SERA Seismology and Earthquake Engineering Research Alliance for Europe

UNIVERSITÀ DEGLI STUDI DI TRENTO

PRESENTATION ON SEISMIC METAMATERIALS

METAMATERIAL-based Foundation system

Optimization in the frequency domain & Experimental evaluation

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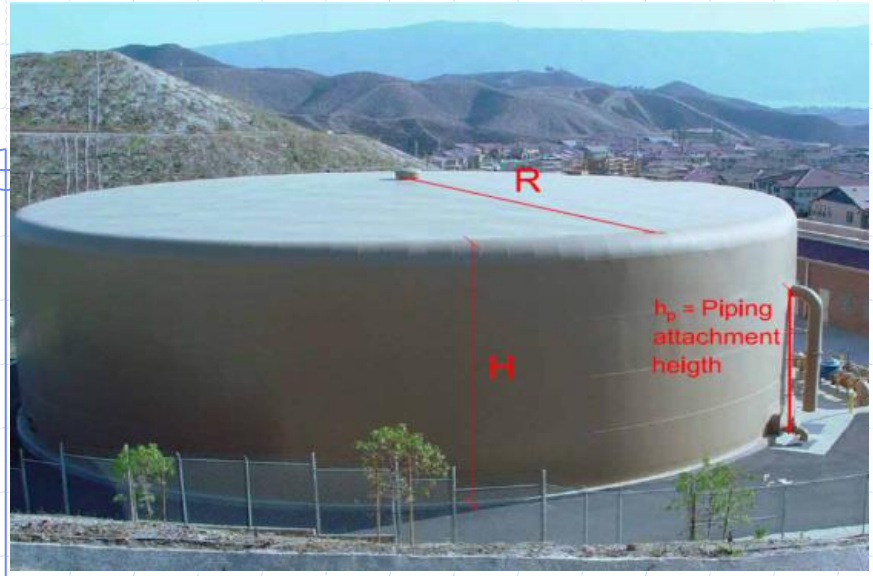
XP-resilience

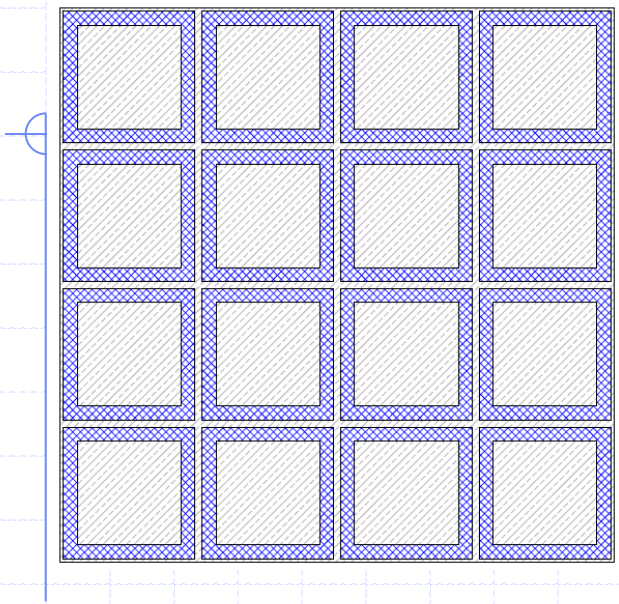
Motivation

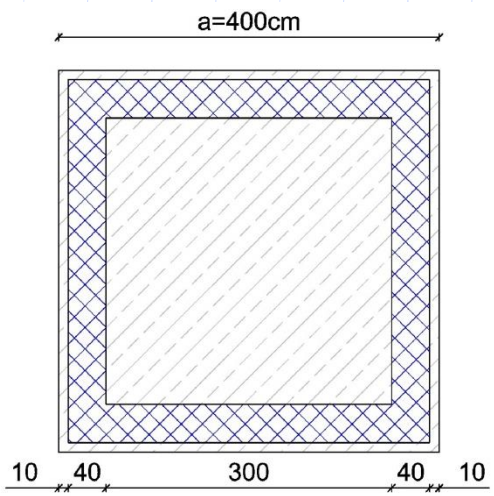


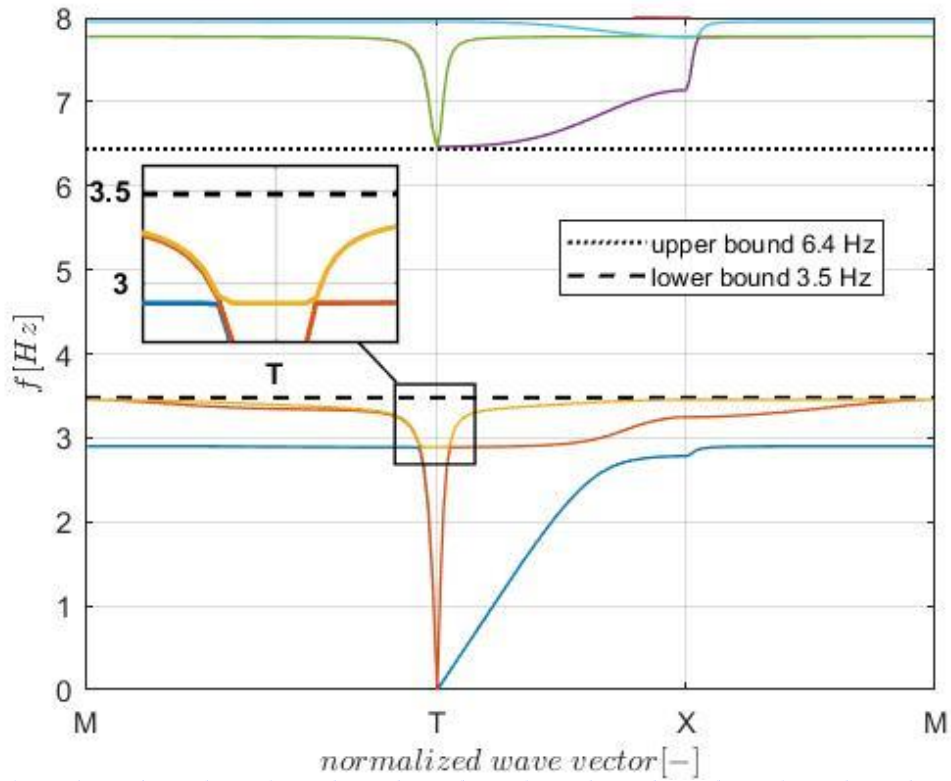
Aspirations:

- Protection of high-risk large structures
- No "Device" is needed
- Vertical component damping
- Simplification of design process
- Damping of multiple frequencies
- Reduction of Stresses and Displacements in attached Piping systems

