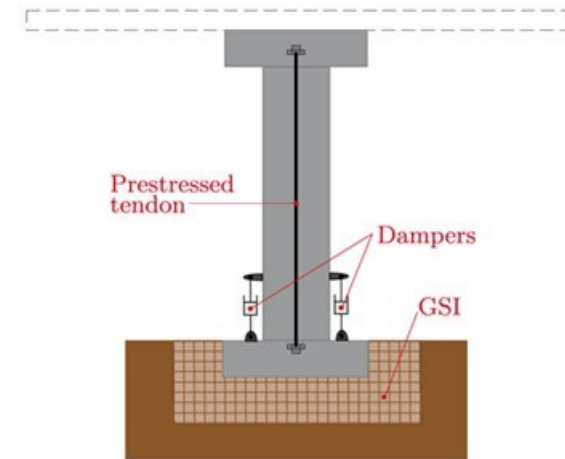
Maksimov, F., Contento, A., Briseghella, B., Cacciola, P. (2026). Nonlinear Soil-Structure Interaction in Geotechnical Seismic Isolation: A Two-Stage DEM-Preisach Formalism Framework. *Computers & Structures*, 323, 108159



### 3. Rocking Piers

#### - Effectiveness of Geotechnical Seismic Isolation for Post-Tensioned Rocking Piers

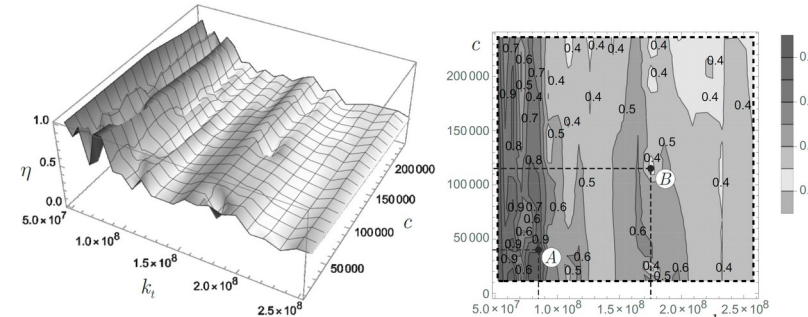
- A Rocking Pier is intended to dissipate energy during the rocking motion.
- The motion in this case is beneficial for the structure.
- Together with dampers and a prestressed tendon for recentering and dissipation Geotechnical Seismic Isolation (GSI) is added for further protection of the structure.
- It is necessary to verify if the two



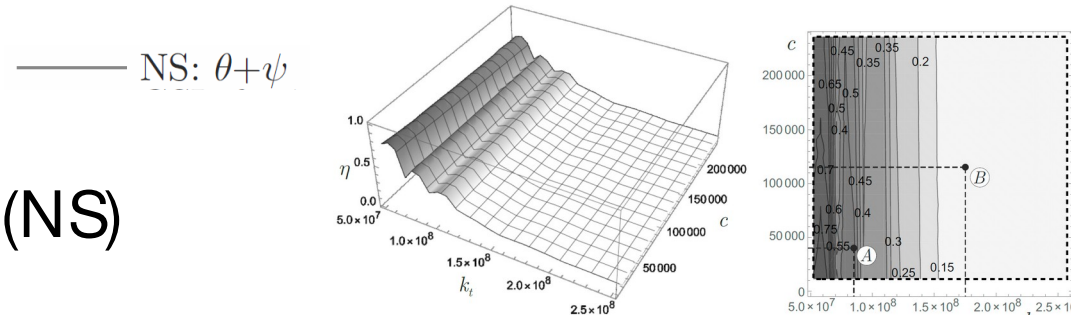
# 3. Rocking Piers

## - Effectiveness of Geotechnical Seismic Isolation for Post-Tensioned Rocking Piers

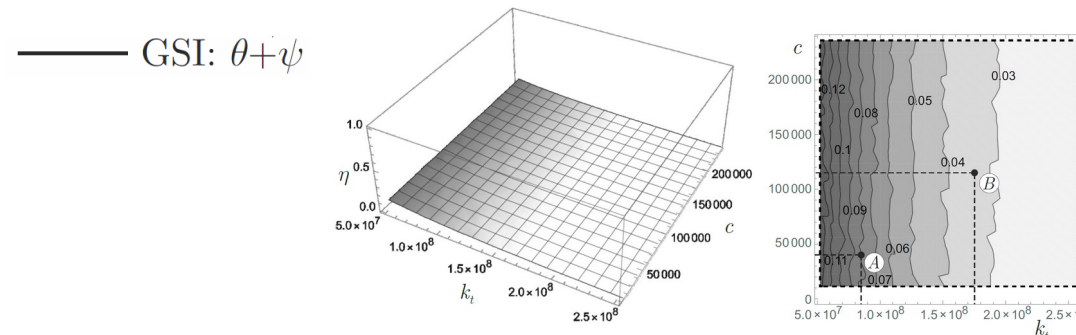
A. Stand-alone block



B. Block on Normal Soil (NS)



C. Block with GSI



-  $\eta$  performance index

$$\eta = \frac{\theta_{\text{Max}}}{\alpha_{\text{cr}}}$$

-  $\theta_{\text{Max}}$  max. rotation

-  $\alpha_{\text{cr}}$  critical angle

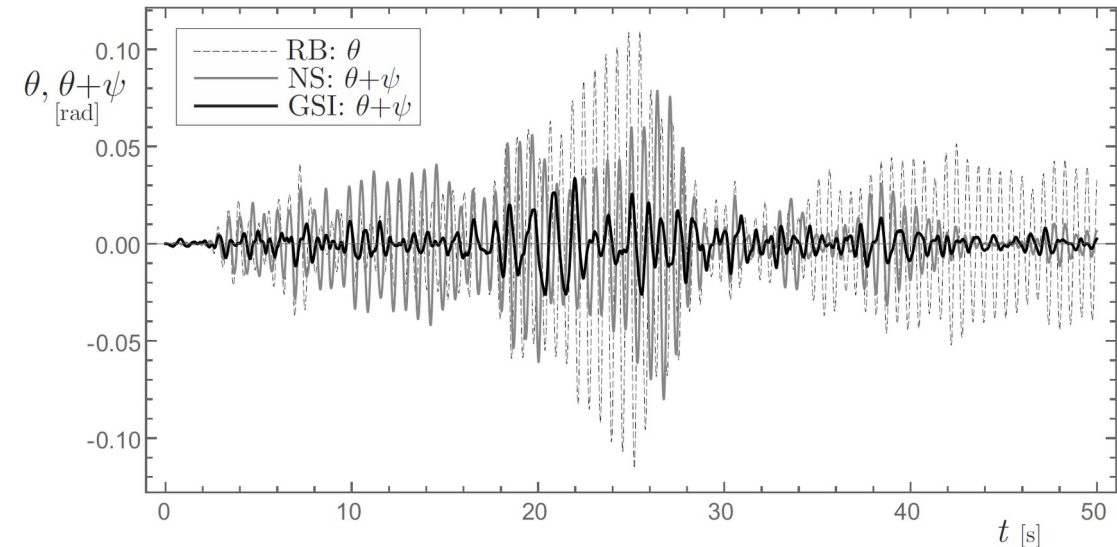
-  $k_t$  tendon stiffness

-  $c$  damping dashpots

### 3. Rocking Piers

#### - Effectiveness of Geotechnical Seismic Isolation for Post-Tensioned Rocking Piers

- The soil regularize the behavior of the pier that becomes almost independent from the dampers.
- The GSI further improves the seismic behavior and regularize it across different values.
- The GSI is more effective than the dampers and tendon.



| Algarrobo, Chile              |                       | Algarrobo, Chile              |                       |
|-------------------------------|-----------------------|-------------------------------|-----------------------|
| Natural Soil (NS)             |                       | GSI-RSM                       |                       |
| $\gamma_{s,eff}$ (%)          | 0.76                  | $\gamma_{s,eff}$ (%)          | 1.80                  |
| $\zeta_{eq}$ (%)              | 22.2                  | $\zeta_{eq}$ (%)              | 27.6                  |
| $G/G_{max}$                   | 0.054                 | $G/G_{max}$                   | 0.119                 |
| $G_{sec}$ (N/m <sup>2</sup> ) | $6.4962 \times 10^6$  | $G_{sec}$ (N/m <sup>2</sup> ) | $6.99720 \times 10^5$ |
| $k_u$ (N/m)                   | $1.24357 \times 10^8$ | $k_u$ (N/m)                   | $1.33948 \times 10^7$ |
| $c_u$ (Ns/m)                  | $3.02855 \times 10^6$ | $c_u$ (Ns/m)                  | $1.07617 \times 10^6$ |
| $k_\psi$ (Nm)                 | $9.82186 \times 10^7$ | $k_\psi$ (Nm)                 | $1.12717 \times 10^7$ |
| $c_\psi$ (Nms)                | $1.77206 \times 10^6$ | $c_\psi$ (Nms)                | $7.09345 \times 10^5$ |

