VIBRATION CONTROL OF AN INDUSTRIAL BUILDING THROUGH THE VIBRATING BARRIER

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

Abstract: 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. However, the use of those vibration control devices implies structural modifications that might be costly or prohibitive. In this context, a novel passive control device called Vibrating Barrier (ViBa) has been recently proposed. The ViBa is a massive structure, hosted in the soil and detached from the other structures, calibrated for absorbing portion of the ground motion input energy. The proposed device is applied to a model of an industrial building. Parametric analyses have been performed considering various soil profiles and mechanical/geometrical properties of the device. Significant reductions of maximum displacements are achieved for short distances and small ViBa damping ratio under harmonic ground motion.

Introduction

The problem of reducing vibrations in structures, generally known as vibration control, arises in various branches of engineering: civil, aeronautical and mechanical. Unpredicted vibrations can lead to the deterioration or collapse of structures. In the field of earthquake engineering, modern strategies of seismic design aim to reduce structural vibrations by: i) increasing the dissipative properties of the structure; ii) moving the natural frequencies of the structure away from the frequencies in which the seismic action possess the highest energy; iii) modifying the energy transferred from the earthquake to the structure. The control of vibrations of structures is currently performed using passive, active or hybrid strategies. In the framework of passive control systems is it possible to categorize the following three general devices: i) tuned mass dampers, manufactured by adding one or more oscillators to the structure; ii) dampers able to transform the seismic energy in heat which is then diffused in the environment; iii) isolation systems, used mainly for earthquake applications, based on the idea of shift the fundamental frequency of the superstructure far from the main frequency of the earthquake. Apart from few attempts to protect existing structures the use of vibration control devices is still restricted to new buildings and/or constructions. One main reason is that the introduction of control devices in existing structures is too invasive, costly and requires the demolishing of some structural and/or non-structural components. This is clearly prohibitive for developing countries and for historical buildings. An alternative solution is to protect the structures introducing trenches or sheet-pile walls in the soil. However this approach seems to be more effective for surface waves coming from railways rather than seismic waves.

Bearing in mind the global necessity to protect existing structures from earthquakes and the limitation of current technologies a novel control strategy is proposed in this paper. The concept is based on the generally known structure-soil-structure interaction (SSSI) and on the findings in the first works of Warburton et al. (1971) and Luco and Contesse (1973). The dynamic structure-soil-structure interaction among the structures occurs through the radiation energy emitted from a vibrating structure to the other structure. Therefore, the dynamic response of one structure cannot be studied independently from the other one. Warburton et al. (1971) studied the dynamic response of two rigid masses in an elastic subspace showing

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the influence of one mass respect to the other. Luco and Contesse (1973) studied the dynamic interaction between two parallel infinite shear walls placed on rigid foundations and forced by vertically incident SH wave. They showed the interaction effects are especially important for a small shear wall located close to a larger structure. Kobori and Kusakabe (1980) extended the structure-soil-structure interaction study to flexible structures and pointed out that the response of a structure might be sensibly smaller due the presence and interaction of another structure. Important studies on SSSI were performed for investigating critical facilities as Nuclear Power Plant building by both experimental tests (Kitada et al., 1999) and numerical simulations (Clouteau et al., 2012). Finally, a recent review of the structure-soil-structure interaction problem can be found in Lou et al. (2011). An extension to the traditional structure-soil-structure interaction problem where only two structures are considered in the study is performed through the site-city interaction problem. Due to the difficulties involved in modelling the multiple interactions and the sustained progress in computational mechanics numerical approaches based on wave propagation and finite or boundary element analysis are usually adopted for the study of site city interaction (Clouteau and Aubry 2001, Chávez-García and Cárdenas-Soto 2002, Kham et al. 2002). Interestingly in Kham et al. 2002 it has been shown as the energy of ground motion at the free field in the city might be reduced by around 50% due to the perturbation induced by resonant buildings. Analytical studies on site-city interaction have also been proposed in the literature by Gueguen et al. (2002) and Boutin and Roussillon (2004). In Gueguen et al. (2002) the effect of the city is accounted for by modelling the structures as a simple oscillator, while in Boutin and Roussillon (2004) the multiple interactions between buildings are studied through homogenization methods.

In this context, a novel passive control device called Vibrating Barrier (ViBa), has been recently proposed by Cacciola (2012). The device is a massive structure, hosted in the soil, calibrated for protecting structures by absorbing portion of the ground motion input energy. The main novelty is the ViBa is designed to protect existing structures without being directly in contact with them. The device has been already investigated by Cacciola and Tombari (2014) for protecting monopiled-structures. The current paper investigates the effect of the ViBa on an industrial building, a large FEM model comprised of the cylindrical reinforced concrete shell with an internal structure located inside the shell. The external and the internal structure are both supported by a common circular rigid concrete basemat and the foundation results to be embedded. The aim of the work is calibrating the ViBa parameters in order to protect the Reactor Building when subjected to seismic excitation. The effects of the ViBa are investigated through parametric studies by considering several spacing and soil profiles. Steady state analyses are carried out for both cases of single structure and structure protected by the ViBa showing the reduction affected by the novel device to the structure in terms of maximum acceleration.