Locally Resonant Metamaterial



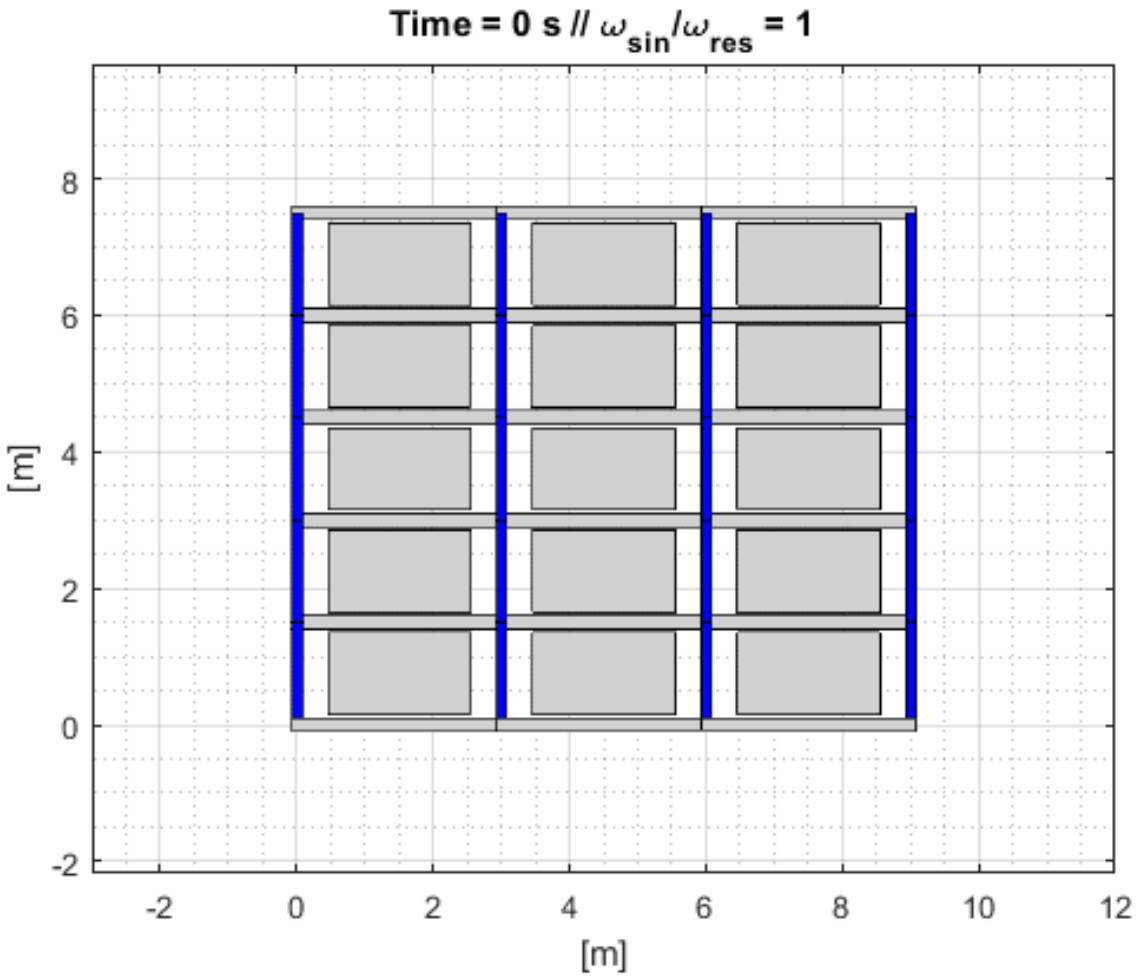




Bandgap behavior

- Elastic waves cannot propagate
- Infinite array of unit cells

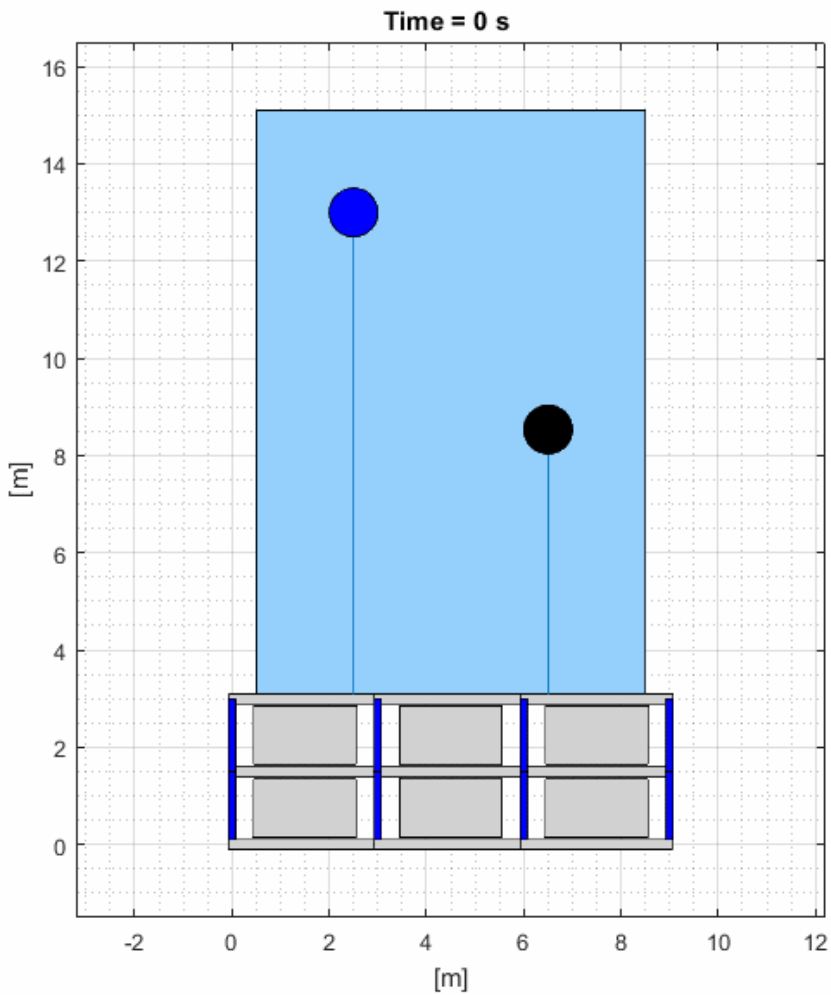
Locally Resonant Metamaterial

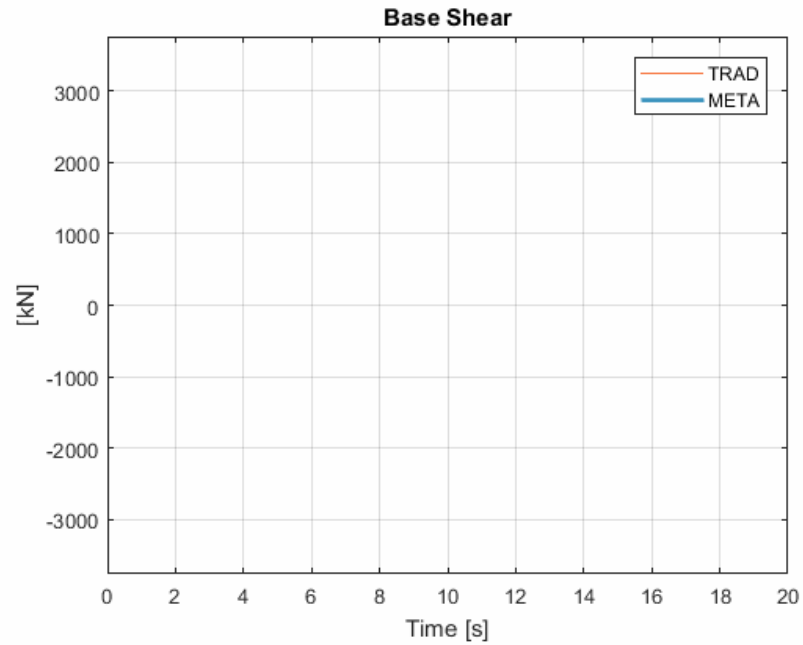


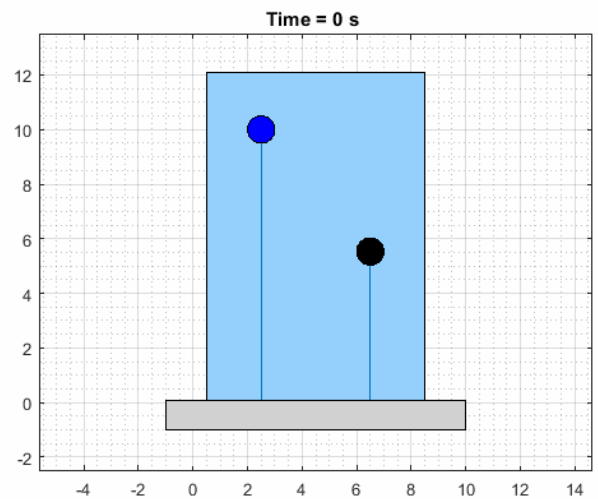
Bandgap behavior

- Elastic waves cannot propagate through the Material
- Wave attenuation when reaching the steady state
- Uncoupled finite material
- Reduction of the Stresses and Displacements at the top

Coupled Structure



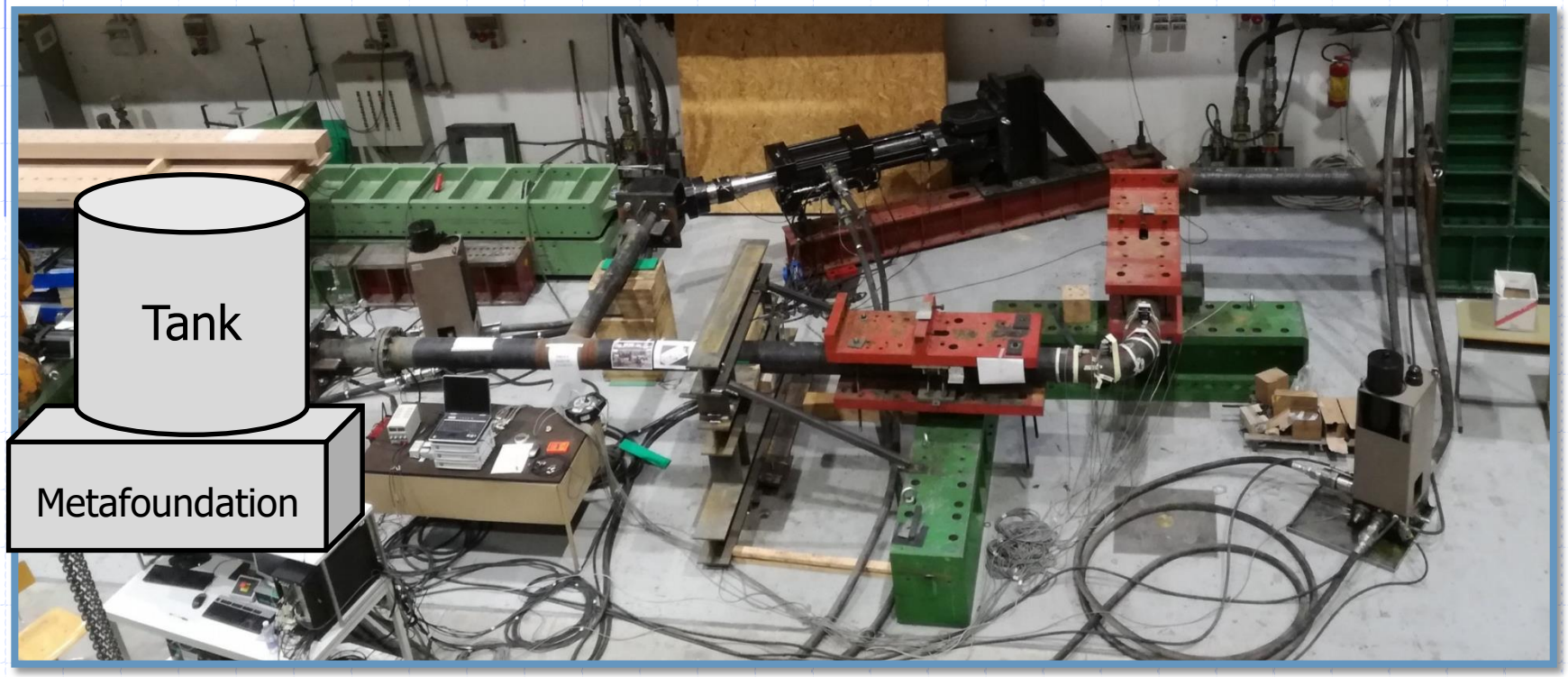




Experimental evaluation

Experimental evaluation of piping strains

- Hybrid Simulation
- Tank-foundation system as Numerical Substructure
- Piping Set-up as Physical substructure
- Critical Elbow Strains



Hot Topics

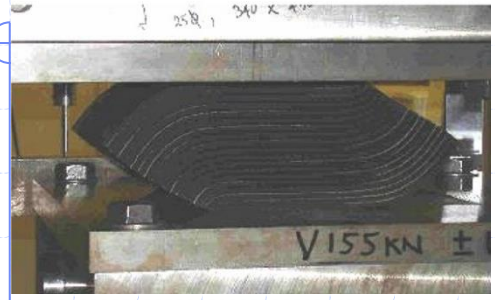
Table of Content

Petrochemical Plants

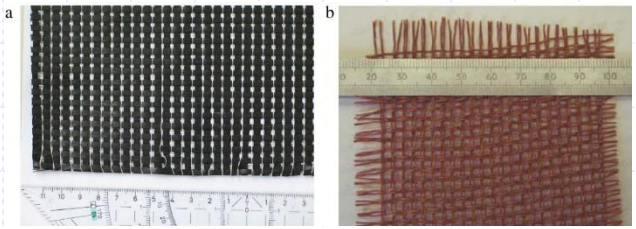
- Variable liquid level -> variable impulsive frequencies
- Danger of Domino-Effect

SOME SOLUTIONS

Isolation of new tanks

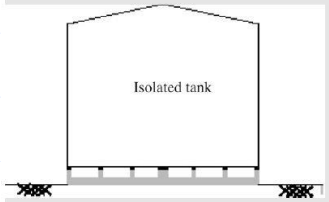


490x490x150 mm rubber bearing with 24 fibre layers and shear modulus 0.45 or 1.02 MPa



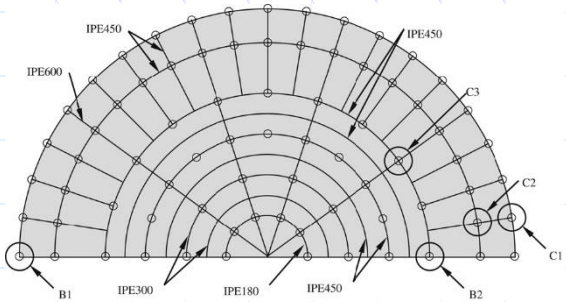
Rubber bearings with interposed bi-directional carbon fibre fabric (a) and twisted bi-directional glass fibre fabric (b)

Main properties of the investigated tank



Stored product	Water
Diameter (m)	24.4
Height (m)	18.3
Volume (m^3)	8560
Ratio height / diameter	0.75 (mean)
Roof type	fixed
Design code	API 650
Year of construction	1986
Roof thickness	8 mm
Lateral shell thickness	18–7 mm variable
Bottom plate thickness	10 mm

Numerical Analysis on a liquid storage tank [1]



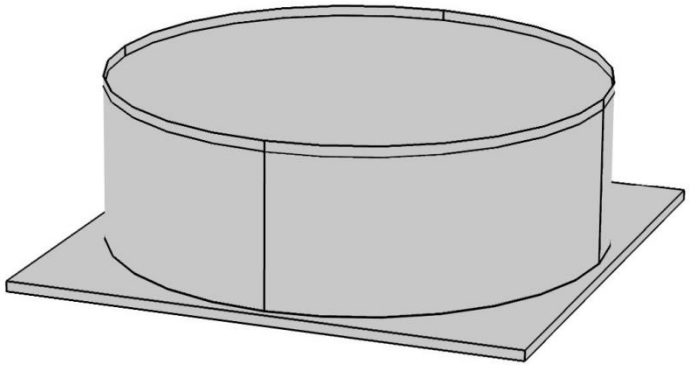
Complicate configuration of the bottom load carrying system

Modal Analysis

	Without isolation	With isolation
Sloshing Mass Frequency [Hz.]	0.18	0.18
Impulsive Mass Frequency [Hz.]	4.74	0.64

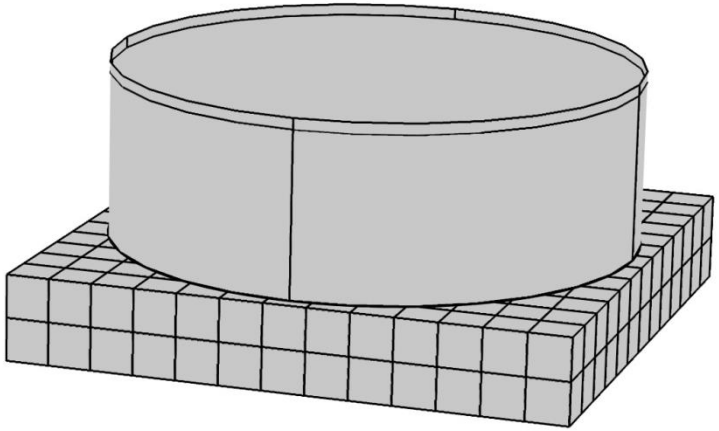
[1] A. Mordini, A. Strauss, An innovative earthquake isolation system using fibre reinforced rubber bearings, Engineering Structures 30 (2008)

Traditional Foundation



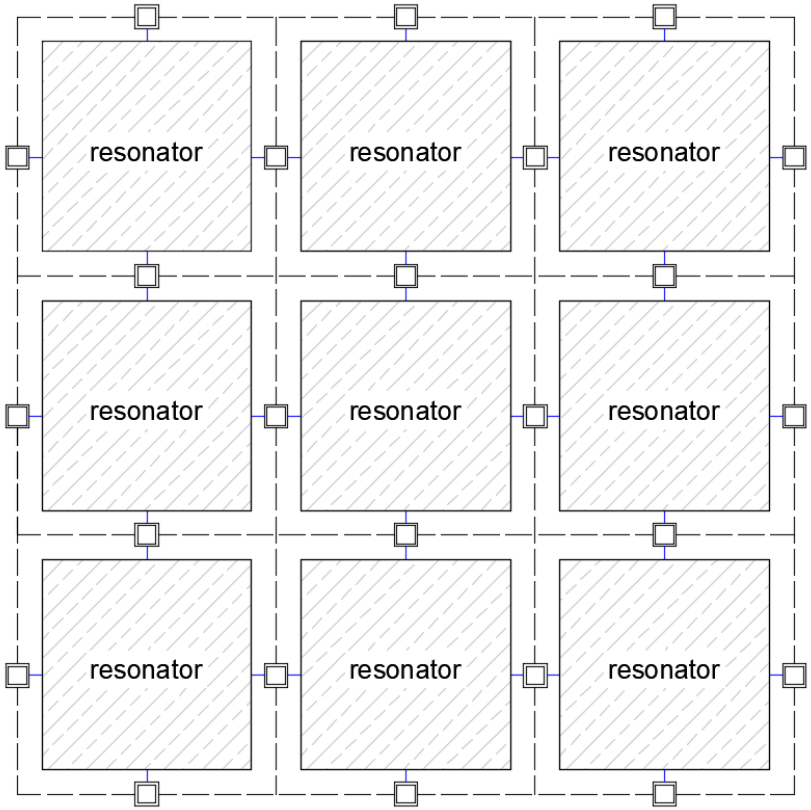
- Concrete baseplate
- Compacted ground
- Usually no isolation

