London 4th February 2016

Vibration control of buildings through Vibrating barriers

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Outline

- Introduction & Motivation
- Overview of the traditional and novel vibration control techniques
- Proposed approach
- Numerical and experimental results
- Concluding remarks

Introduction & Motivation

- Existing Buildings: Vibration Control devices rarely used in developing countries and for heritage buildings despite they are efficient. Why?

- Needing to find alternative approaches. What about protect a structure without altering it? What about try to protect more than one building with a single device?

Overview of the traditional vibration control techniques

Local/idividual protection

- **The use of vibration control devices is restricted to individual structures, and is therefore too localized to provide larger scale protection from seismic action, which remains an unsolved challenge, especially those in developing countries.**

- **Devices such as isolators, dampers and tuned mass dampers are now widely used in the construction industry for earthquake engineering to reduce vibration in new and, in a few cases, existing buildings.**

Non-local protection

Woods RD. 1968 Screening of surface waves in soils. J. Soil Mech. Found. Eng. Div. 94, 951–979

Field Experiments on Wave Propagation and Vibration Isolation by Using Wave Barriers

Seyhan Fırat[1], Erkan Çelebi[2], Günay Beyhan[3], İlyas Çankaya[4], Osman Kırtel[2] and İsa Vural[1]

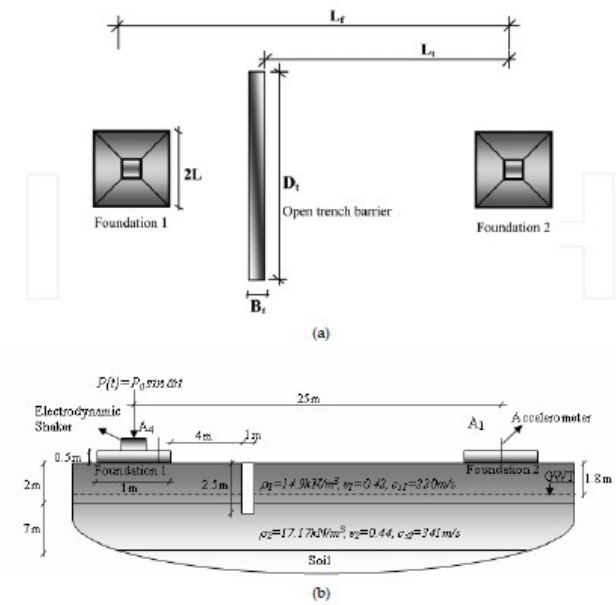


Fig. 3. Trench barriers: a) Open trench, b) Water filled trench, c) Bentonite filled trench and d) Concrete filled trench.

Railways applications

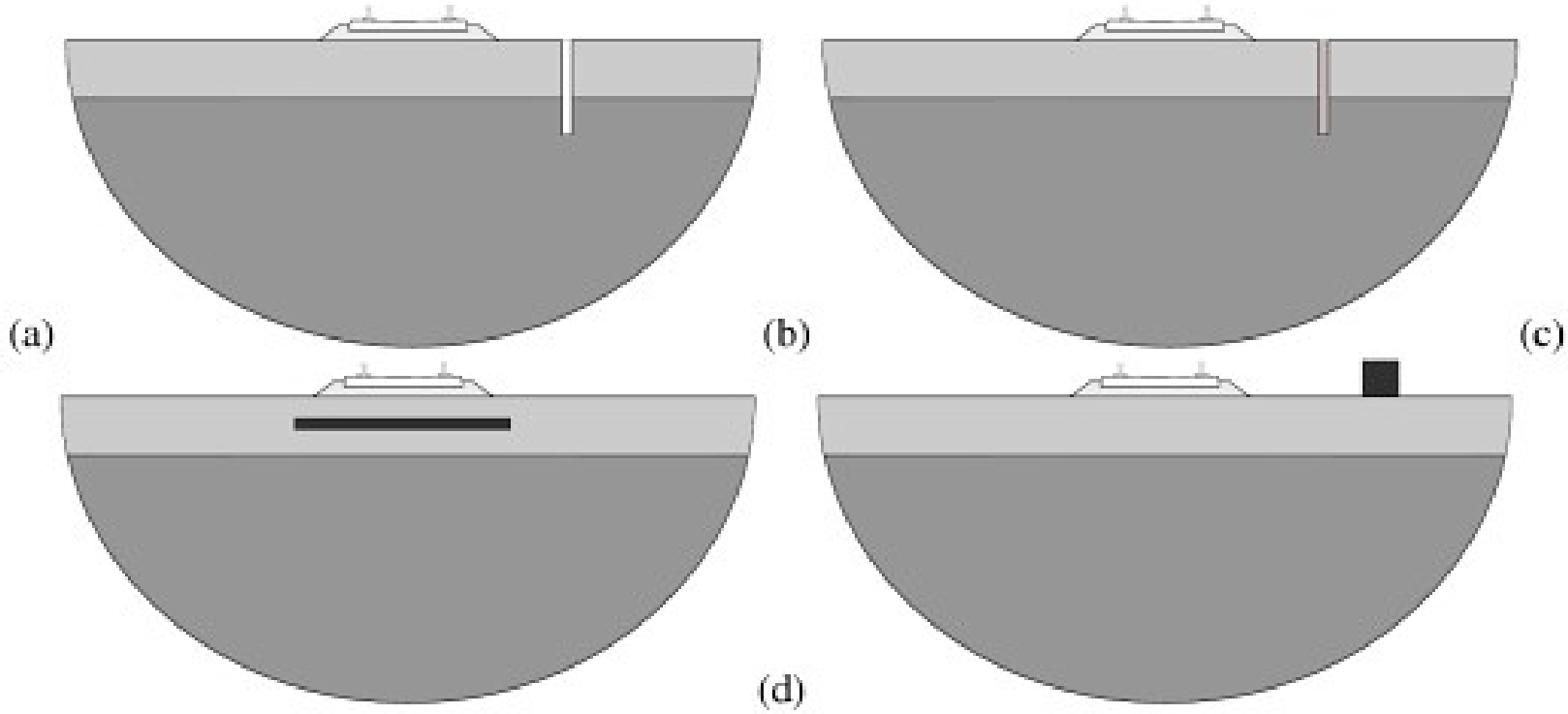


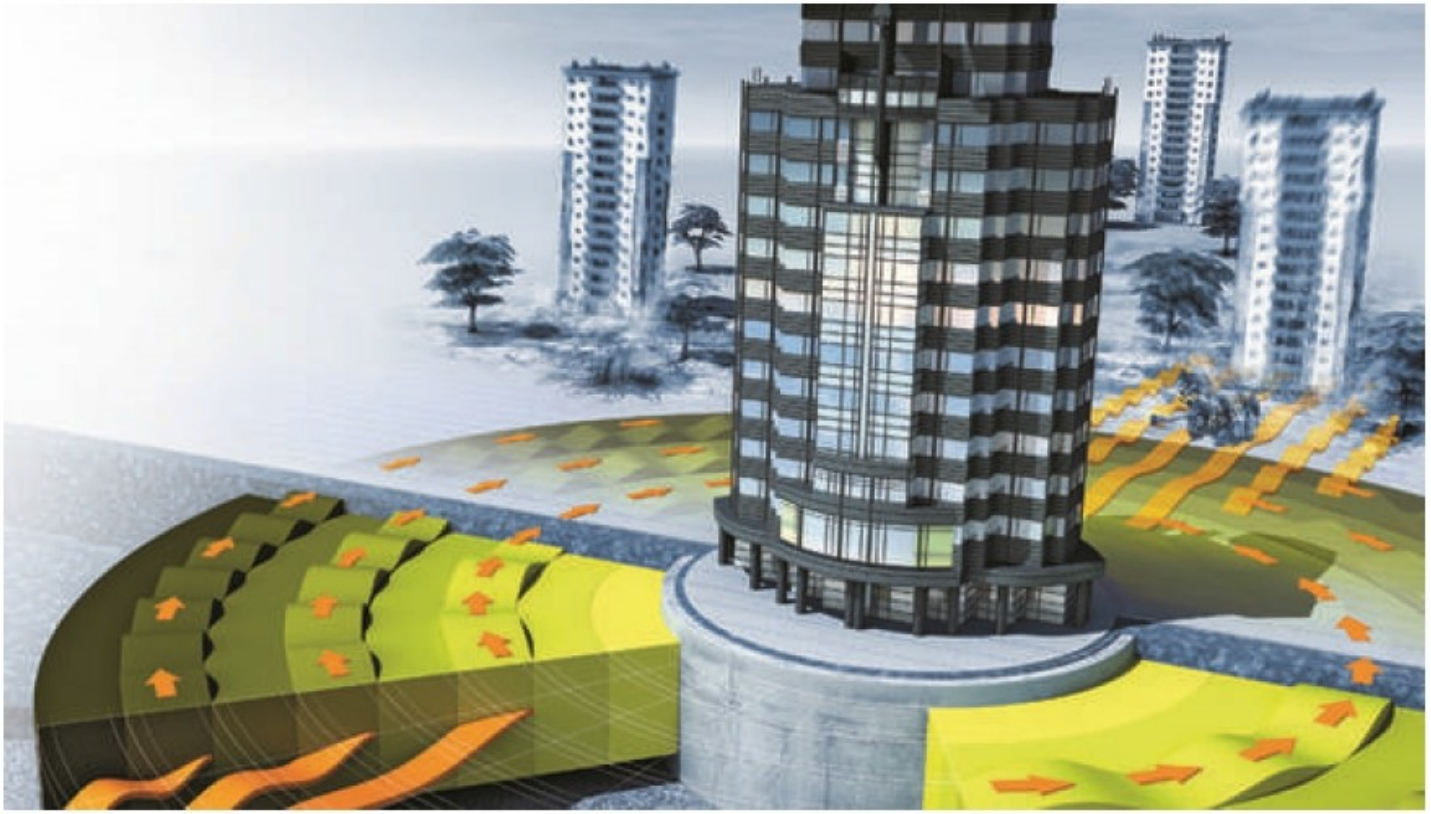
Fig. 8. Vibration mitigation measures on the transmission path: (a) open trech, (b) soft or stiff wave barrier, (c) wave impeding block, and (d) heavy masses next to the track

SCIENCE

SEISMIC INVISIBILITY CLOAK COULD HIDE BUILDINGS FROM EARTHQUAKES

ENGINEERING A PRECISE SERIES OF RING-SHAPED SHIELDS TO DEFLECT EARTHQUAKES AROUND A BUILDING

By Dan Smith Posted June 26, 2009



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Expcriment'i on Scisrnic l\1ctamaterials: l\lolding Surface \Vavcs

S. Brfile,mE. H. Javelaud,mS. Enoch,[2] and *S*. Guenneau[2]
[1]*Meno.rd, 91 620 Nowy, France*
[1]*Aix-Marseille Universite, CNRS, C.enrral-e Marseille, In. tirur Fresne' UMR 7249, J3013 Marseille, France*
{Received 18 May 2013; published 31 March 20 14)

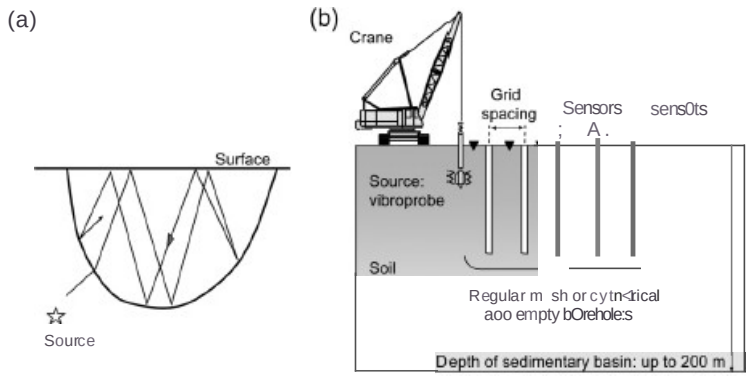
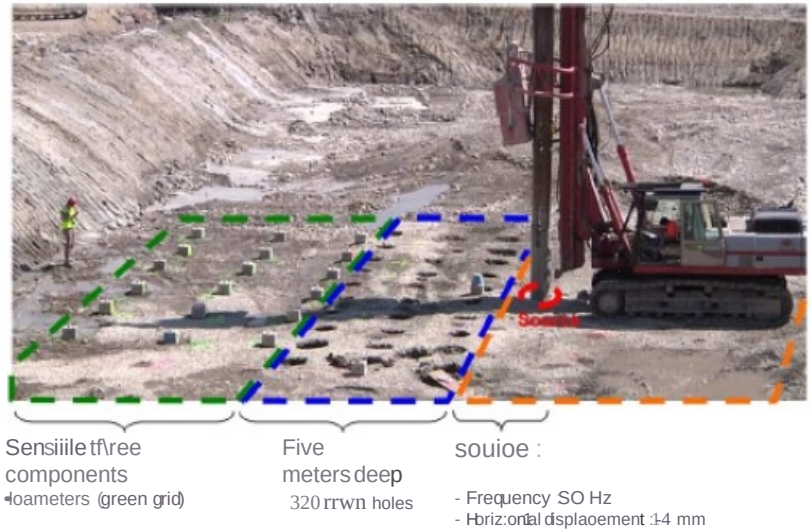


FIG. 1. Schematics of (a) a seismic wave in an alluvium basin and (b) the seismic testing device cross section in the *X-Z* plane (see Fig. 3 for a photograph of the experiment).



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First Grant - Revised 2009
PROPOSAL

Document Status: With Council
EPSRC Reference: EP/K004867/1

Organisation where the Grant would be held

Organisation	University of Brighton	Research Organisation Reference:	ViBa
Division or Department	Sch of Environment and Technology		

Project Title [up to 150 chars]

Vibrating Barriers for the control of seismic waves (ViBa)

Start Date and Duration

a. Proposed start date	01 January 2013	b. Duration of the grant (months)	24

Applicants

Role	Name	Organisation	Division or Department	How many hours a week will the investigator work on the project?
Principal Investigator	Dr Pierfrancesco Cacciola	University of Brighton	Sch of Environment and Technology	7.5

Proposed approach

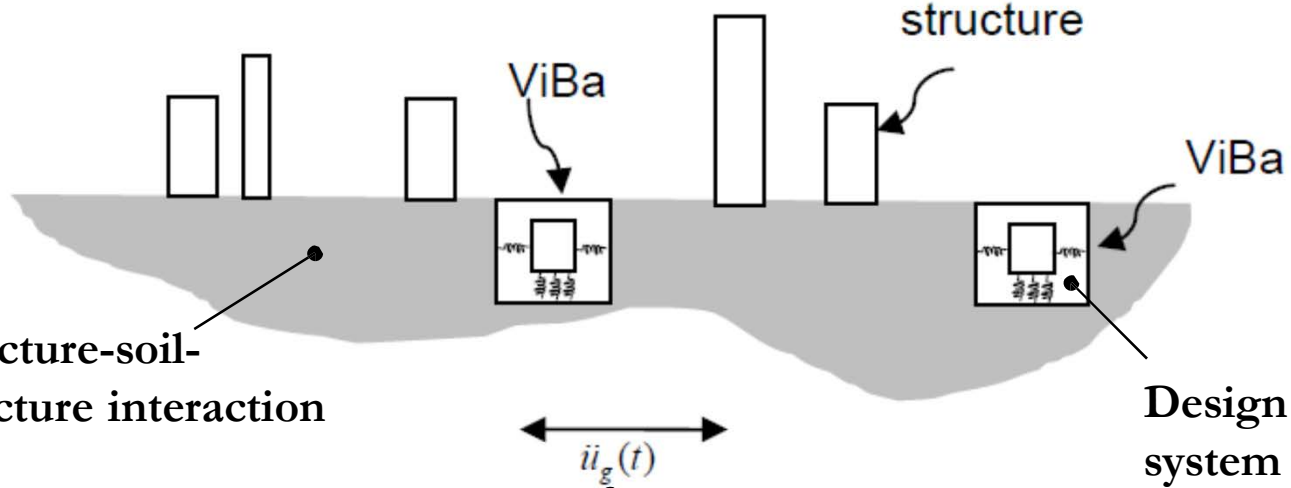


Figure 1: Sketch of the proposed Vibrating Barrier

Structure-soil-structure interaction

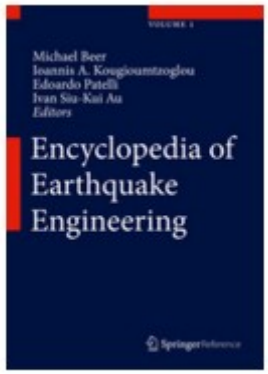
Design of the control system (ViBa)

Modelling of the seismic actions

Modelling of the seismic action

- Selected recorded time histories

- Simulated artificial (response-spectrum-compatible time histories)



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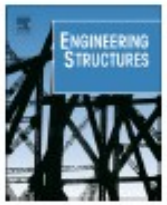

New insights in the analysis of the structural response to response-spectrum-compatible accelerograms

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[a] School of Environment and Technology, University of Brighton, Lewes Road, BN24GJ Brighton, UK
[b] LaMSID UMR EDF-CNRS-CEA, Clamart, France

Proposed approach

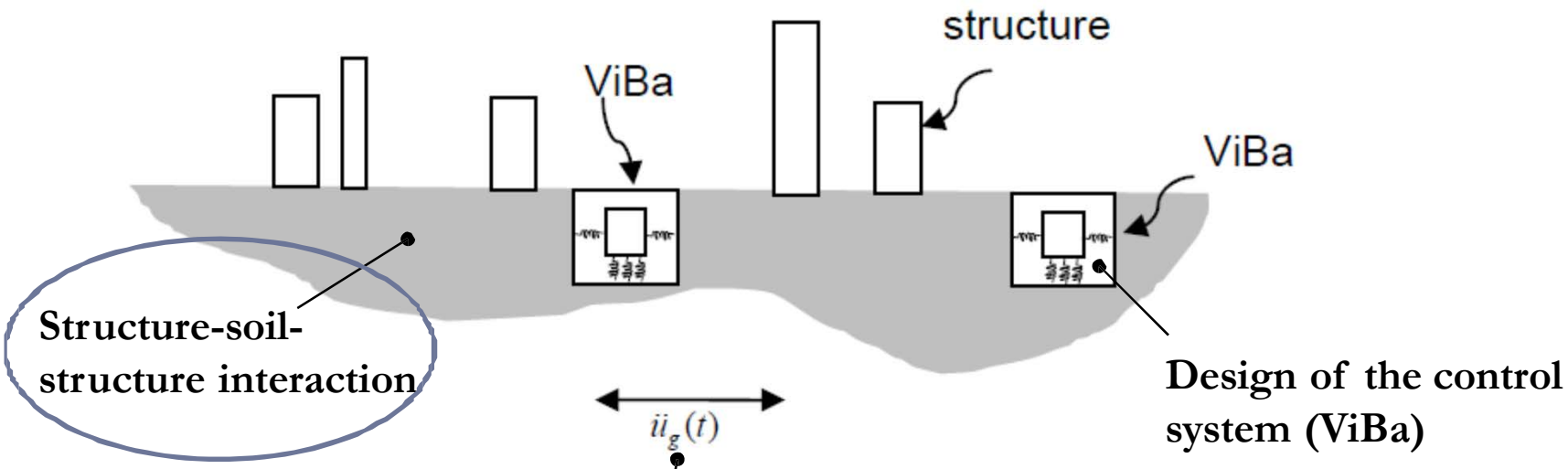


Figure 1: Sketch of the proposed Vibrating Barrier

Structure-soil-structure interaction

Design of the control system (ViBa)

Modelling of the seismic actions

Structure-soil-structure interaction

- Warburton GB, Richardson JD, Webster JJ. *1971 Forced vibrations of two masses on an elastic half space. J. Appl. Mech. 38, 148.*

- Luco JE, Contesse L. *1973 Dynamic structure–soil–structure interaction. Bull. Seismol. Soc. Am. 63, 1289–303*

- Kham M, Semblat J-F, Bard P-Y,Dangla P. *2006 Seismic site-city interaction: main governing phenomena through simplified numerical models. Bull. Seismol. Soc. Am. 96, 1934–1951*

Nupec experimental studies (2003)

