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Vibration Control of an existing building through the Vibrating Barrier

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Abstract

Vibration control of structures is normally addressed through devices such as isolators, dampers and tuned mass dampers. Although those devices are technically sound their use might become unpractical in existing buildings such as heritage structures, whereas the alteration of part of the structure is forbidden for various socio-economic issues. In this context, a novel passive control device called Vibrating Barrier (ViBa) has been recently proposed. The Vibrating Barrier is a massive structure, hosted in the soil and detached from the existing building, calibrated for absorbing portion of the ground motion input energy. The working principle is based on the generally know structure-soil-structure interaction between two vibrating structures and the soil.

In this paper the Vibrating Barrier is designed to control the vibration of an existing masonry structure forced by ground motion acceleration. The structure, the soil and the ViBa are assumed to be linear behaving and modelled through a pertinent Finite Element approach. The design is pursued through a simplified discrete model of the structure and the ViBa in which the soil is represented by linear elastic springs. Significant reduction of the dynamic response has been achieved manifesting the potential of the Vibrating Barrier to be a valid alternative whereas the traditional vibration control techniques cannot be applied.

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Keywords: structure-soil-structure interaction; heritage buildings; vibration control; vibrating barrier; earthquake.

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1. Introduction

Historic structures in seismic prone areas are extremely vulnerable. The main reason is that such structures have not been properly designed to withstand earthquakes and also because the construction materials normally deteriorate with the time. The most recent earthquakes, such as the one in Norcia 2016 are clear examples manifesting the necessity to act promptly to protect heritage structures from such natural disaster. Up to now the problem of protecting structures by seismic action has been managed using localised solutions such as isolators and dampers. 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 component. For heritage structures clearly such technologies cannot be applied and therefore no seismic protection actions are currently taken to protect such artistic treasure.

Bearing in mind the global necessity to protect existing structures from earthquakes and the limitation of current technologies the novel vibrating barrier (ViBa) control strategy has been recently proposed (Cacciola and Tombari 2015). The ViBa device is a massive structure, hosted in the soil, calibrated for protecting structures by absorbing portion of the ground motion input energy. As a difference with other technologies buried in the soil (i.e. trenches and sheet piles) that are focused on surface waves only (see e.g. Woods 1968; Adam and von Estorff 2005), the ViBa is designed to absorb seismic body waves. In its simplest configuration it is made by a mass spring system buried in the soil and able to vibrate. 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). Specifically, Warburton et al. (1971) studied the dynamic response of two rigid masses in an elastic subspace showing 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).

The paper investigates the effect of the ViBa on an existing heritage building, the Slovenian Philharmonic in Ljubljana built in 1891. A finite element formulation is used for modelling the building, the soil as well as the ViBa. Seismic analyses are carried out by considering local registrations of earthquake events. Results show a relevant reduction of the structural response.

2. Problem position

Consider the schematic representation in Fig. 1 where a single building and the ViBa are both depicted. The problem to be addressed is the design of the ViBa structural parameters so to reduce the dynamic response of the existing structure.

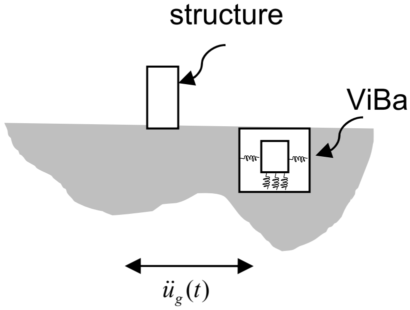

Fig. 1. Schematic representation of the Vibrating Barrier device and the structure to be controlled