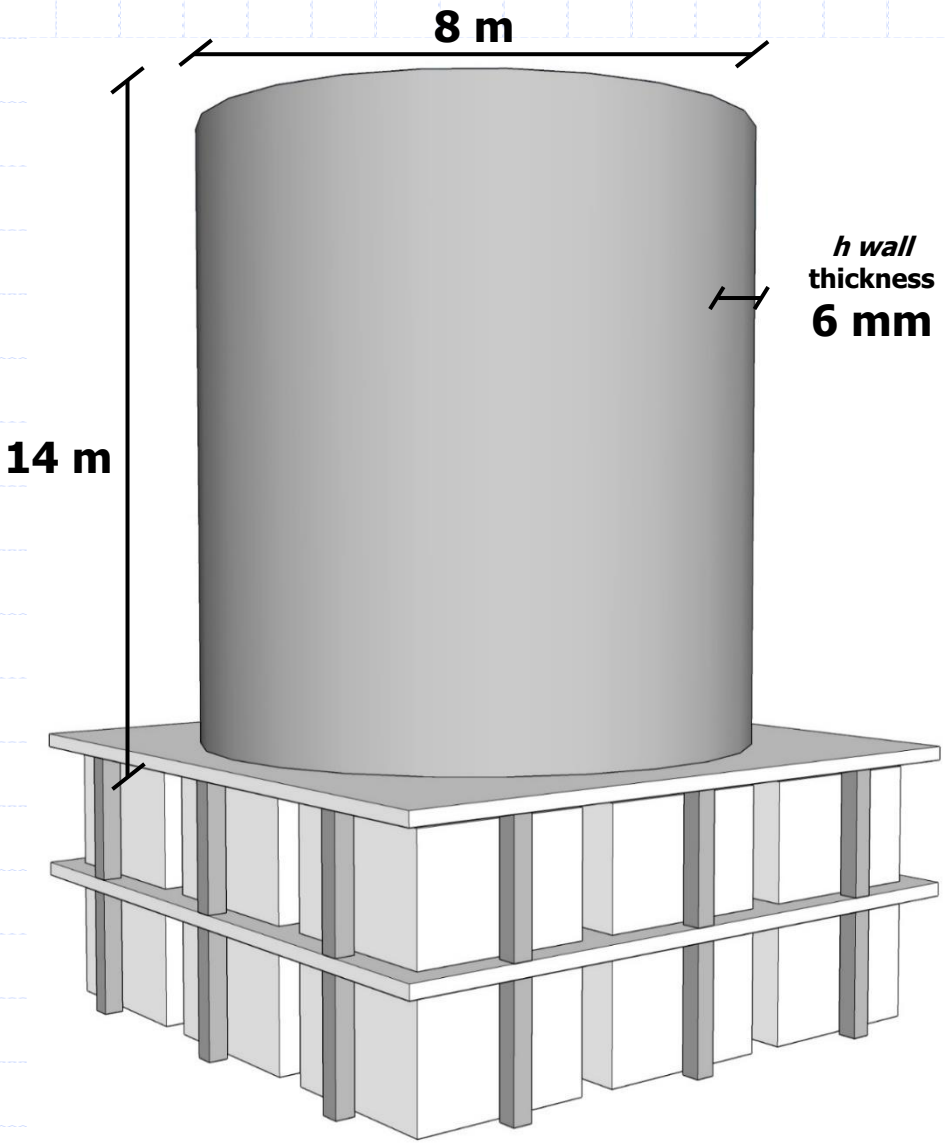
Smart Foundation



- Lattice of unit cells
- Seismic Isolation
- Concrete and spring components

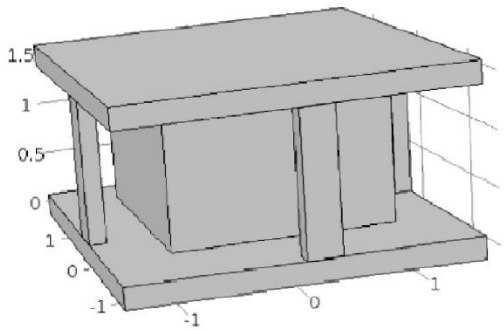
Metafoundation for the isolation of a slender tank



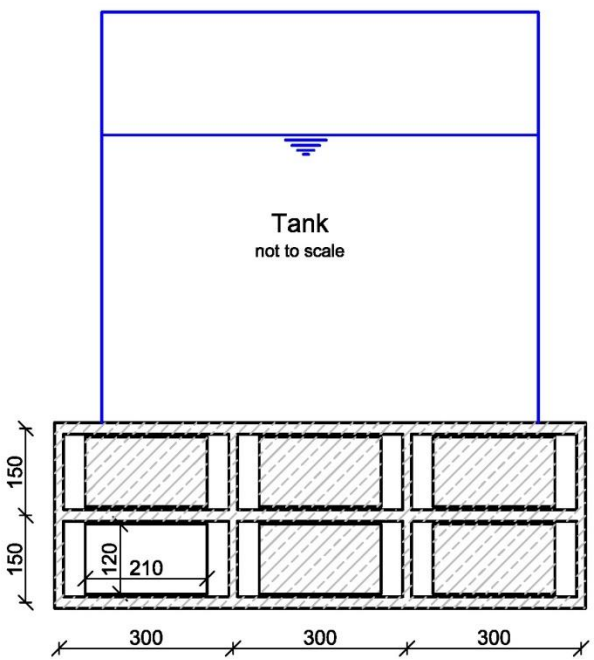


Periodicity

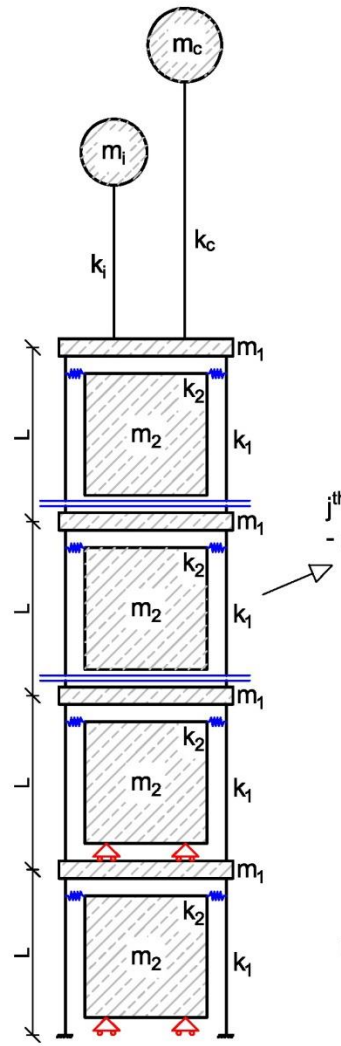
Unit Cell



Tank foundation system



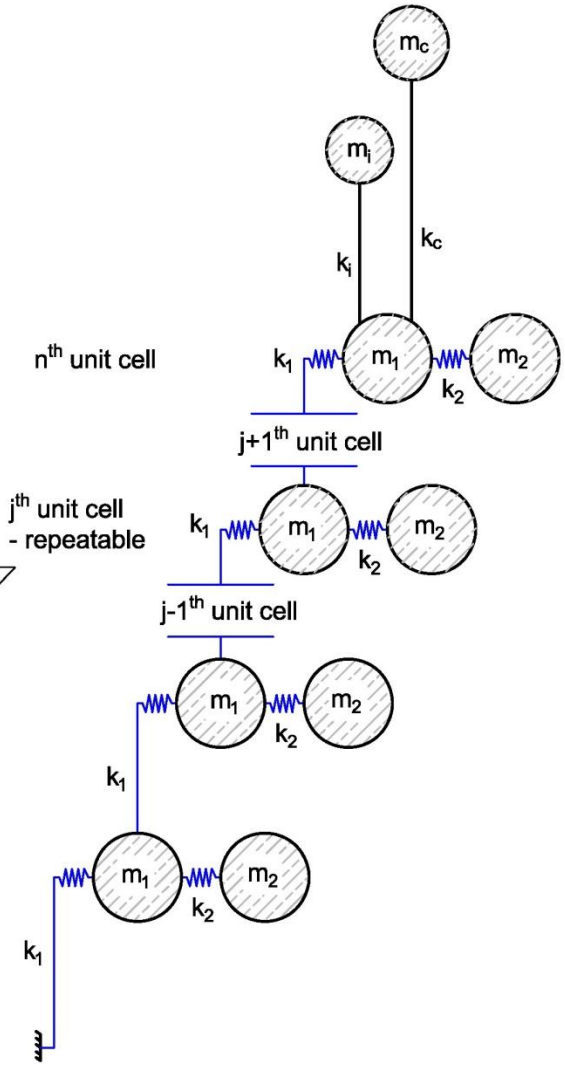
horizontal shear type model



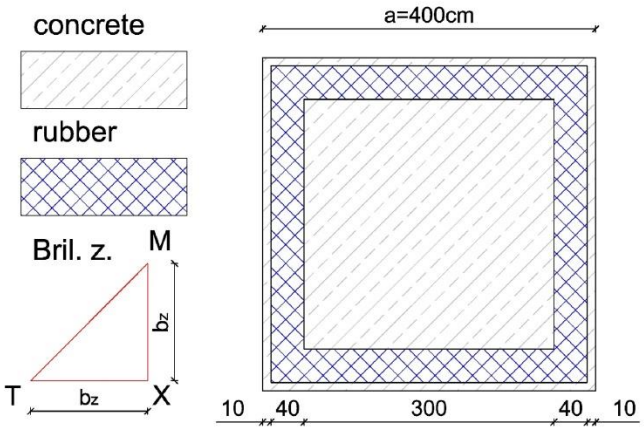
n^{th} unit cell

j^{th} unit cell
- repeatable

1D MDOF model



Floquet–Bloch Theorem



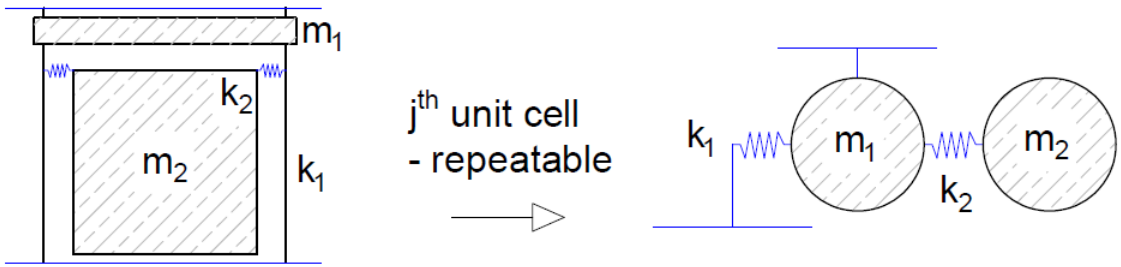
$$\sum_{j=1}^{3} \frac{\partial \sigma_{ij}}{\partial x_j} + F_i = \rho \frac{\partial^2 u_i}{\partial t^2} \qquad i = 1,2,3$$

$$\sigma_{ij} = \mu(\boldsymbol{x})\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \lambda(\boldsymbol{x})\delta_{ij}\mathrm{div}(\boldsymbol{u}(\boldsymbol{x}))$$