# 4. Pile-Isolation System

## - Damping pre-hole technology for IABs

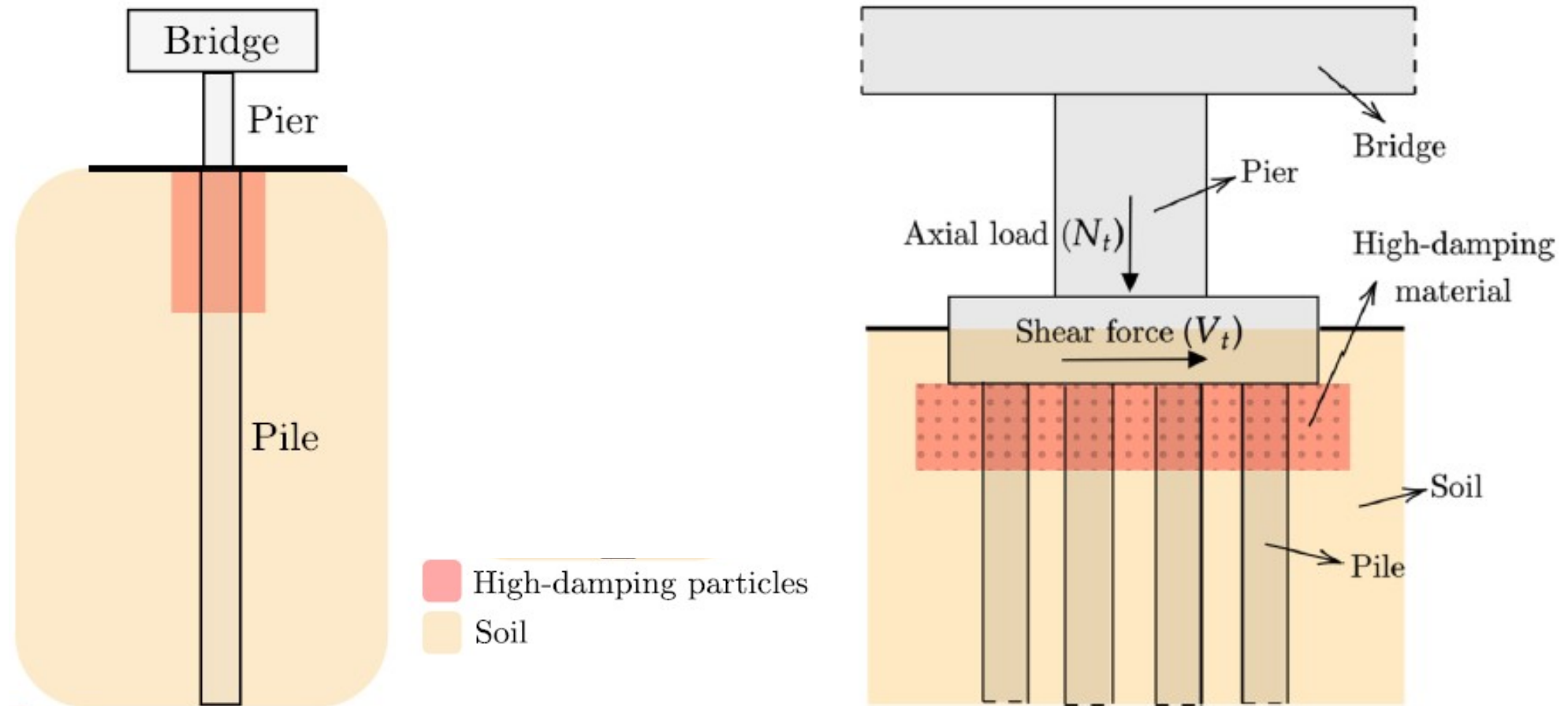
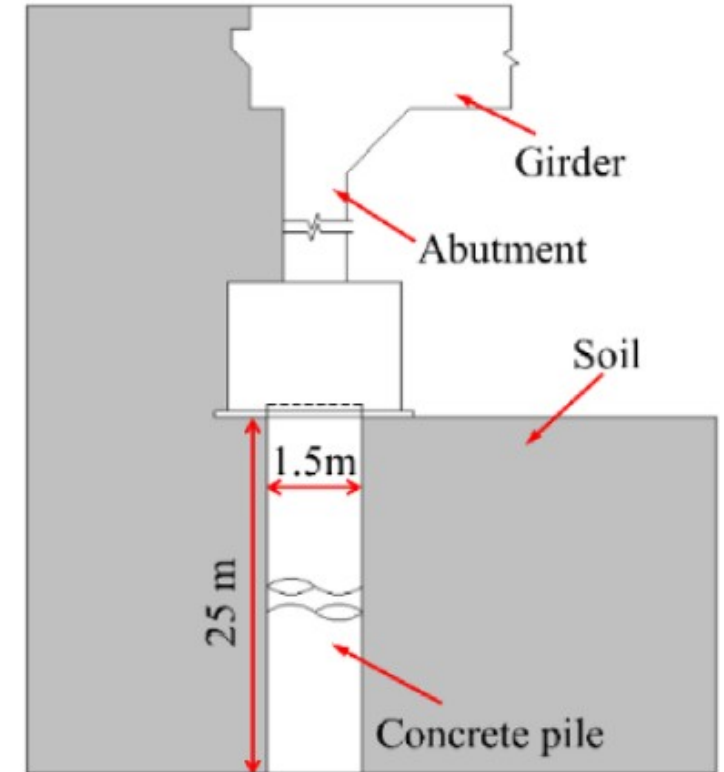


Illustration of the damping pre-hole technology for IABs

# 4. Pile-Isolation System

## - Application to a Case Study

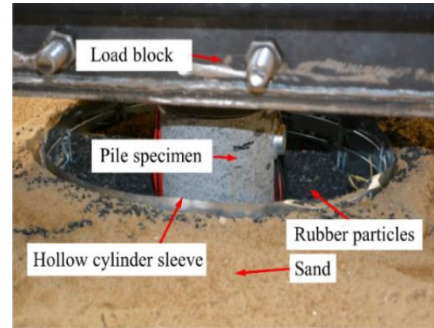
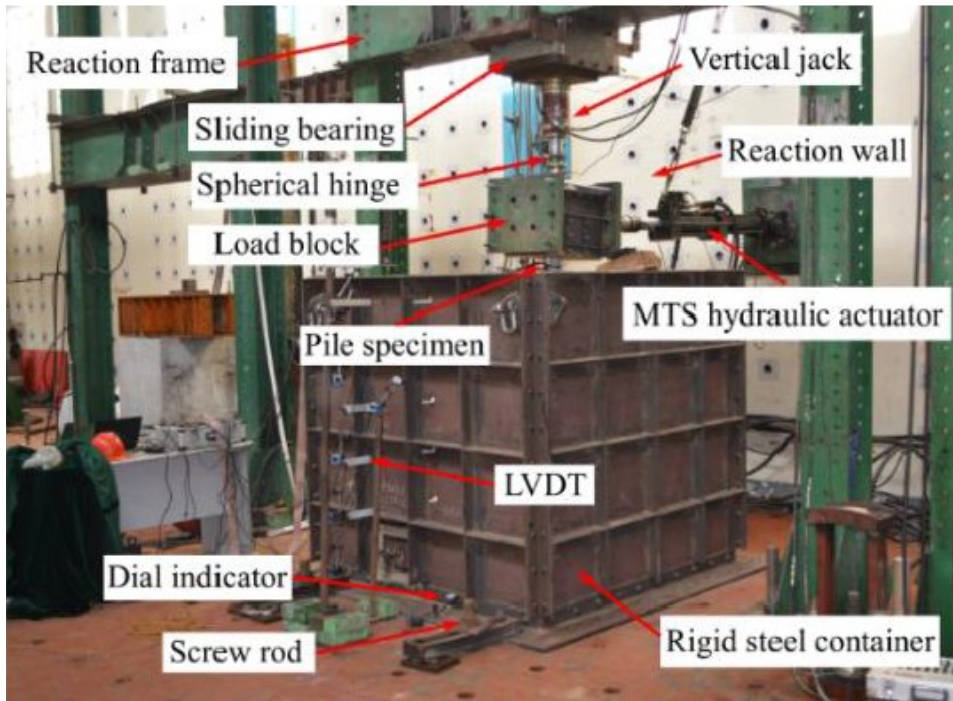


Maluanshan bridge (Shenzhen,  $L=3\times30$  m): (a) overall view of IAB, (b) details of integral abutment and pile