Problem formulation

The investigation of the effects of the ViBa device on the Industrial Building involves dealing with Structure-Soil-Structure Interaction problems. Consider the large global n-degree of freedom (n-DOF) structural linear system depicted in Figure 1. The dynamic governing equations of motion are casted in the frequency domain as follows:

$$\left[\mathbf{K}_{\mathrm{glob}}(\omega) - \omega^2\mathbf{M}_{\mathrm{glob}} + i\omega\mathbf{C}_{\mathrm{glob}}\right]\mathbf{u}(\omega) = \mathbf{f}(\omega) \tag{1}$$

where $i = \sqrt{-1}$; $\mathbf{M}_{\mathrm{glob}}$, $\mathbf{C}_{\mathrm{glob}}$, and $\mathbf{K}_{\mathrm{glob}}(\omega)$ are the real [n x n] global mass, damping and stiffness matrices respectively ; $\mathbf{u}(\omega)$ and $\mathbf{f}(\omega)$ corresponds to the [n x 1] vectors of the nodal absolute displacements and the applied forces in the frequency domain (ω is the circular frequency).

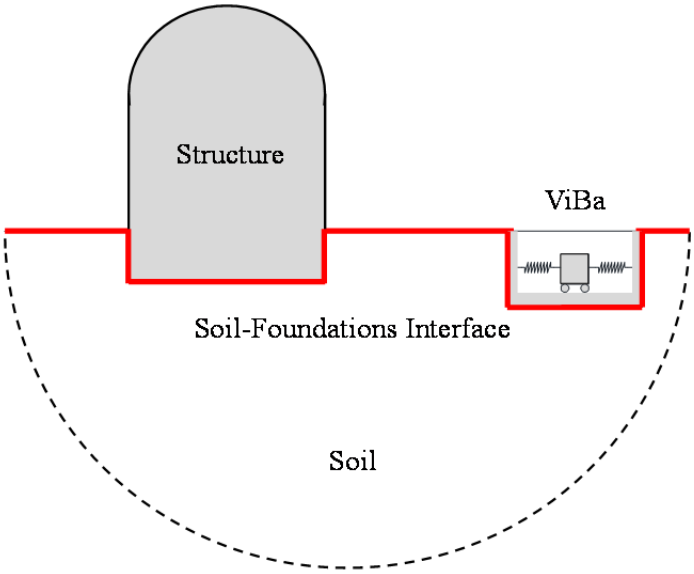

Figure 1 Subdomains of the considered global problem

The global system is partitioned in three subdomains or sub-structures, namely the structure to be protected hereafter referred in the paper by the subscript $[\cdot]_{\mathrm{str}}$, the proposed device ViBa, indicated by the subscript $[\cdot]_{\mathrm{ViBa}}$, and the soil-foundations interface denoted by $[\cdot]_{\mathrm{SF}}$. Therefore, Eq. (1) is restated as:

$$\left\{\begin{bmatrix} \mathbf{K}_{\mathrm{ViBa}} & \mathbf{0} & \mathbf{K}_{\mathrm{ViBa,SF}} \\ \mathbf{0} & \mathbf{K}_{\mathrm{str}} & \mathbf{K}_{\mathrm{str,SF}} \\ \mathbf{K}_{\mathrm{SF,ViBa}} & \mathbf{K}_{\mathrm{SF,str}} & \mathbf{K}_{\mathrm{SF}} \end{bmatrix} - \omega^2 \begin{bmatrix} \mathbf{M}_{\mathrm{ViBa}} & \mathbf{0} & \mathbf{M}_{\mathrm{ViBa,SF}} \\ \mathbf{0} & \mathbf{M}_{\mathrm{str}} & \mathbf{M}_{\mathrm{str,SF}} \\ \mathbf{M}_{\mathrm{SF,ViBa}} & \mathbf{M}_{\mathrm{SF,str}} & \mathbf{M}_{\mathrm{SF}} \end{bmatrix} + i\omega \begin{bmatrix} \mathbf{C}_{\mathrm{ViBa}} & \mathbf{0} & \mathbf{C}_{\mathrm{ViBa,SF}} \\ \mathbf{0} & \mathbf{C}_{\mathrm{str}} & \mathbf{C}_{\mathrm{str,SF}} \\ \mathbf{C}_{\mathrm{SF,ViBa}} & \mathbf{C}_{\mathrm{SF,str}} & \mathbf{C}_{\mathrm{SF}} \end{bmatrix}\right\} \begin{bmatrix} \mathbf{u}_{\mathrm{ViBa}}(\omega) \\ \mathbf{u}_{\mathrm{str}}(\omega) \\ \mathbf{u}_{\mathrm{SF}}(\omega) \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{f}_{\mathrm{SF}}(\omega) \end{bmatrix} \tag{2}$$