The solution **u**(x,t) for a periodic structure is

$$\mathbf{u}(x,t) = \mathbf{u}_k \, e^{i(\mathbf{q}x - \omega t)}$$

where $\mathbf{q}=[q_x \; q_y \; q_z]^T$ is the wave vector



Boundary Condition

$$u(x+R) = u(x)\, e^{iq_x R}$$

Eigenvalue Problem

$$(K - \omega^2 M)\, u = 0$$

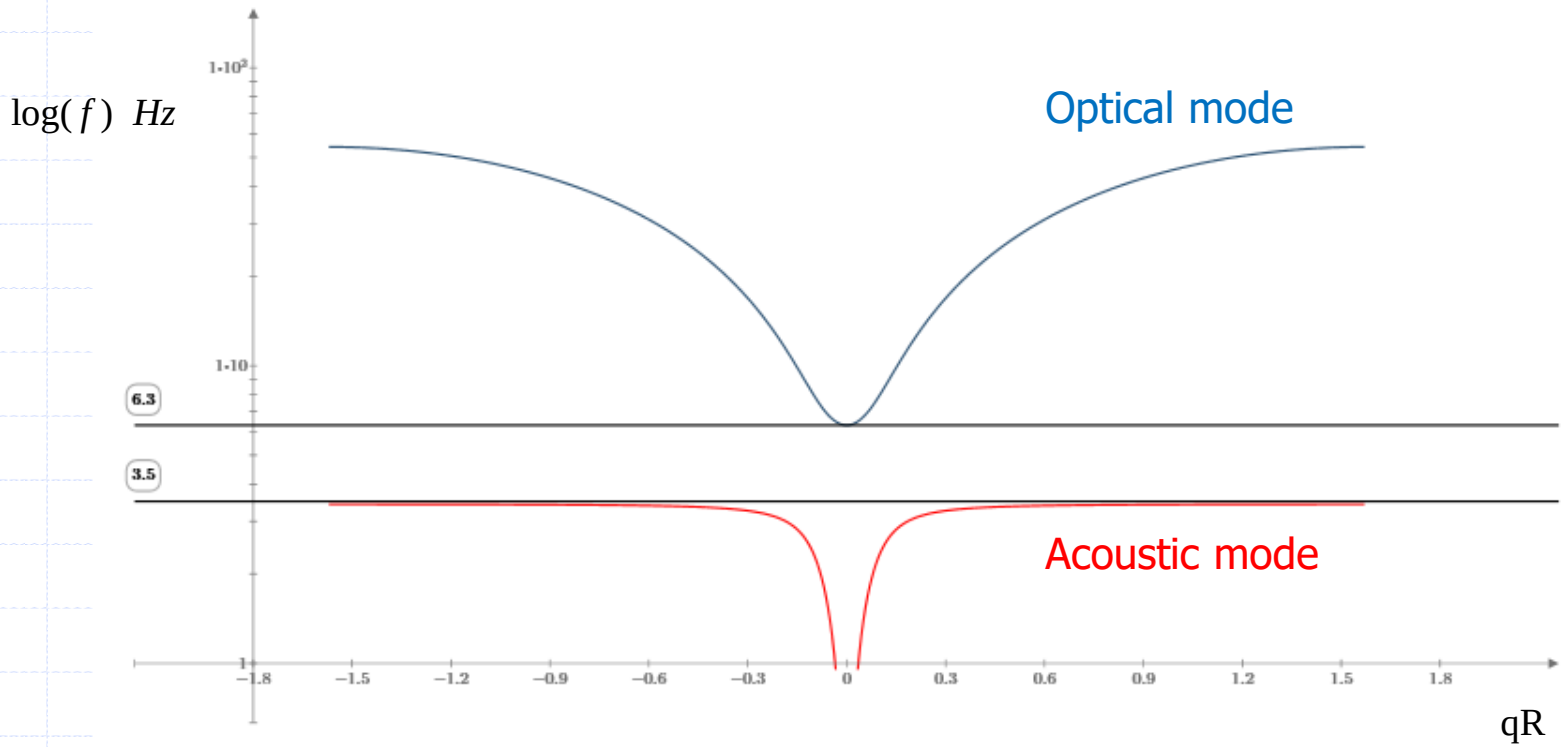
Equations of Motion

$$m_1^j \ddot{u}_1^j - k_1 u_1^{j-1} + k_1 u_1^j + k_2 u_1^j + k_1 u_1^j - k_2 u_2^j - k_1 u_1^{j+1} = 0$$

$$m_2^j \ddot{u}_2^j - k_2 u_1^j + k_2 u_2^j = 0$$

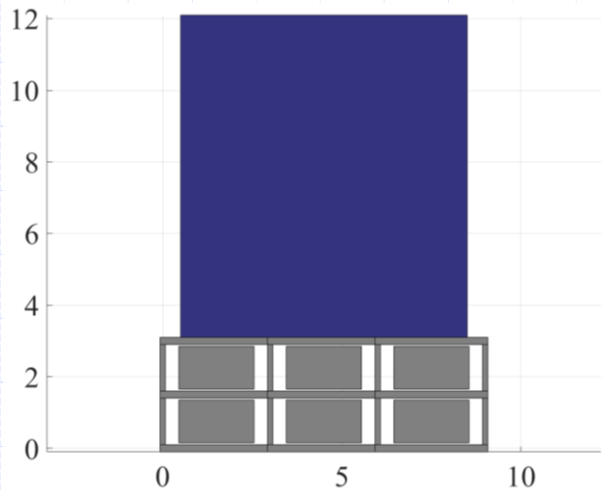
Dispersion Diagram

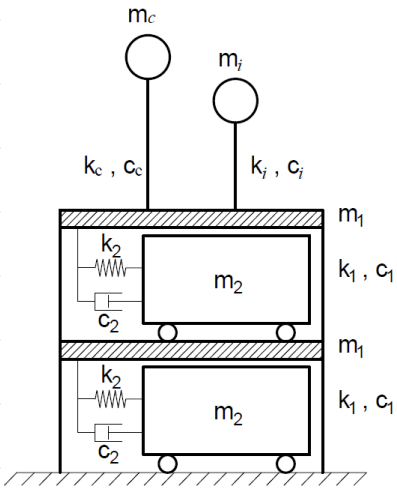
$$m_1 m_2 \omega^4 - \left[(m_1 + m_2)k_2 + 2m_2 k_1 (1 - \cos(qR))\right]\omega^2 + 2k_1 k_2 (1 - \cos(qR)) = 0$$

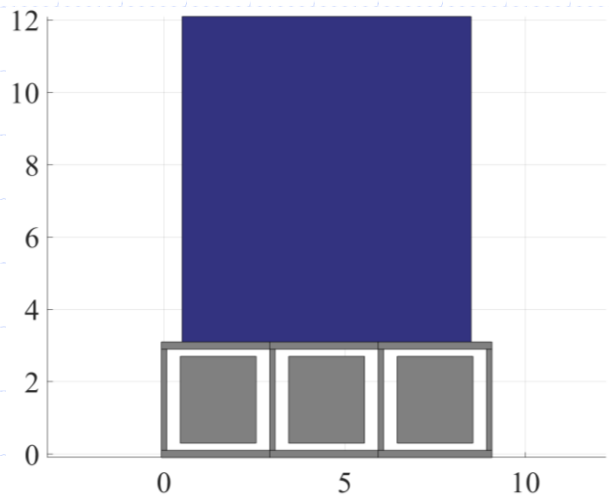


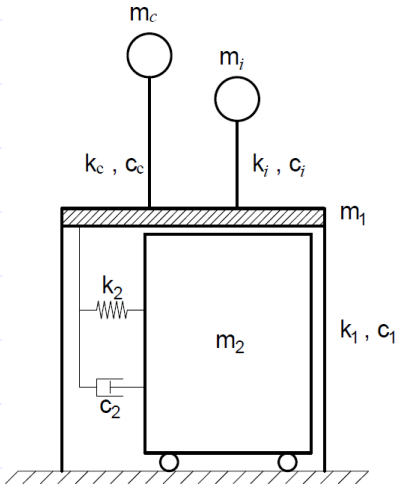
Modeling

Resonators have the same mass and stiffness.
Degrees of freedom of each layer can be condensed to a single degree of freedom

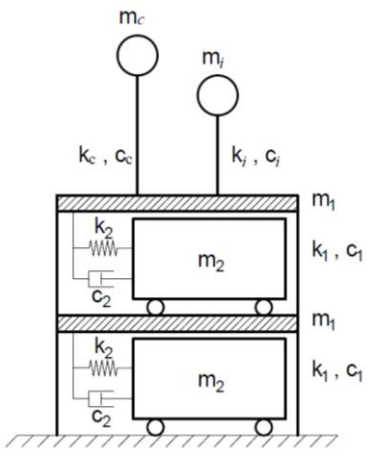


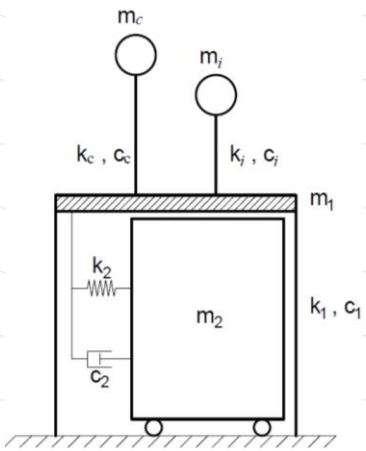






Modeling





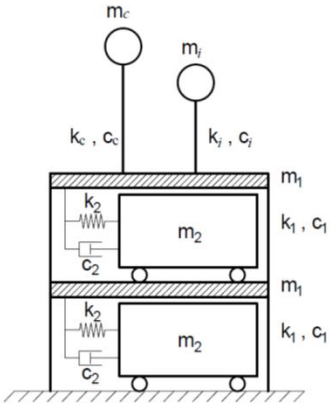
$$\mathbf{M} = \begin{bmatrix} m_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_1 + m_s & 0 & 0 & 0 \\ 0 & 0 & 0 & m_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_c & 0 \\ 0 & 0 & 0 & 0 & 0 & m_i \end{bmatrix}$$

$$\mathbf{K} = \begin{bmatrix} 2k1 + k_2 & -k_2 & -k_1 & 0 & 0 & 0 \\ -k_2 & k_2 & 0 & 0 & 0 & 0 \\ -k1 & 0 & k_1 + k_2 + k_c + k_i & -k_2 & -k_c & -k_i \\ 0 & 0 & -k_2 & k_2 & 0 & 0 \\ 0 & 0 & -k_c & 0 & k_c & 0 \\ 0 & 0 & -k_i & 0 & 0 & k_i \end{bmatrix}$$

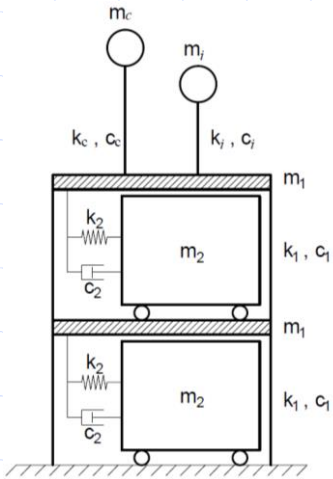
$$\mathbf{M} = \begin{bmatrix} m_1 + m_s & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_c & 0 \\ 0 & 0 & 0 & m_i \end{bmatrix}$$

$$\mathbf{K} = \begin{bmatrix} k_1 + k_2 + k_c + k_i & -k_2 & -k_c & -k_i \\ -k_2 & k_2 & 0 & 0 \\ -k_c & 0 & k_c & 0 \\ -k_i & 0 & 0 & k_i \end{bmatrix}$$

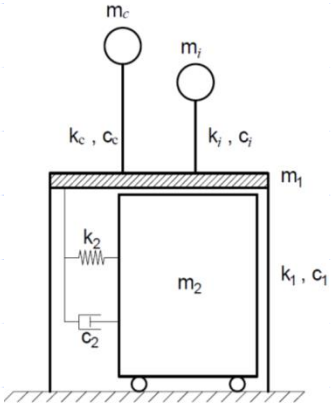
Case studies



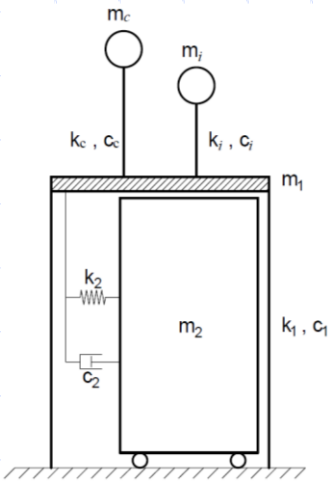
L2H3
2 layers
H = 3 m



L2H4
2 layers
H = 4 m

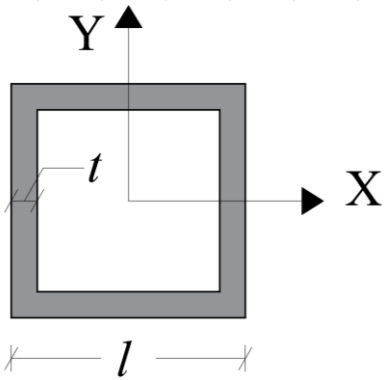


L1H3
1 layer
H = 3 m



L1H4
1 layer
H = 4 m

Hollow steel section



Cross-section dimension of columns

Section	L2H3	L2H4	L1H3	L1H4
l [mm]	220	270	270	330
t [mm]	30	30	30	30

Optimization in the frequency domain based on stationary inputs

Fourier Transformation of EOMs

$$\boldsymbol{M}\,(-\omega^2\boldsymbol{X}(\omega)) + \boldsymbol{C}\,(i\omega\boldsymbol{X}(\omega)) + \boldsymbol{K}(\boldsymbol{X}(\omega)) = \boldsymbol{P}(\omega)$$

$$(-\boldsymbol{M}\omega^2 + i\omega\boldsymbol{C} + \boldsymbol{K})\,\boldsymbol{X}(\omega) = \boldsymbol{P}(\omega)$$