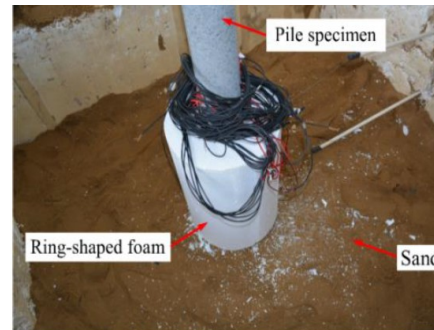


# 4. Pile-Isolation System

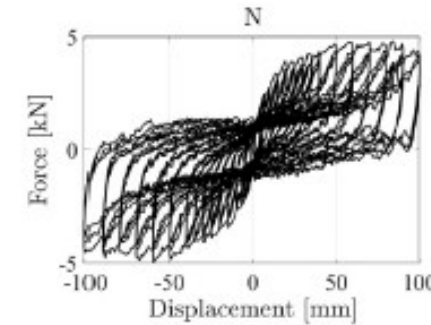
## - Experimental tests



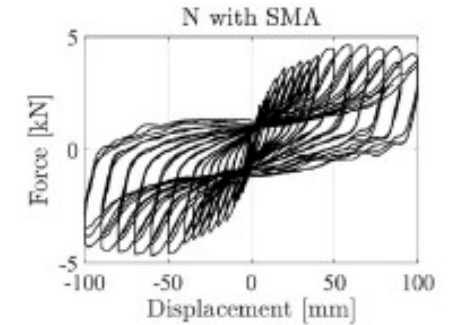
(a)



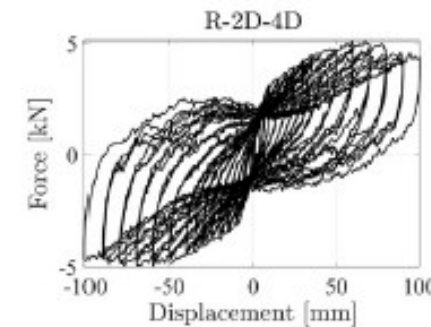
(b)



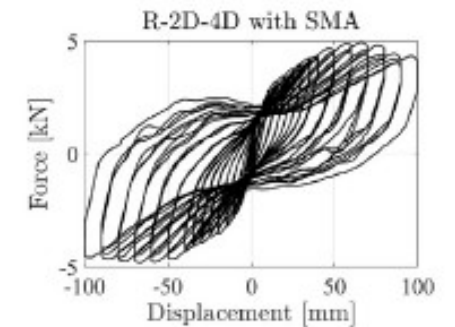
(a)



(b)



(c)



(d)

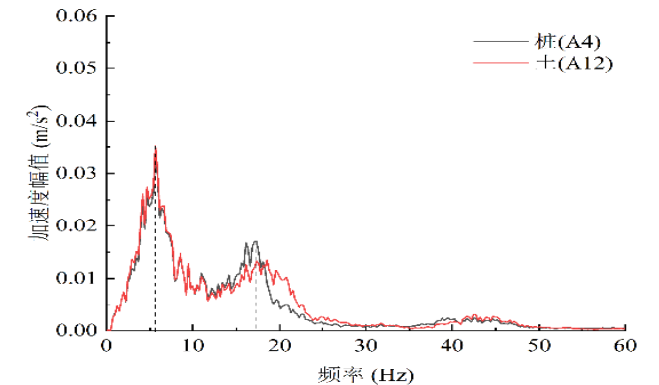
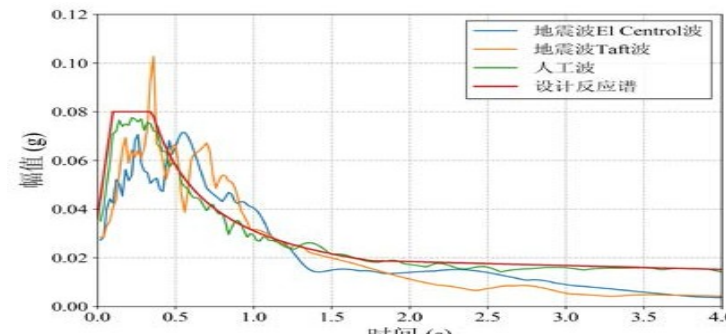
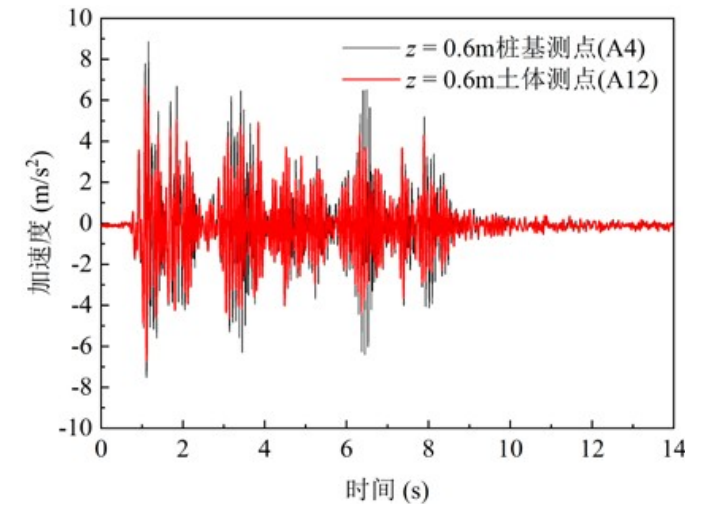
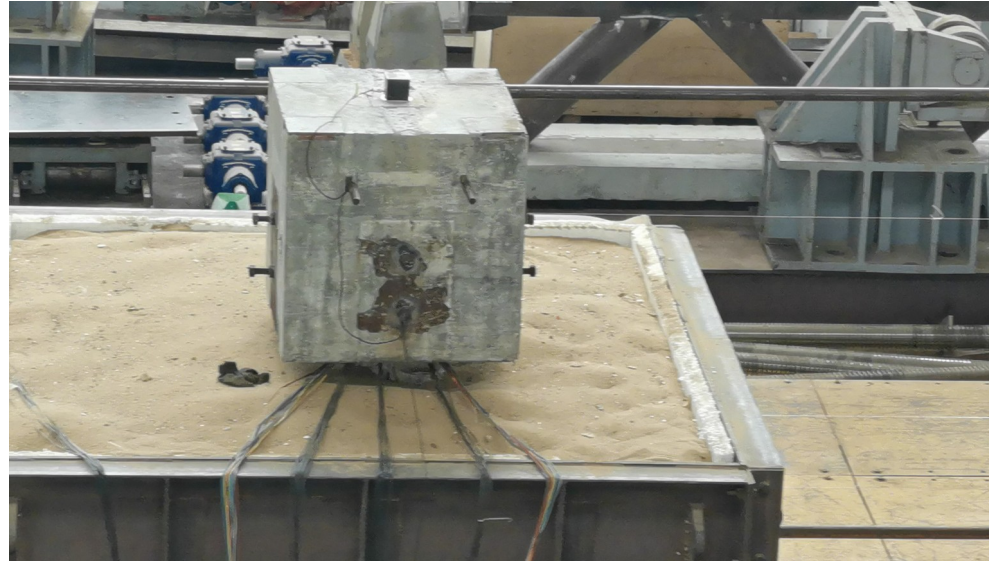
Test Setup and specimens. Filling material installation: (a) hollow cylinder sleeve and rubber particles, (b) ring-shaped foam

