Mechanical Systems and Signal Processing 101 (2018) 219–236

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Vibration control of a cluster of buildings through the Vibrating Barrier

A. Tombari [a,*], M. Garcia Espinosa [b], N.A. Alexander [c], P. Cacciola [a]

[a] University of Brighton, United Kingdom
[b] University of Oxford, United Kingdom
[c] University of Bristol, United Kingdom

ARTICLE INFO

Article history:
Received 28 February 2017
Received in revised form 16 August 2017
Accepted 20 August 2017

Keywords:
Vibrating Barrier
ViBa
Structure-soil-structure interaction
Cluster of buildings
Shake table testing
Seismic vibration control

ABSTRACT

A novel device, called Vibrating Barrier (ViBa), that aims to reduce the vibrations of adjacent structures subjected to ground motion waves has been recently 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. In this paper the efficiency of the ViBa is investigated to control the vibrations of a cluster of buildings. To this aim, a discrete model of structures-site interaction involving multiple buildings and the ViBa is developed where the effects of the soil on the structures, i.e. the soil-structure interaction (SSI), the structure-soil-structure interaction (SSSI) as well as the ViBa-soil-structures interaction are taken into account by means of linear elastic springs. Closed-form solutions are derived to design the ViBa in the case of harmonic excitation from the analysis of the discrete model. Advanced finite element numerical simulations are performed in order to assess the efficiency of the ViBa for protecting more than a single building. Parametric studies are also conducted to identify beneficial/adverse effects in the use of the proposed vibration control strategy to protect cluster of buildings. Finally, experimental shake table tests are performed to a prototype of a cluster of two buildings protected by the ViBa device for validating the proposed numerical models.

1. Introduction

Recent earthquake events such as L'Aquila in Italy, 2009, Port-au-Prince in Haiti, 2010, Lamjung in Nepal, 2015, and Amatrice in Italy, 2016, pointed out the problematic of protecting wide urban areas in which historical buildings are hosted.

Whilst seismic protection of new buildings is commonly addressed through a proper seismic design of the structure or by using devices such as isolators, dampers as well as tuned mass dampers, the rehabilitation of existing buildings is a complex task that generally requires impacting structural interventions that, in case of heritage buildings, can alter their architectural value. Furthermore, similar expensive interventions are rarely employed for private constructions letting a huge number of towns and cities worldwide below the adequate level of seismic safety. This situation is extremely concerning because in

* Corresponding author.
E-mail addresses: a.tombari@brighton.ac.uk (A. Tombari), maria.garciaespinosa@linacre.ox.ac.uk (M. Garcia Espinosa), Nick.Alexander@bristol.ac.uk (N.A. Alexander), p.cacciola@brighton.ac.uk (P. Cacciola).

http://dx.doi.org/10.1016/j.ymssp.2017.08.034
0888-3270/

addition to the need of conservation of the architectural value and the relevant economic impact still a large death toll are occurring after a strong earthquake event.

Therefore, as traditional localised solutions might become impractical or difficult to apply to existing buildings alternative solutions need to be pursued. One possible strategy is to protect the structures through trenches or sheet-pile walls in the soil (see e.g. Woods, [1]) for altering the displacement field based on the reflection, scattering and diffraction of dynamic surface waves or through the use of most innovative solutions, such as the resonant metawedge (Colombi et al., [2]) and other engineering metamaterials (see e.g. [3–7]) for controlling the flow of Rayleigh waves. However, this approach is more effective for surface waves rather than body waves. Cacciola and Tombari [8] introduced for the first time, a non-localized solution, called Vibrating Barrier (ViBa), hosted in the soil and detached from the structures, that exploits the structure-soil-structure mechanism for reducing the vibrations of structures due to ground motion excitation. Analyses on the efficiency of the ViBa in protecting a single building are reported in Cacciola and Tombari [8], in Cacciola et al. [9] for structure founded on monopile foundation and in Tombari et al. [10] for an industrial building.