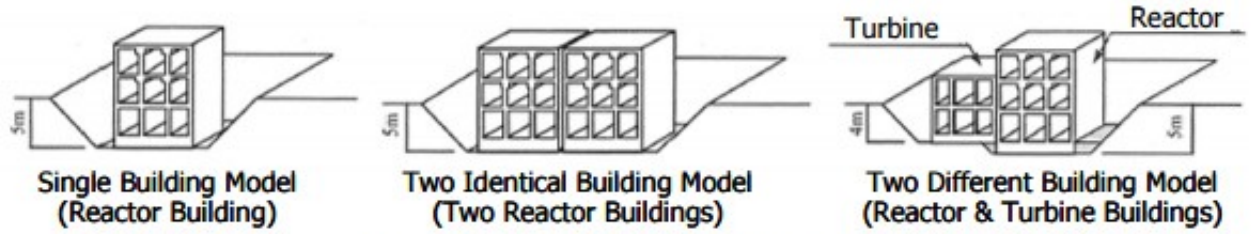


Figure 4 Building Model Arrangement

5

Two Identical Building Model

Figure 5 Building models in field Test

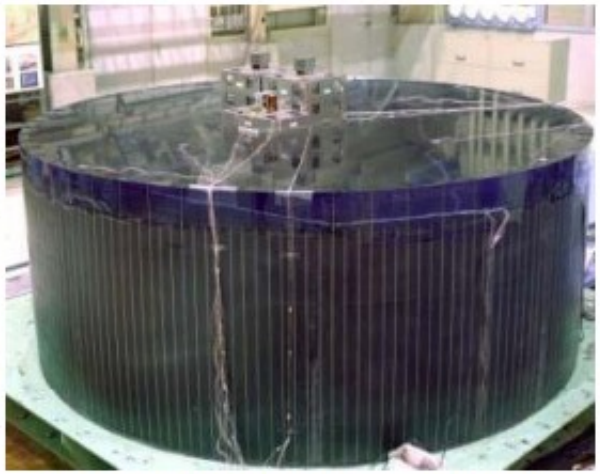


Figure 6 Vibration test using shaker

Proposed approach

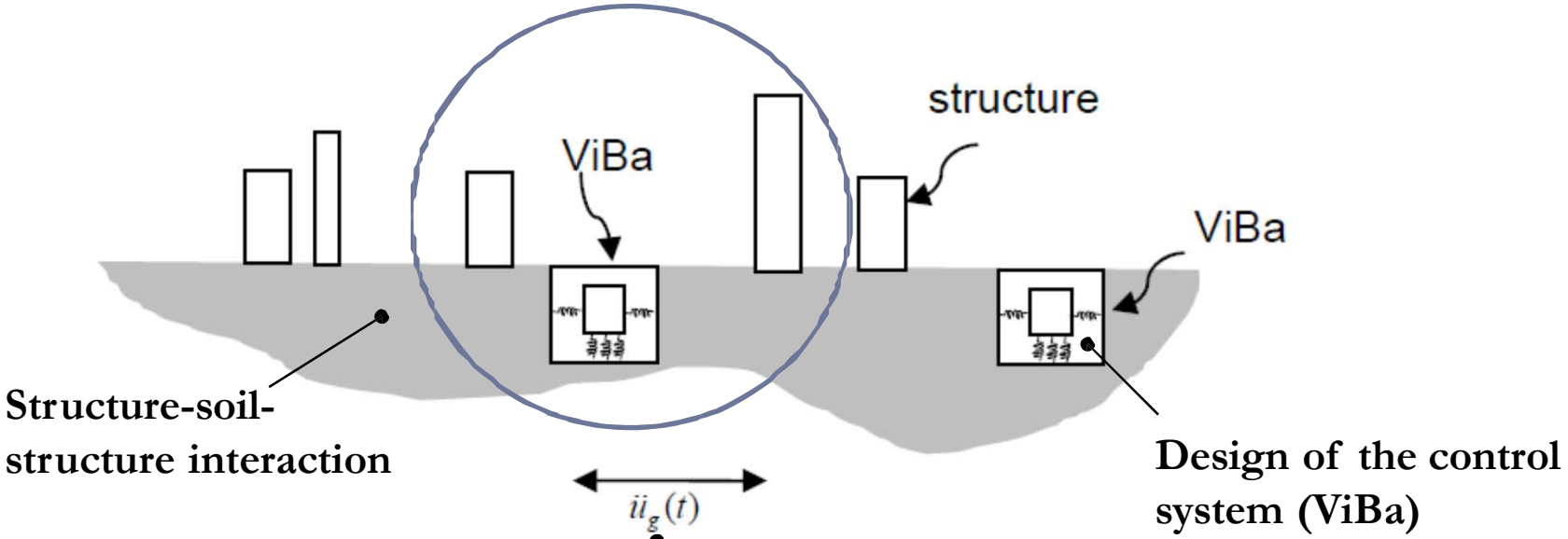
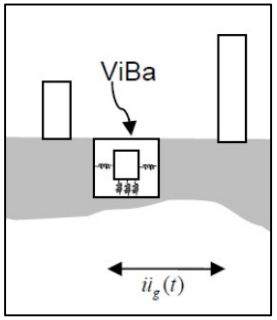


Figure 1: Sketch of the proposed Vibrating Barrier

Discrete model



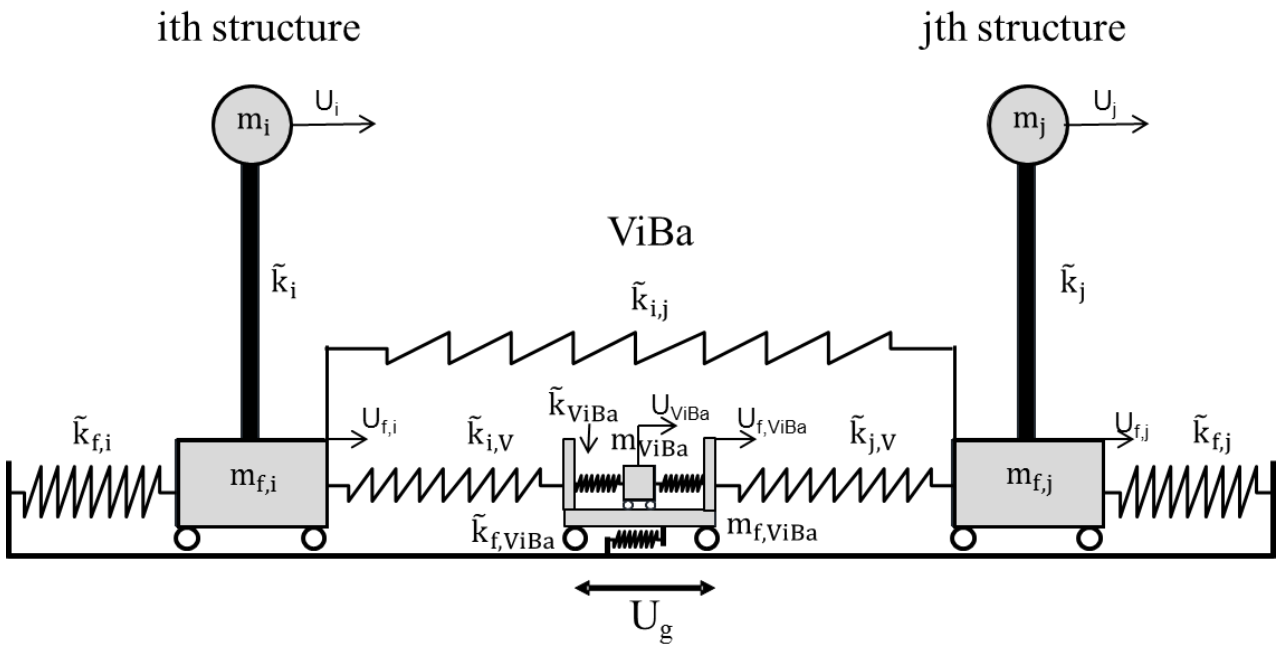


Figure 2 Discrete model for protection of two structures by the ViBa

Equations of motion: discrete model

- $\left(\widetilde{\mathbf{K}} - \omega^2 \mathbf{M}\right)\mathbf{U}(\omega) = \mathbf{Q}\, \mathrm{U_g}(\omega)$

  - $\mathbf{U}(\omega)$ is the vector of absolute displacements

$$\mathbf{U}^{\mathrm{T}}(\omega) = [\mathrm{U_i}(\omega) \quad \mathrm{U_{f,i}}(\omega) \quad \cdots \quad \mathrm{U}_n(\omega) \quad \mathrm{U_{f,}}_n(\omega) \quad \mathrm{U_{Vi}}$$

  - Influence vector

$$\mathbf{Q}^{\mathrm{T}} = \left[0 \quad \tilde{\mathrm{k}}_{\mathrm{f,i}} \quad \cdots \quad 0 \quad \tilde{\mathrm{k}}_{\mathrm{f,}n} \quad 0 \quad \tilde{\mathrm{k}}_{\mathrm{f,ViBa}}\right]$$

Mass matrix

- Lumped mass model

$$\mathbf{M} = \begin{bmatrix} \mathbf{M}_1 & \mathbf{0} & \cdots & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_\mathrm{i} & & \mathbf{0} & \mathbf{0} \\ \vdots & & \ddots & \vdots & \\ \mathbf{0} & \mathbf{0} & & \mathbf{M}_n & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0} & \mathbf{M}_\mathrm{V} \end{bmatrix}$$

$$\mathbf{M}_\mathrm{i} = \begin{bmatrix} \mathrm{m_i} & 0 \\ 0 & \mathrm{m_{f,i}} \end{bmatrix} \qquad \mathbf{M}_\mathrm{V} = \begin{bmatrix} \mathrm{m_{ViBa}} & 0 \\ 0 & \mathrm{m_{f,ViBa}} \end{bmatrix}$$

Complex Stiffness matrix

$$\widetilde{\mathbf{K}} = \begin{bmatrix} \widetilde{\mathbf{K}}_1 & \widetilde{\mathbf{K}}_{1,\mathrm{i}} & \cdots & \widetilde{\mathbf{K}}_{1,n} & \widetilde{\mathbf{K}}_{1,\mathrm{V}} \\ \widetilde{\mathbf{K}}_{\mathrm{i},1} & \widetilde{\mathbf{K}}_{\mathrm{i}} & & \widetilde{\mathbf{K}}_{\mathrm{i},n} & \widetilde{\mathbf{K}}_{\mathrm{i},\mathrm{V}} \\ \vdots & & \ddots & & \vdots \\ \widetilde{\mathbf{K}}_{n,1} & \widetilde{\mathbf{K}}_{n,\mathrm{i}} & & \widetilde{\mathbf{K}}_{n} & \widetilde{\mathbf{K}}_{n,\mathrm{V}} \\ \widetilde{\mathbf{K}}_{\mathrm{V},1} & \widetilde{\mathbf{K}}_{\mathrm{V},\mathrm{i}} & \cdots & \widetilde{\mathbf{K}}_{\mathrm{V},\mathrm{n}} & \widetilde{\mathbf{K}}_{\mathrm{V}} \end{bmatrix}$$

- Hysteretic damping model

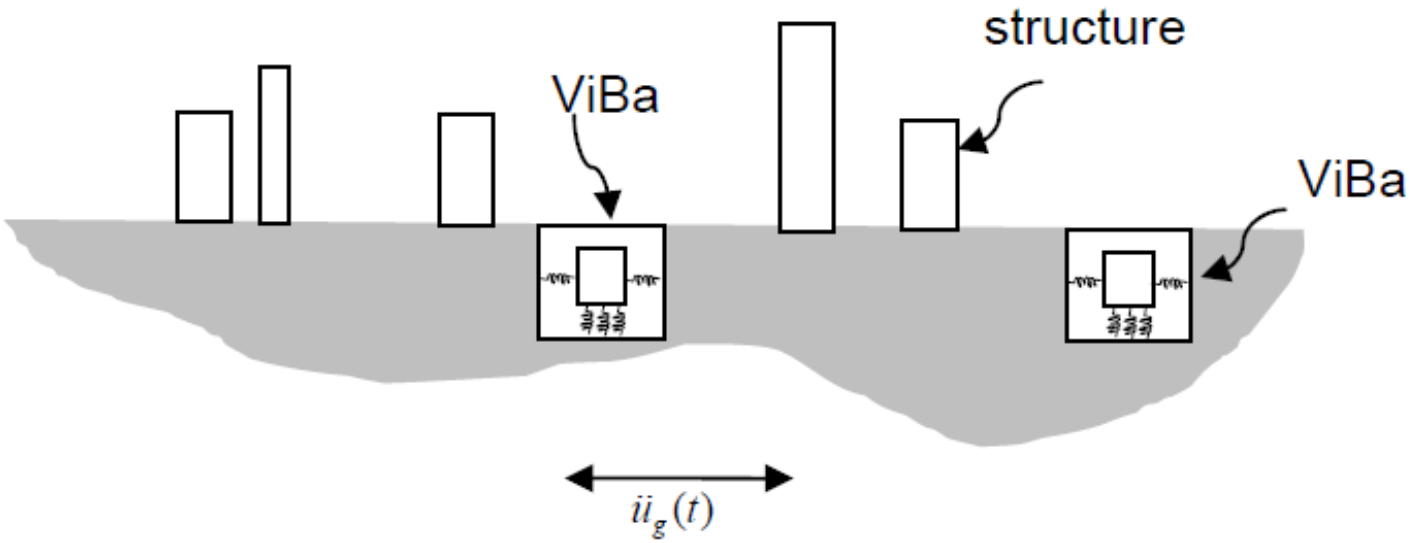
$$\tilde{\mathrm{k}} = \mathrm{k}(1 + i\eta)$$

$$\widetilde{\mathbf{K}}_{\mathrm{i}} = \begin{bmatrix} \tilde{\mathrm{k}}_{\mathrm{i}} & -\tilde{\mathrm{k}}_{\mathrm{i}} \\ -\tilde{\mathrm{k}}_{\mathrm{i}} & \tilde{\mathrm{k}}_{\mathrm{i}} + \tilde{\mathrm{k}}_{\mathrm{f,i}} + \tilde{\mathrm{k}}_{\mathrm{i,V}} + \sum_{\mathrm{r}=1\neq\mathrm{i}}^{\mathrm{n}-1} \tilde{\mathrm{k}}_{\mathrm{i,r}} \end{bmatrix}$$

$$\widetilde{\mathbf{K}}_{\mathrm{V}} = \begin{bmatrix} \tilde{\mathrm{k}}_{\mathrm{ViBa}} & -\tilde{\mathrm{k}}_{\mathrm{ViBa}} \\ -\tilde{\mathrm{k}}_{\mathrm{ViBa}} & \tilde{\mathrm{k}}_{\mathrm{ViBa}} + \tilde{\mathrm{k}}_{\mathrm{f,ViBa}} + \sum_{\mathrm{i}=1}^{\mathrm{n}-1} \tilde{\mathrm{k}}_{\mathrm{i,V}} \end{bmatrix}$$

$$\widetilde{\mathbf{K}}_{\mathrm{i,j}} = \begin{bmatrix} 0 & 0 \\ 0 & -\tilde{\mathrm{k}}_{\mathrm{i,j}} \end{bmatrix} \qquad \widetilde{\mathbf{K}}_{\mathrm{i,V}} = \begin{bmatrix} 0 & 0 \\ 0 & -\tilde{\mathrm{k}}_{\mathrm{i,V}} \end{bmatrix} \quad \widetilde{\mathbf{K}}_{\mathrm{V,i}} = \begin{bmatrix} 0 & 0 \\ 0 & -\tilde{\mathrm{k}}_{\mathrm{V,i}} \end{bmatrix}$$

Design of the ViBa



$$\min\{U_i^{r,max}(\boldsymbol{\alpha})\} \quad i = 1, \dots, n$$
$$\boldsymbol{\alpha} = \{k_{ViBa}, m_{ViBa}, \eta_{ViBa}\} \in \mathbb{R}_0^+$$

Vibration control of a single structure through the ViBa

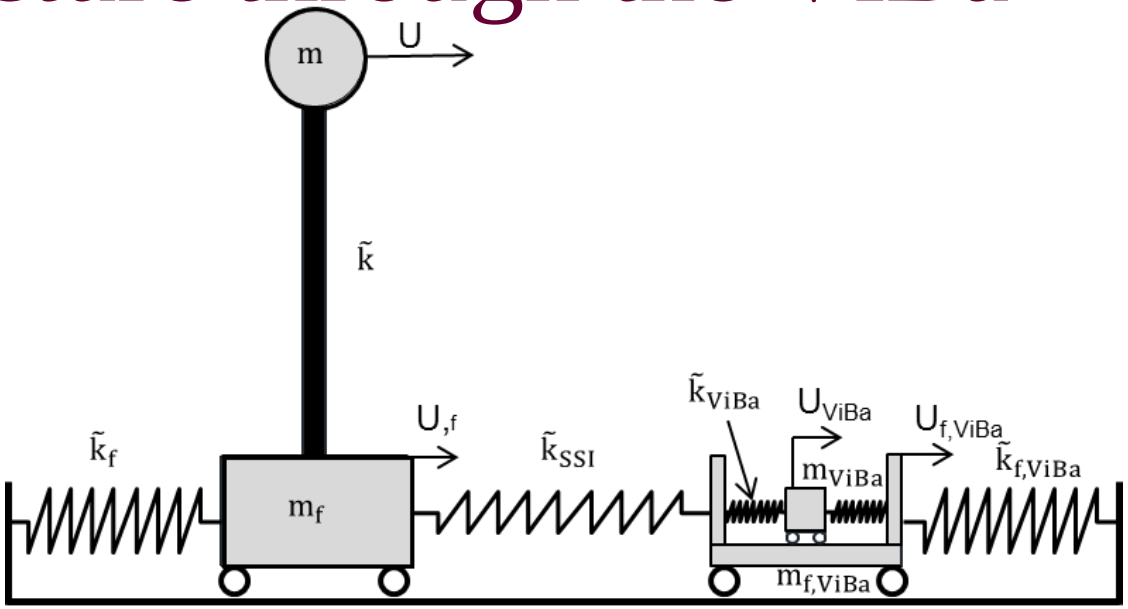


Figure 4 Discrete model for single structure protected by the ViBa

$$\left\{\begin{bmatrix} \tilde{k} & -\tilde{k} & 0 & 0 \\ -\tilde{k} & \tilde{k}+\tilde{k}_f+\tilde{k}_{SSSI} & 0 & -\tilde{k}_{SSSI} \\ 0 & 0 & \tilde{k}_{ViBa} & -\tilde{k}_{ViBa} \\ 0 & -\tilde{k}_{SSSI} & -\tilde{k}_{ViBa} & \tilde{k}_{ViBa}+\tilde{k}_{f,ViBA}+\tilde{k}_{SSSI} \end{bmatrix} - \omega^2 \begin{bmatrix} m & 0 & 0 & 0 \\ 0 & m_f & 0 & 0 \\ 0 & 0 & m_{ViBa} & 0 \\ 0 & 0 & 0 & m_{f,ViBa} \end{bmatrix}\right\} \begin{bmatrix} U(\omega) \\ U_f(\omega) \\ U_{ViBa}(\omega) \\ U_{f,ViBa}(\omega) \end{bmatrix} = \begin{bmatrix} 0 \\ \tilde{k}_f \\ 0 \\ \tilde{k}_{f,ViBa} \end{bmatrix} U_g(\omega)$$

$$\mathbf{H}(\boldsymbol{\alpha},\omega) = \widetilde{\mathbf{K}}_{\mathrm{dyn}}^{-1}(\boldsymbol{\alpha},\omega)\mathbf{Q} = [\mathrm{H}(\boldsymbol{\alpha},\omega) \quad \mathrm{H}_{\mathrm{f}}(\boldsymbol{\alpha},\omega) \quad \mathrm{H}_{\mathrm{ViBa}}(\boldsymbol{\alpha},\omega) \quad \mathrm{H}_{\mathrm{f,ViBa}}(\boldsymbol{\alpha},\omega)]^{\mathrm{T}}$$

$$\mathrm{H}(\boldsymbol{\alpha},\omega) = \frac{\mathrm{U}(\omega)}{\mathrm{U_g}(\omega)} = \frac{\tilde{\mathrm{k}} \cdot \left[\left(\tilde{\mathrm{k}}_{\mathrm{SSSI}} \cdot \tilde{\mathrm{k}}_{\mathrm{f,ViBa}} + \tilde{\mathrm{b}} \cdot \tilde{\mathrm{k}}_{\mathrm{f}}\right)\left(\tilde{\mathrm{k}}_{\mathrm{ViBa}} - \omega^2 \mathrm{m}_{\mathrm{ViBa}}\right) - \tilde{\mathrm{k}}_{\mathrm{ViBa}}^2 \cdot \tilde{\mathrm{k}}_{\mathrm{f}}\right]}{\left(\tilde{\mathrm{k}} \cdot \tilde{\mathrm{k}}_{\mathrm{ViBa}}\right)^2 - \left(\tilde{\mathrm{k}}_{\mathrm{ViBa}}^2 \cdot \tilde{\mathrm{a}}\right)\left(\tilde{\mathrm{k}} - \omega^2 \mathrm{m}\right) + \left[\left(\tilde{\mathrm{a}} \cdot \widetilde{\mathrm{b}} - \tilde{\mathrm{k}}_{\mathrm{SSSI}}^2\right)\left(\tilde{\mathrm{k}} - \omega^2 \mathrm{m}\right) - \left(\tilde{\mathrm{k}}^2 \cdot \tilde{\mathrm{b}}\right)\right]\tilde{\mathrm{c}}}$$

where $\widetilde{\omega}^2 = \tilde{\mathrm{k}}/\mathrm{m}$ and $\widetilde{\omega}_{\mathrm{ViBa}}^2 = \tilde{\mathrm{k}}_{\mathrm{ViBa}}/\mathrm{m}_{\mathrm{ViBa}}$; furthermore, the following positions have been made: $\tilde{\mathrm{a}} = \tilde{\mathrm{k}} + \tilde{\mathrm{k}}_{\mathrm{f}} + \tilde{\mathrm{k}}_{\mathrm{SSSI}} - \omega^2 \mathrm{m}_{\mathrm{f}}$, $\tilde{\mathrm{b}} = \tilde{\mathrm{k}}_{\mathrm{ViBa}} + \tilde{\mathrm{k}}_{\mathrm{f,ViBa}} + \tilde{\mathrm{k}}_{\mathrm{SSSI}} - \omega^2 \mathrm{m}_{\mathrm{f,ViBa}}$ and $\tilde{\mathrm{c}} = \tilde{\mathrm{k}}_{\mathrm{ViBa}} - \omega^2 \mathrm{m}_{\mathrm{VIBa}}$.