To this aim the equations governing the motion of the whole structure-soil-ViBa system can be cast in frequency domain in terms of absolute displacements as follows:

$$\left(\tilde{\mathbf{K}} - \omega^2\mathbf{M}\right)\mathbf{U}(\omega) = \mathbf{Q}\,\mathrm{U_g}(\omega) \tag{1}$$

where $\mathbf{U}(\omega)$ is the absolute displacement vector, $\mathbf{M}$ is the global mass matrix and $\tilde{\mathbf{K}}$ is the complex stiffness matrix. The complex formulation of the stiffness, $\tilde{\mathbf{K}}$, is obtained by populating each component of the matrix with the hysteretic damping model, $\tilde{k} = k(1 + i\eta)$, in which $\mathrm{i} = \sqrt{-1}$ and η is the material loss factor. Also the symbol $\tilde{\square}$ indicates the complex stiffness quantities. In Equation (1) $\mathbf{Q} = \tilde{\mathbf{K}}\boldsymbol{\tau}$ with $\boldsymbol{\tau}$ the influence vector listing unitary values in correspondence of the degrees of freedom in the direction of the seismic action and having zeros elsewhere. Finally $\mathrm{U_g}(\omega)$ is the Fourier transform of the ground displacements. Therefore, the optimization problem is set as:

$$\min\left\{u^{\mathrm{r,max}}(\boldsymbol{\alpha})\right\}\ , \boldsymbol{\alpha} = \left\{\mathrm{k_V^{ij}}, \eta_\mathrm{V}^{\mathrm{ij}}, \mathrm{m_V^{ii}}\right\} \in \mathbb{R}_0^+ \tag{2}$$

where $\mathrm{k_V^{ij}}$ and $\eta_\mathrm{V}^{\mathrm{ij}}$ are the stiffness and damping components of the matrix $\tilde{\mathbf{K}}$ and $\mathrm{m_V^{ii}}$ is the mass component of $\mathbf{M}$ pertinent to the ViBa degrees of freedom, $u_\mathrm{i}^{\mathrm{r,max}}(\boldsymbol{\alpha})$ is the maximum displacement of the structure relative to its foundation:

$$u_\mathrm{i}^{\mathrm{r,max}} = \max(u - u_{f,\mathrm{i}}) \tag{3}$$

It is noted that different optimization criteria and/or penalty function can be used to determine the optimal ViBa parameter and as a consequence the optimization problem can be pursued either in frequency or in the time domain.

3. Design of the ViBa for a simplified system

In this section a simplified strategy to determine the relevant ViBa structural parameter is presented. This approach is particular suitable for regular structures for which the 3D analysis can be decomposed in two independent 2D study. The simplified model depicted in Fig. 2 is used for this purpose. Specifically, both the structure and the ViBa are modelled by two-DoF systems encompassing the horizontal displacements of superstructure and the foundation, connected to the soil and between them by Winkler type elastic springs.

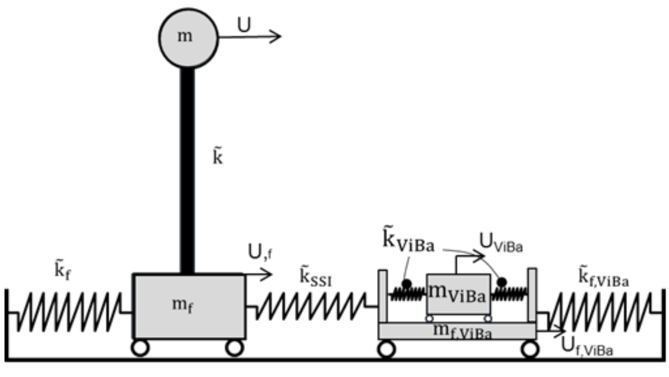

Fig. 2 Discrete model used for the vibration control of a single structure through the ViBa.