Transmission Matrix

$$\boldsymbol{H}(\omega) = (-\boldsymbol{M}\omega^2 + i\omega\boldsymbol{C} + \boldsymbol{K})^{-1}$$

$\boldsymbol{H}(\omega)$ numerical Optimization

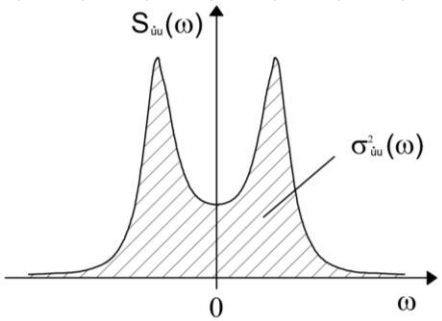
$$\boldsymbol{H}(\omega, k_2, c_2) = (-\boldsymbol{M}\omega^2 + i\omega\boldsymbol{C}(c_2) + \boldsymbol{K}(k_2))^{-1}$$

Power Spectral Density - Response

$$\boldsymbol{S_Q}(\omega, k_2, c_2) = |\boldsymbol{H}(\omega, k_2, c_2)|^2\boldsymbol{S_P}$$

Variance of the Response

$$\sigma_{qi}^2(k_2, c_2) = \int_{-\infty}^{+\infty} S_{QI}(\omega, k_2, c_2)\,d\omega$$

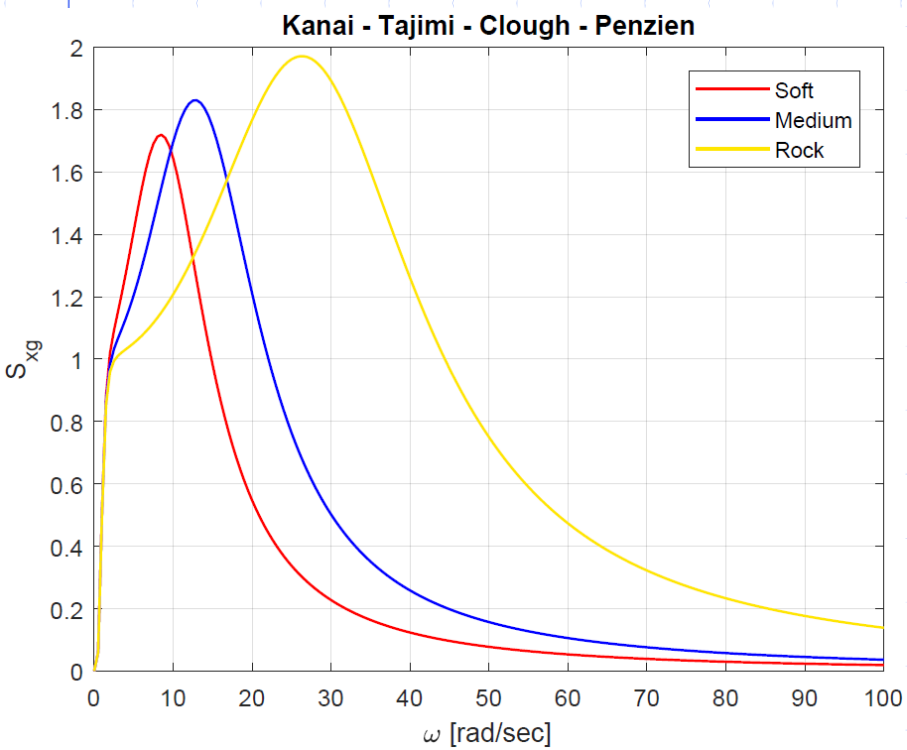


<u>Performance Index</u>

$$PI(k_2, c_2) = \frac{\sigma_{meta}^2(k_2, c_2)}{\sigma_{trad}^2}$$

Optimization in the frequency domain based on stationary inputs

Kanai-Tajimi Filter modified by Clough-Penzien



$$S_{\ddot{u}_g}(\omega) = S_0 \; H_{KT}^2 \; H_{CP}^2$$

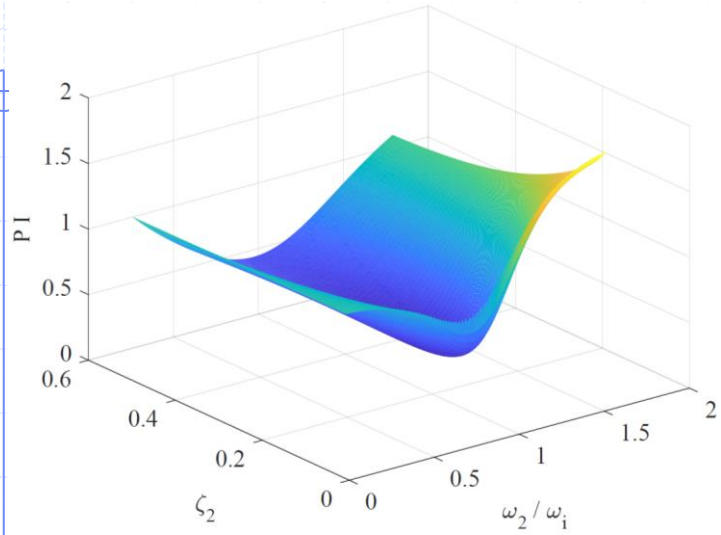
$$H_{KT}(\omega) = \frac{1 + 2i\xi_g^2\omega/\omega_g}{(1-\omega^2/\omega_g^2) + 2i\xi_g\omega/\omega_g}$$

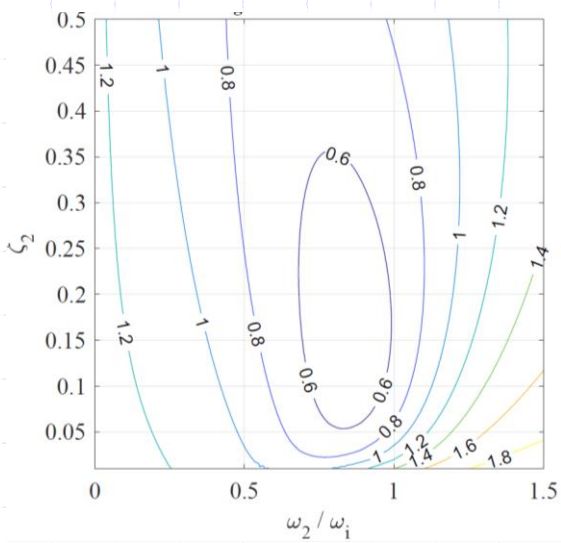
$$H_{CP}(\omega) = \frac{\omega^2/\omega_1^2}{(1-\omega^2/\omega_1^2) + 2i\xi_1\omega/\omega_1}$$

	Soft soil	Medium soil	Rock soil
ω_1	1.0	1.0	1.0
ζ_1	0.7	0.7	0.7
ω_g	10.5	15.6	31.4
ζ_g	0.65	0.60	0.55