Design for harmonic excitation

$$\min\{H(\boldsymbol{\alpha}, \omega_0)\}$$

$$\boldsymbol{\alpha} = \{k_{ViBa}, m_{ViBa}, \eta_{ViBa}\} \in \mathbb{R}_0^+$$

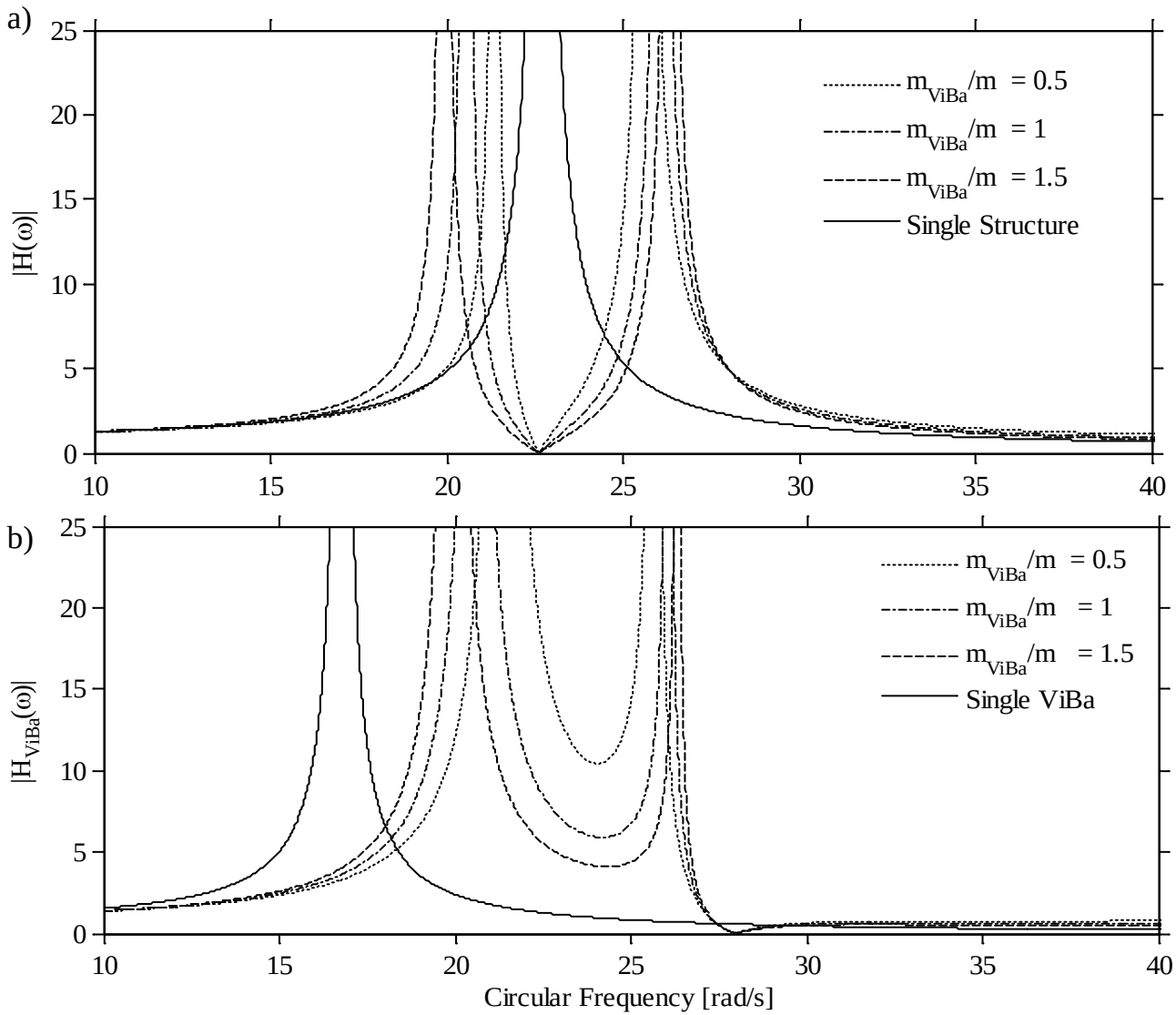
- Closed form solution

$$\tilde{k}_{ViBa}^{optimal}(\omega_0) = \frac{(\omega_0^2 m_{ViBa})\left[\tilde{k}_{f,ViBa} + \tilde{k}_{SSSI}\left(1 + \frac{\tilde{k}_{f,ViBa}}{\tilde{k}_f}\right) - \omega_0^2 m_{f,ViBa}\right]}{\tilde{k}_{f,ViBa} + \tilde{k}_{SSSI}\left(1 + \frac{\tilde{k}_{f,ViBa}}{\tilde{k}_f}\right) - \omega_0^2 (m_{f,ViBa} + m_{ViBa})}$$

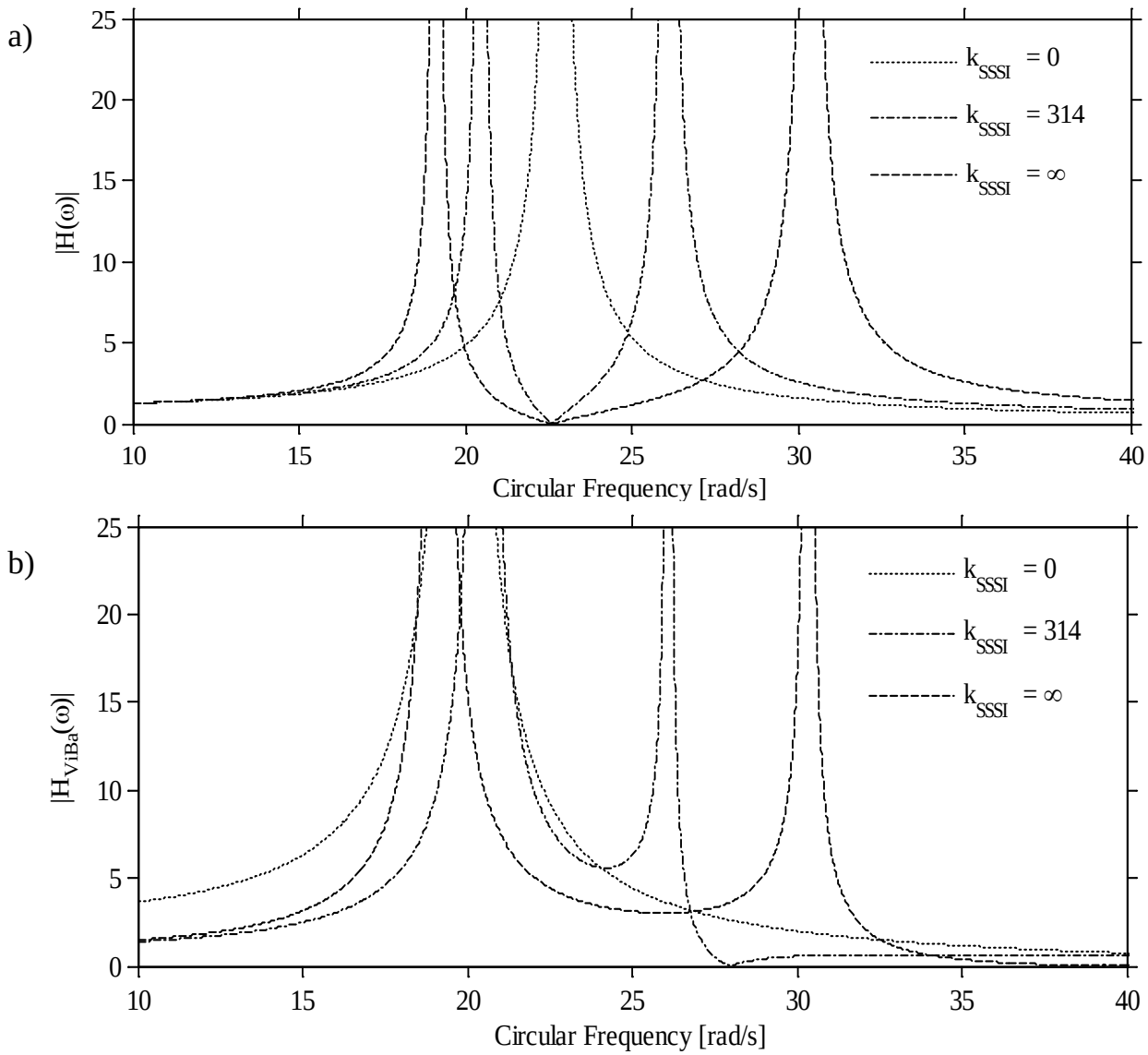
$$k_{ViBa}^{optimal} = k_{ViBa}^{real}(\omega)$$

$$\eta_{ViBa}^{optimal} = \frac{k_{ViBa}^{imag}(\omega)}{k_{ViBa}^{real}(\omega)}$$

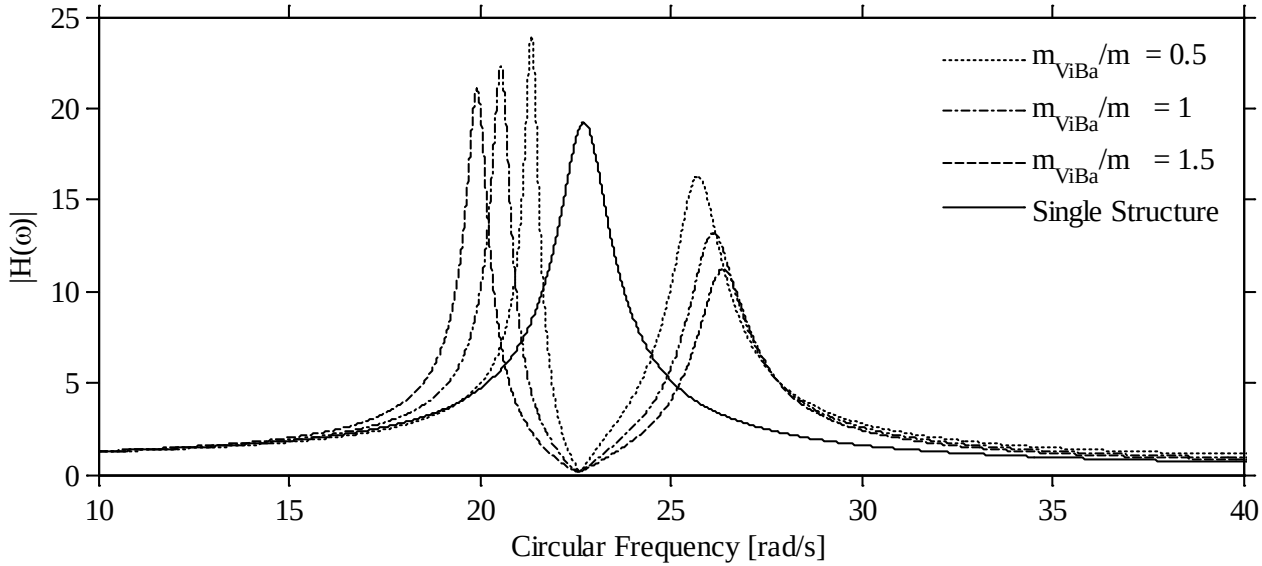
Transfer functions of the undamped system for the a) structure and b) ViBa obtained for different mass ratio



Transfer functions of the undamped system for the a) structure and b) ViBa obtained for different coupling stiffness value.



Transfer functions of the a) structure and b) ViBa obtained for different mass ratio and null ViBa loss factor.



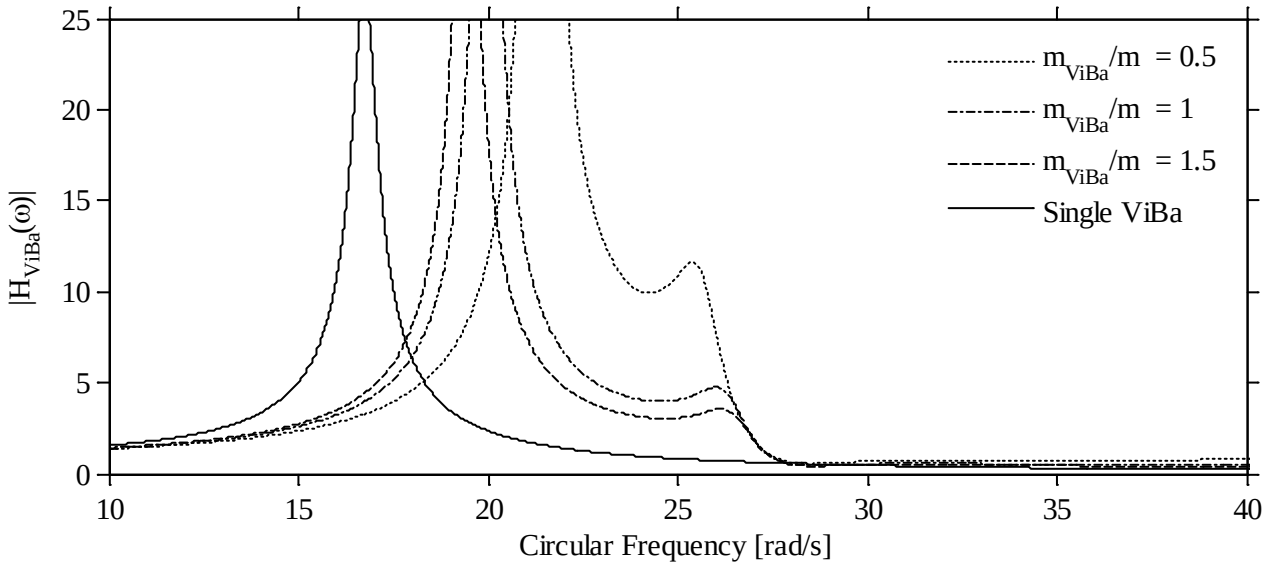
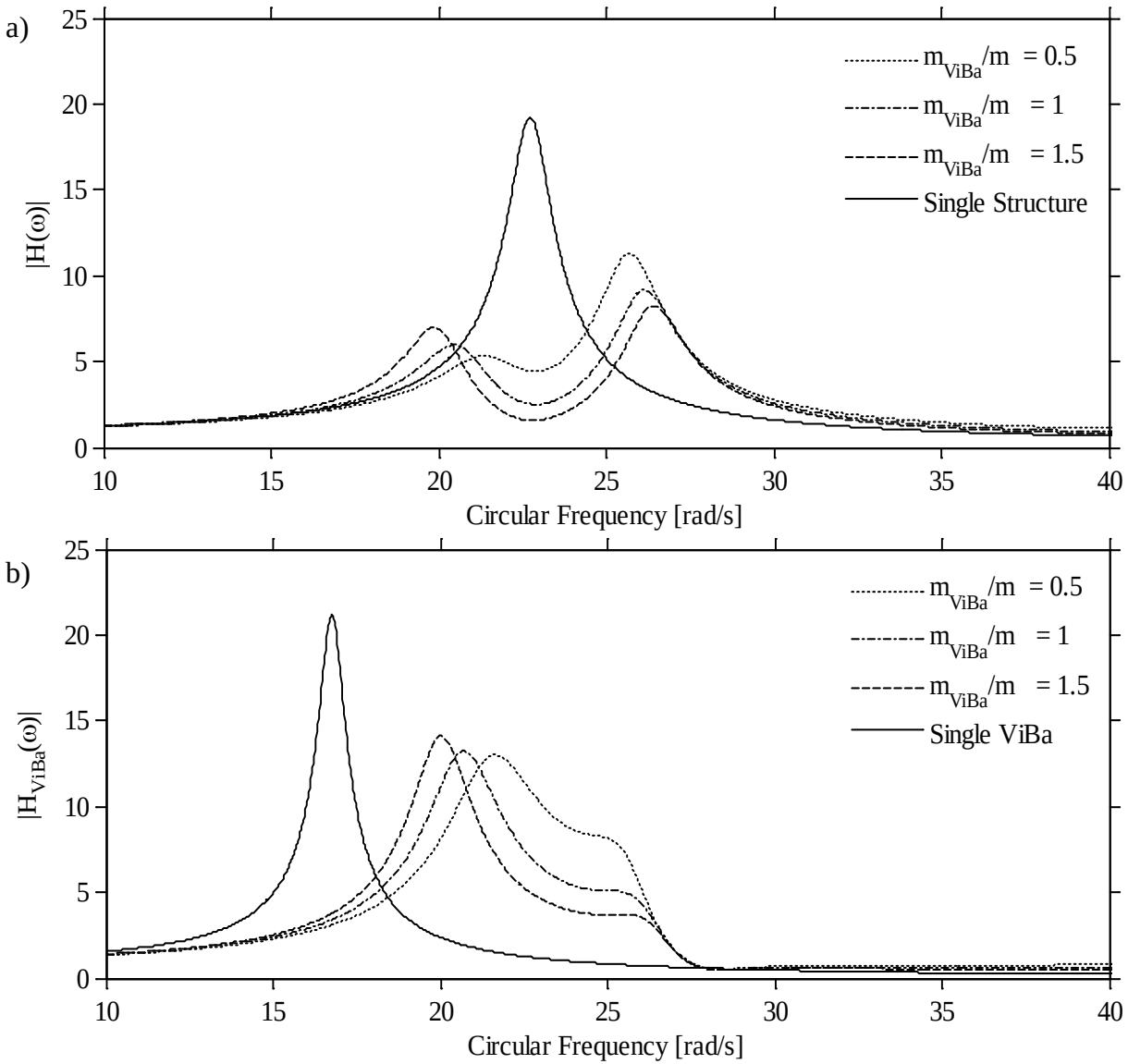
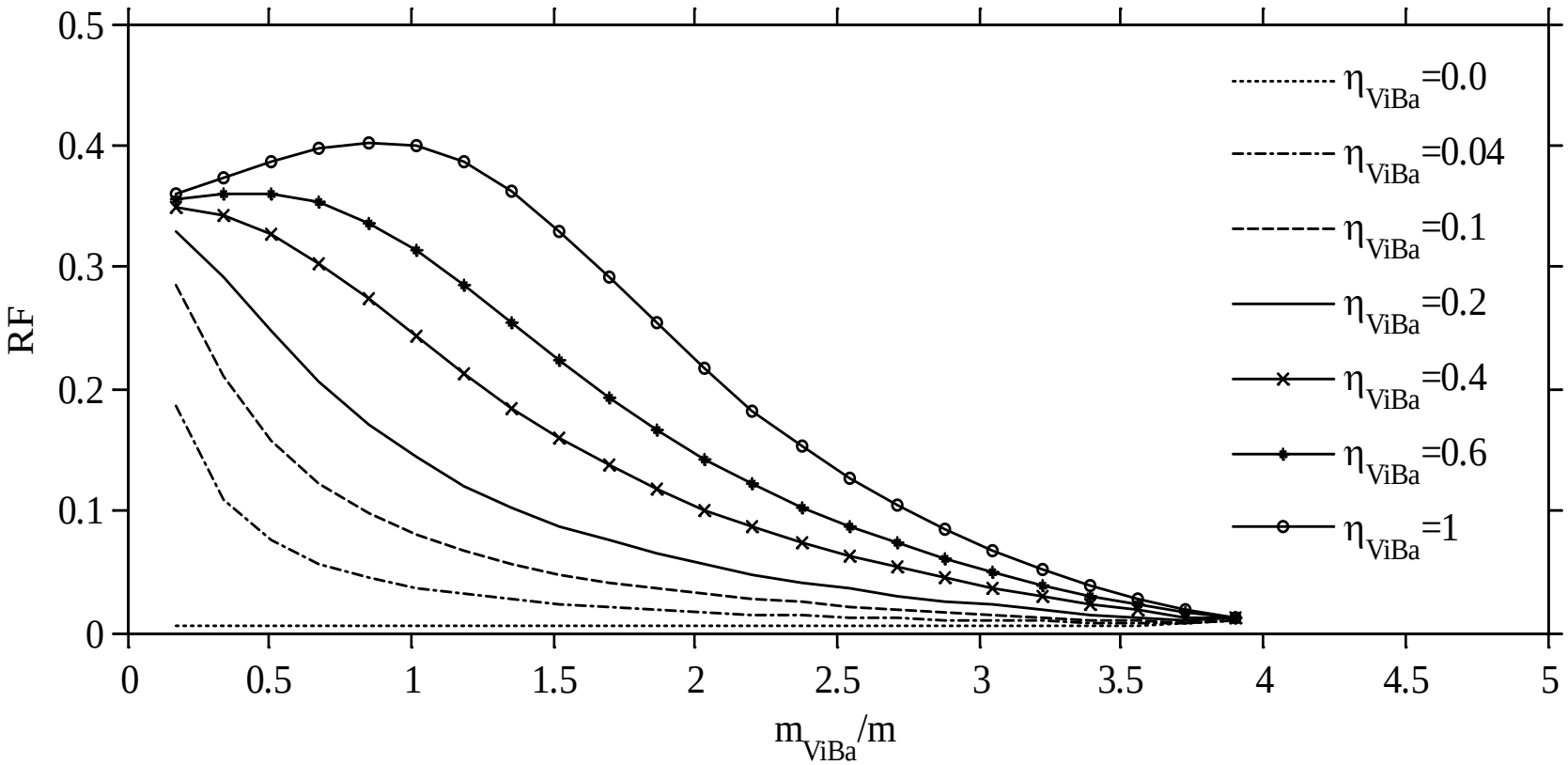


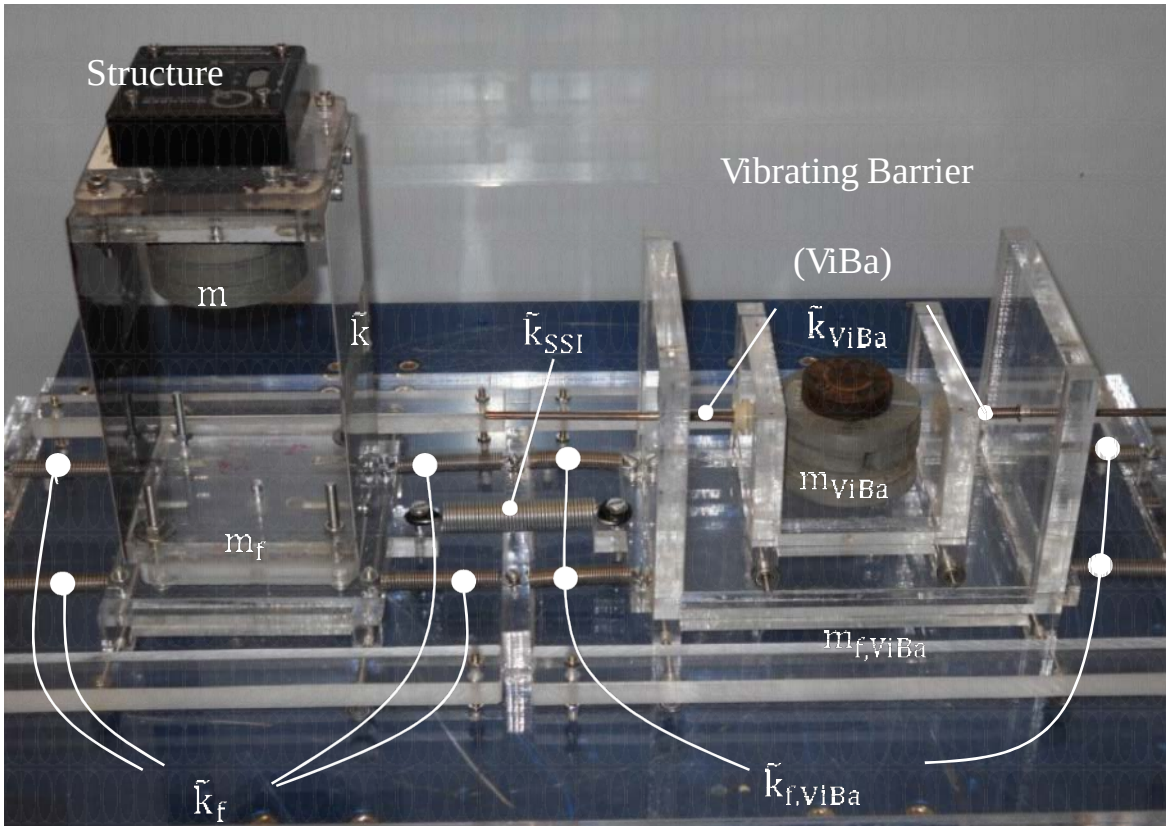
Figure 9 Transfer functions of the a) structure and b) ViBa obtained for different mass ratio and ViBa loss factor η_{ViBa} = 0.18.