The vector $\mathbf{u}(\omega)$ is hence divided into the [p x 1]-vector of the ViBa, $\mathbf{u}_{\mathrm{ViBa}}$, the [q x 1]-vector of the structure, $\mathbf{u}_{\mathrm{str}}$, and the [r x 1]-vector of the soil-foundations system $\mathbf{u}_{\mathrm{SF}}$. The mass, damping and stiffness [q x q]-matrices of the structure to be protected, that is $\mathbf{M}_{\mathrm{str}}$, $\mathbf{C}_{\mathrm{str}}$, $\mathbf{K}_{\mathrm{str}}$ respectively, are derived by a traditional finite element approach. Same approach is used for the [p x p]-matrices, $\mathbf{M}_{\mathrm{ViBa}}$, $\mathbf{C}_{\mathrm{ViBa}}$, $\mathbf{K}_{\mathrm{ViBa}}$ of the proposed device, the ViBa and for the matrices related to the coupling between structure and foundations indicated by the subscript $[\cdot]_{\mathrm{SF,ViBa}}$ and by the subscript $[\cdot]_{\mathrm{SF,str}}$ and their transpose matrices indicated by the subscript $[\cdot]_{\mathrm{ViBa,SF}}$ and by the subscript $[\cdot]_{\mathrm{str,SF}}$. The [r x r]-matrices $\mathbf{M}_{\mathrm{SF}}$, $\mathbf{C}_{\mathrm{SF}}$, and $\mathbf{K}_{\mathrm{SF}}$ are the matrices of the nodes at the soil-foundations interface determined by the substructure approach proposed by Kausel (1978); by defining $\mathbf{K}_{\mathrm{dyn}}(\omega)$ as the dynamic stiffness matrix, that can be decomposed in the real part (Re) and imaginary part (Im) as:

$$\mathbf{K}_{\mathrm{dyn}}(\omega) = \mathrm{Re}\{\mathbf{K}_{\mathrm{dyn}}(\omega)\} + i\mathrm{Im}\{\mathbf{K}_{\mathrm{dyn}}(\omega)\} \tag{3}$$

the following relations are derived:

$$\mathbf{M}_{\mathrm{SF}} = \mathbf{M}_{\mathrm{F}} \tag{4}$$

$$\mathbf{C}_{\mathrm{SF}} = \mathbf{C}_{\mathrm{F}} + \mathrm{Im}\{\mathbf{K}_{\mathrm{dyn}}(\omega)\}/\omega \tag{5}$$

$$\mathbf{K}_{\mathrm{SF}} = \mathbf{K}_{\mathrm{F}} + \mathrm{Re}\{\mathbf{K}_{\mathrm{dyn}}(\omega)\} \tag{6}$$

$\mathbf{M}_{\mathrm{F}}$, $\mathbf{C}_{\mathrm{F}}$, and $\mathbf{K}_{\mathrm{F}}$ the mass, damping and stiffness [r x r]-matrices of the foundation itself, respectively.
The dynamic stiffness matrix $\mathbf{K}_{\mathrm{dyn}}(\omega)$ is determined in order to take into account the effects of the soil, such as the soil-foundation interaction, the foundation-soil-foundation interaction, the hysteretic damping as well as the radiation or geometric damping without resorting to a large finite element model of the soil. The dynamic impedance matrix is computed by condensing out the entire soil-foundations system onto the foundation interfaces in the frequency domain. It relates the displacements in the nodes on the structure-soil interface to the interaction forces $\mathbf{f}_{\mathrm{s}}(\omega)$ of the unbounded soil. Both dynamic impedance matrix $\mathbf{K}_{\mathrm{dyn}}(\omega)$ and the interaction force vector $\mathbf{f}_{\mathrm{s}}(\omega)$ are obtained from linear elastodynamic problems solved by means of Boundary Element Method (BEM) approach. The vector $\mathbf{f}_{\mathrm{SF}}(\omega)$ collects the loads at the soil-foundation interface due to the free-field motion as follows:

$$\mathbf{f}_{\mathrm{SF}}(\omega) = \mathbf{f}_{\mathrm{s}}(\omega)\mathrm{u}_{\mathrm{g}}(\omega) \tag{7}$$