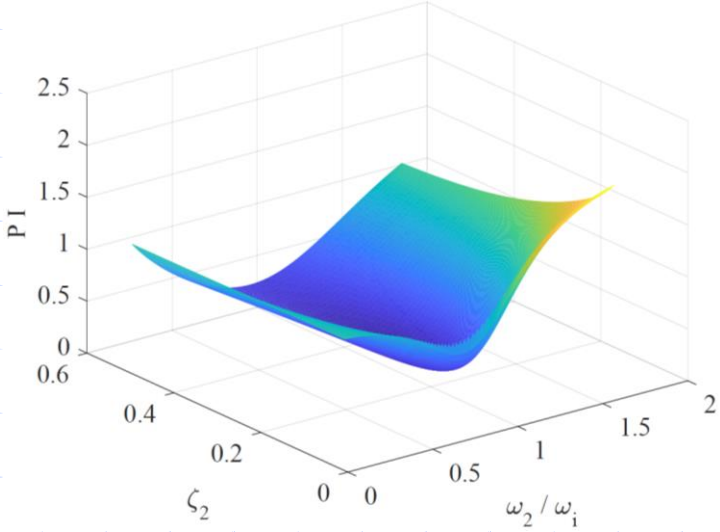
Outcome of optimization

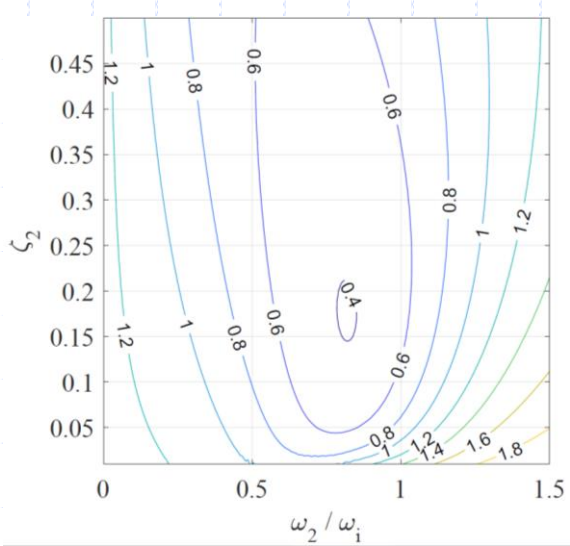
L2H3





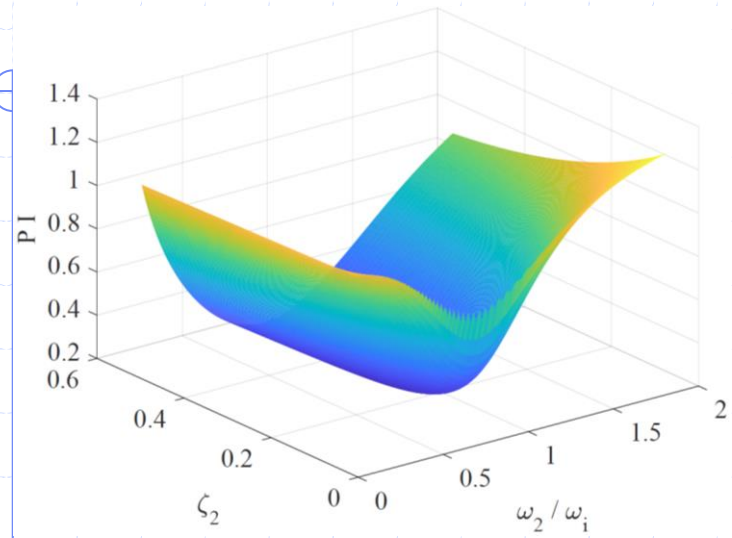
L2H4

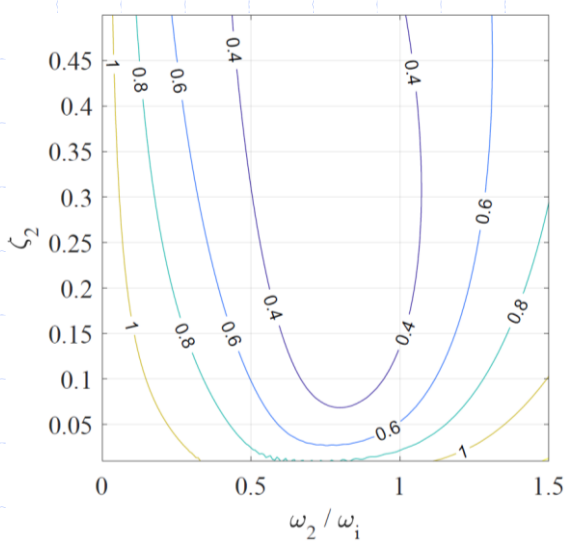




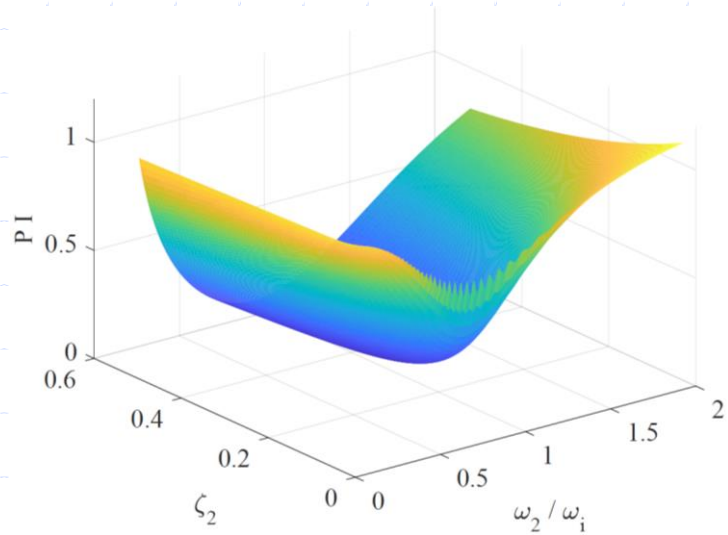
Outcome of optimization

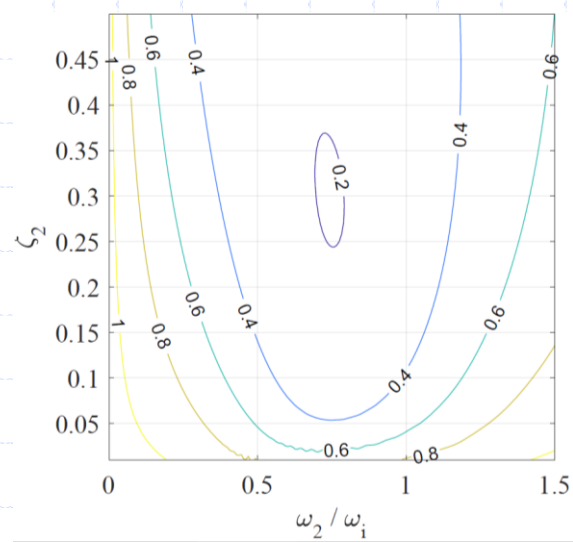
L1H3





L1H4



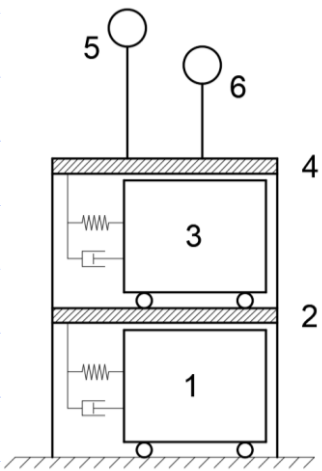


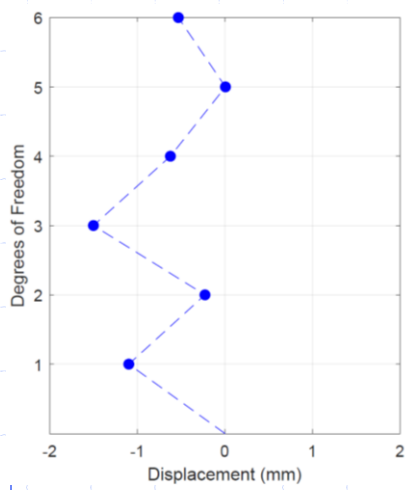
Optimized parameters for each considered case

		L2H3	L2H4	L1H3	L1H4
soft soil	P I	0.78	0.74	0.68	0.63
	$\zeta_{2,opt}$	0.16	0.20	0.26	0.30
	$\omega_{2,opt}$ [rad/s]	26.60	23.60	18.60	15.20
medium soil	P I	0.76	0.71	0.61	0.53
	$\zeta_{2,opt}$	0.16	0.20	0.25	0.28
	$\omega_{2,opt}$ [rad/s]	26.40	23.40	18.80	16.00
rock soil	P I	0.48	0.39	0.26	0.20
	$\zeta_{2,opt}$	0.14	0.18	0.25	0.30
	$\omega_{2,opt}$ [rad/s]	27.80	25.60	21.60	19.00