Reduction factor curves versus mass ratio for several ViBa loss factors.

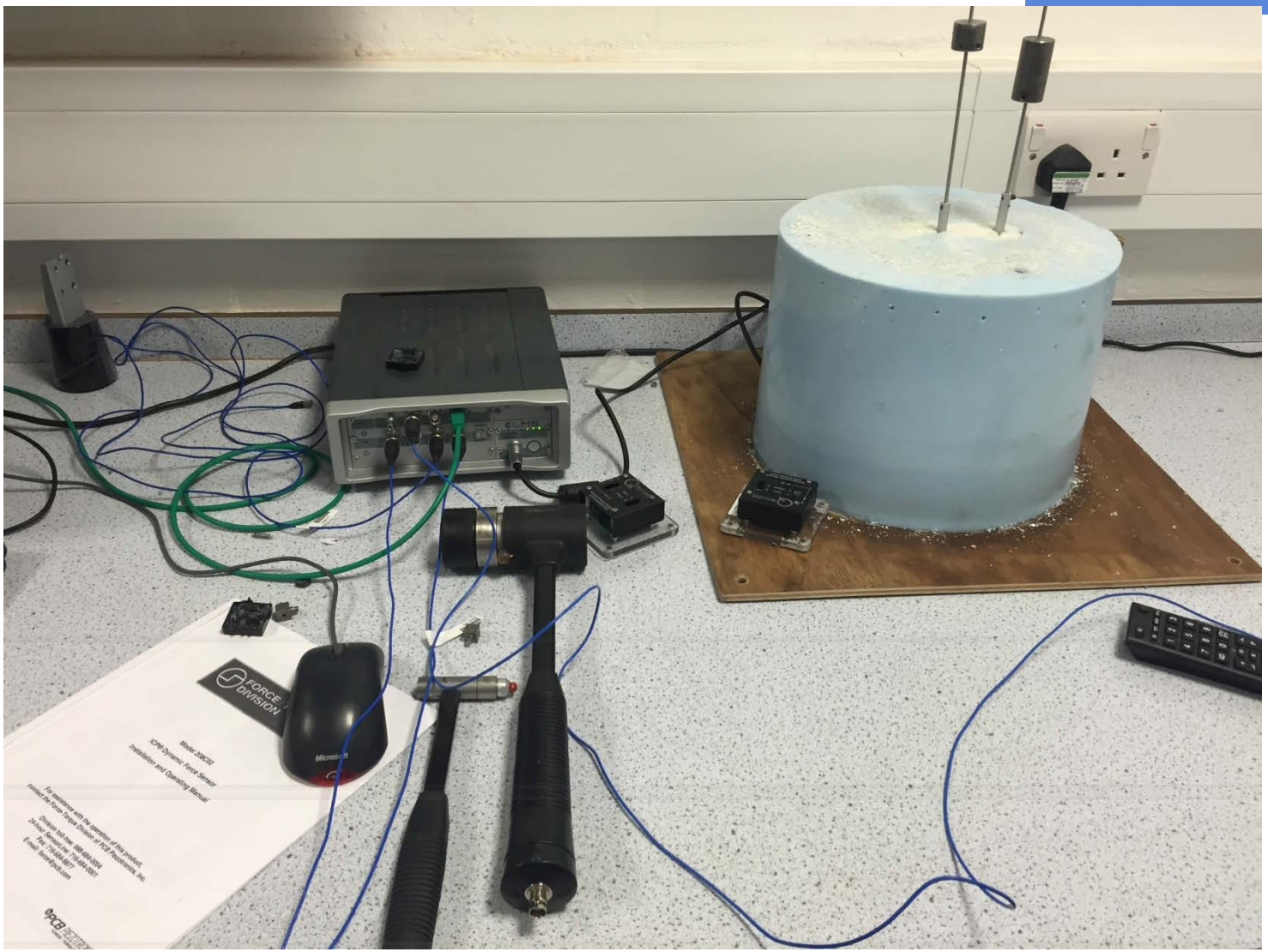


Prototype structure protected by the ViBa.

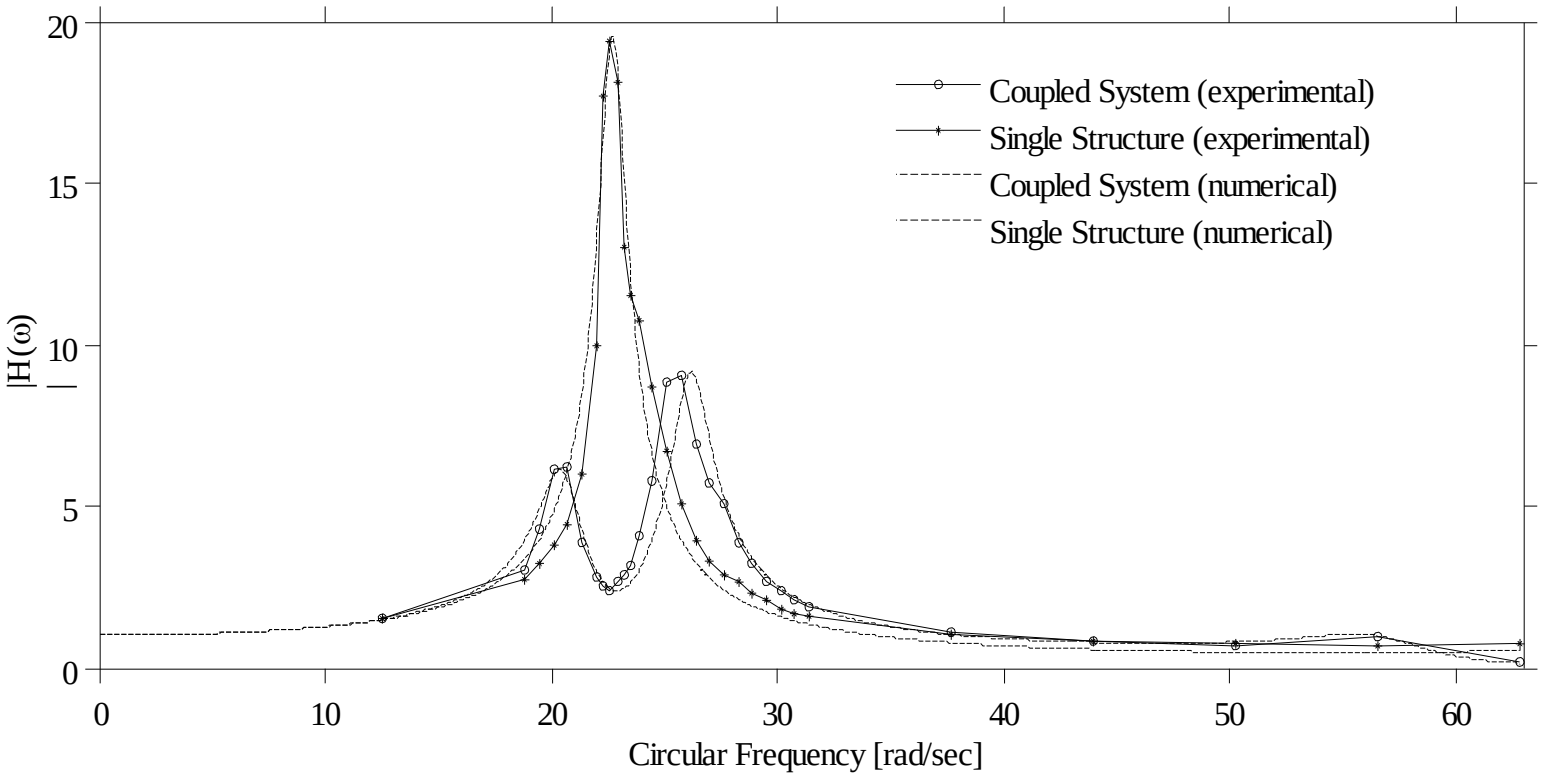


Dynamics of Structures Lab

LMS/Siemens Acquisition system

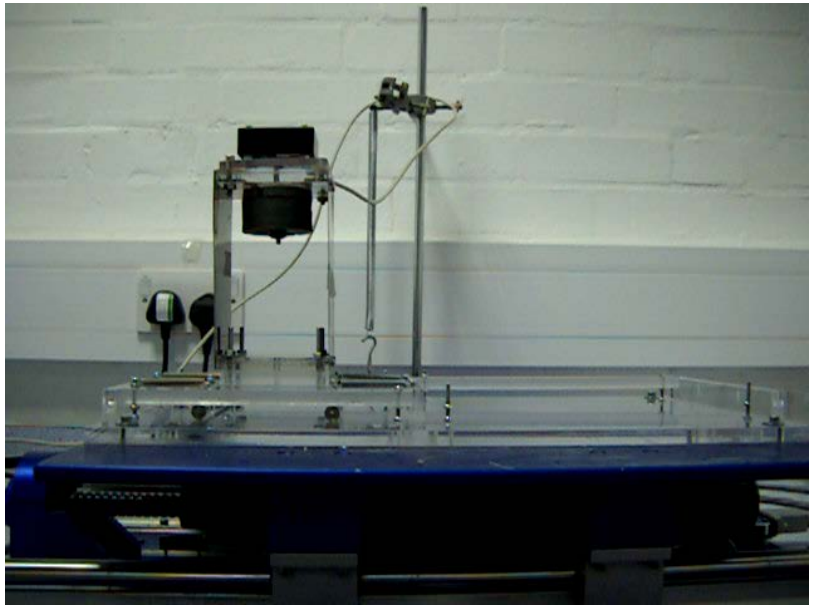


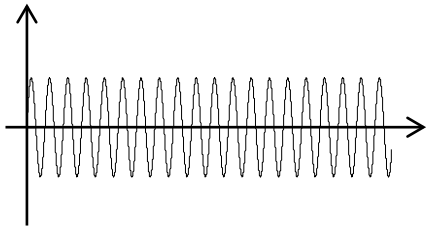
Experimentally evaluated transfer functions of the structure for the uncoupled and coupled case and comparison with numerical results.



Experimental tests: single structure

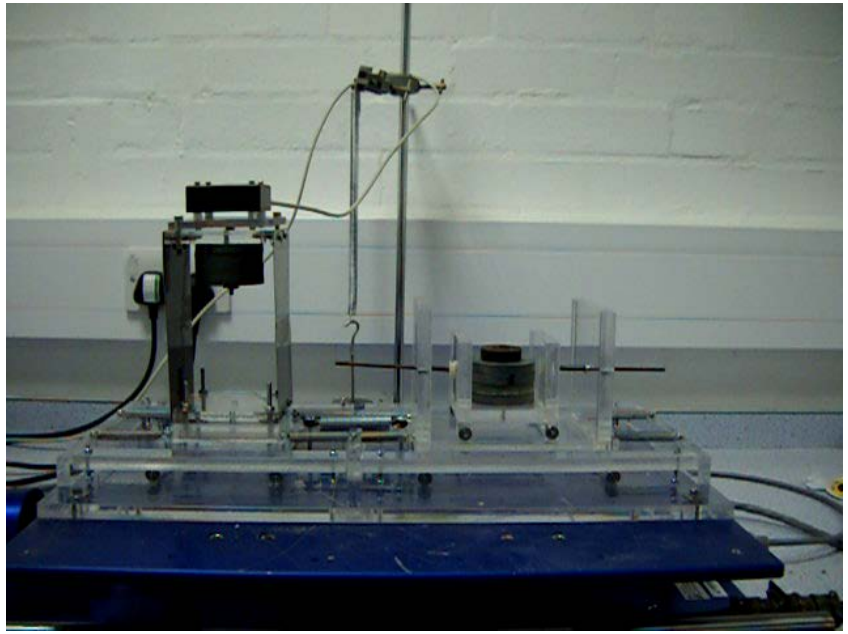
Single Structure

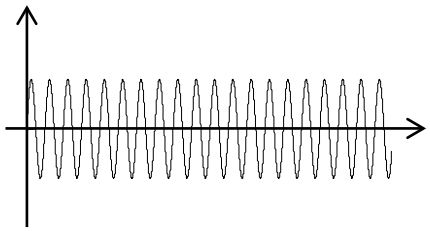




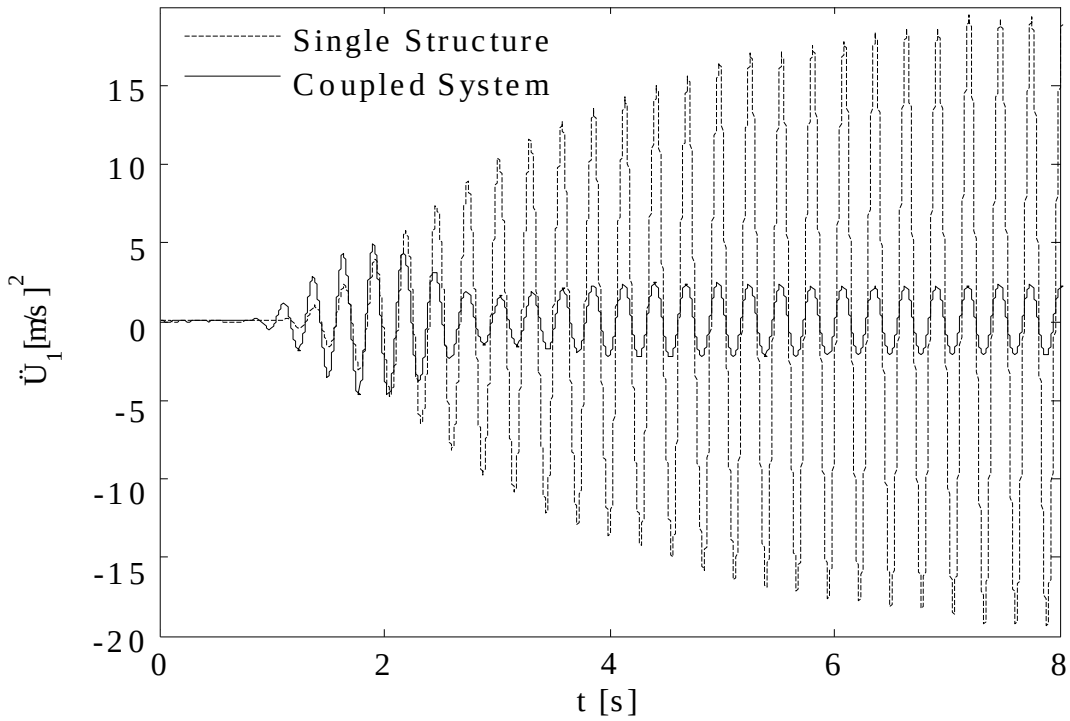
same harmonic signal !

Structure - ViBa





Recorded acceleration of the structure subjected to harmonic base motion at the circular frequency= 22.62 rad/s in the case of single structure and structure coupled with ViBa



SECED 2015 Conference: Earthquake Risk and Engineering towards a Resilient World
9-10 July 2015, Cambridge UK

VIBRATION CONTROL OF AN INDUSTRIAL BUILDING THROUGH THE VIBRATING BARRIER

Pierfrancesco CACCIOLA[1], Alessandro TOMBARI[2] and Irmela ZENTNER[3]

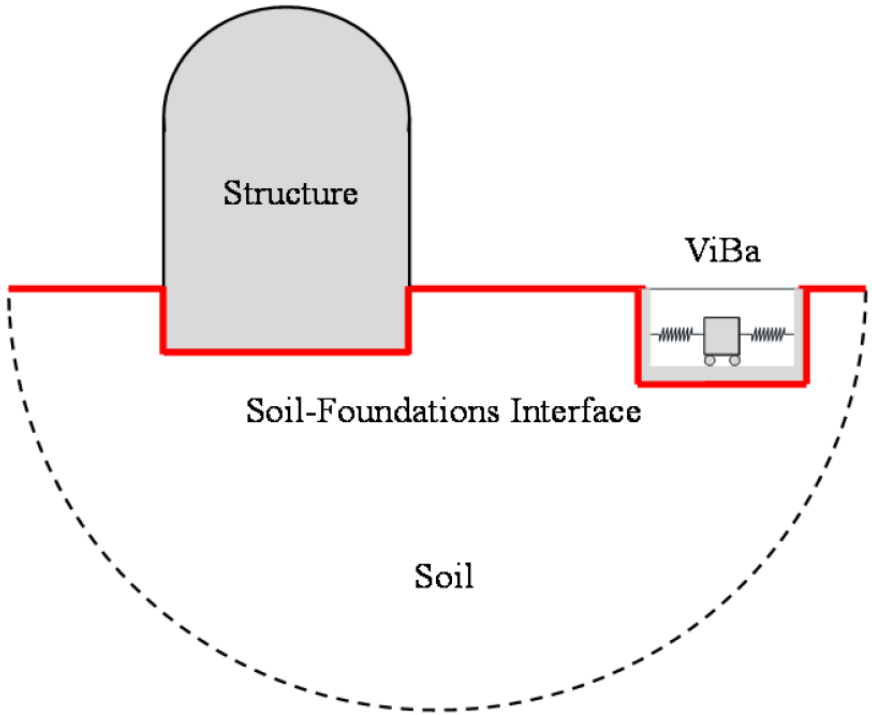


Figure 1 Subdomains of the considered global problem

Proposed approach

-Equation of motion

$$\left[\mathbf{K}_{\mathrm{glob}}(\omega) - \omega^2\mathbf{M}_{\mathrm{glob}} + i\omega\mathbf{C}_{\mathrm{glob}}\right]\mathbf{u}(\omega) = \mathbf{f}(\omega)$$

-Craig-Bampton method

$$\begin{bmatrix}\mathbf{u}_{\mathrm{ViBa}}\\ \mathbf{u}_{\mathrm{str}}\\ \mathbf{u}_{\mathrm{SF}}\end{bmatrix} = \mathbf{P}\begin{bmatrix}\mathbf{q}_{\mathrm{ViBa}}\\ \mathbf{q}_{\mathrm{str}}\\ \mathbf{u}_{\mathrm{SF}}\end{bmatrix} \qquad \mathbf{P}_{[\mathrm{nxm}]} = \begin{bmatrix}\boldsymbol{\psi}^{\mathrm{ViBa}}_{[\mathrm{pxi}]} & \mathbf{0}_{[\mathrm{pxl}]} & \boldsymbol{\phi}^{\mathrm{ViBa}}_{[\mathrm{pxr}]}\\ \mathbf{0}_{[\mathrm{qxi}]} & \boldsymbol{\psi}^{\mathrm{str}}_{[\mathrm{qxl}]} & \boldsymbol{\phi}^{\mathrm{str}}_{[\mathrm{qxr}]}\\ \mathbf{0}_{[\mathrm{rxi}]} & \mathbf{0}_{[\mathrm{rxl}]} & \mathbf{I}_{[\mathrm{rxr}]}\end{bmatrix}$$

$$\left[\mathbf{P}^{\mathrm{T}}\mathbf{K}_{\mathrm{glob}}(\omega)\mathbf{P} - \omega^2\mathbf{P}^{\mathrm{T}}\mathbf{M}_{\mathrm{glob}}\mathbf{P} + i\omega\mathbf{P}^{\mathrm{T}}\mathbf{C}_{\mathrm{glob}}\mathbf{P}\right]\mathbf{u}(\omega) = \mathbf{P}^{\mathrm{T}}\mathbf{f}(\omega)$$