Experimental cyclic response of the tested specimens



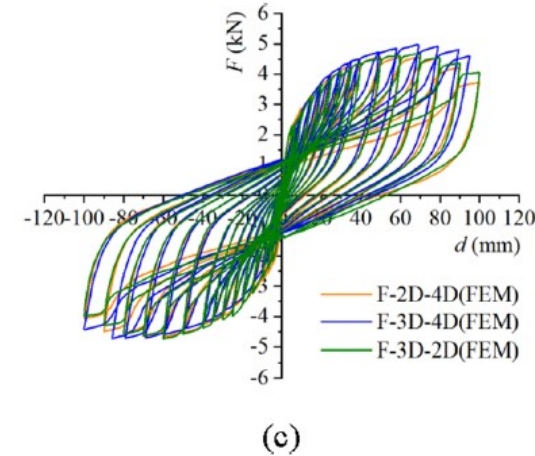
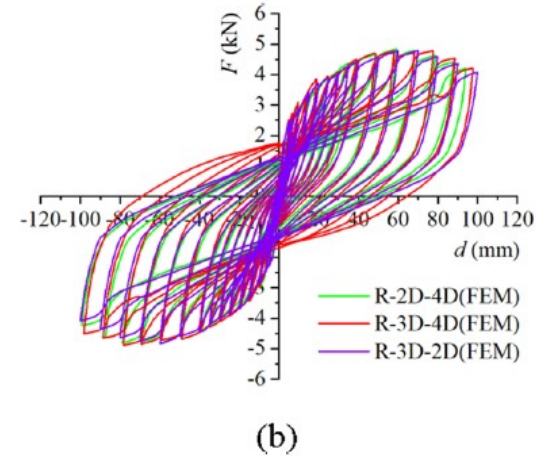
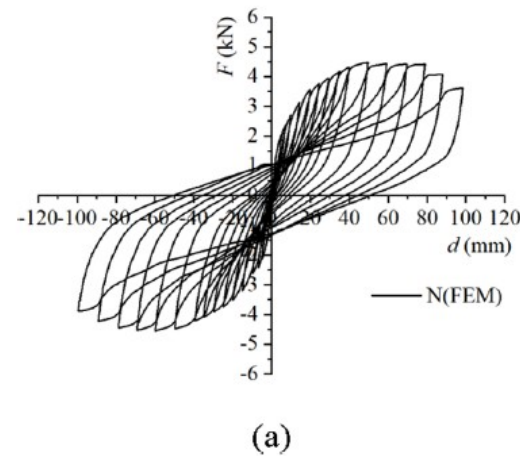
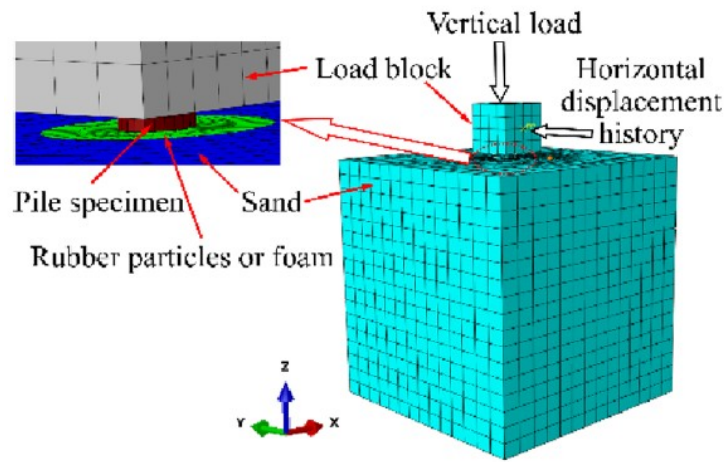
# 4. Pile-Isolation System

## - Experimental tests



# 4. Pile-Isolation System

## - Numerical Analyses. FEM in Abaqus



## - P-y Curves

$$P = \frac{y}{\frac{1}{k^*} + \frac{y}{BP_u^*}}$$

$$k^* = AK_h d_s$$

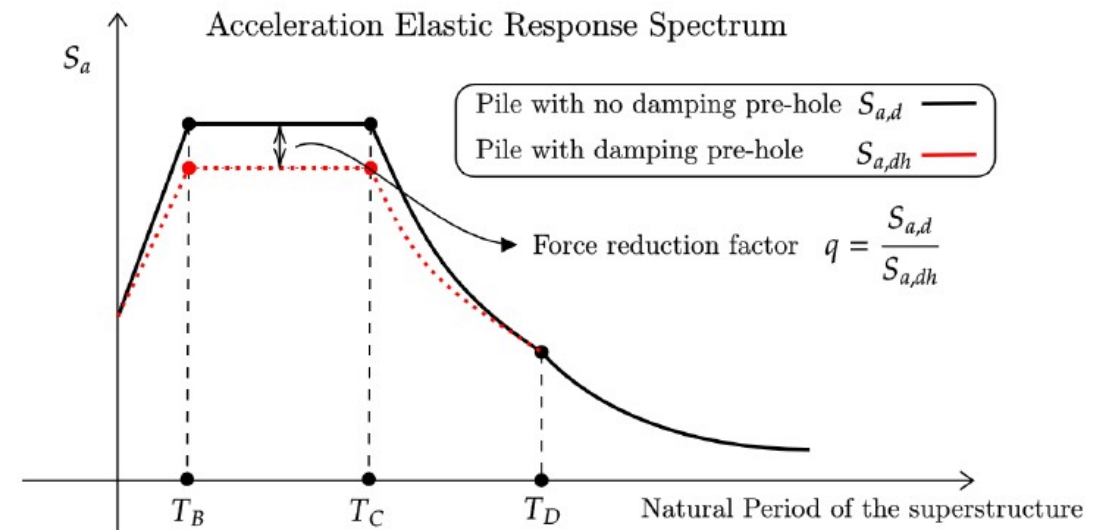
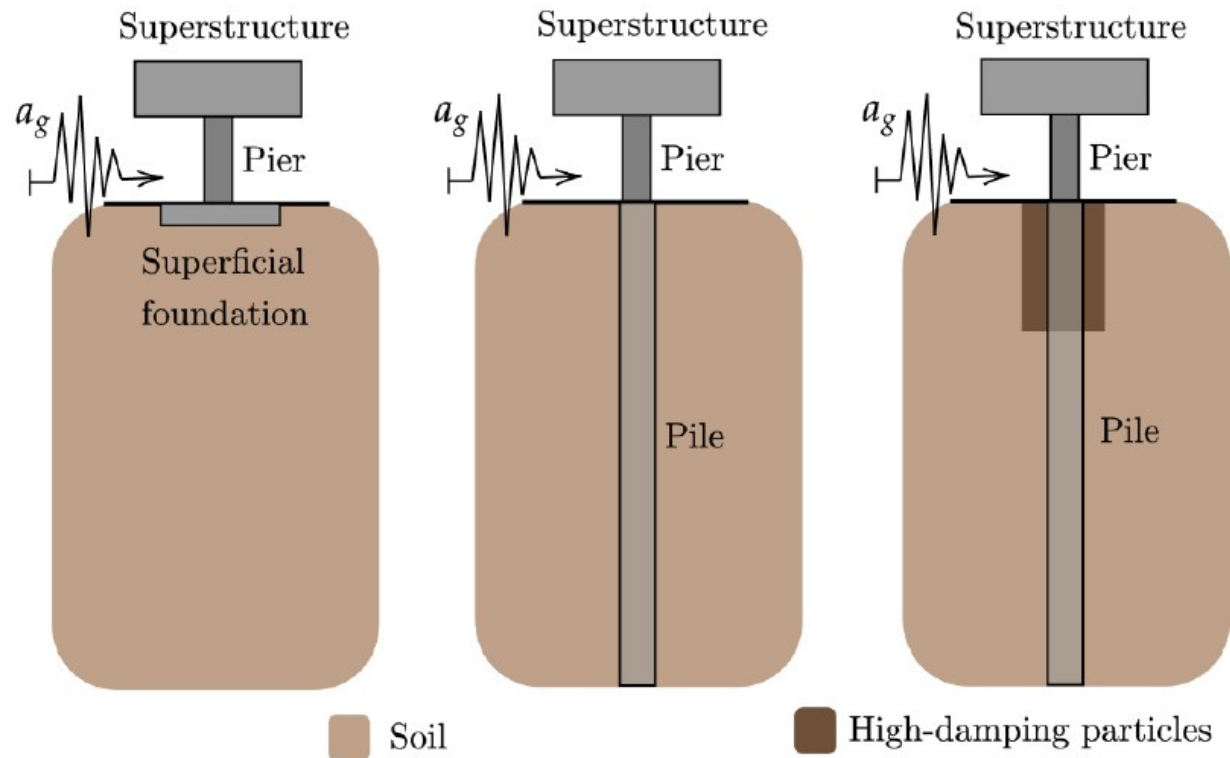
$$P_u^* = 2K_p \gamma' d_s^{1.38n} D$$

where  $A$  is the reduction factor of  $K_h$ , which is the average  $K_{hP}/K_{hN}$ ;  $B$  is the reduction factor of  $P_u$ , which is the average  $P_{uP}/P_{uN}$ ;  $k^*$  and  $P_u^*$  are the modified initial horizontal subgrade modulus and the ultimate soil resistance, respectively.