Furthermore, as non-local solution, the Vibrating Barrier can be used to mitigate more than one building making it suitable for its installation in the urban environment.

The seismic free-field wavefield is greatly affected by the collective behaviour of the buildings especially in densely populated urban environment; this effect is referred to as "city effect" or "site-city Interaction", and several studies have been undertaken in the last decades in this regard, see e.g. Clouteau and Aubry [11], Chávez-García and Cárdenas [12], Guéguen et al. [13], Kham et al. [14], Ghergu and Ionescu [15], Isbiliroglu et al. [16], Schwan et al. [17] and Guéguen and Colombi [18], just to cite a few. In particular, Kham et al. [14] showed that the energy of ground motion in a city can be reduced or increased due to the perturbation induced by resonant buildings. This phenomenon, that globally governs the site–city effects, can be seen as an extension of the structure–soil–structure interaction (SSSI).

In particular, the first studies on SSSI were carried out by Warburton et al. [19] on the dynamic response of two rigid masses in an elastic subspace, where they highlighted the influence of one mass on the dynamic response of the other. The dynamic interaction between two parallel infinite shear walls placed on rigid foundations and forced by a vertically incident shear (SH) wave was investigated by Luco and Contesse [20]. Wong and Trifunac [21] extended the previous case for non-vertically incident plane SH waves by investigating the significance of the angle of incidence. A comprehensive review of the SSSI problem can be found in Lou et al. [22].

In this framework, the Vibrating Barrier interacts with the adjacent structures and mitigates their vibrations if opportunely designed. It is noted that this approach differs substantially from the recent proposed seismic metamaterials (see e.g. [2–7]), which aim to deviate the surface seismic waves away from the structure, while the Vibrating Barrier is conceived to absorb the seismic body waves. Also, it has to be emphasized that the ViBa, as a difference from the metamaterials, exploits the structure-soil-structure interaction phenomenon that modifies the dynamic properties of the neighbouring structures. The tuning of the ViBa is addressed via a discrete model, following the approach proposed in literature for discrete SSSI problems. Specifically, Kobori et al. [23] defined a multi-spring–mass system for investigating the dynamic coupling of two adjacent square superficial foundations. Mulliken and Karabalis [24] defined a simple discrete model for predicting the dynamic interaction between adjacent rigid surface foundations supported by a homogeneous, isotropic and linear elastic half-space. Recently, Alexander et al. [25] developed a discrete model to study the SSSI problem of surface foundations by considering stochastic ground motion excitation which has been extended by Aldaikh et al. [26,27] to the case of three buildings and validated by means of experimentally shake-table testing.

In this paper, a discrete model comprised of masses and linear visco-elastic springs is used for simulating the soil-structure interaction (SSI), the structure-soil-structure interaction (SSSI) as well as the ViBa-soil-structure interaction. An analytical formula for tuning the ViBa in the case of two adjacent buildings, is determined. A parametric investigation is also performed to highlight the efficiency of the ViBa. A prototype comprised of two structures and the ViBa is realized and pertinent experimental tests have been also conducted. Specifically, the soil is represented by silicone rubber material, following the approach of Niwa et al. [28] and Kitada et al. [29] for the study of the SSSI for nuclear power plants. Furthermore, finite element analyses, validated through the experimental results, have been determined for evaluating the influence of the position of the ViBa on the dynamic response of the structures. The main aim of this paper is to demonstrate the efficiency of the Vibrating Barrier (originally proposed by Cacciola and Tombari [8]) for a cluster of buildings under harmonic excitations, through extensive parametric, numerical and experimental approaches.

2. General formulation of the governing equations

The problem analysed in this paper deals with the design of the Vibrating Barrier (ViBa) in order to reduce the vibration of the surrounding buildings as depicted in Fig. 1a. The vibration control of a cluster of buildings is carried out by deriving the dynamic governing equations in finite element formulation as illustrated in Fig. 1b; therefore, in this section, a general matrix formulation of the global problem is addressed. The mathematical expression, derived in terms of absolute displacements as it is conventional in soil-structure interaction, is stated as:

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