Proposed approach

- Proof of concept – Design for harmonic excitation
- Simplified model

$$\left\{\begin{bmatrix} \tilde{k} & -\tilde{k} & 0 & 0 \\ -\tilde{k} & \tilde{k}+\tilde{k}_f+\tilde{k}_{SSSI} & 0 & 0 \\ 0 & 0 & \tilde{k}_{ViBa} & -\tilde{k}_{ViBa} \\ 0 & 0 & -\tilde{k}_{ViBa} & \tilde{k}_{ViBa}+\tilde{k}_{f,ViBA}+\tilde{k}_{SSSI} \end{bmatrix} - \omega^2 \begin{bmatrix} m & 0 & 0 & 0 \\ 0 & m_f & 0 & 0 \\ 0 & 0 & m_{ViBa} & 0 \\ 0 & 0 & 0 & m_{f,ViBa} \end{bmatrix}\right\} \begin{bmatrix} U(\omega) \\ U_f(\omega) \\ U_{ViBa}(\omega) \\ U_{f,ViBa}(\omega) \end{bmatrix} = \begin{bmatrix} 0 \\ \tilde{k}_f \\ 0 \\ \tilde{k}_{f,ViBa} \end{bmatrix} u_g(\omega)$$

$$\tilde{k}_{ViBa}^{optimal} = \frac{(\omega_0^2 m_{ViBa})\left[\tilde{k}_{f,ViBa} + \tilde{k}_{SSSI}\left(1+\frac{\tilde{k}_{f,ViBa}}{\tilde{k}_f}\right) - \omega_0^2 m_{f,ViBa}\right]}{\tilde{k}_{f,ViBa} + \tilde{k}_{SSSI}\left(1+\frac{\tilde{k}_{f,ViBa}}{\tilde{k}_f}\right) - \omega_0^2 (m_{f,ViBa} + m_{ViBa})}$$

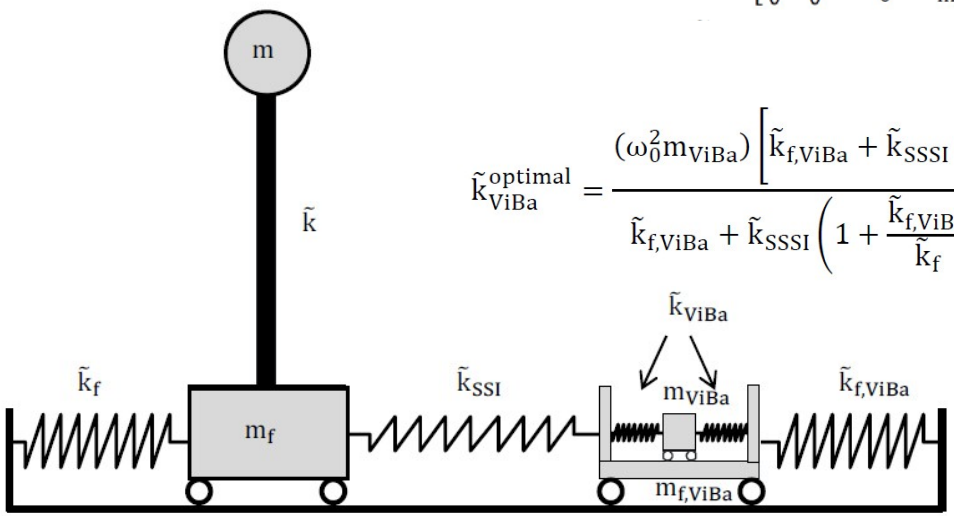


Figure 2 Simplified model

$$\min\{H(\boldsymbol{\alpha}, \omega)\}$$

$$\boldsymbol{\alpha} = \{k_{ViBa}, m_{ViBa}, \eta_{ViBa}\} \in \mathbb{R}_0^+$$

$$\mathbf{H}(\omega) = \left[\mathbf{K}_{simp} - \omega^2 \mathbf{M}_{simp}\right]^{-1} \mathbf{Q}$$

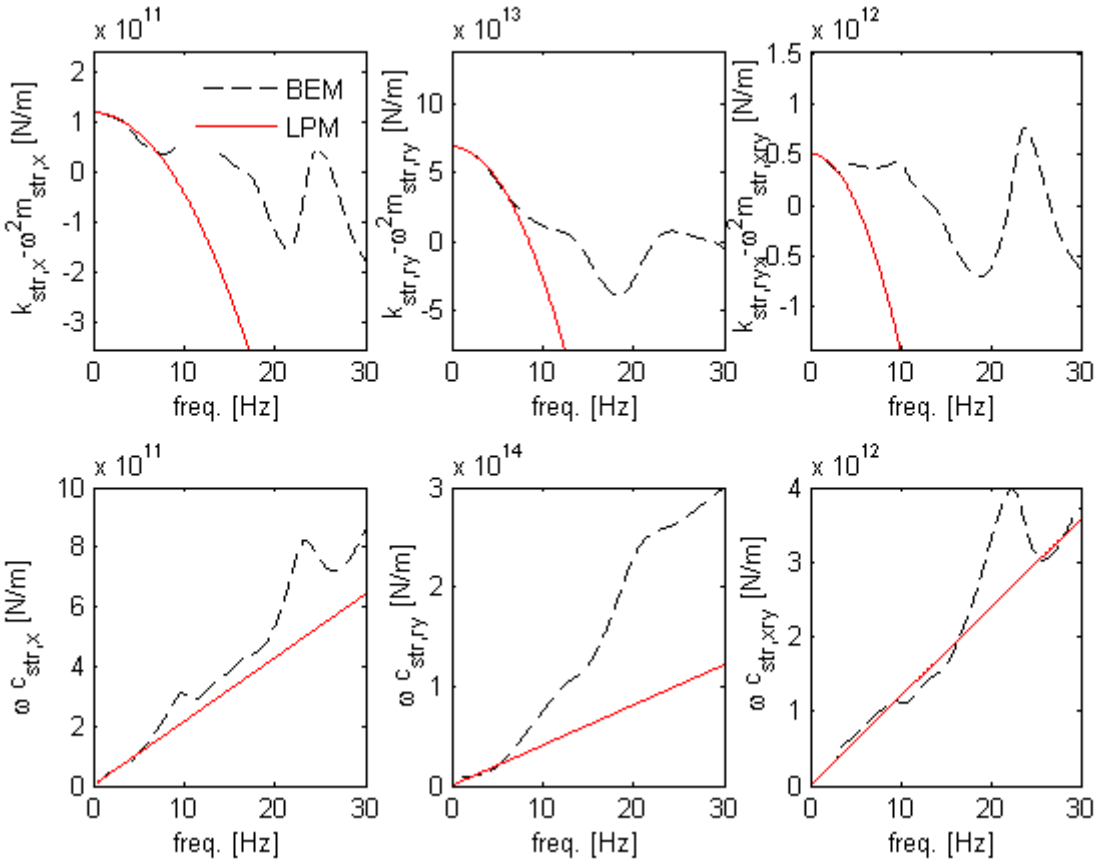


Figure 2 Approximate structural impedances of the LPM compared to those evaluatedby BEM

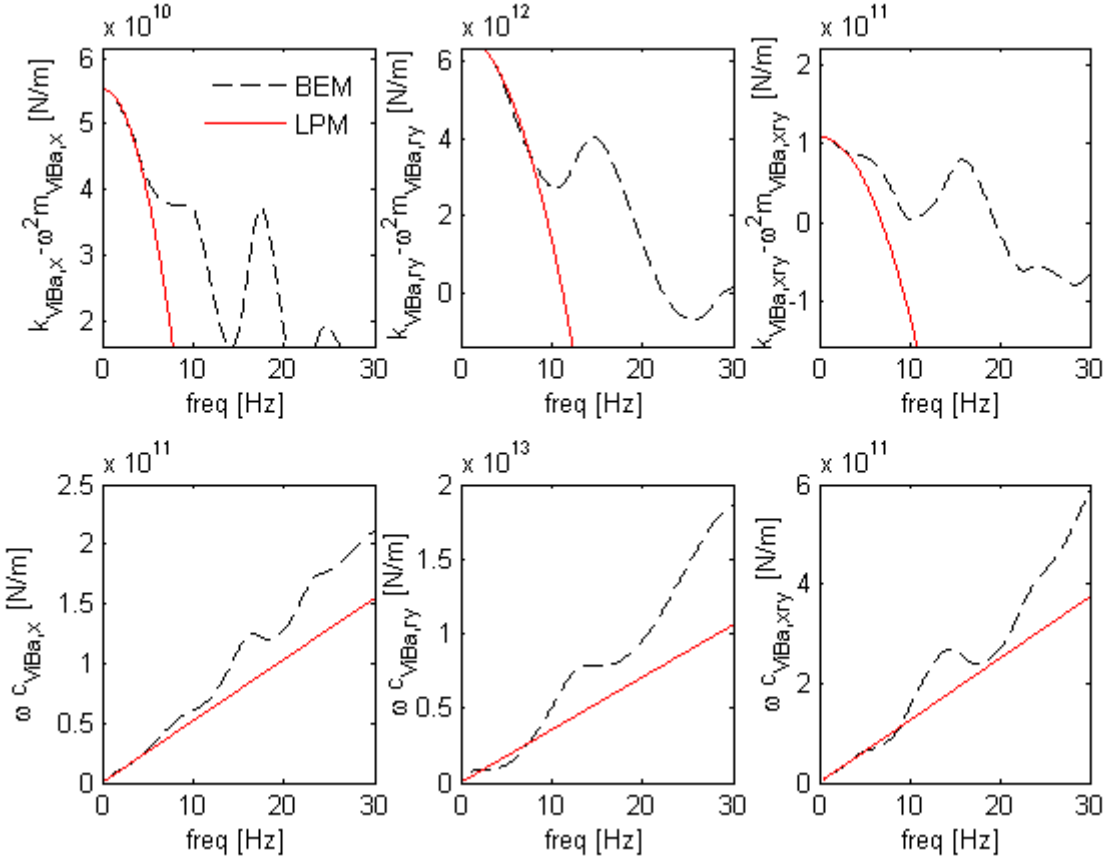


Figure 3 Approximate ViBa impedances of the LPM compared to those evluated by BEM

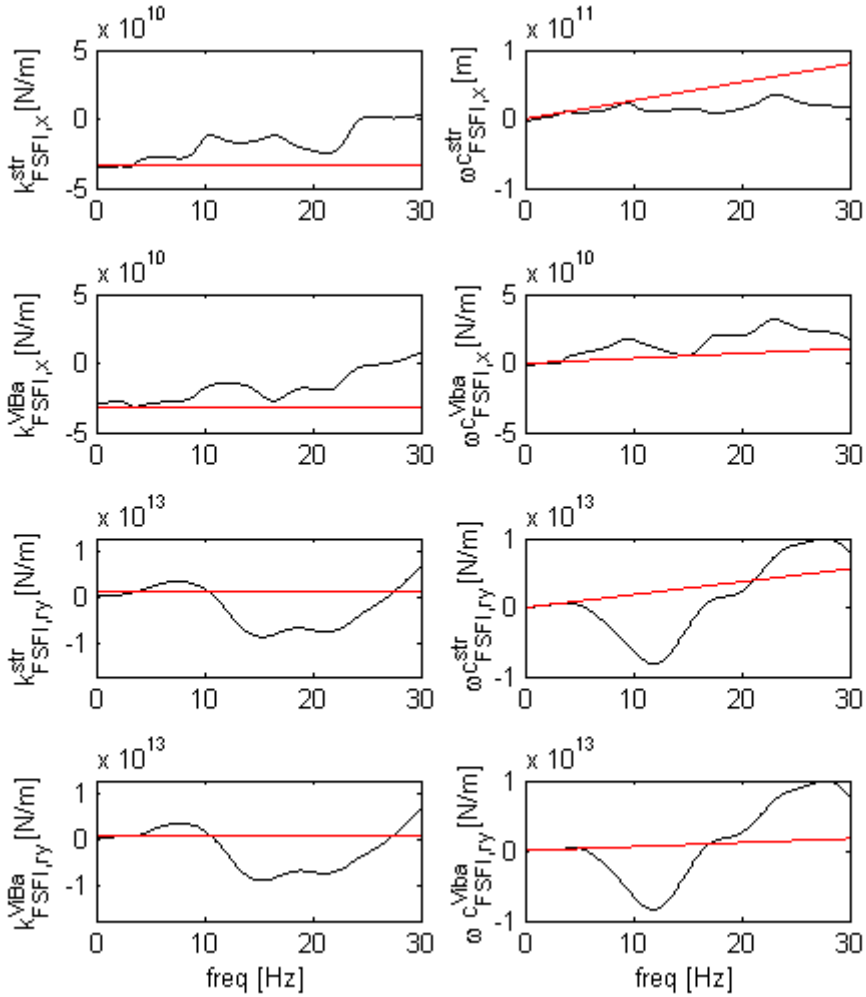


Figure 4 Approximate coupling impedances of the LPM (red curve) compared o those evaluated by BEM (black curve)

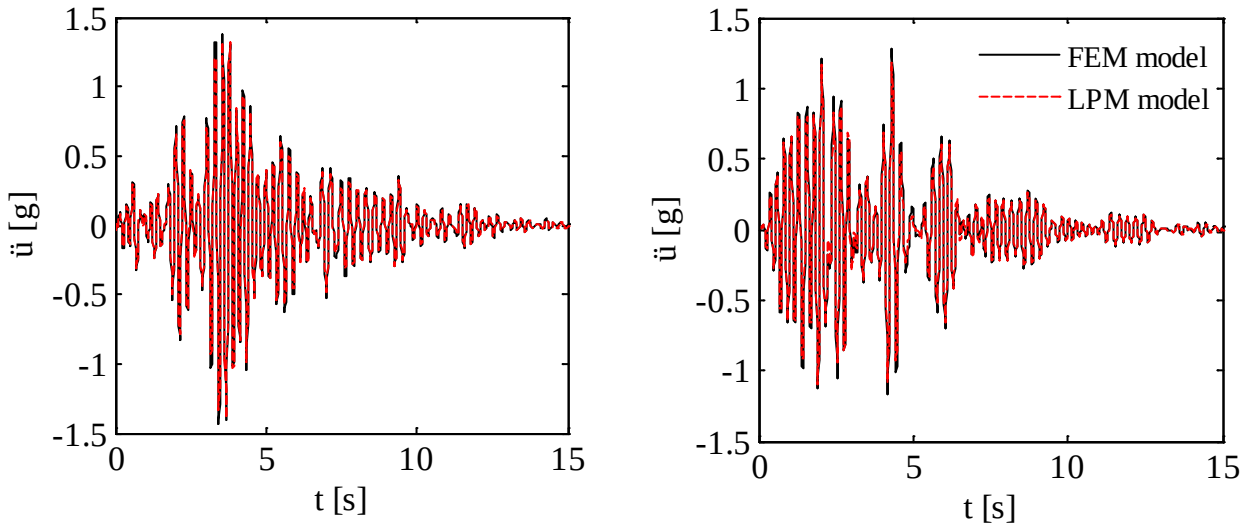


Figure 1 Comparison between two trajectories of the top of the structure obtained from the FEM and the LPM model

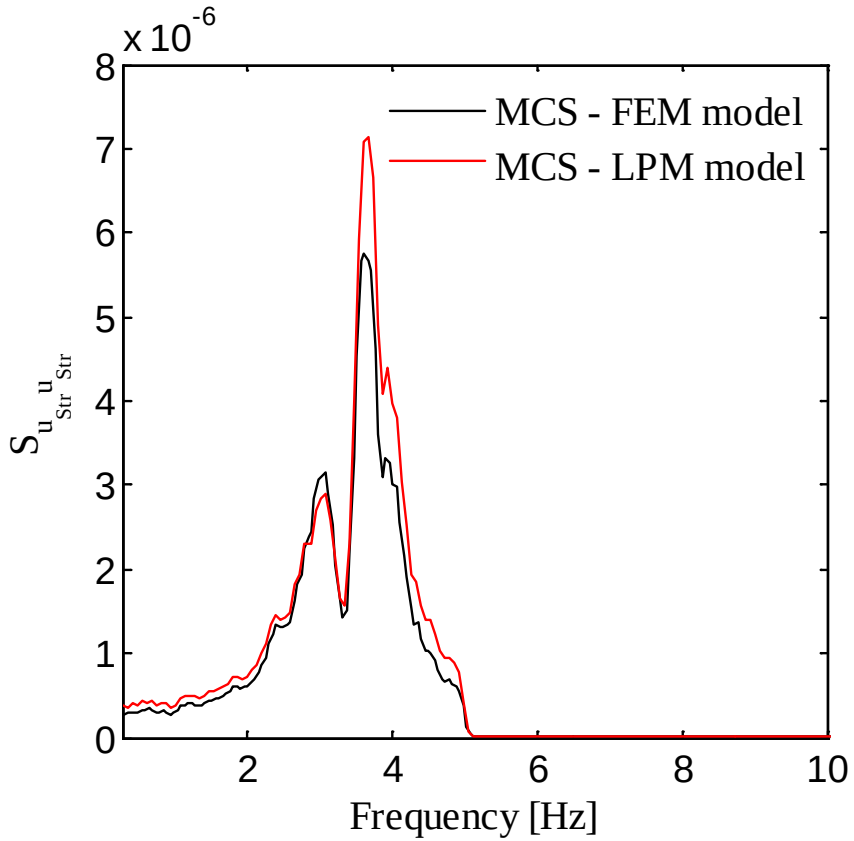


Figure 1 Comparison between power spectral density functions obtained from FEM and LPM models.

Numerical results

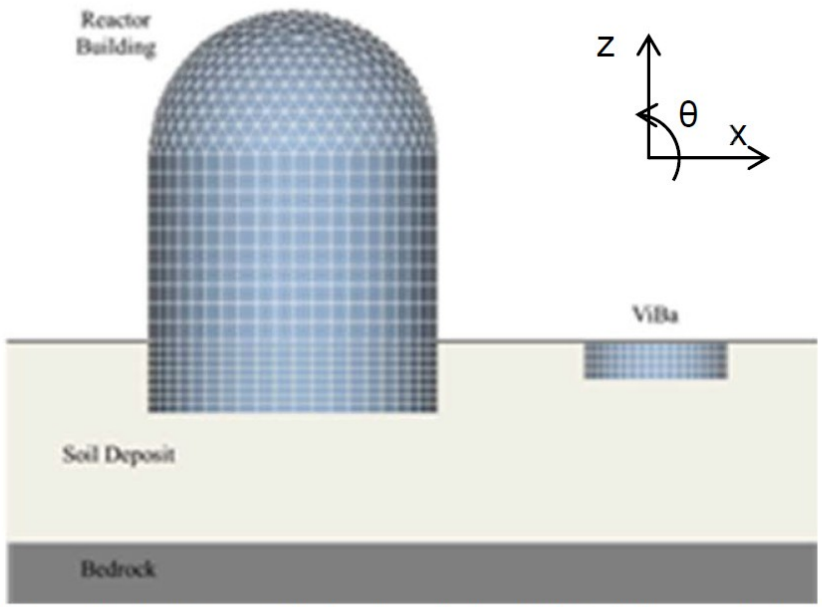


Figure 4 Investigated Case Study of an Industrial Building protected by ViBa

- The industrial building has been modelled according to the finite element approach by means of the Code_Aster open source FE-software whereas the BEM formulation has been used to model the soil by means of Miss3D.