where $\mathbf{f}_{\mathrm{s}}(\omega)$ is the [r x 1] seismic force vector calculated at the interface for an unit harmonic displacement by means of the BEM analysis and $\mathrm{u}_{\mathrm{g}}(\omega)$ is the free field motion displacement at the ground surface.
Afterwards, Craig-Bampton (1968) method is applied to the system in order to reduce the number of DOFs of the global system. The method consists of partitioning the global system into two or more subdomains by holding the boundary conditions fixed and then combining the fixed base modal shapes with the constraint modes of the common interface by means of a modal synthesis. The advantages of the method lie in i) to reduce the number of equations in the nodal space by projecting the problem to the so-called generalized space along with the modal truncation of higher modes; ii) independent analysis of each subdomain and, iii) the responses for various motions of the boundary degree of freedoms to one subdomain are determined without repeating the entire coupled analysis. Hereafter, the formulation is specialized to the specific case involved in the paper and depicted in Figure 1 even though it can be easily generalized to include more structures and ViBa devices. The physical coordinates $\mathbf{u}$, are transformed to a hybrid set of physical coordinates at the boundary $\mathbf{u}_{\mathrm{SF}}$, and modal coordinates at the interior points of the structure, $\mathbf{q}_{\mathrm{str}}$, and of the ViBa, $\mathbf{q}_{\mathrm{ViBa}}$. By truncating the modal coordinates to smaller sets, let us consider $\boldsymbol{\psi}_{[\mathrm{pxi}]}^{\mathrm{ViBa}}$ and $\boldsymbol{\psi}_{[\mathrm{qxl}]}^{\mathrm{str}}$ as the [p x i] - and [q x l]-matrices of the dynamic modal shapes obtained by conventional eigenvalues problem; $\boldsymbol{\phi}_{[\mathrm{pxr}]}^{\mathrm{ViBa}}$ and $\boldsymbol{\phi}_{[\mathrm{qxr}]}^{\mathrm{str}}$ as the [p x r] and [q x r] matrices of interface modal shapes of ViBa and structure, respectively. The constraint modes or interface modes $\boldsymbol{\phi}$ relate the rigid body static unit displacements at the interface $\mathbf{u}_{\mathrm{SF}}$ to the physical displacements of the elastic degrees of freedom $\mathbf{u}$. Furthermore, in case of rigid foundation, the number of constraint modes contained in $\boldsymbol{\phi}$ is sensibly reduced according to the number of degree of freedoms of the foundation master nodes. Therefore, the generalized coordinate [m= i+l+r]-vector $\mathbf{q}^{\mathrm{T}}$ listed as (the superscript T indicates the transpose operator):

$$\mathbf{q}^{\mathrm{T}} = [\mathbf{q}_{\mathrm{ViBa}}\ \mathbf{q}_{\mathrm{str}}\ \mathbf{u}_{\mathrm{SF}}\ ] \tag{8}$$

is related to the physical coordinates $\mathbf{u}$, by means of the following relation:

$$\begin{bmatrix} \mathbf{u}_{\mathrm{ViBa}} \\ \mathbf{u}_{\mathrm{str}} \\ \mathbf{u}_{\mathrm{SF}} \end{bmatrix} = \mathbf{P} \begin{bmatrix} \mathbf{q}_{\mathrm{ViBa}} \\ \mathbf{q}_{\mathrm{str}} \\ \mathbf{u}_{\mathrm{SF}} \end{bmatrix} \tag{9}$$

where **P** is the reduced Craig-Bampton transformation matrix:

$$\mathbf{P}_{[nxm]} = \begin{bmatrix} \boldsymbol{\psi}_{[pxi]}^{ViBa} & \mathbf{0}_{[pxl]} & \boldsymbol{\phi}_{[pxr]}^{ViBa} \\ \mathbf{0}_{[qxi]} & \boldsymbol{\psi}_{[qxl]}^{str} & \boldsymbol{\phi}_{[qxr]}^{str} \\ \mathbf{0}_{[rxi]} & \mathbf{0}_{[rxl]} & \mathbf{I}_{[rxr]} \end{bmatrix} \tag{10}$$

Note that the physical displacements of the interior points are computed by

$$\begin{cases} \mathbf{u}_{ViBa} = \boldsymbol{\psi}^{ViBa}\mathbf{q}_{ViBa} + \boldsymbol{\phi}^{ViBa}\mathbf{u}_{SF} \\ \mathbf{u}_{str} = \boldsymbol{\psi}^{str}\mathbf{q}_{str} + \boldsymbol{\phi}^{str}\mathbf{u}_{SF} \end{cases} \tag{11}$$

The projection of the dynamic governing Eq. (1) over the base **P**, yields to the Craig-Bampton equation of motion of the reduced model in the frequency domain:

$$\left[\mathbf{P}^T\mathbf{K}_{glob}(\omega)\mathbf{P} - \omega^2\mathbf{P}^T\mathbf{M}_{glob}\mathbf{P} + i\omega\mathbf{P}^T\mathbf{C}_{glob}\mathbf{P}\right]\mathbf{u}(\omega) = \mathbf{P}^T\mathbf{f}(\omega) \tag{12}$$

where the size of each reduced matrices $\mathbf{P}^T\mathbf{MP}$, $\mathbf{P}^T\mathbf{CP}$, and $\mathbf{P}^T\mathbf{KP}$ is [m x m] with m << n. Furthermore, in case of rigid foundation, the number of constraint modes is sensibly reduced to r = 12 corresponding to the degree of freedoms of the master nodes of the two foundations involved in this paper.