# 4. Pile-Isolation System

## - Effect of pre-hole with damping material on the inelastic response



(a) The three structural archetypes: a superficial foundation, a non-dissipative pile foundation, and a dissipative pile foundation and (b) Inelastic response spectra and the force reduction factor

Aloisio, A., Pellicciari, M., Xue, J., Fragiaco, M., Briseghella, B. (2023). Effect of pre-hole filled with high-damping material on the inelastic response spectrum of Integral Abutment Bridges. *Journal of Earthquake Engineering*, 27 (12), 3319–3340

# 4. Pile-Isolation System

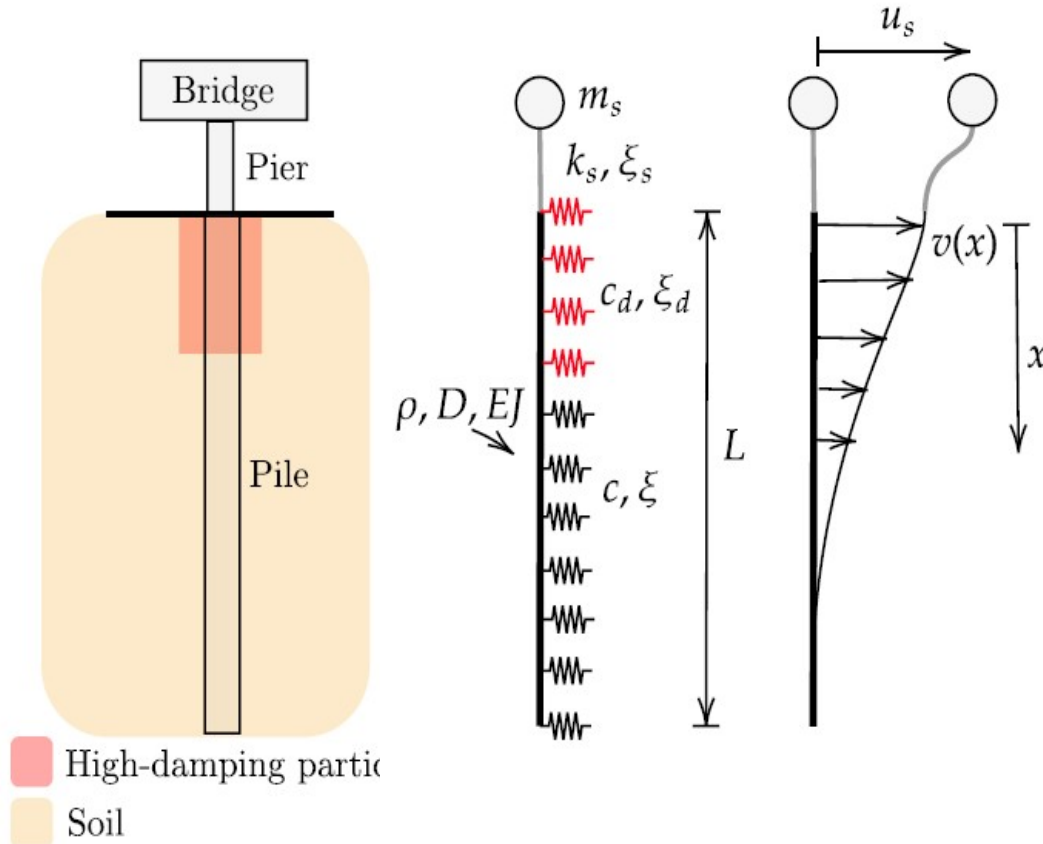
## - Probabilistic formulation for q-factor

Physical and mathematical models of the considered IAB archetype:

The probabilistic model obtained using the Bayesian regression is:

$$\hat{q}(\mathbf{x}) = \theta_3 D + \theta_{11} D^2 + \theta_{12} c^2 + \theta_{20} L \xi_d + \theta_{27} D c + \theta_{35} \xi \frac{L_d}{L} + \theta_{39} D^{-1} + \theta_{40} c^{-1} + \theta_{50} \sqrt{\frac{L_d}{L}} + \sigma \varepsilon.$$

The results of the model selection and calibration show that the **diameter of the pile** and the **subgrade stiffness** are the most significant predictors for  $\hat{q}$ .

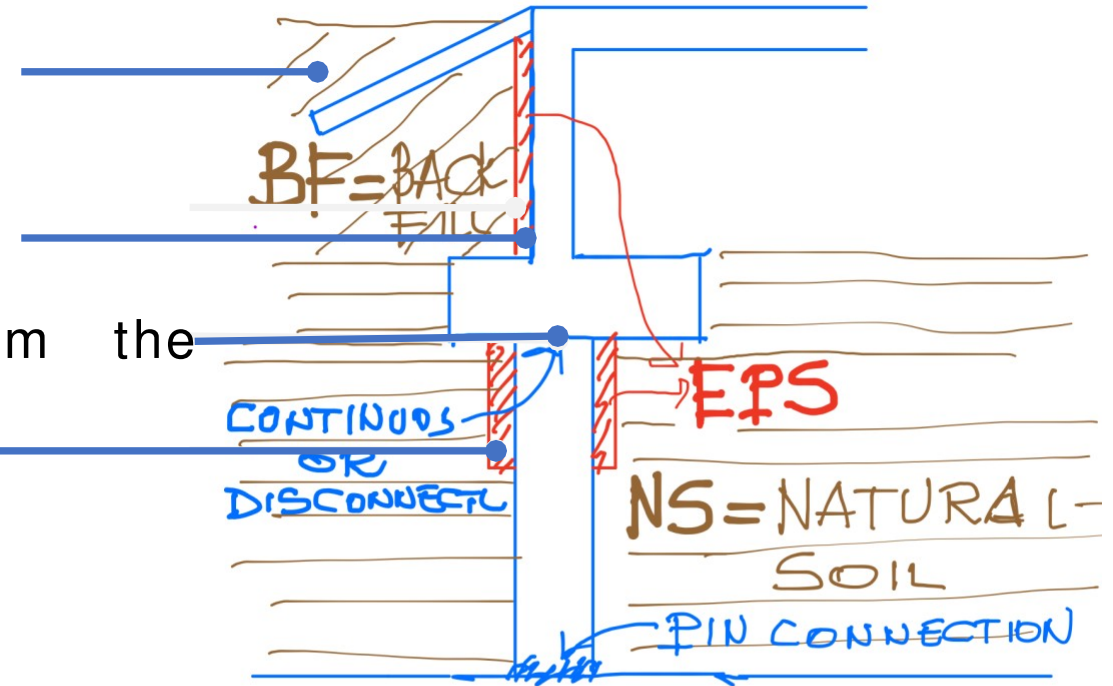




# 5. Novel Integral Abutment Bridges

## - Main Concept

- a) Backfill with shredded tyres – sand mixtures and geotextile
- b) EPS Geofoam placed between the abutment wall and the backfill
- c) Pile head connected/disconnected from the foundation
- d) Pile pre-hole with EPS Geofoam

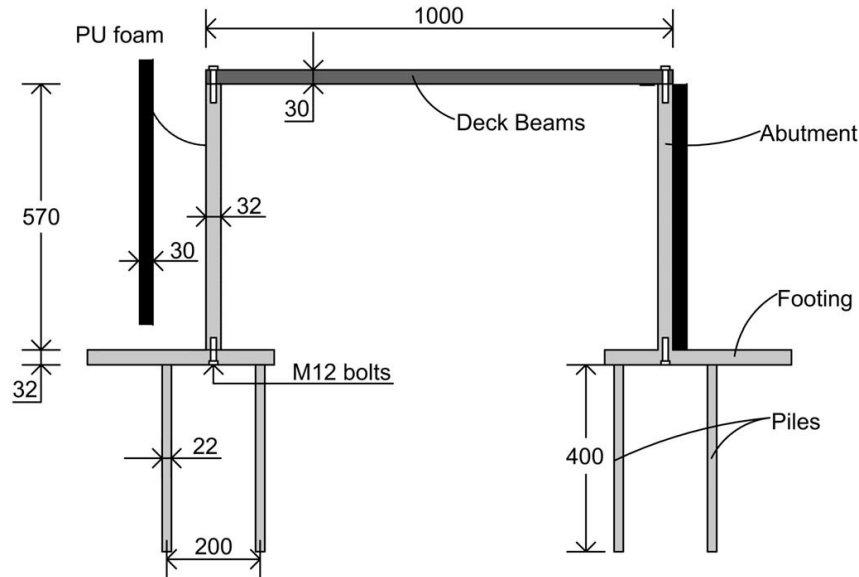


Research project: SERA - H2020 - INFRAIA-2016-2017/H2020-INFRAIA-2016-1; Members: Roma Tre University (Italy), Technische Universitaet Kaiserslautern (Germany), Universidade do Porto (Portugal), University of Ljubljana (Slovenia), Fuzhou University (China); TA Facility: EQUALS – University of Bristol