Numerical results

Table 1 Significant dimensions of the Reactor Building

Reactor Building shell radius	25.8 m
Basement shell radius	25.8 m
Height of springline above basemat	46.12 m
Embedded height	12.9 m
Wall thickness	1.07 m
Basemat thickness	3.05 m

Table 2 Dynamic properties of the soil deposits used in the work

Soil Type	V_S [ms^{-1}]	V_P [ms^{-1}]	G [GPa]	ρ [kg/m^3]	η	ν
A	800	2653	3.9	2100	0.1	0.45
B	400	1327	0.97	2100	0.1	0.45
C	200	663	0.24	2100	0.1	0.45
BEDROCK	800	2653	0.06	2100	0.05	0.45

Numerical results

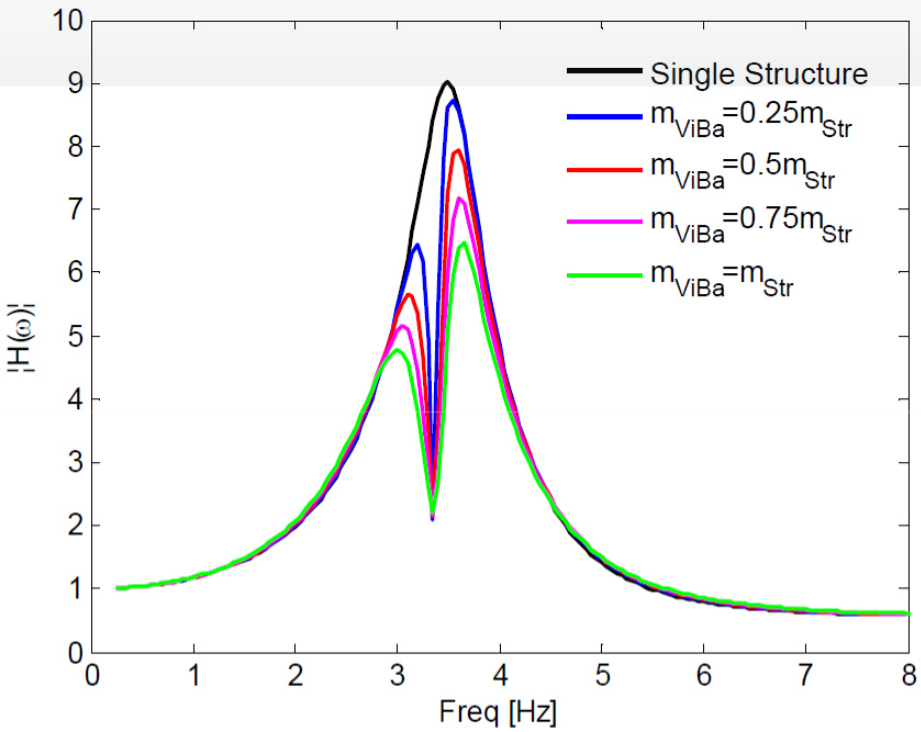


Figure 6 Amplification function of the node at the top of the dome for several mass ratio e ViBa damping set to 0 for case with the soil type B and ViBAD05

$$RF = \frac{\left|U^{str}_{coupled}(\omega_0)\right|}{\left|U^{str}_{uncoupled}(\omega_0)\right|}$$

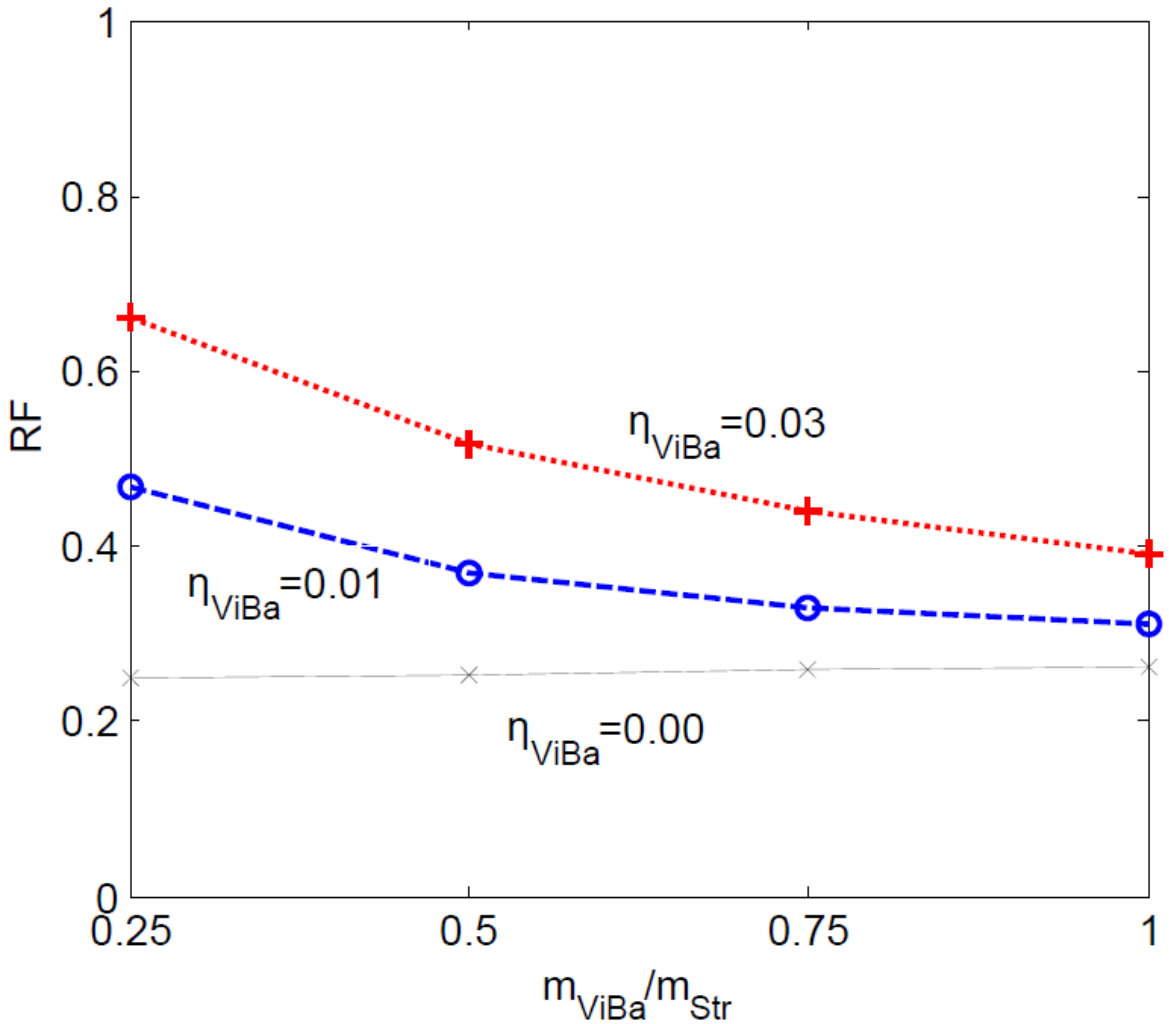


Figure 7 RF curves obtained for case with the soil type B and ViBAD05

Numerical results

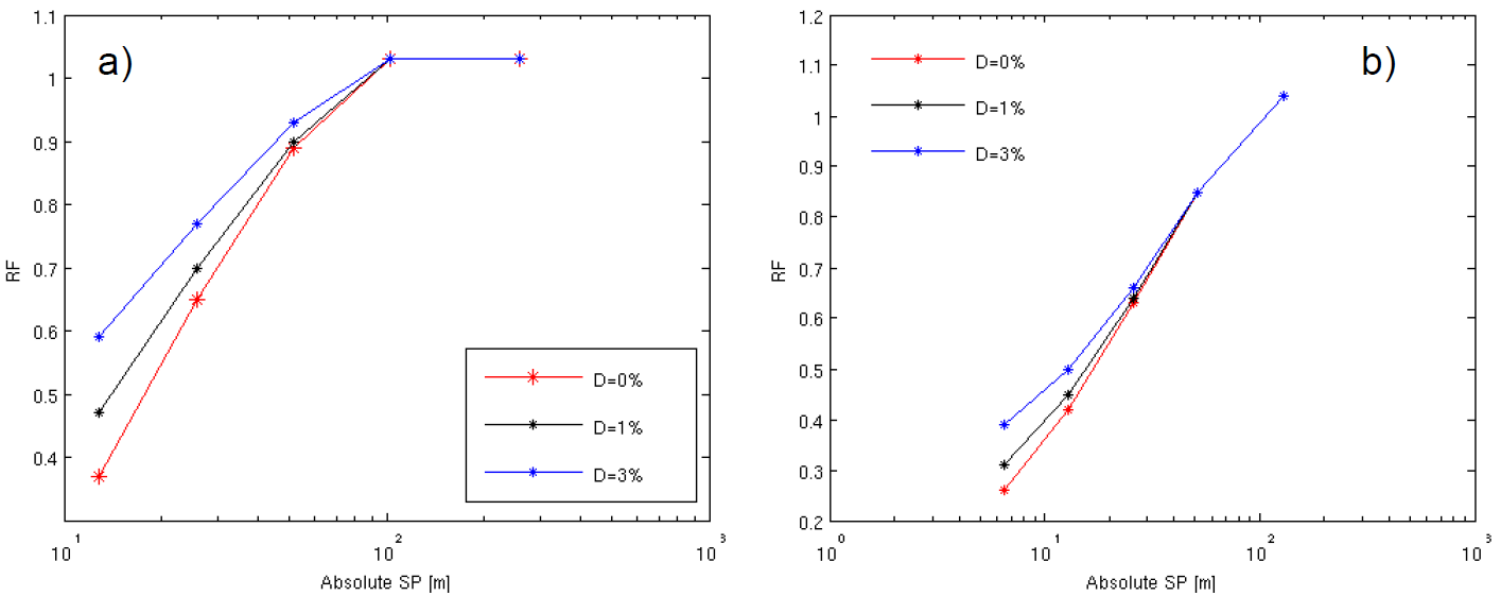
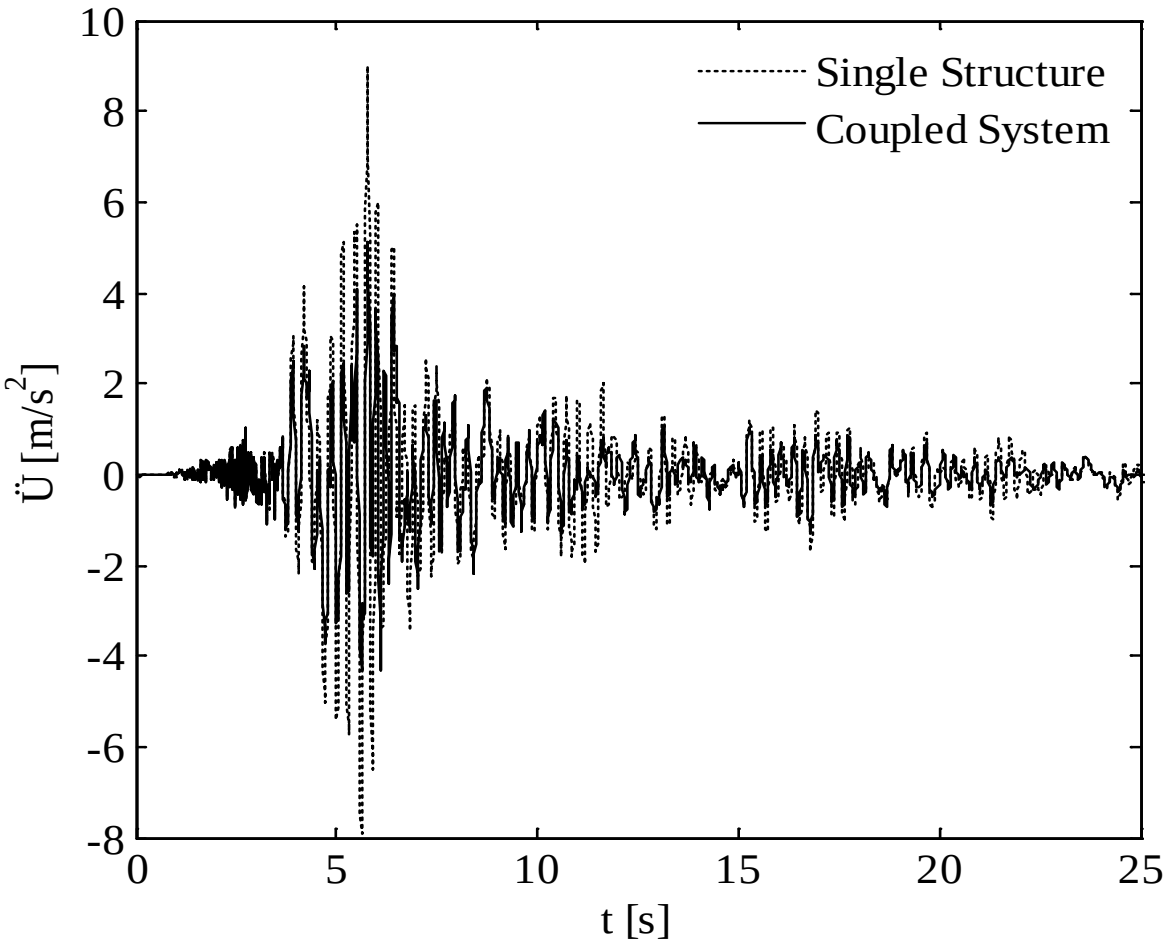


Figure 7 Top Dome RFs curves for several damping and spacing for case a) ViBAD1 and b) ViBAD05

Time-history acceleration response of the node at the top of the dome in case of single structure and structure coupled with ViBa for the 1989 Loma Prieta earthquake event



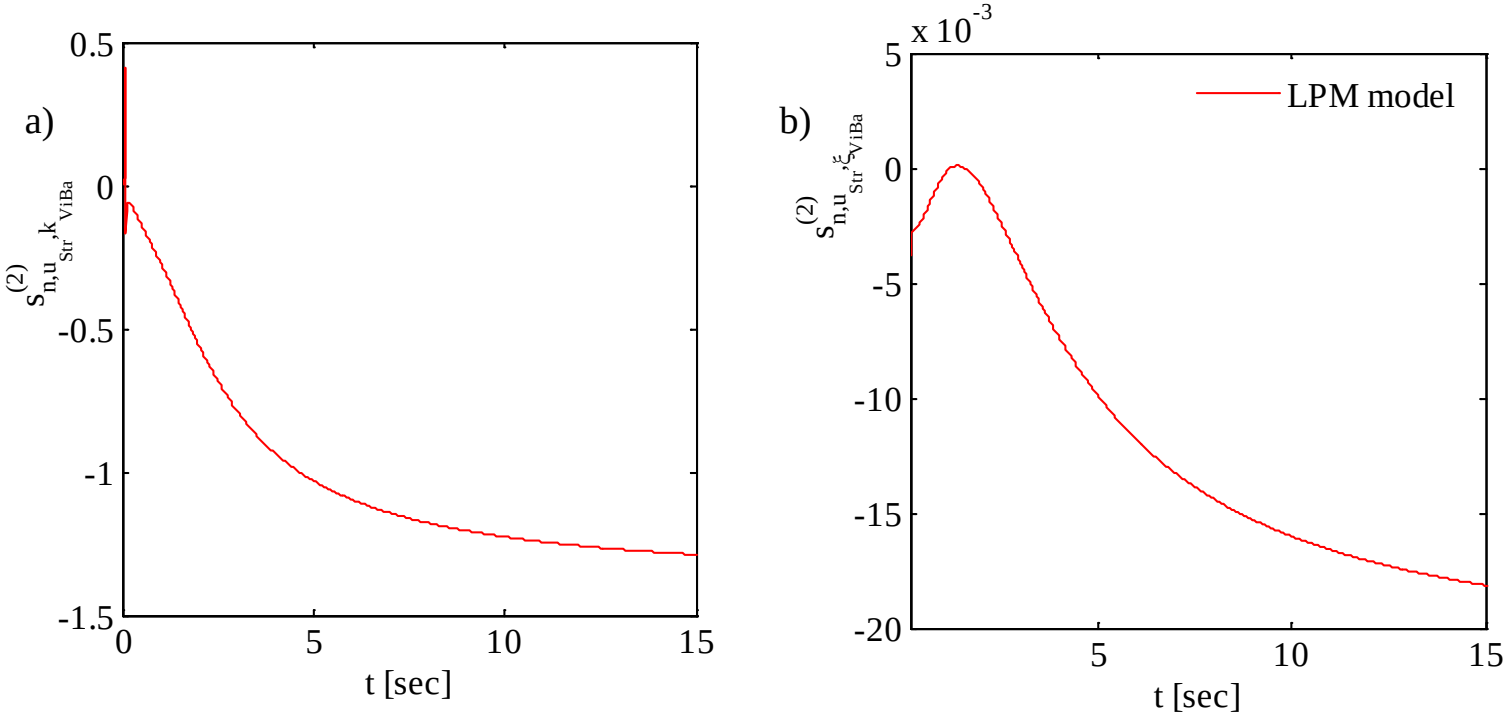


Figure 1 Non-dimensional sensitivity of the second-order statistical moments of the nodal displacement of the structure with respect to the a) stiffness and the b) damping of the ViBa

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Vibration control of piled-structures through structure-soil-structure-interaction

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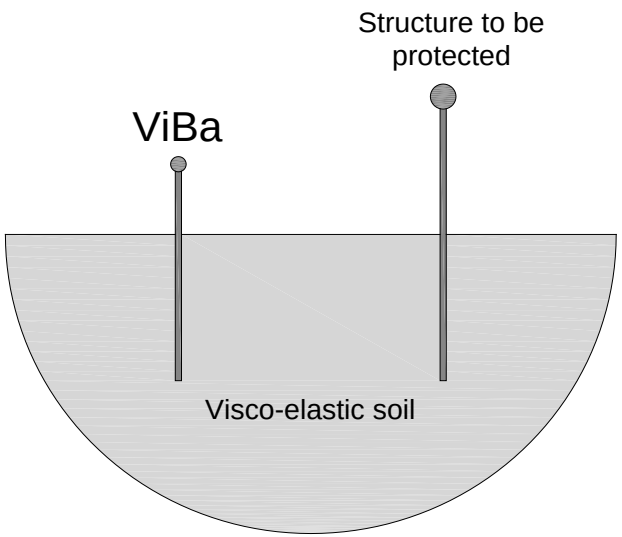
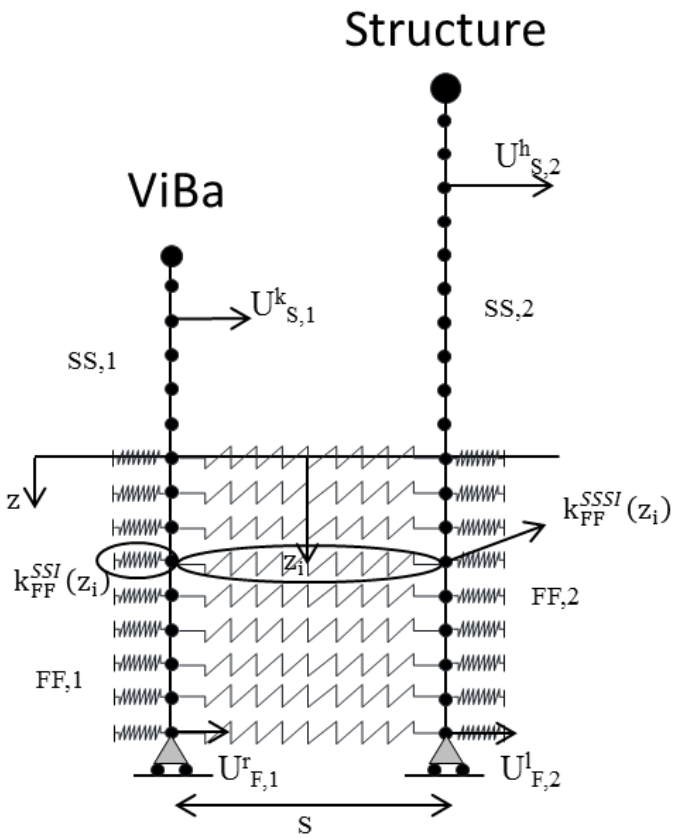


ViBa-soil-structure system

Discrete ViBa-soil-structure interaction model



$$\left(\widetilde{\mathbf{K}}(\omega) - \omega^2\mathbf{M}\right)\mathbf{U}(\omega) = \mathbf{F}(\omega)$$

$$\left(\begin{bmatrix} \widetilde{\mathbf{K}}_{SS,1} & \widetilde{\mathbf{K}}_{SF,1} & 0 & 0 \\ \widetilde{\mathbf{K}}_{FS,1} & \widetilde{\mathbf{K}}_{FF,1}(\omega) & \widetilde{\mathbf{K}}_{FF,c}(\omega) & 0 \\ 0 & \widetilde{\mathbf{K}}_{FF,c}(\omega) & \widetilde{\mathbf{K}}_{FF,2}(\omega) & \widetilde{\mathbf{K}}_{FS,2} \\ 0 & 0 & \widetilde{\mathbf{K}}_{SF,2} & \widetilde{\mathbf{K}}_{SS,2} \end{bmatrix} - \omega^2 \begin{bmatrix} \mathbf{M}_{SS,1} & 0 & 0 & 0 \\ 0 & \mathbf{M}_{FF,1} & 0 & 0 \\ 0 & 0 & \mathbf{M}_{FF,2} & 0 \\ 0 & 0 & 0 & \mathbf{M}_{SS,2} \end{bmatrix}\right) \begin{Bmatrix} \mathbf{U}_{S,1}(\omega) \\ \mathbf{U}_{F,1}(\omega) \\ \mathbf{U}_{F,2}(\omega) \\ \mathbf{U}_{S,2}(\omega) \end{Bmatrix} = \begin{Bmatrix} 0 \\ \mathbf{F}_{F,1}(\omega) \\ \mathbf{F}_{F,2}(\omega) \\ 0 \end{Bmatrix}$$

$\widetilde{\mathbf{K}}_{rs,i} = \mathbf{K}_{rs,i}(1 + j\eta_{rs,i})$ (i=1,2; r=F,S; s=F,S)