It has been shown (Cacciola and Tombari, 2015) that the solution of the optimization problem given in Equation (2) for the system in Fig. 2, for a selected mass of the ViBa m_{ViBa}, is determined in closed form for harmonic excitation and it leads the following value for the optimal stiffness:

$$\tilde{k}_{ViBa}^{optimal}(\omega_0) = \frac{(\omega_0^2 m_{ViBa})\left[\tilde{k}_{f,ViBa} + \tilde{k}_{SSSI}\left(1 + \frac{\tilde{k}_{f,ViBa}}{\tilde{k}_f}\right) - \omega_0^2 m_{f,ViBa}\right]}{\tilde{k}_{f,ViBa} + \tilde{k}_{SSSI}\left(1 + \frac{\tilde{k}_{f,ViBa}}{\tilde{k}_f}\right) - \omega_0^2 (m_{f,ViBa} + m_{ViBa})} \tag{4}$$

where ω_0 is the selected frequency to be absorbed by the ViBa. Also it is noted that in Equation (4) only the structural foundation parameters appears along with the soil stiffness interaction values.

4. Numerical Results

In this section, the efficiency of the Vibrating Barrier is used for protecting a model (Fig. 3) of the Slovenian Philharmonic in Ljubljana (Banjanac, 2016). The building is a masonry structure 37.8m long by 25.2m width, with a maximum height of 16.7m. Basement walls extend 3.6m underneath the ground floor and lie on masonry strip foundations. A concrete extension is located at the bottom of the building with columns at the basement level as depicted in in Fig. 3 with a grey colour. The inner and outer stone masonry walls have a thickness varying from 0.32m-0.9m. Floors and roof are made of timber trusses and beams. The global 3D FEM model comprised of walls, frames and soil is realized by using 8-node solid hexahedral elements. Elastic properties of the walls are defined by Young's modulus equal to 1.9 GPa, Poisson coefficient equal to 0.22, and unit weight of 1.9 Mg/m^3. The building is resting on 40m alluvial soil consisted of silt, sand, clay as well as poorly graved gravelly-sandy soft soil. The soil is characterized by Young's modulus equal to 0.318 GPa, Poisson coefficient equal to 0.42 and unit weight of 2.1 Mg/m^3. Equal constraints are applied to the model boundaries at each depth, in order to simulate the shear behaviour of the soil during soil wave propagation from the bedrock to the ground surface. Finally, an equivalent modal damping of 10% is applied to the soil, 5% for the masonry and 1% for the ViBa. In Fig. 3a it is also depicted in green the trench that will host the moving mass of the ViBa in order to highlight the influence of the dynamic versus the static counterpart of the Vibrating Barrier, see Fig. 3(a) and (b). The mass of the ViBa is assigned for illustrative purpose as half of the mass of the whole building.

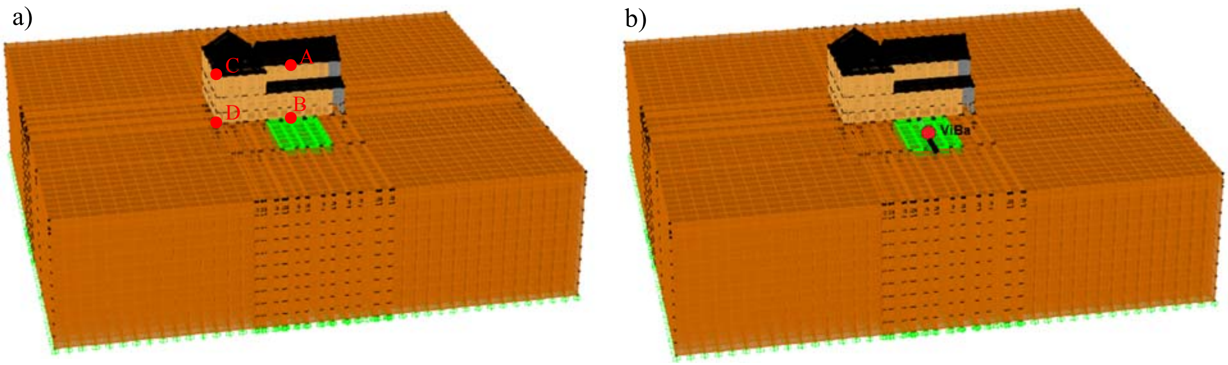

Fig. 3. Numerical model (a) single building; (b) building coupled with ViBa.