# 5. Novel Integral Abutment Bridges

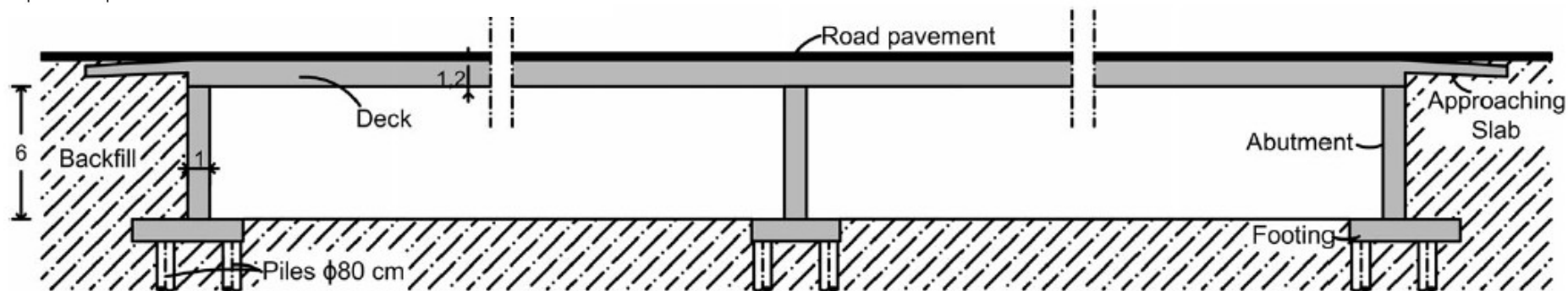
## - Shaking Table Tests. EQUALS Bristol



Dimensions: 3m x 3m  
Degrees Freedom: 6 DOF  
Max payload: 15 tonnes  
Horizontal displac.:  $\pm 150\text{mm}$

Box internal dimensions:

- 4.8 m long
- 1.2 m height
- about 1 m wide



Fiorentino, G.,.....Briseghella, B.,....., Sextos, A., Nuti, C. (2021). Integral abutment bridges: Investigation of seismic soil-structure interaction effects by shaking table testing. *Earthquake Engineering and Structural Dynamics*, 50 (6), 1517-1538

# 5. Novel Integral Abutment Bridges

## - Shaking Table Tests. Different Configurations



- **Configuration 1.** 6 cm PU (Polyurethane) foam and piles **connected**



- **Configuration 2.** 3 cm PU (Polyurethane) foam and piles **connected**



- **Configuration 3.** **NO** PU (Polyurethane) foam and piles **connected**



- **Configuration 4.** **NO** PU (Polyurethane) foam and **NO** piles **connected**

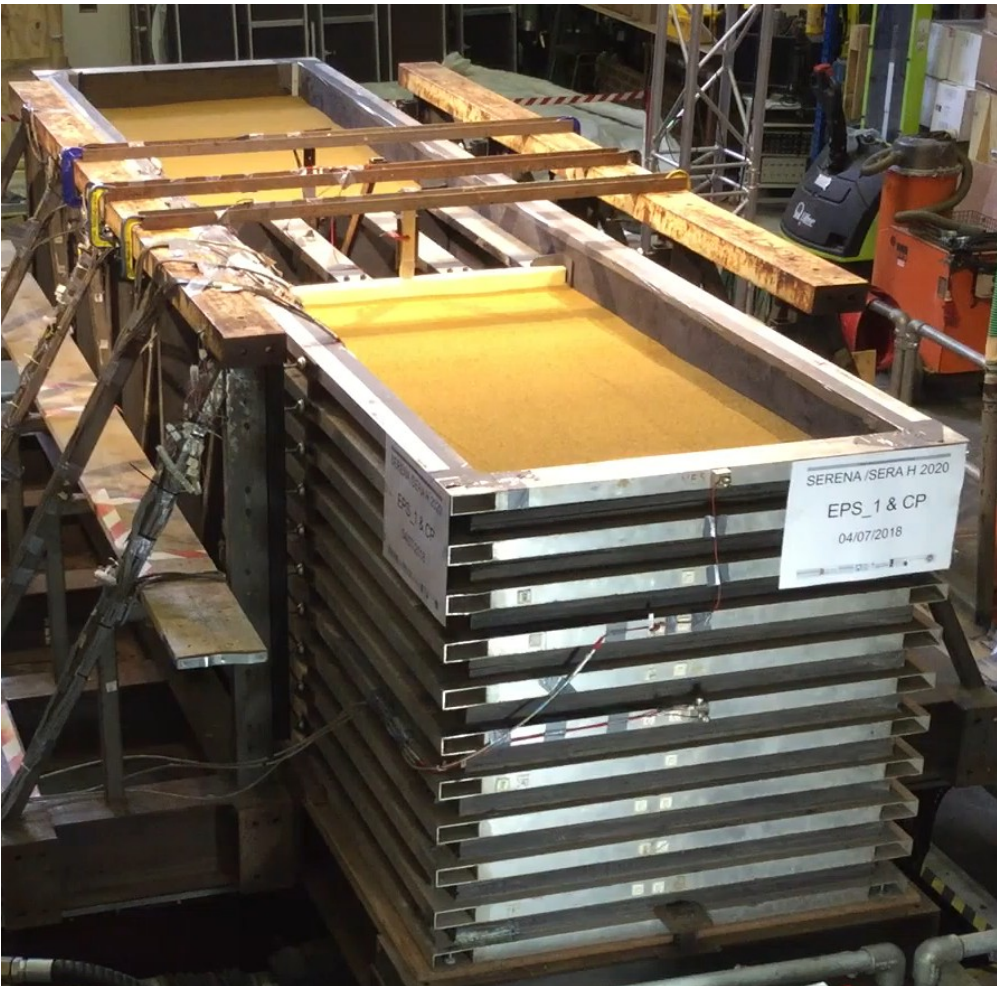


- **Configuration 5.** 3 cm PU (Polyurethane) foam and **NO** piles **connected**

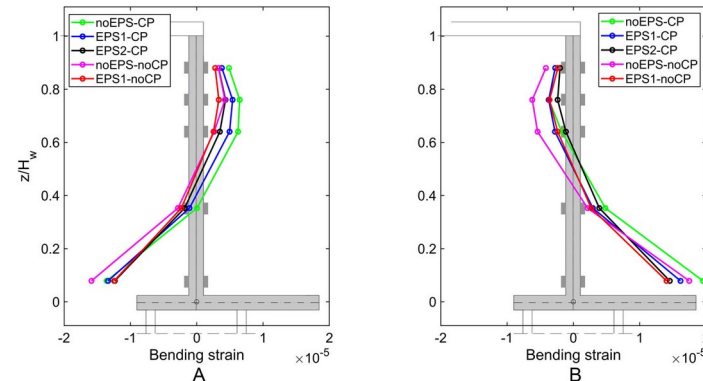


# 5. Novel Integral Abutment Bridges

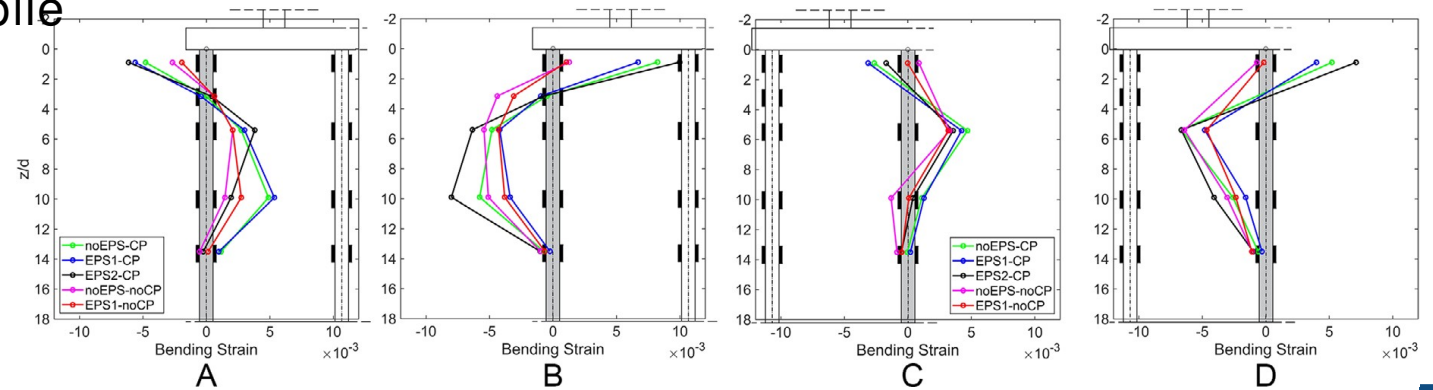
## - Shaking Table Tests. EQUALS Bristol