ViBa design

A reduced model is considered for determining the optimal design parameters of the ViBa by accounting only the translational components of the motion and by considering the first natural modes of both the industrial building and the ViBa. In the nodal space, the reduced model is representing through a simplified mechanical system as depicted in Figure 2 whose adopted kinematics is illustrated in Figure 3. Consequently, Eq. (12) is simplified as follows:

$$\left(\widetilde{\mathbf{K}}_{simp} - \omega^2\mathbf{M}_{simp}\right)\mathbf{U}(\omega) = \mathbf{Q}\,u_g(\omega) \tag{13}$$

or in expanded form :

$$\left\{\begin{bmatrix} \tilde{k} & -\tilde{k} & 0 & 0 \\ -\tilde{k} & \tilde{k}+\tilde{k}_f+\tilde{k}_{SSSI} & 0 & 0 \\ 0 & 0 & \tilde{k}_{ViBa} & -\tilde{k}_{ViBa} \\ 0 & 0 & -\tilde{k}_{ViBa} & \tilde{k}_{ViBa}+\tilde{k}_{f,ViBA}+\tilde{k}_{SSSI} \end{bmatrix} - \omega^2\begin{bmatrix} m & 0 & 0 & 0 \\ 0 & m_f & 0 & 0 \\ 0 & 0 & m_{ViBa} & 0 \\ 0 & 0 & 0 & m_{f,ViBa} \end{bmatrix}\right\}\begin{bmatrix} U(\omega) \\ U_f(\omega) \\ U_{ViBa}(\omega) \\ U_{f,ViBa}(\omega) \end{bmatrix} = \begin{bmatrix} 0 \\ \tilde{k}_f \\ 0 \\ \tilde{k}_{f,ViBa} \end{bmatrix} u_g(\omega) \tag{14}$$

The use of the tilde $\tilde{\square}$ indicates the complex nature of the stiffness since the dissipation of energy is simulated according to the hysteretic damping model by introducing the complex stiffness as generally indicated below:

$$\tilde{k} = k(1 + i\eta) \tag{15}$$

where η is the loss factor.

In Eq. (14) the unknown parameters are the mass m_{ViBa}, the stiffness k_{ViBa}, and the loss factor η_{ViBa}, i.e. the parameters of the internal unit of the ViBa device. The determination of these parameters is achieved by means of the optimization procedure aimed to reduce the structural response as:

$$\begin{gathered} \min\{H(\boldsymbol{\alpha}, \omega)\} \\ \boldsymbol{\alpha} = \{k_{ViBa}, m_{ViBa}, \eta_{ViBa}\} \in \mathbb{R}_0^+ \end{gathered} \tag{16}$$

where the steady state response of the structure subjected to harmonic excitation namely the transfer function is the component related to the structure of the matrix defined as follows:

$$\mathbf{H}(\omega) = \left[\mathbf{K}_{simp} - \omega^2\mathbf{M}_{simp}\right]^{-1}\mathbf{Q} \tag{17}$$

For harmonic loads at the circular frequency ω_0 the optimization procedure is simplified in $H(\boldsymbol{\alpha}, \omega_0) = 0$; after simple algebra, the following formula for the ViBa calibration is achieved:

$$\tilde{k}_{ViBa}^{optimal} = \frac{(\omega_0^2 m_{ViBa})\left[\tilde{k}_{f,ViBa} + \tilde{k}_{SSSI}\left(1 + \frac{\tilde{k}_{f,ViBa}}{\tilde{k}_f}\right) - \omega_0^2 m_{f,ViBa}\right]}{\tilde{k}_{f,ViBa} + \tilde{k}_{SSSI}\left(1 + \frac{\tilde{k}_{f,ViBa}}{\tilde{k}_f}\right) - \omega_0^2\left(m_{f,ViBa} + m_{ViBa}\right)} \tag{18}$$

where $\tilde{k}_{ViBa}^{optimal} = k_{ViBa}(1 + i\eta_{ViBa})$ while the mass m_{ViBa} is assigned. Eq. (18) leads to an easy and fast tuning of the ViBa parameters by considering only the values of the soil impedances evaluated at the circular frequency ω_0. It should be emphasized that through Eq. (18), the structure is completely stopped ($U(\omega) = 0$) since the ViBa is absorbing all the input energy.