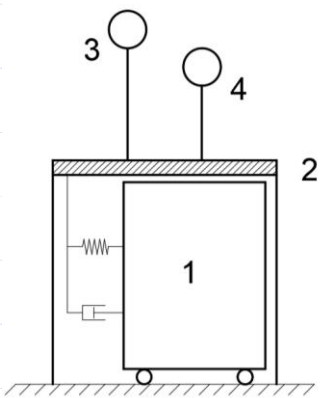
Best case

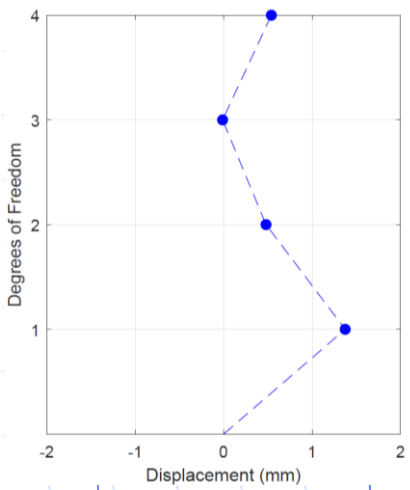
L2H4 – II mode





L1H3 – II mode

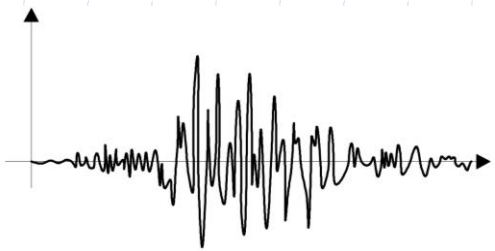


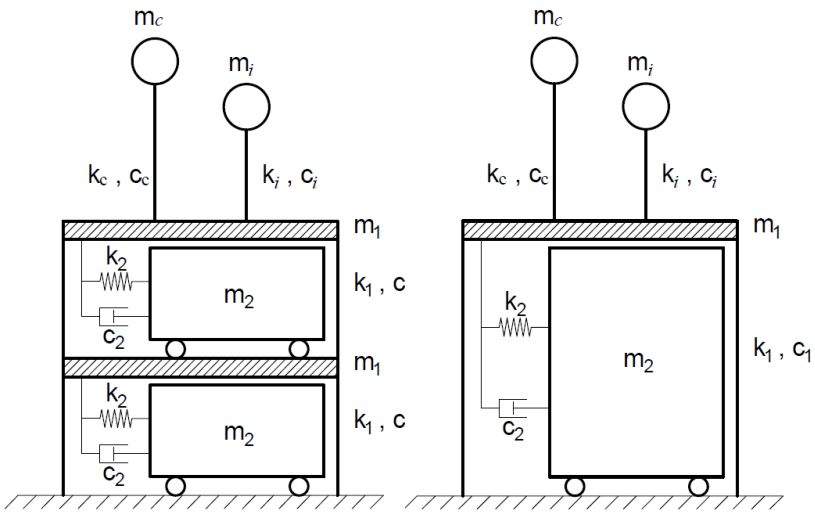


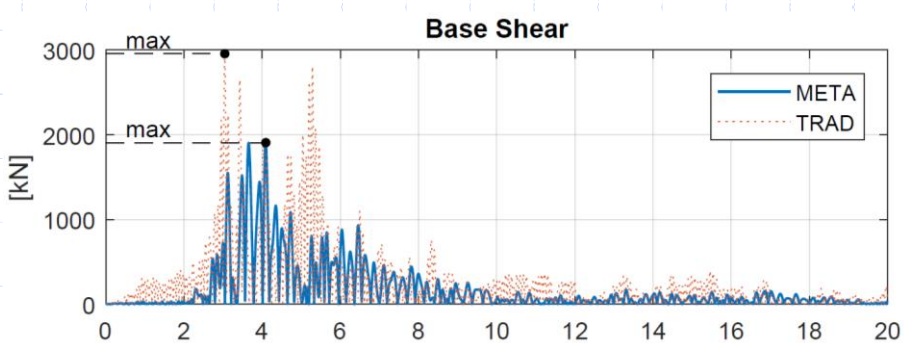
Time history analysis

T_R = 475 years

T_R = 2475 years







- Max value

$$m\ddot{u} + c\dot{u} + ku = 0$$

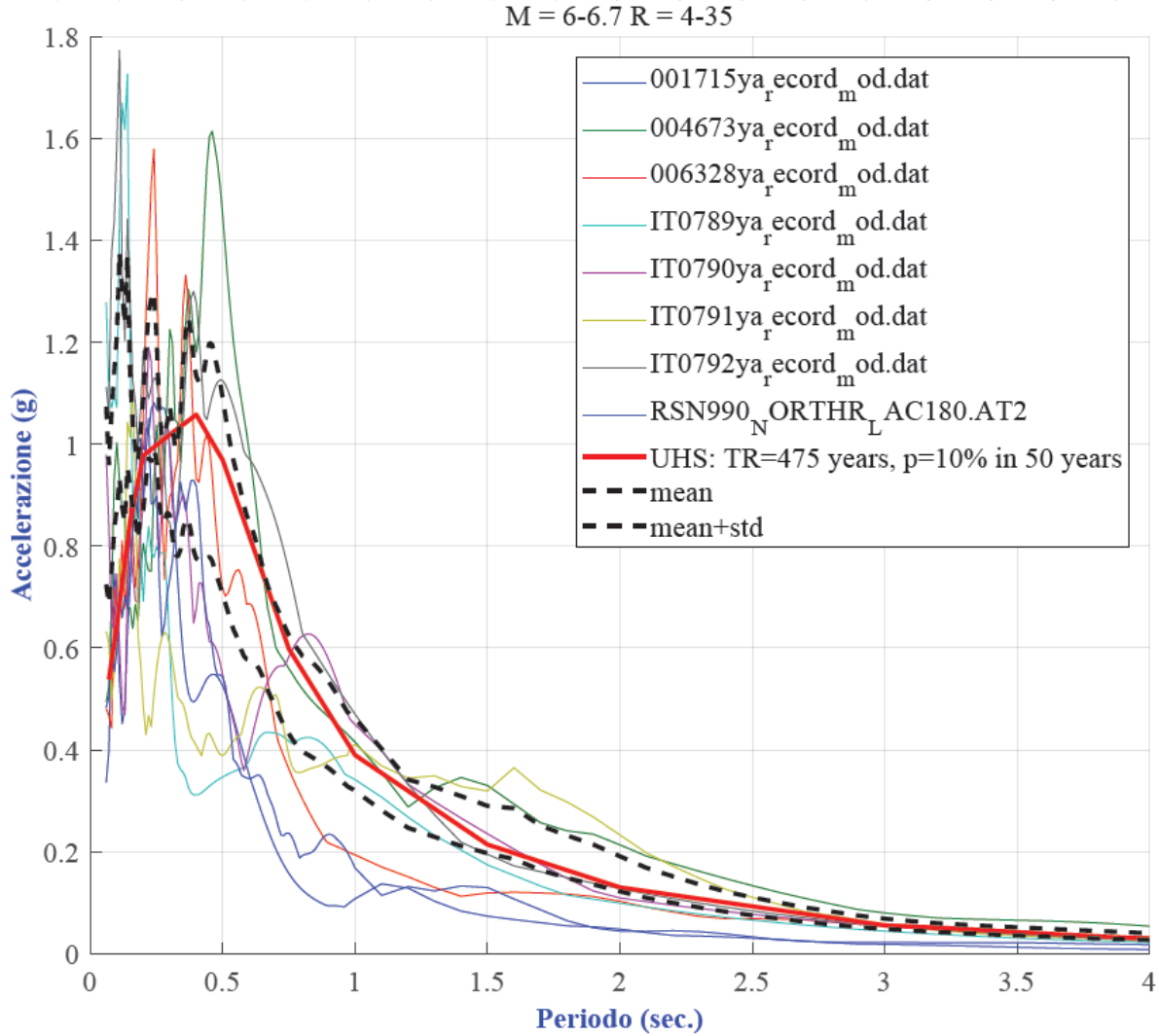
$$|m\ddot{u}_{abs}| = |-ku_{max}|$$

- Root mean square

$$Q_{RMS} = \sqrt{\frac{1}{n}\sum_{i}^{n} Q_i^2}$$

Response spectrum

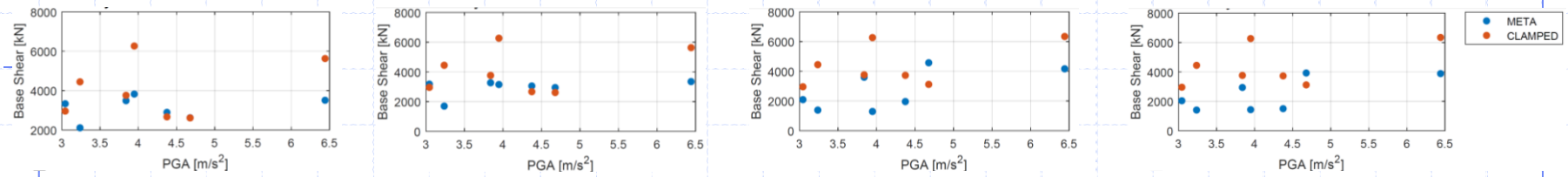
T_R=475 years



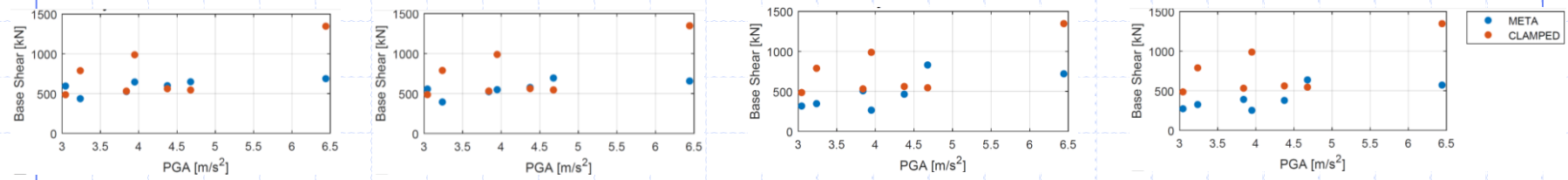
Return Period 475 years

L2H3 **L2H4** **L1H3** **L1H4**

Max values



Root mean square

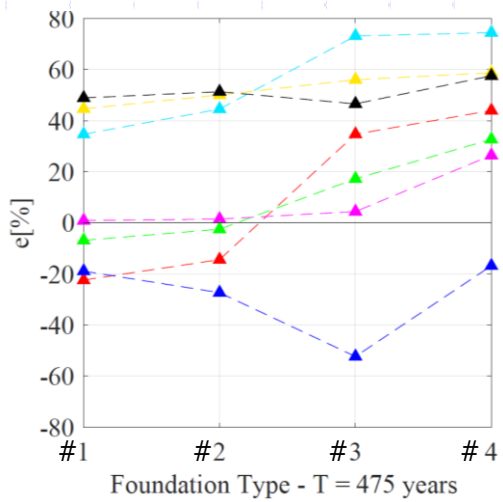


Percentage variation

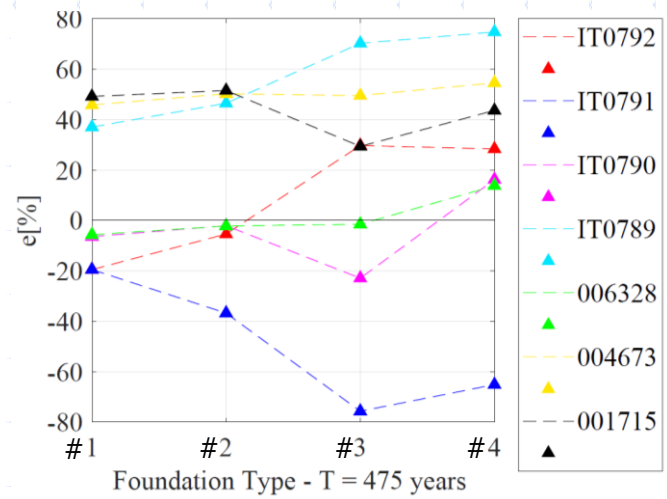
$$e = \frac{Q_{RMS,trad} - Q_{RMS,meta}}{Q_{RMS,trad}} \; [\%]$$

Metafoundation	
#1	L2H3
#2	L2H4
#3	L1H3
#4	L1H4

Base shear – medium soil



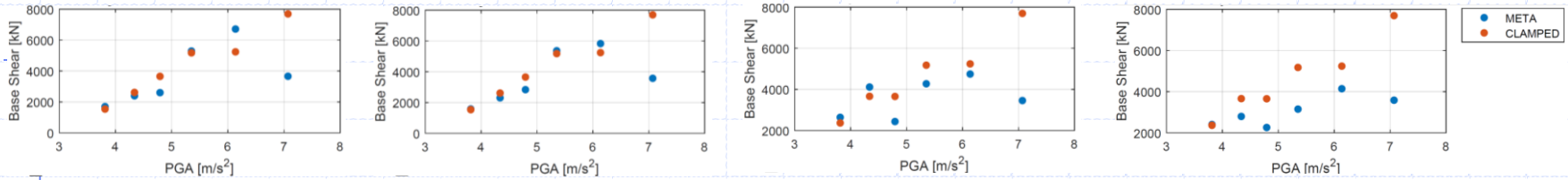
Base shear – rock soil



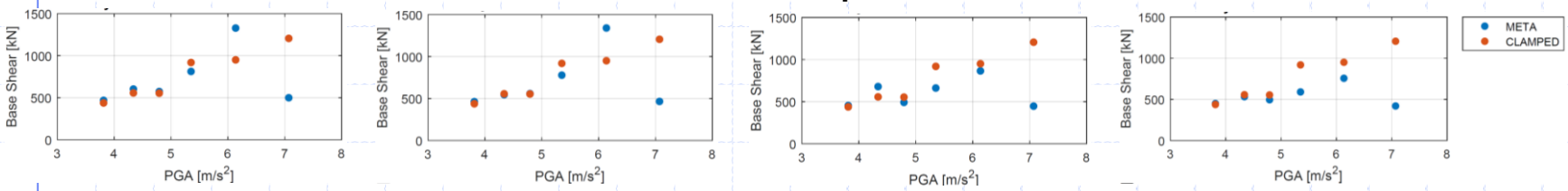
Return Period 2475 years

L2H3 **L2H4** **L1H3** **L1H4**

Max values



Root mean square

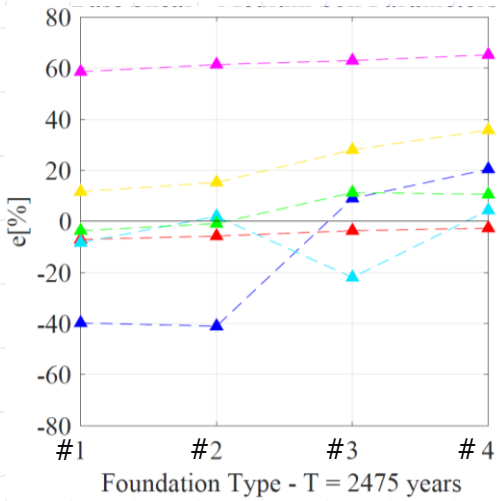


Percentage variation

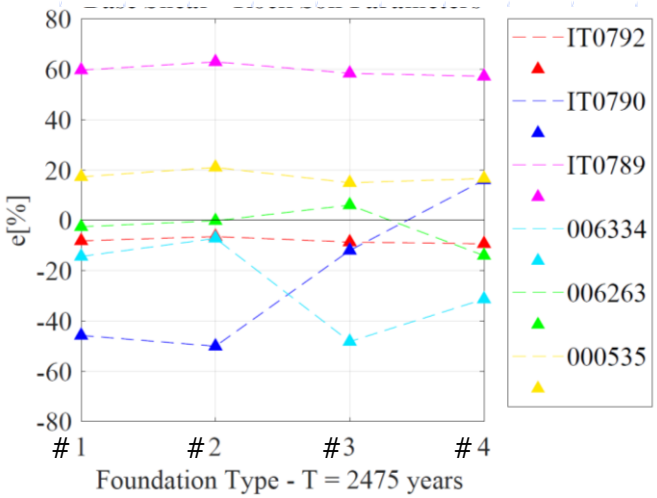
$$e = \frac{Q_{RMS,trad} - Q_{RMS,meta}}{Q_{RMS,trad}} \; [\%]$$