**Abutment Wall:** A, Maximum; and B, minimum bending strain on the abutment wall



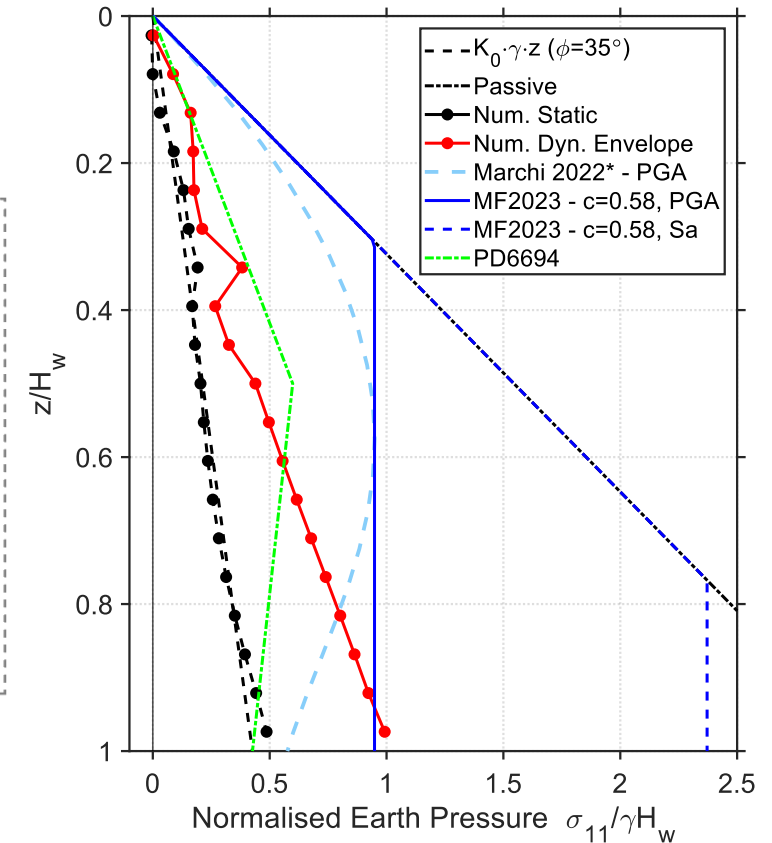
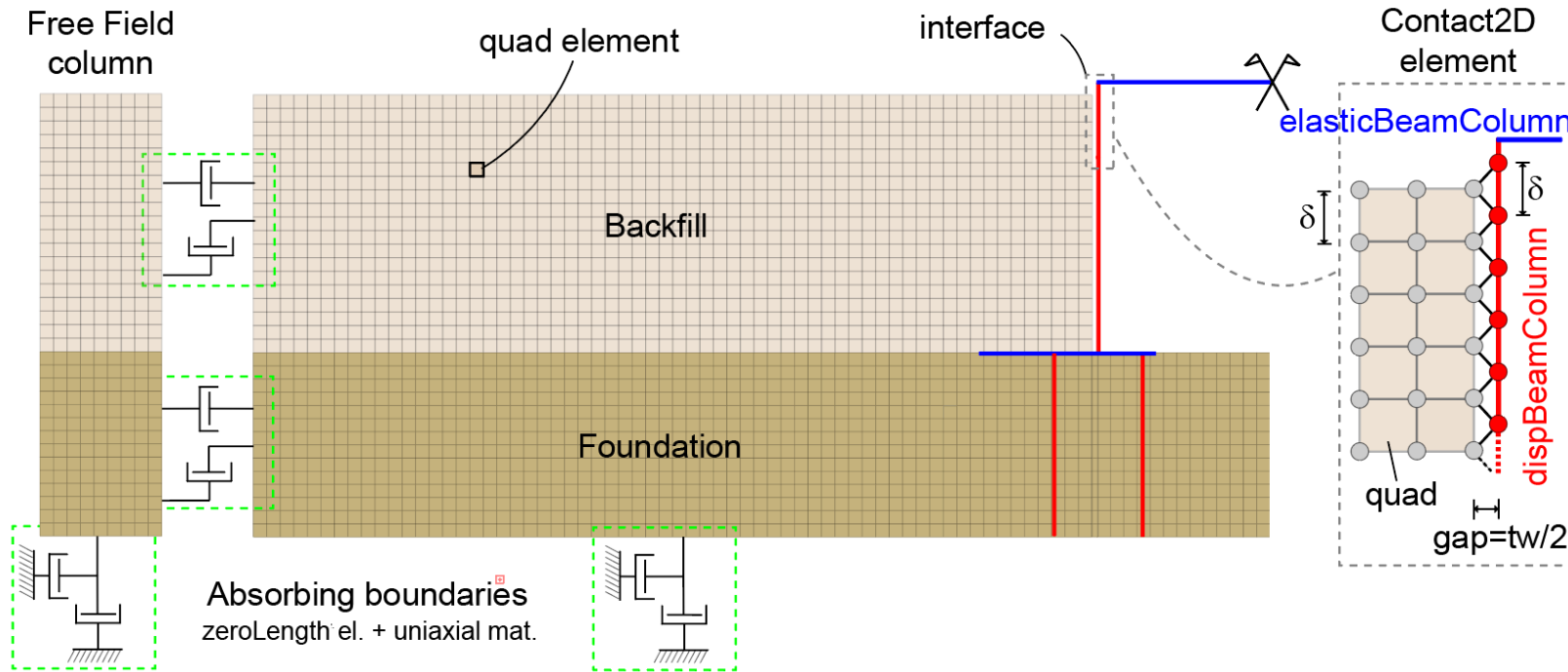
**Piles:** A, Maximum, and B, minimum pile bending strain on the East pile; C, maximum, and D, minimum pile bending strain on the West pile





# 5. Novel Integral Abutment Bridges

## - Numerical Simulation



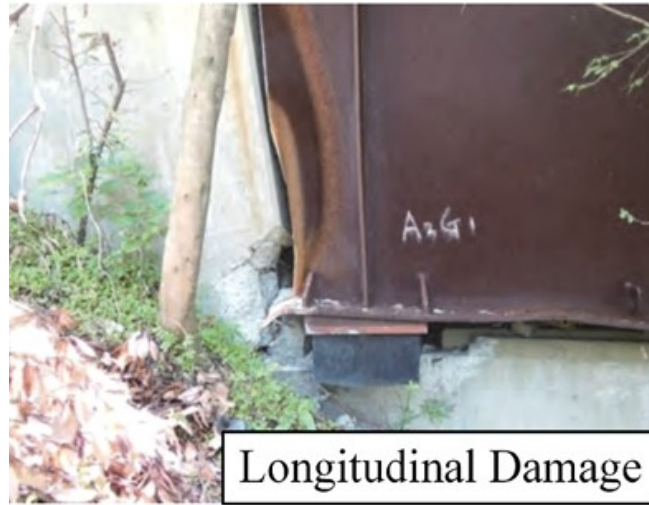
2D Finite Element model implemented in OpenSees/STKO wall

Earth pressures behind the abutment

Fiorentino, G., De Risi, R., De Luca, F., Mylonakis, G., Briseghella, B., Nuti, C., Sextos, A. (2024). SSI-induced seismic earth pressures on an Integral Abutment Bridge model: experimental measurements vs numerical simulations and code provisions. *Earthquake Engineering and Structural Dynamics*, 53 (14),

# 6. Deck Pounding

## - Seismic Pounding Damage



## 6. Deck Pounding

### - Open Issues

- Conventional analysis does not adequately capture the highly coupled interaction among the deck, backwall, and surrounding backfill soil that governs seismic pounding between bridge decks and seat-type abutments.
- Backwall design philosophy: a) in North American practice, the backwall is treated as a sacrificial component that slides horizontally under seismic demand, mobilizing passive earth pressure approximately uniformly over its height; b) in contrast, Eurocode 8 Part 2 requires a ductile backwall that develops a flexural plastic hinge at its base, producing a non-uniform displacement profile and depth-dependent backfill engagement.