Parametric analyses

Parametric analyses considering various soil profiles as well as mechanical and geometrical properties of the ViBa are performed for testing its efficiency on protecting an Industrial Building from dynamic loads as depicted in Figure 4. The investigated industrial building is reproduced by means of the Code_Aster open source FE-software (2013) according to the case study described in the report EPRI (2006). Significant dimensions are reported in Table 1. The ViBa is externally modelled as a circular embedded foundation; two different dimensions of the radius and the embedded height are considered, the first, referred to ViBaD1 has the same dimensions of the Industrial Building foundation and the second, referred to ViBaD05, has the radius and the embedded height halved than the previous one. Three linear elastic homogenous soil deposits of 30-meter thickness resting on bedrock are investigated; their properties are summarized in Table 2 representing the soil categories A-B-C defined in the Eurocode 8. The soil impedances are derived from the impedance matrix obtained by BEM formulation by means of Miss3D (Clouteau, 2005). The analyses are conducted by solving Eq. (12) where the assumption of rigid foundations has been done. The aim is to decrease the maximum acceleration of the dome of the Industrial Building subjected to the harmonic load at the frequency ω_0 =21.05 rad/s. The reduced model is derived by considering the first natural modes of the structures and the ViBa and the horizontal components of the soil movements. Therefore, Eq. (18) is applied for calibrating the internal unit of the ViBa in order to absorb the harmonic load at the frequency ω_0 =21.05 rad/s. The optimal damping derived from Eq. (18) yields a negative value of the critical damping; thus the minimum real value $\eta_{ViBa} = 0$ is assigned. Figure 5 shows the real part of the soil impedances used for applying Eq. (18); the quantities are evaluating at the frequency ω_0 =21.05 rad/s indicated by the dashed line. Figure 6 shows the amplification function of the nodal displacement of the top of the dome obtained by Code_Aster, for the case of Industrial Building protected by ViBaD05 placed at a distance of 6.45m. Several mass ratio m_{ViBa}/m where m is the mass of the Industrial Building, are considered. The response at the circular frequency ω_0 shows a minimum value due to the effect of coupling with the ViBa. This minimum is almost independent of the mass ratio. The efficiency of the ViBa is evaluated in terms of reduction factor (RF) defined as the ratio between the maximum nodal displacement of the structure in the case of coupling $U_{coupled}^{str}$ and uncoupling $U_{uncoupled}^{str}$ with the ViBa, under the harmonic excitation at a given frequency ω_0, as follows:

$$RF = \frac{\left|U_{coupled}^{str}(\omega_0)\right|}{\left|U_{uncoupled}^{str}(\omega_0)\right|} \tag{19}$$

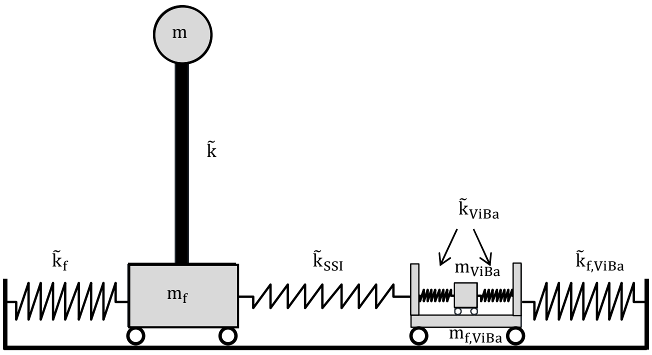

Figure 2 Simplified model

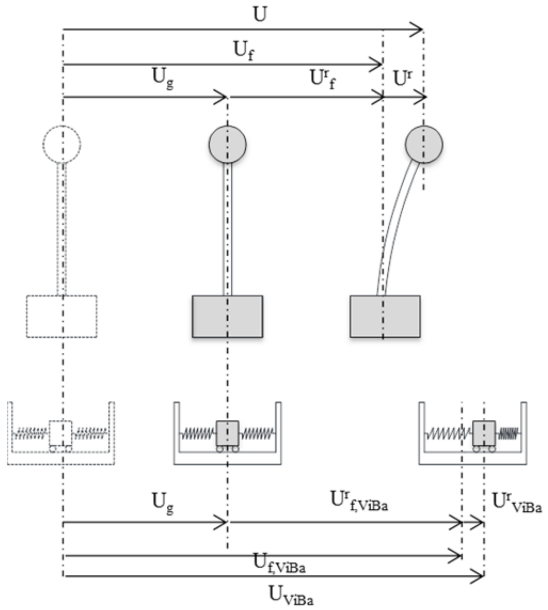

Figure 3 Kinematics of the system

The calculated RF is 0.25 for each considered case; therefore, a relevant reduction of the 75% is achieved. A summary of the results for the same is reported in **Error! Reference source not found.** by applying increasing ViBa loss factors. The efficiency of the ViBa increases with the increase of the mass and decreases with the increase of the loss factor. Finally, in Figure 7 are depicted the RF curves by varying the spacing from the Industrial Building for the two types of ViBa, i.e. ViBaD05 and ViBaD1. It is worth emphasized that the best results are obtained with the smaller ViBa (ViBaD05) than the larger one since the RF is lower at the same considered distance.