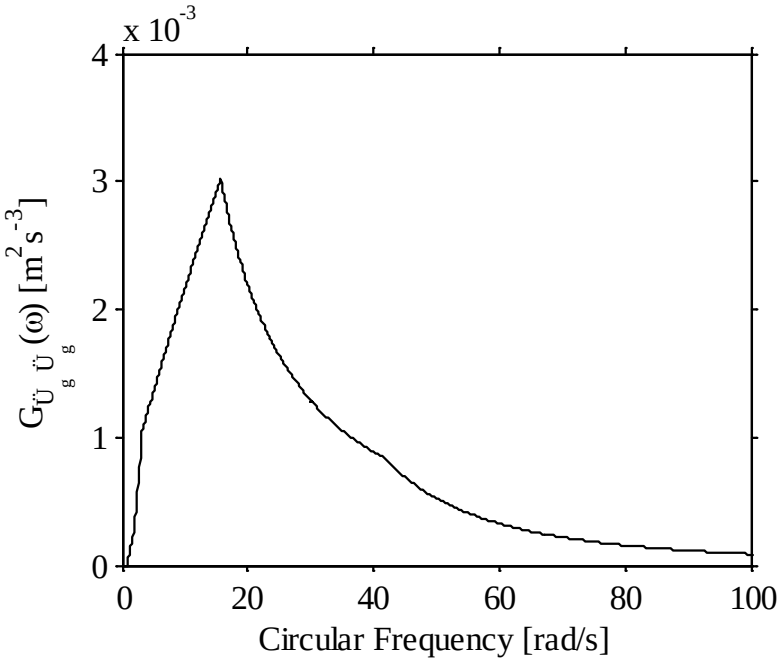
Input PSD function defined at bedrock

$$\boldsymbol{\beta} = \left[\mathbf{M}_{\mathrm{SS},1}; \mathbf{K}_{\mathrm{SS},1}; \eta_{ss,1}\right]$$

$$\mathbf{G}_{\mathrm{UU}}(\omega, \boldsymbol{\beta}) = \mathbf{H}_{\mathrm{glob}}(\omega, \boldsymbol{\beta})\mathbf{H}^{*}_{\mathrm{glob}}(\omega, \boldsymbol{\beta})\mathrm{G}_{\mathrm{U_g U_g}}(\omega)$$

$$\mathbf{H}_{\mathrm{glob}}(\omega) = \widetilde{\mathbf{K}}^{-1}{}_{\mathrm{dyn}}(\omega, \boldsymbol{\beta})\mathbf{Q}(\omega)\mathbf{H}_{\mathrm{soil}}(\omega)$$

$$min\left\{\mathrm{X}_{Ur}(Ts, p, \boldsymbol{\beta}) = \eta_{Ur}(Ts, p, \boldsymbol{\beta})\sqrt{\lambda_{0,Ur}(\boldsymbol{\beta})}\right\},$$
$$\boldsymbol{\beta}_{min} < \boldsymbol{\beta} < \boldsymbol{\beta}_{max}$$



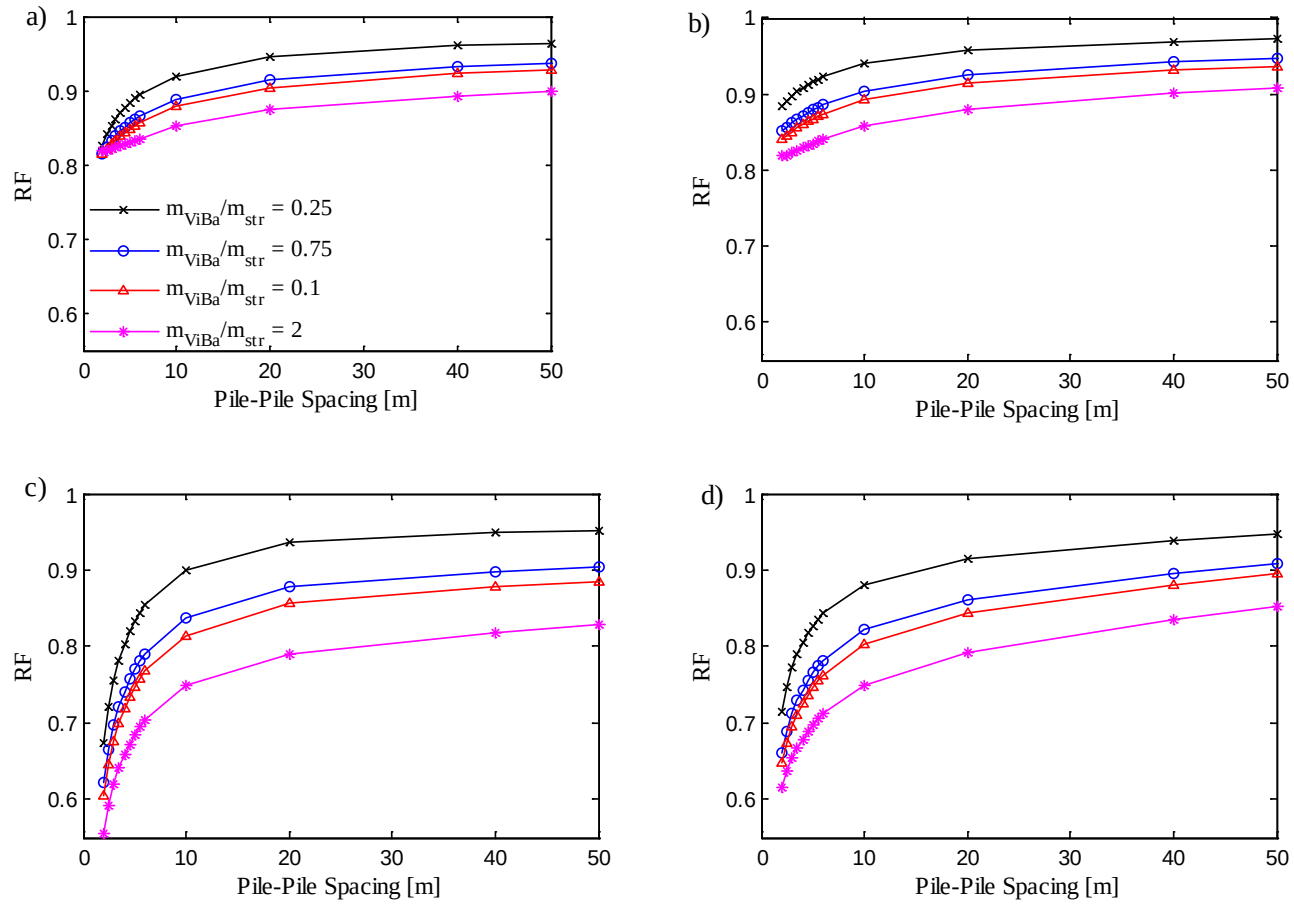
$$\eta_{Ur}(Ts, p) = \sqrt{2\ln\left\{2N_{Ur}\left[1 - \exp\left[-\delta_{Ur}^{1.2}\sqrt{\pi\ln(2N_{Ur})}\right]\right]\right\}}$$

$$G_{\ddot{\mathrm{U}}_{\mathrm{g}}\ddot{\mathrm{U}}_{\mathrm{g}}}(\omega_i) = \frac{4\zeta_0}{\omega_i\pi - 4\zeta_0\omega_{i-1}}\left(\frac{RSA(\omega_i, \zeta_0)^2}{\eta_u^2(\omega_i, \zeta_0)} - \Delta\omega\sum_{k=1}^{i-1} G_{\ddot{\mathrm{U}}_{\mathrm{g}}\ddot{\mathrm{U}}_{\mathrm{g}}}(\omega_i)\right)$$

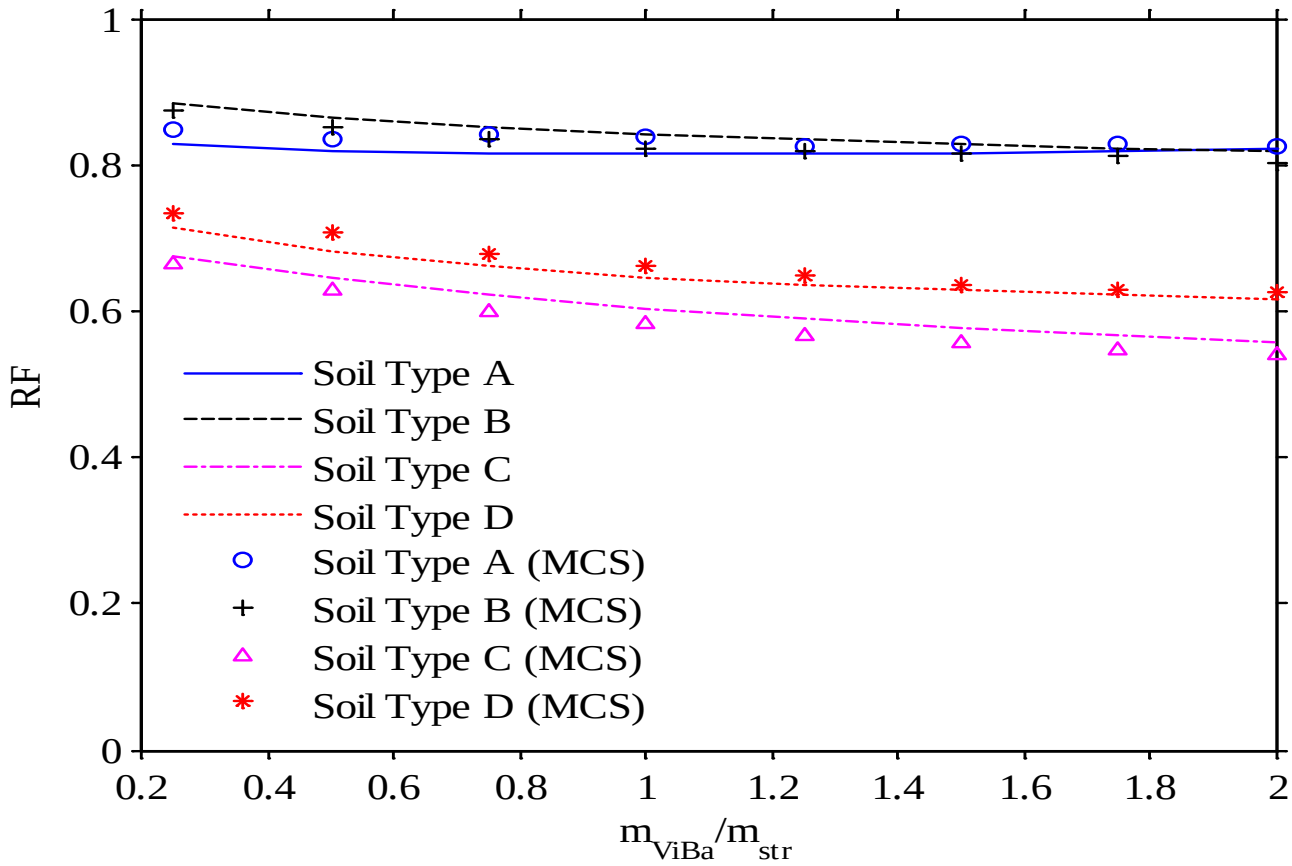
$$\lambda_{i,Ur} = \int_0^{+\infty} \omega^i \mathrm{G}_{UrUr}(\omega)d\omega$$

Reduction factor curves for soil type a) A, b) B, c) C, and d) D

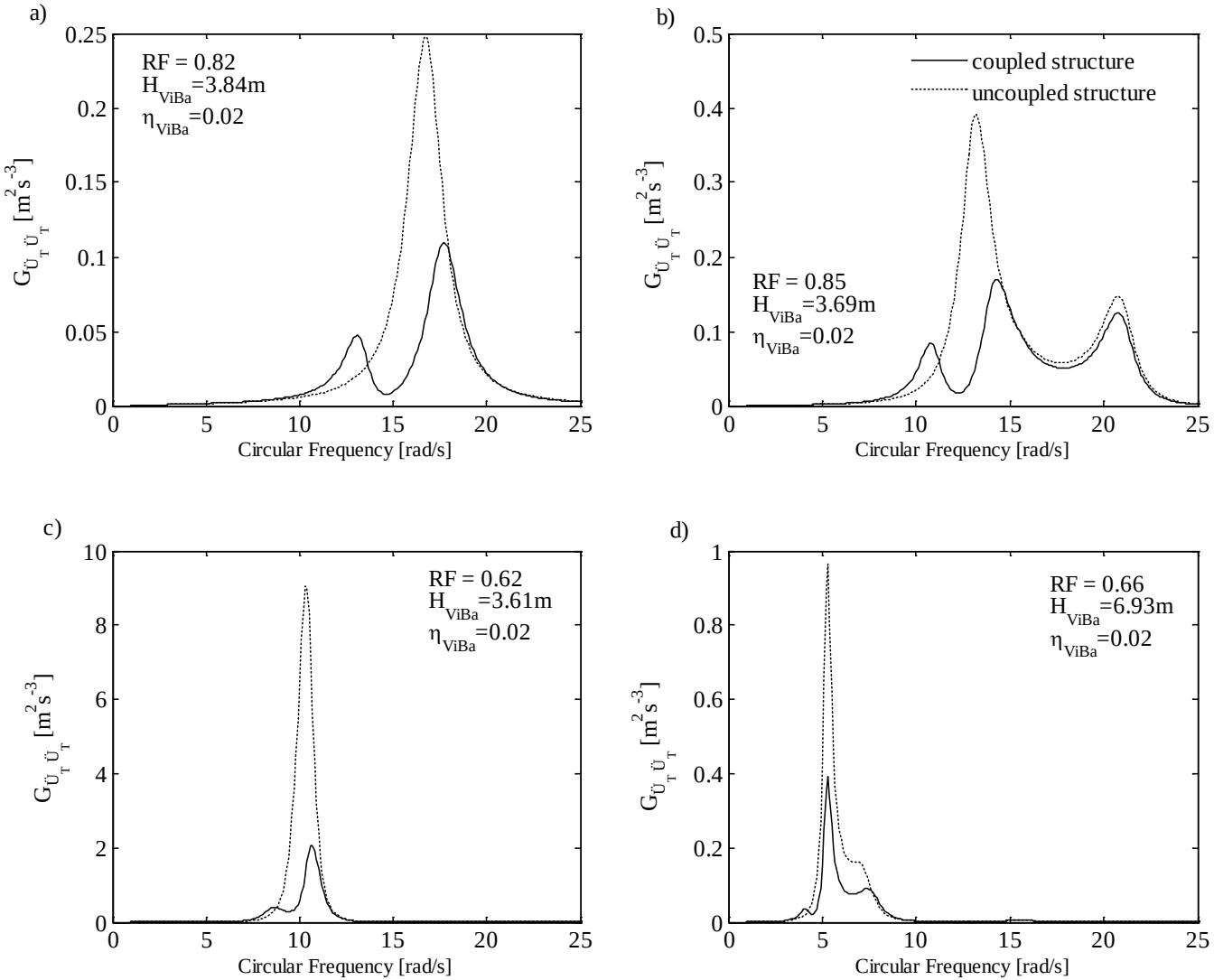
$$\mathrm{RF} = \frac{X_{\mathrm{U}_{Ur}^{coupled}}}{X_{\mathrm{U}_{Ur}^{uncoupled}}}$$



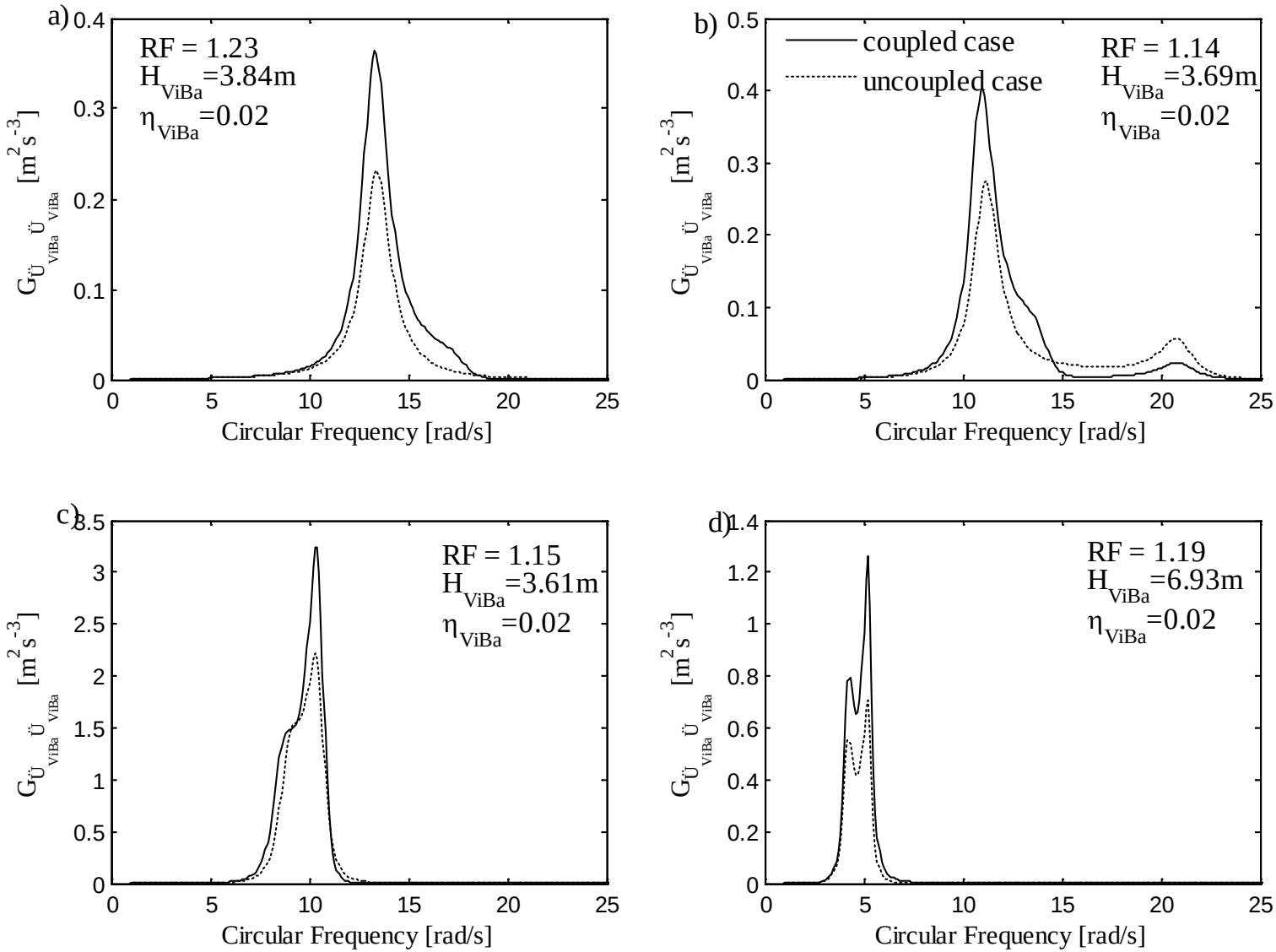
RF curves obtained for several soil types after tuning the ViBa for spacing = 1 m



Acceleration PSD functions for soil type a) A, b) B, c) C, and d) D obtained for mass ratio = 0.75 and spacing = 1m



Acceleration PSD functions of the ViBa for soil type a) A, b) B, c) C, and d) D obtained for mass ratio = 0.75 and spacing = 1m



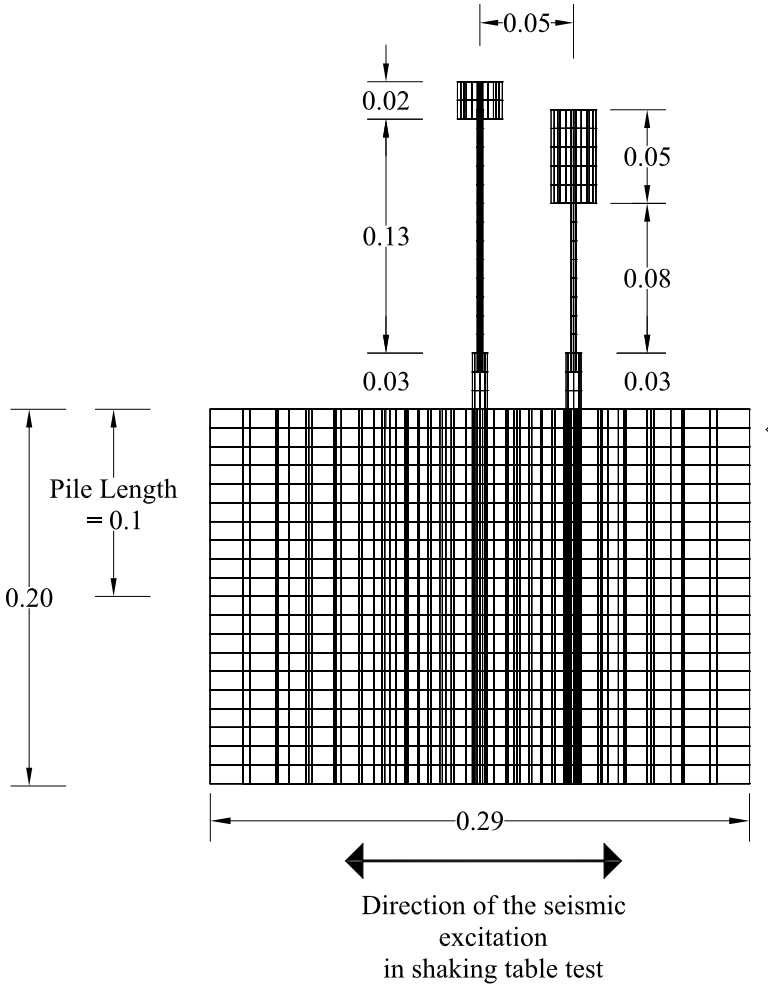


Figure 1 Set up of the experiment for shaking table (case with structure protected by ViBa device)

a) b)