Metafoundation	
#1	L2H3
#2	L2H4
#3	L1H3
#4	L1H4

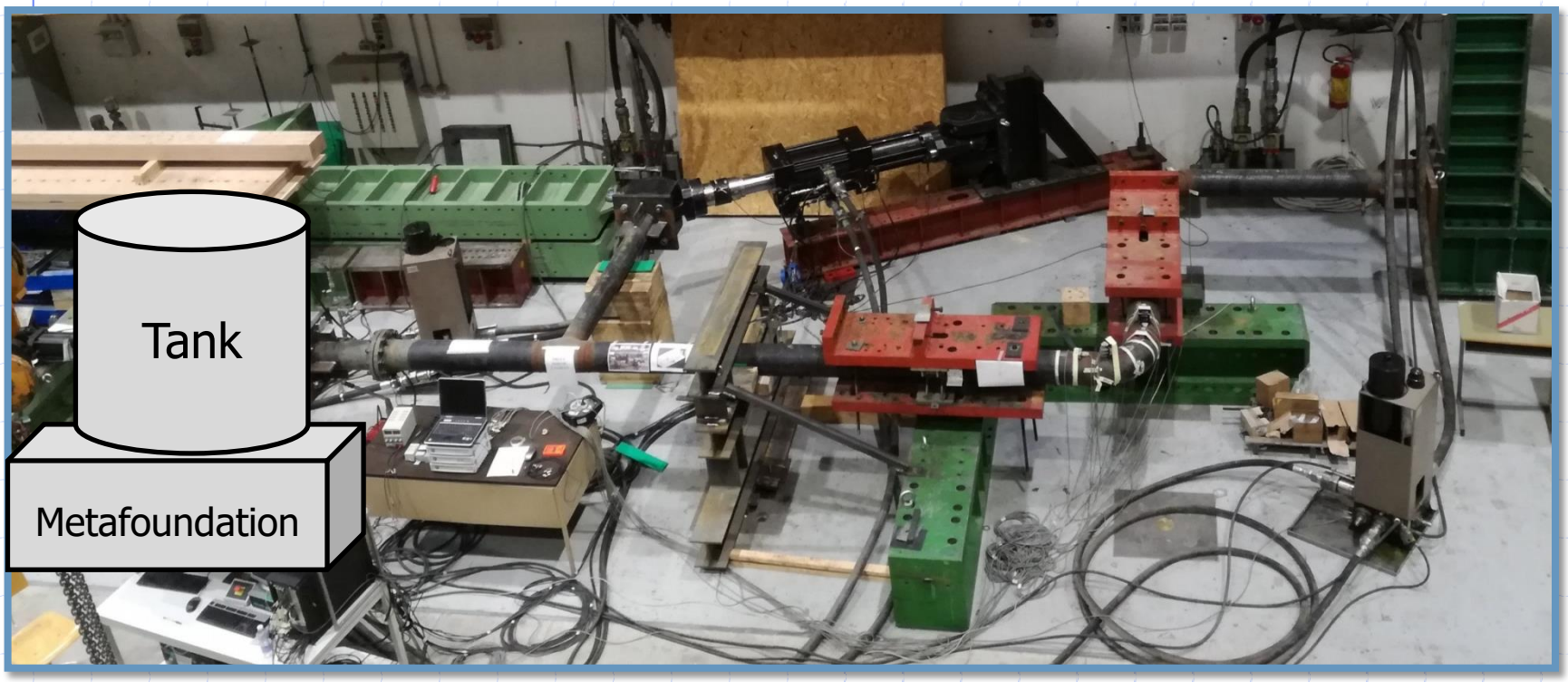
Base shear – medium soil



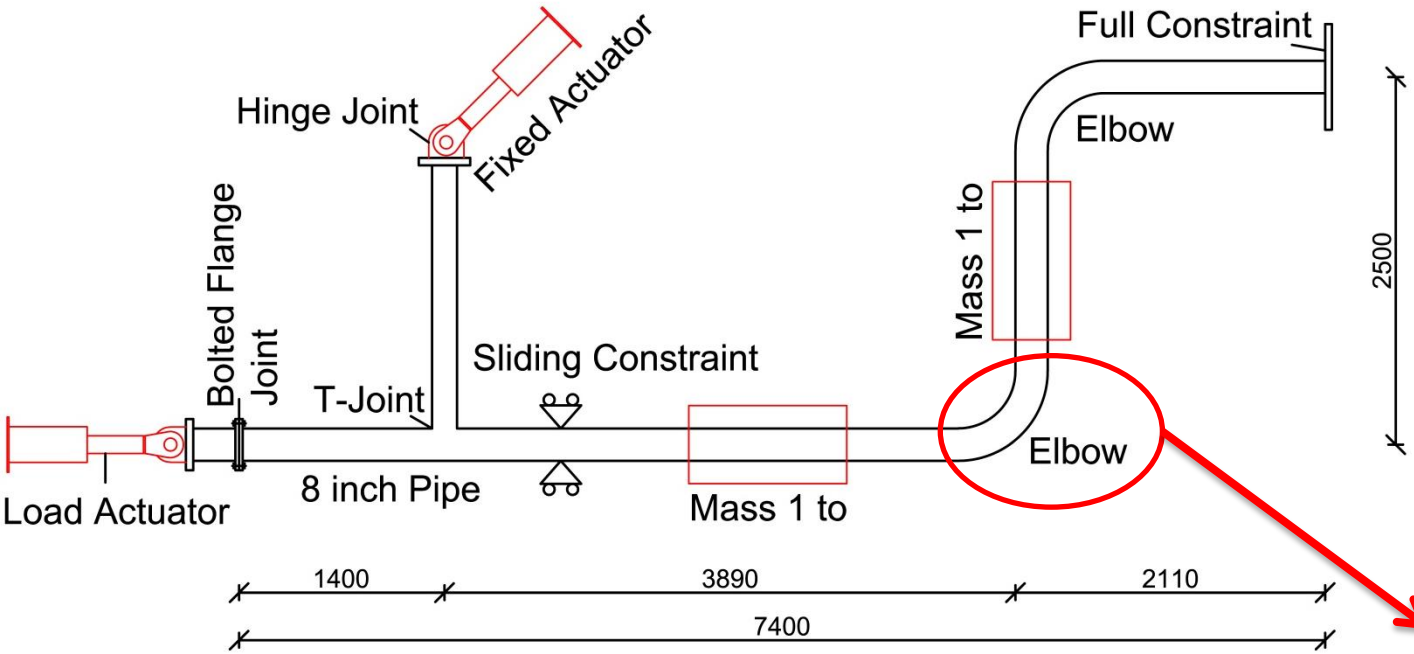
Base shear – rock soil

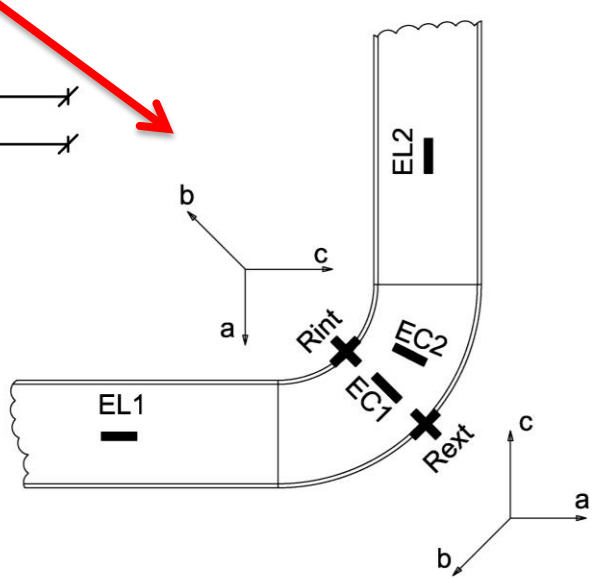


Experimental evaluation of Elbow strains



Experimental evaluation of Elbow strains

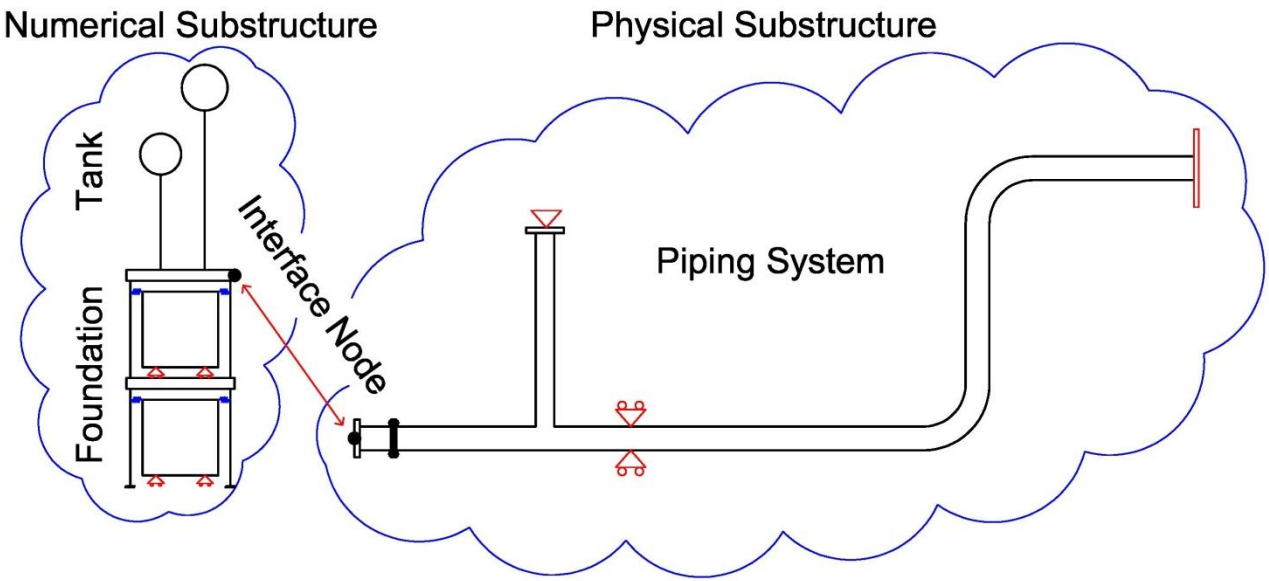




Critical Components:

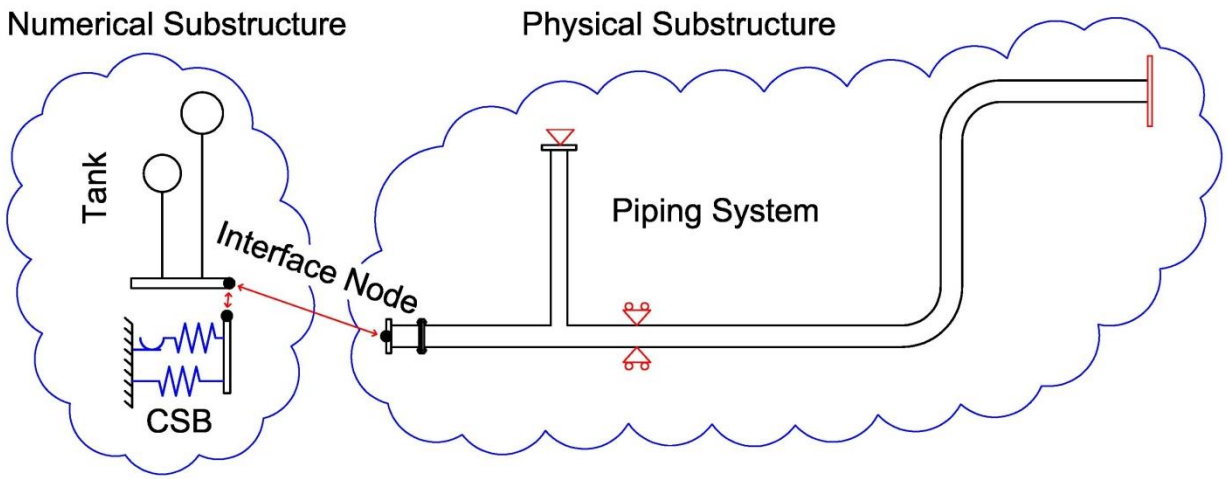
- Elbows (in particular hoop strains)
- T-joint
- Bolted flange joint (prestressed)

Experimental evaluation of Elbow strains

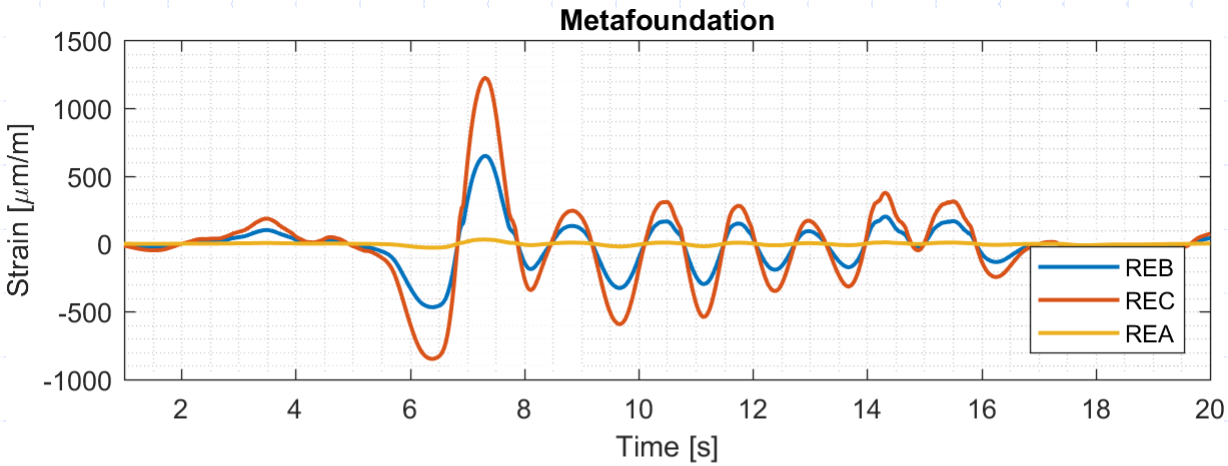


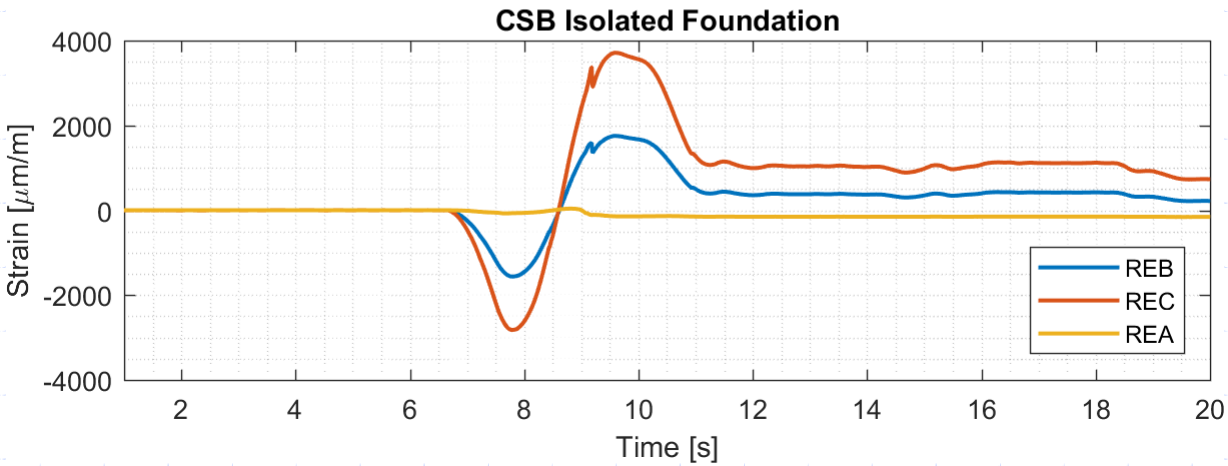
Metafoundation
- Tank
- 2 Layered Foundation

Isolatad Tank
- Tank
- Concave Spherical Sliding Bearings



Experimental evaluation of Elbow strains





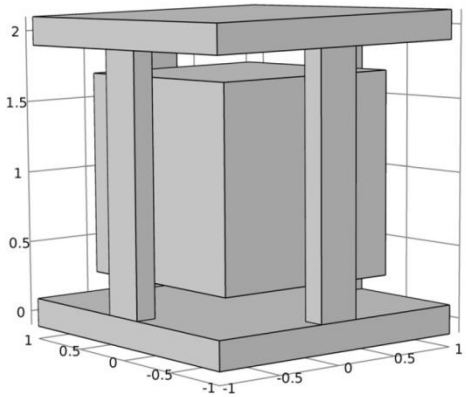
T [yrs]	Event ID	META REC [μm/m]	CSB REC [μm/m]
475	004673	801.75	864.75
	IT0791	518.75	1085.25
	IT0792	1139.75	977.50
2475	IT0789	721.50	377.50
	000535	1219.75	3713.50

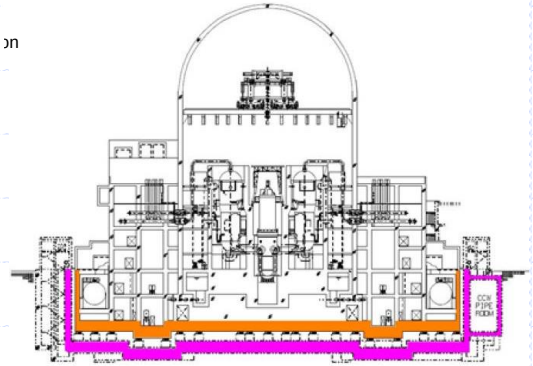
Conclusions

- General trend shows that the Metafoundation reduces the base shear with respect to the traditional foundation
- The optimization needs to take the Superstructure (Tank) into account
- Elbow strains may be reduced with proper tuning of the Resonators
- The ground motion spectrum should be adapted to the site specific needs

Future developments

- Optimization procedures
- Different tuning of each resonator may improve the performance
- Further improvements for the vertical component
- Support conditions of the Resonators





Acknowledgements

1. The speaker gratefully acknowledges EGU as well as the Local Organizing Committee

2. The author deeply acknowledges the financial support from the European Union through:

- the SERA project (Project Reference: 730900);

- the XP-Resilience project (Project Reference: 721816);