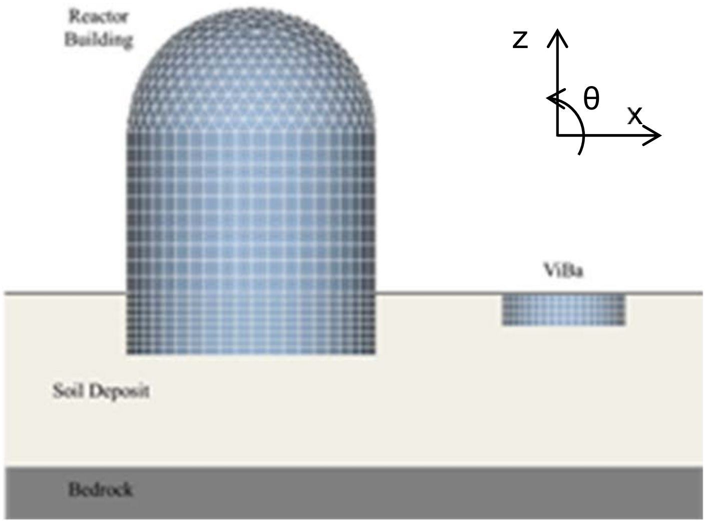

Figure 4 Investigated Case Study of an Industrial Building protected by ViBa

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

Concluding Remarks

The paper presents the application of the Vibrating Barrier (ViBa) on a model of Industrial Building. 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. The design of the ViBa has been performed through the mean of a reduced model derived by means of the Craig-Bampton procedure in the frequency domain. The calibration has been verified through comparison between dynamic response of the exact and reduced model. Parametric analysis has been carried out by varying the type of soil, distance between ViBa and structure as well as the geometric and mechanical properties of the ViBa. Under ground motion harmonic loads, reductions of the maximum displacement of the dome of the Industrial Building up to 75% have been achieved even for small mass ratio between structure and ViBa.

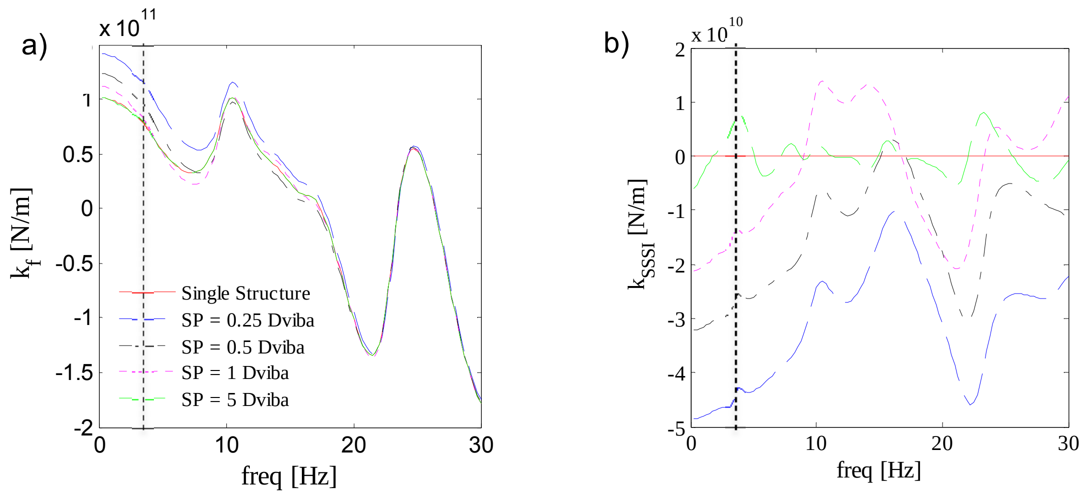

Figure 5 Real part of the soil impedances a)SSI and b)SSSI for case with the soil type B and ViBAD05 by varying the distance; the dashed line indicates the frequency of calibration for the reduced model