Steady-state analyses are performed for both cases without (i.e. with trench only) and with the protection offered by the ViBa neglecting the site response amplification. The tuning is obtained by means of the formula in Eq. (4) where each term is derived by using a direct stiffness approach of a finite element model with foundations only. The Vibrating Barrier is tuned to reduce the vibrations induced by a harmonic input at the frequency $f_0 = 4.10$ Hz ($\omega_0 = 25.76$ rad/s) corresponding to the first natural frequency of the structure in the direction of the input. Results are presented in terms of modulus of the displacement response $U_{A,C}(f)$ in the frequency domain of the selected points A and C depicted in Fig. 3 (a). The efficiency of the ViBa is evaluated in terms of reduction index calculated as follows:

$$\mathrm{IR} = 1 - |\mathrm{U_i}(\mathrm{f_0})|/|\mathrm{U}_i^{unc}(\mathrm{f_0})| \text{ for } i = \mathrm{A, B} \tag{5}$$

in which $\mathrm{U}_i^{unc}(\mathrm{f_0})$ is the structural response related to the case of uncoupled single building of Fig. 3(a). The displacement responses in the frequency domain are illustrated in Fig 4. (a) and (b) for the selected point A and C, respectively. It can be observed that the ViBa affects the structural response by achieving a reduction at the selected frequency IR=82.32% and IR=81.92% for the mid-point A and corner point C, respectively.

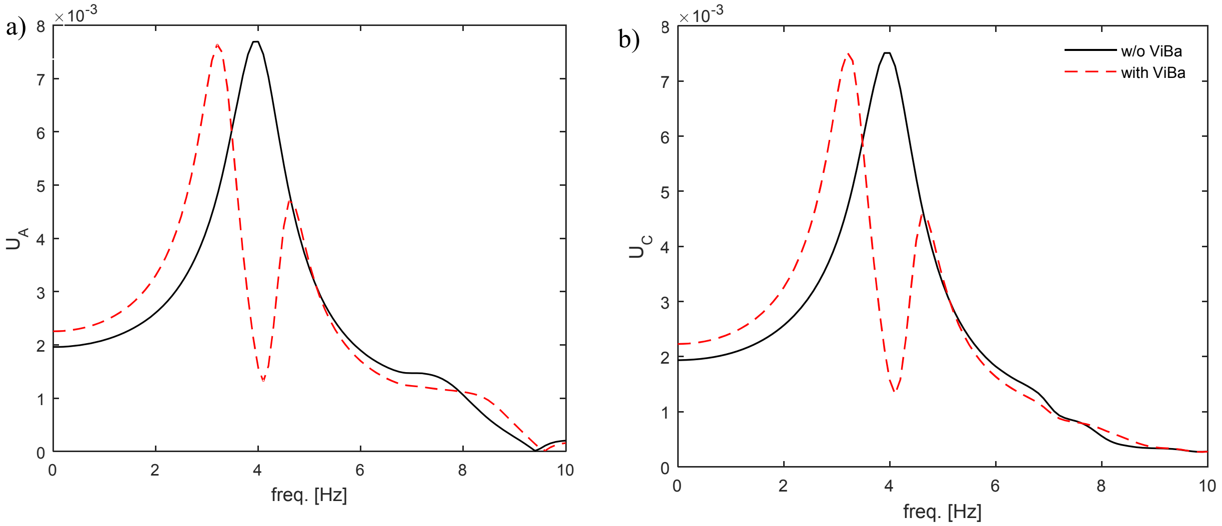

Fig. 4. Steady state response in displacement recorded at the (a) mid-point A and at the (b) corner point C (in meters).