## 6. Deck Pounding

### - Open Issues

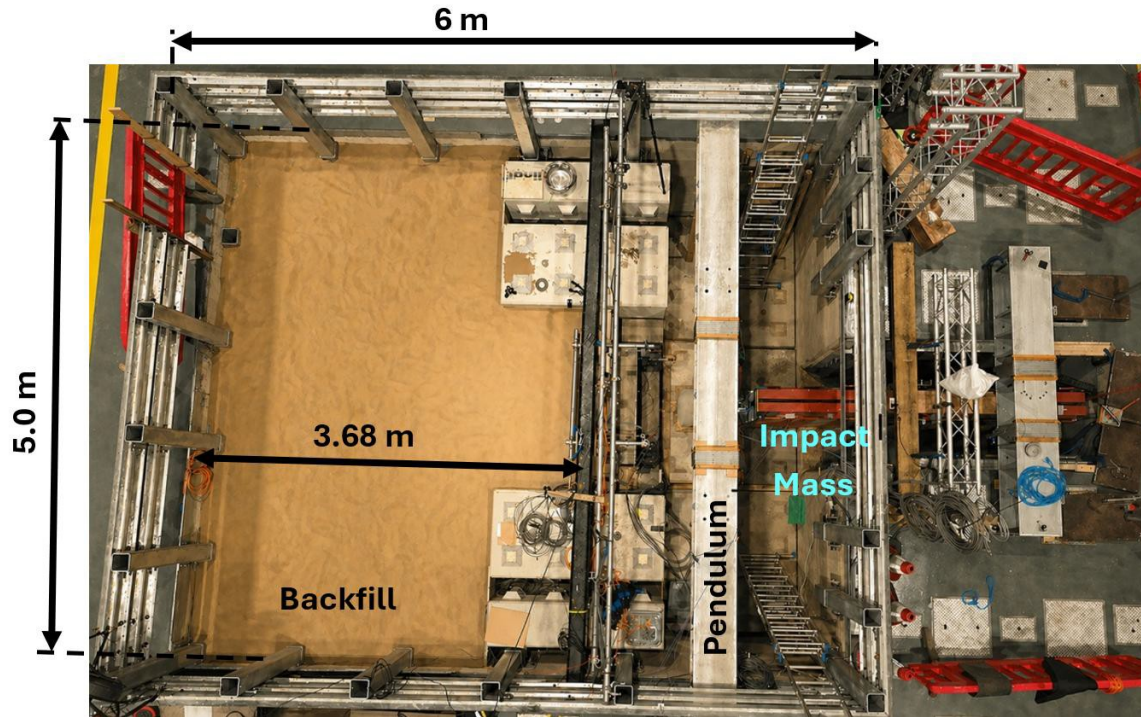
- Conventional analysis does not adequately capture the highly coupled interaction among the deck, backwall, and surrounding backfill soil that governs seismic pounding between bridge decks and seat-type abutments.
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- ERIES PoundBack2 project: a large-scale experimental investigation of seismic deck–abutment pounding conducted at the SoFSI facility, University of Bristol (UK).



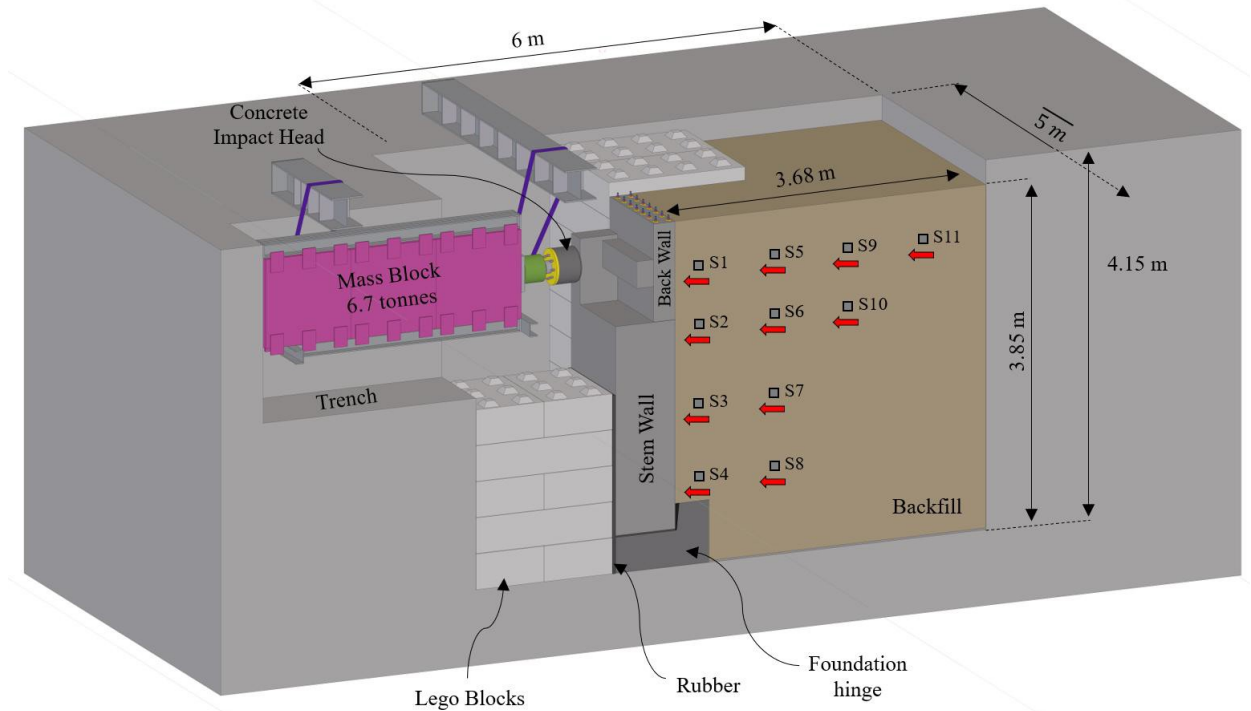


## 6. Deck Pounding

### - Experimental Setup (SoFSI-Soil Pit facility at Bristol University)



Geotechnical pit: 6x5x4(depth)



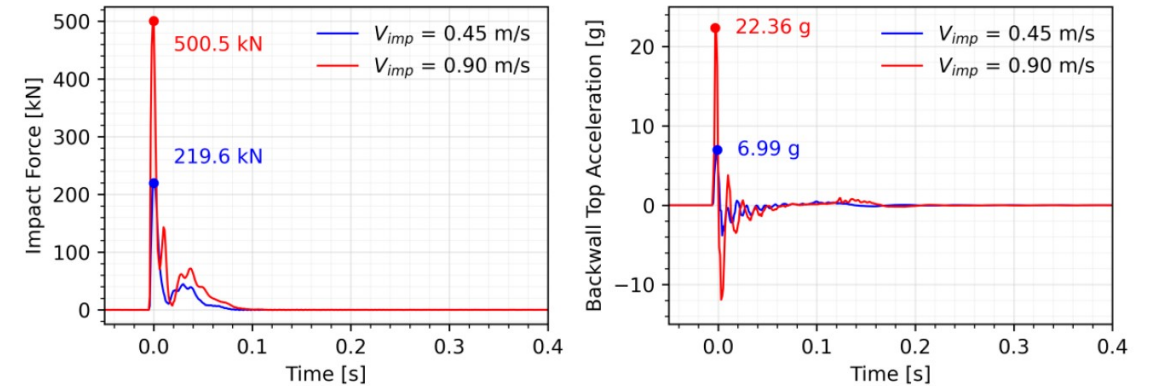
View of the experimental setup and

The ERIES PoundBack2 project is the first: a) to study pounding on a specimen that explicitly incorporates a full-height compacted backfill; b) to directly compare sliding-shear sacrificial and monolithic flexural backwall configurations.

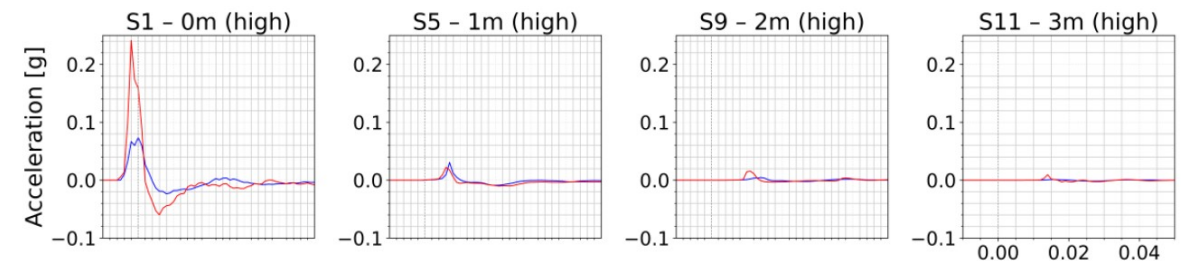
Gokce, T., et al. (2026). Influence of backwall-stemwall damage on deck-abutment-backfill interaction under seismic pounding. *18th European Conference on Earthquake Engineering (ECEE2026)*

# 6. Deck Pounding

## - Tests Results



Impact force and backwall top acceleration



Backfill acceleration time histories

## 7. Conclusions

- This research advances next-generation bridge seismic protection through innovative foundation-level isolation techniques.
- A novel dual-step procedure, combining the Distinct Element Method with Preisach formalism, efficiently balances accuracy and computational cost for GSI-protected bridges while addressing soil uncertainties.
- Geotechnical Seismic Isolation using a Rubber-Soil Mixture enhances bridge resilience by stabilizing critical foundation responses.
- Applying GSI to Post-Tensioned Rocking Piers reveals a powerful synergy: it improves seismic response and reduces performance sensitivity to key parameters, enabling more robust, predictable behavior.
- Advanced application of GSI to Integral Abutment Bridges enhances resilience without compromising durability.
- Together, these findings offer engineers validated structural systems, probabilistic tools, and efficient analysis methods for designing predictably more resilient bridges.



# 5<sup>th</sup> International Bridge Seismic Workshop (5IBSW)

## Changsha, May 5-8, 2026

谢谢 thank you! grazie!

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