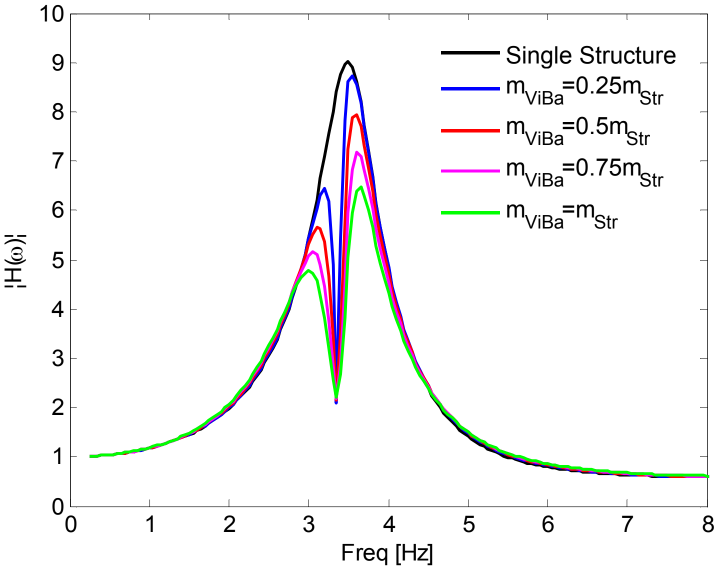

Figure 6 Amplification function of the node at the top of the dome for several mass ratio e ViBa damping set to 0 for case with the soil type B and ViBAD05

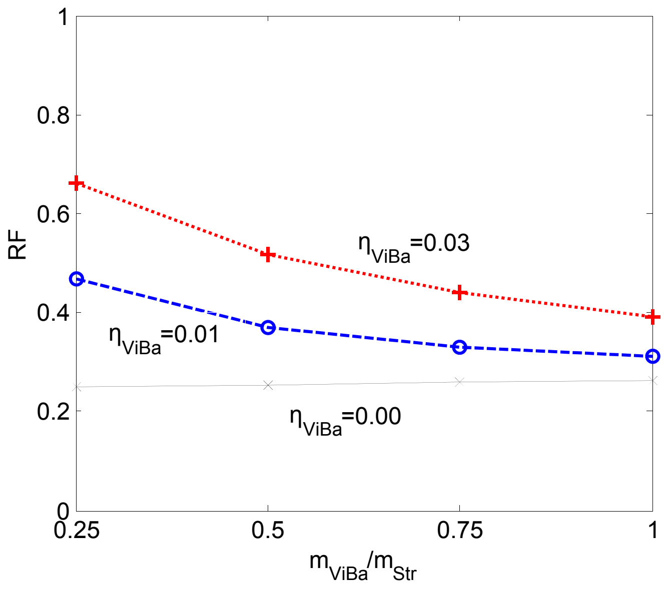

Figure 7 RF curves obtained for case with the soil type B and ViBAD05

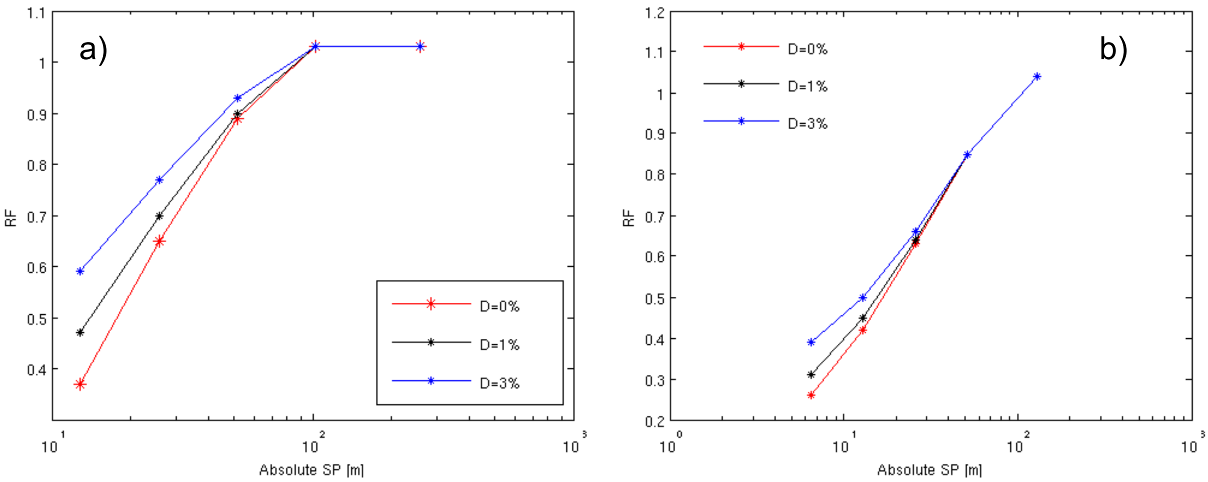

Figure 7 Top Dome RFs curves for several damping and spacing for case a) ViBAD1 and b) ViBAD05

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