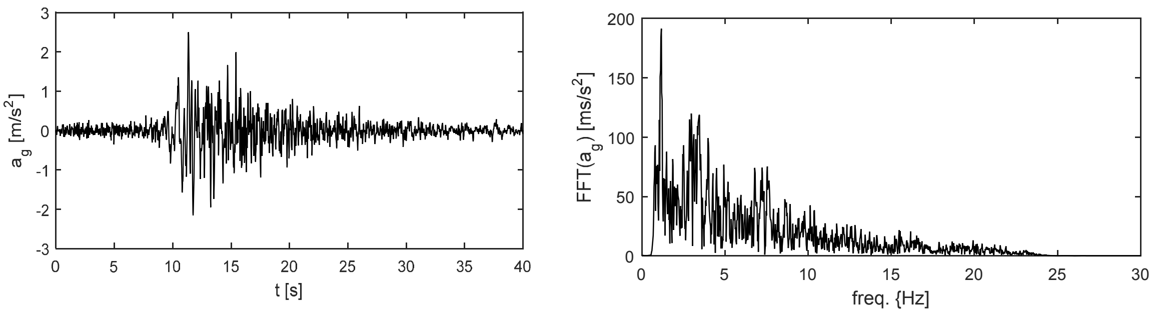

Fig. 5. Ground motion input signal of the Bovec earthquake event (a) time history and (b) Fourier transform.

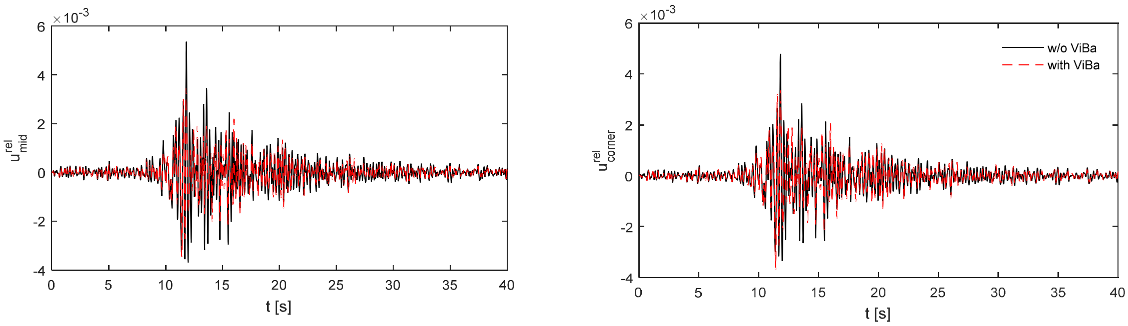

Fig. 6. Relative displacements due to the Bovec earthquake between (a) selected points A and B and (b) selected points C and D (in meters).

Finally, the performance of the ViBa is tested for the Bovec ground motion time history (1998) recorded in Slovenia and shown in Fig. 5 (a) and Fig. 5 (b) through an approximated modal time history analysis. It is worth mentioning that the same parameters used to tuning the ViBa under harmonic signals, are here adopted. It is noted that different optimization procedures can be adopted for real earthquake ground motions as discussed in (Cacciola et al. 2015 and Tombari et al. 2016). The results are shown in terms of relative displacements between the selected points A and B, i.e. $u_{mid}^{rel}(t)$, and relative displacements between the selected points C and D, i.e. $u_{corner}^{rel}(t)$. Structural responses are depicted in Fig. (a)-(b); the ViBa protects the heritage building by achieving a reduction of 35.36% and 22.96%, respectively.

4. Concluding Remarks

The efficiency of the novel Vibrating Barrier for the control of an existing building has been addressed in this paper. A Finite Element model of the Slovenian Philharmonic in Ljubljana built in 1891 has been used as case study for this purpose. Furthermore a simplified formula to calibrate the stiffness parameters of the ViBa has been adopted for illustrative purpose. From the analysis conducted it is evident that the ViBa produced a beneficial effect by reducing of 35.36% and 22.96%, the target relative horizontal displacements due to a recorded ground motion time history. It has to be emphasized that further reductions can be achieved via either the increment of the ViBa mass or by optimizing the stiffness and damping parameter of the ViBa for broad band signals (see Cacciola et al. 2015).

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