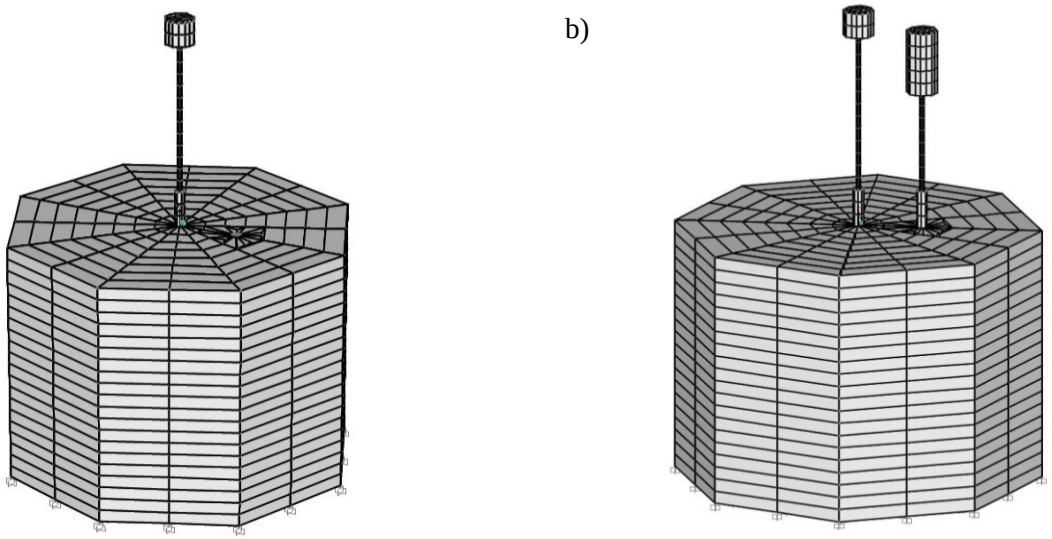


Figure 1 Reproduction of the experimental test by SAP2000 for both cases: a) without and b) with the protection by ViBa

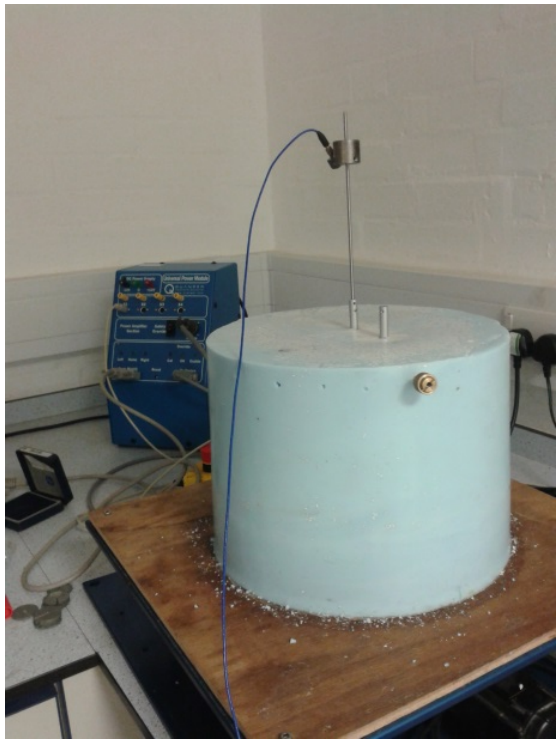


Figure 1 Test models realized in the laboratory and placed over a shaking table for a)single structure and b)structure coupled with ViBa.

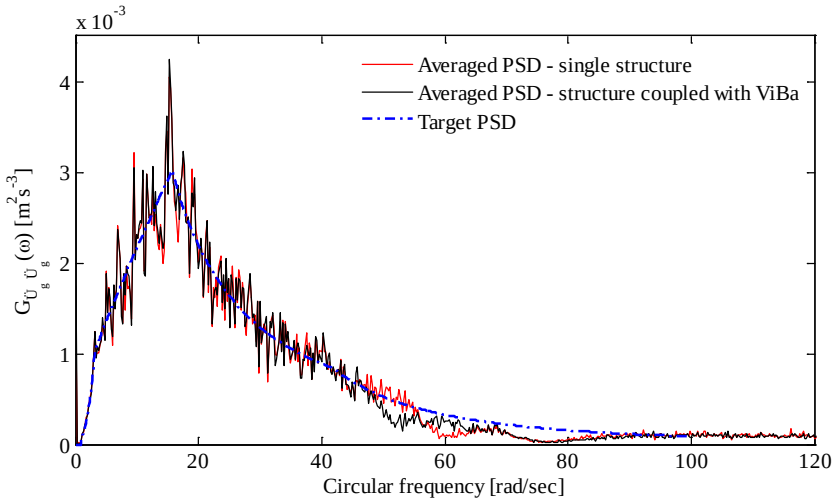


Figure 1 Comparison between desired and measured Power Spectral Density curves at the shake table platform

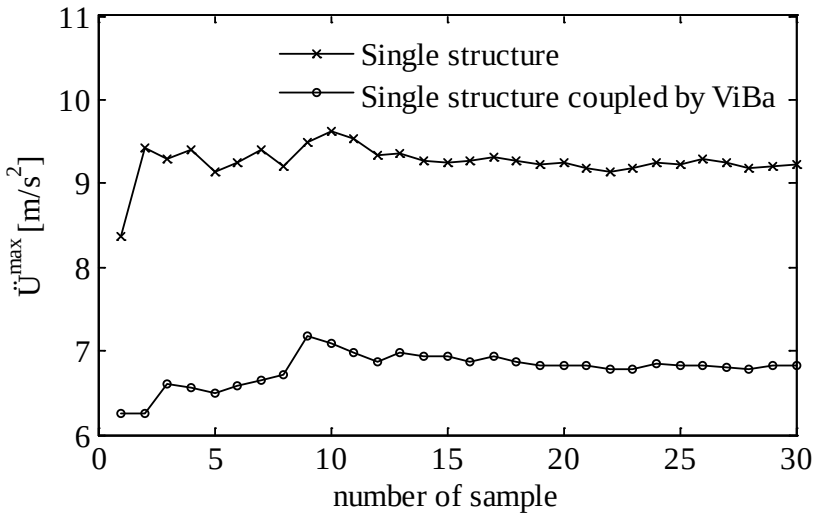


Figure 1 Cumulative average of the recorded maximum accelerations of the structure for single structure and structure coupled by ViBa

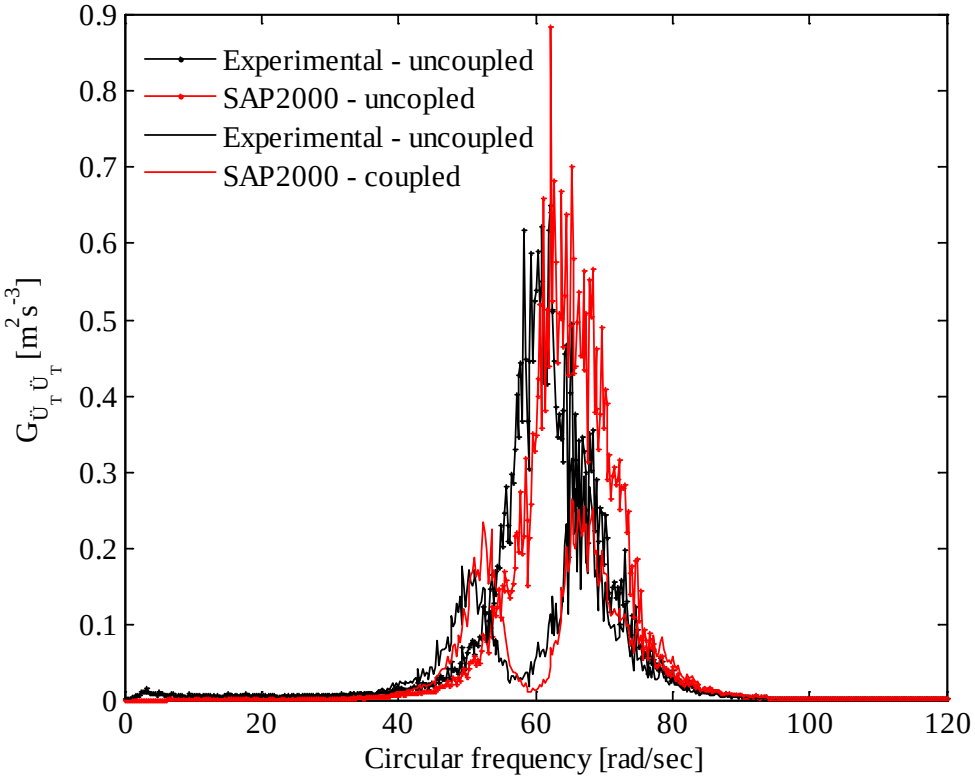
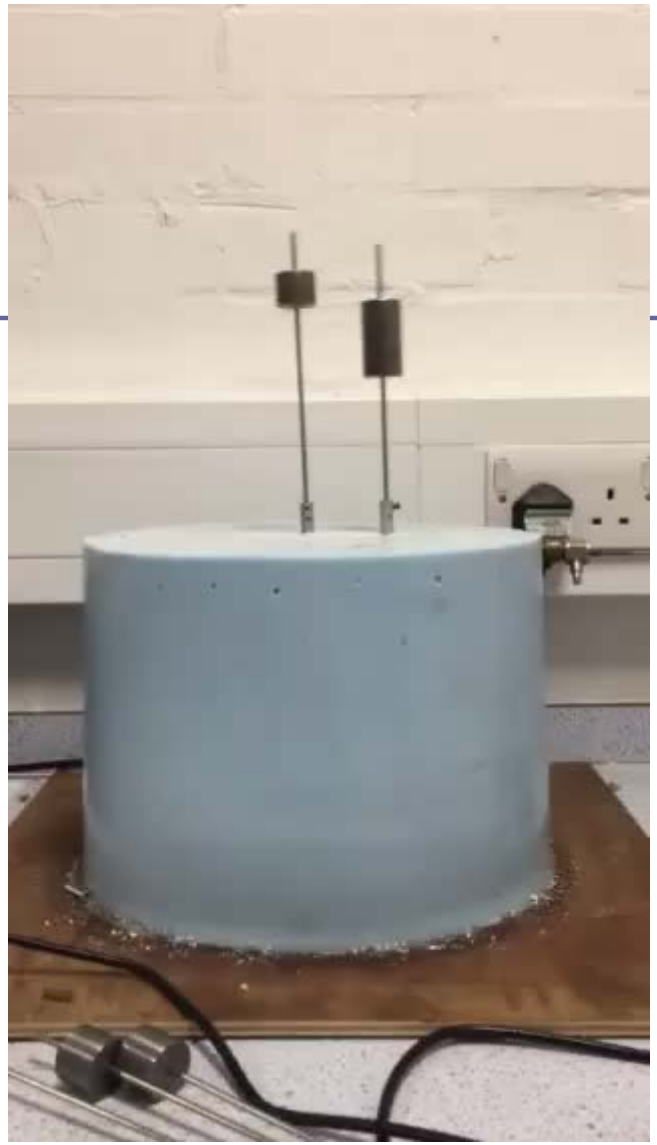


Figure 1 Numerical and experimental averaged power spectral density functions of the recorded accelerograms of the structure without and with the coupling of the ViBa

Single strucutre



ViBa not
well designed

ViBa well
designed

Cluster of buildings

Remarks

1) The direction of the seismic wave is irrelevant
2) Out of plane protection
3) All of them benefit from the precence of the ViBa

Forbes / Tech

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CASE STUD

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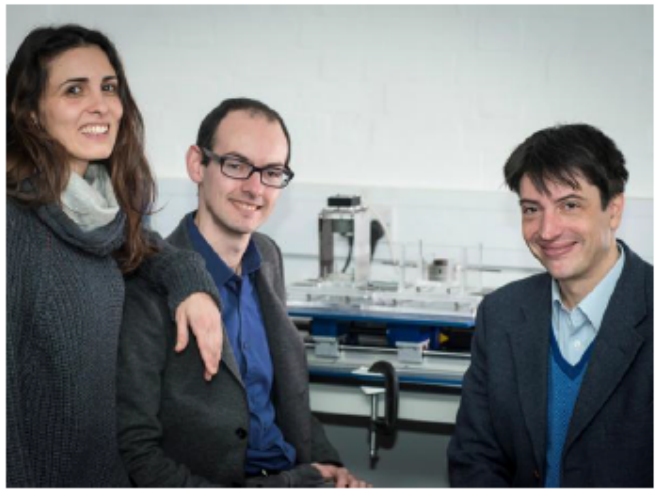
/ NEWS

PROTEZIONE

«Una scatola nelle case per assorbire l'energia dei terremoti»

Il brevetto di un ricercatore italiano in Inghilterra: «ViBa attutisce dal 40 all'80 per cento di una scossa e può essere inserita in edifici esistenti senza alterarli»

di ANDREA INDIANO



Pierfrancesco Cacciola, a destra, dirige il dipartimento di Built Environment e Civil Engineering dell'università di Brighton. Dietro ViBa

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ti è una delle
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ello del Nepal a
mero di morti,
ive le immagini
devastanti dei sismi avvenuti in Giappone e ad Haiti negli ultimi anni. Per l'Italia non si può dimenticare il terremoto dell'Aquila del 2009. Ormai molti edifici vengono costruiti con sistemi antisismici all'avanguardia in

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B8-0964/2015

Motion for a European Parliament resolution on the importance of the building sector in relation to seismic activity

The European Parliament,

– having regard to the objectives of the European Institute of Innovation and Technology,

– having regard to paragraphs 17 and 19 of Decision No 1386/2013/EU,

– having regard to paragraph 10 of Decision No 553/2014/EU,

– having regard to Rule 133 of its Rules of Procedure,

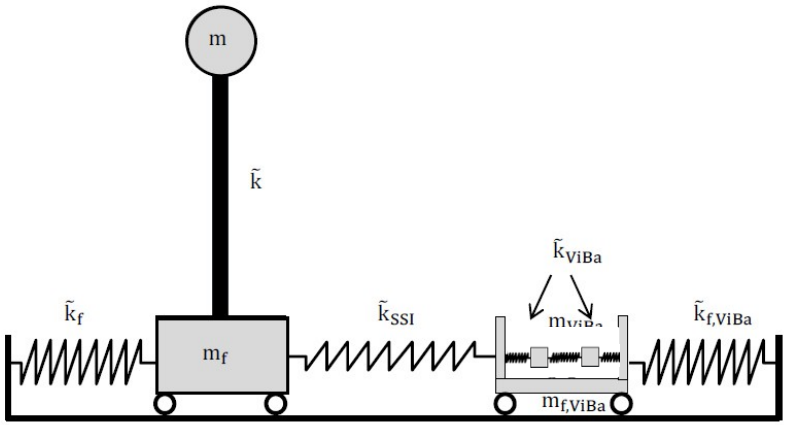
A. whereas at the Built Environment and Civil Engineering Department of the University of Brighton, the ViBa vibrating barrier has been invented, an instrument which absorbs the impact of an earthquake by 40-80% and can be inserted into existing buildings without modifying them;

B. whereas, in recent years, several earthquake disasters have caused millions of casualties all over the world, including the earthquake in L'Aquila, Italy, in 2009;

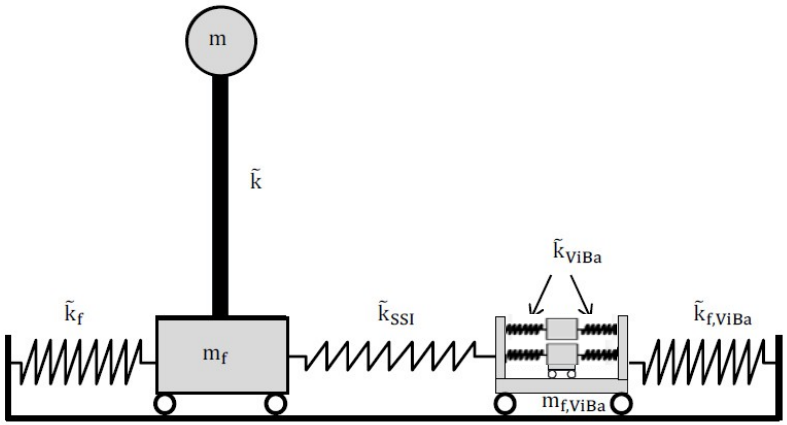
C. whereas investing in housing which includes innovative instruments to combat seismic activity also contributes to the economic development of the building sector;

1. Calls on the Commission to establish a fund to finance building companies which intend to invest in innovation with a view to tackling seismic activity.

Future and ongoing developments ViBa (series and parallel)



series



parallel

Future developments A-ViBa

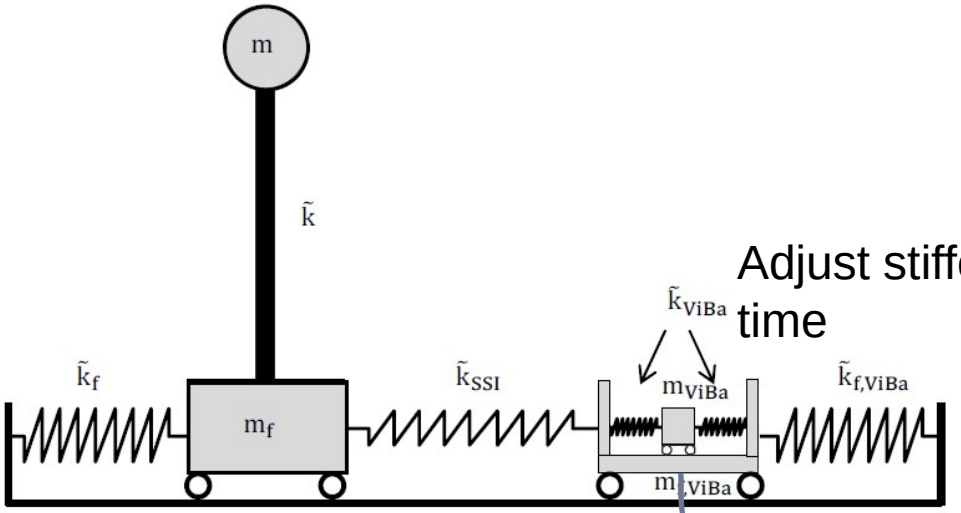


Figure 2 Simplified model

Adjust stiffess in real time

Measure FFT input

Future developments L-ViBa

Future developments

- Numerical and exerimental model of the ViBa in urban environment
- Technological development with industrial support

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Research

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Vibrating barrier: a novel device for the passive control of structures under ground motion

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A novel device, called vibrating barrier (ViBa), that aims to reduce the vibrations of adjacent structures subjected to ground motion waves is proposed. The ViBa is a structure buried in the soil and detached from surrounding buildings that is able to absorb a significant portion of the dynamic energy arising from the ground motion. The working principle exploits the dynamic interaction among vibrating structures due to the propagation of waves through the soil, namely the structure–soil–structure interaction. The underlying theoretical aspects of the novel control strategy are scrutinized along with its numerical modelling. Closed-form solutions are also derived to design the ViBa in the case of harmonic excitation. Numerical and experimental analyses are performed in order to investigate the efficiency of the device in mitigating the effects of ground motion waves on the structural response. A significant reduction in the maximum structural acceleration of 87% has been achieved experimentally.

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Vibration control of piled-structures through structure-soil-structure-interaction

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ABSTRACT

This paper deals with the vibration control of existing structures forced by earthquake induced ground motion. To this aim it is proposed for the first time to exploit the structure–soil–structure mechanism to develop a device, hosted in the soil but detached from the structure, able to absorb part of the seismic energy so to reduce the vibration of neighbourhood structures. The design of the device is herein addressed to protect monopile structures from earthquake induced ground motion. By modelling the ground motion as zero-mean quasi-stationary response-spectrum-compatible Gaussian stochastic process, the soil as visco-elastic medium and the target monopiled-structure as a linear behaving structure the device, herein called Vibrating Barrier (ViBa), has been designed through an optimization procedure. Various numerical and experimental results are produced to show the effectiveness of the ViBa. Remarkably, a significant reduction of the structural response up to 44% has been achieved.

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Sensitivity of the stochastic response of structures coupled with vibrating barriers

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ABSTRACT

The sensitivity of the stochastic response of linear behaving structures controlled by the novel Vibrating Barrier (ViBa) device is scrutinized. The Vibrating Barrier (ViBa) is a massive structure, hosted in the soil, calibrated for protecting structures by exploiting the structure–soil–structure interaction effect. Therefore the paper addresses the study of the sensitivity of soil–structure coupled systems in which the soil is modelled as a linear elastic medium with hysteretic damping. In order to accomplish efficient sensitivity analyses, a reduced model is determined by means of the Craig–Bampton procedure. Moreover, a lumped parameter model is used for converting the hysteretic damping soil model rigorously valid in the frequency domain to the approximately equivalent viscous damping model in order to perform conventional time-history analysis. The sensitivity is evaluated by determining a semi-analytical method based on the dynamic modification approach for the case of multi-variate stochastic input process. The ground motion is modelled as non-stationary zero-mean Gaussian random process defined by a given evolutionary Power Spectral Density function. The paper presents the sensitivity of the response statistics of a model of an industrial building, passively controlled by the ViBa, to relevant design parameters. Comparisons with pertinent Monte Carlo Simulation will show the effectiveness of the proposed approach.

Concluding remarks

It is worth investigating !!

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