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Soil-buried wave barriers for vibration control of structures subjected to vertically incident shear waves

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ABSTRACT

Traditionally, the effects of seismic forces on structures have been mitigated by installing supplemental energy dissipation systems. In this paper, a new approach is explored for the mitigation of earthquake-induced vibrations by obstructing the entrance of seismic energy to the structure through the insertion of some concrete wave barriers within the soil domain. To do so, genetic algorithm (GA) based adaptive optimization methodology is utilized that is capable of finding the efficient layout of the concrete barriers in a manipulated soil zone around the structure. The optimization methodology is coupled with finite element (FE) method for analyzing the complex wave propagation phenomenon in the medium. To investigate the effect of frequency, three single-degree-of-freedom (SDOF) structures with the natural frequencies of 1, 2, and 3 Hz are subjected to the time history ground motions with the predominant frequencies up to 8 Hz. The optimization analyses are performed in the frequency domain, and the efficiency of the obtained solutions is examined by applying time history ground motions in the time domain. The results show that the performance of the buried wave barriers is a complex function of the wave barriers layout, natural frequency of the structure, and the frequency content of the loading. It is observed that some optimal layouts of limited volume can attenuate the elastic demands of the structures to the extent of 30–80%.

1. Introduction

Throughout the last decades, vibration control of important structures such as nuclear power plants, hospitals, and museums is of the highest interest in the community of structural control. In general, structural vibration can be controlled through various approaches. Among these approaches, implementing dampers within the structural frames [1] and exerting base isolators on the structure's foundation level have widely been used worldwide. Embedding wave barriers (WBs) into the ground by creating trenches is another way, which is primarily utilized to attenuate the noise caused by train-induced surface waves.

Based on the relative position of the barriers and the source of waves, embedding the WBs into the ground can be referred to either as an active or a passive control methodology [2]. If the barriers are installed close enough to the vibration source, it tends to be called active control; however, if the barriers are placed around the desired protecting zone, it is known as passive control [2]. The efficiency of the WBs in vibration reduction has been proved in various industrial projects including a printing plant in Berlin, in which the barriers mitigated the vertical amplitude of the ground surface displacement as much as 50% [2]. As another example, some sheet piles and trenches were utilized for controlling vibrations in an acceleration-sensitive laboratory [2]. Gao et al. [3] studied the effect of horizontal blocks in vibration reduction of machine foundation. They concluded that wave impedance blocks are more effective in vibration reduction at higher frequencies. Turan et al. [4] focused on the use of inclined micro-pile walls as active vibration barriers. They found that changing the inclination of the micro-piles is an influential factor for vibration reduction.

Higher impedance mismatch between the WBs and soil domain results in the change of wave-front direction and the amount of stress waves passing from the media. Considering this physical fact, different materials can be used for designing the efficient WB systems. The application of EPS geofoam that has an extremely low wave velocity and water-filled WBs were investigated by Ekanayake et al. [5]. They observed that EPS geofoam can significantly reduce the vibrations caused by Rayleigh waves. In another research, Zoccali et al. [6] explored the effects of the length and material properties of the filled trenches. They found that to obtain similar amount of velocity mitigation, it is required to tune the length of the trench with respect to the material properties.

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Thus, it can be seen that both geometry and material properties of the inhomogeneities have influenced the vibration reduction. Huang and Shi [7] studied the effects of periodic infinite piles on the vertical displacement amplitude of ground surface. It was concluded that based on the impedance mismatch between the soil and pile, there are different frequency ranges in which a significant amount of attenuation could be observed. In addition, initial stress could affect the frequency bands with higher amount of reduction in the displacement amplitude of the soil surface [8].

It should be mentioned that in all above-mentioned researches, the free-field behavior of the ground was considered and no attention was paid to the effect of the structure. Within this context, Cacciola et al. [9] used an independent structure with a pile foundation as a wave absorber for mitigating the vibration intensity in an adjacent target structure. In an earlier work, Warburton et al. [10] explored the effect of a second mass on the response of an excited mass rested on the surface of the elastic half space. Rovithis et al. [11] looked into the response of a structure–soil–pile model using three-dimensional (3D) finite element (FE) modeling under earthquake loads. They concluded that the reduction of the natural frequency of the system is achieved when a stiff structure is built on a loose soil. Furthermore, swaying–rocking stiffness of top of the pile has a significant role in changing the dynamic characteristics of the system due to the soil–structure interaction. There are also other researches, which have explored the efficacy of vibration barriers [12–15]. The idea of using wave barriers as a way to mitigate the seismic vibrations is almost new [16]. In this context, Lombardi et al. [17] and Flora et al. [18] proposed using thin soft grouted layer under the foundation. They found that higher impedance mismatch between the soil and grouted material, i.e. the lower stiffness of the grouted layer, lead to the more reduction of seismic demands. In another study, Miniaci et al. [19] utilized in-field metamaterial configurations in order to protect structures against the earthquake waves by applying the concept of phononic crystals and locally resonant structures. They concluded that the proposed system is capable of mitigating both bulk and surface waves with frequencies within the range of the frequency content of the most earthquake loadings.

In most of the aforementioned studies, the researchers have mainly focused on the use of barriers in the ground for vibration mitigation induced by surface waves generated by the passage of high-speed trains. Furthermore, they have performed parametric studies for finding the effective mechanical and geometrical properties of the controlling systems. However, due to the complex nature of the problem and interdependency of the various parameters, it is required to develop a robust methodology for designing WBs. The major purpose of this paper is to develop a vibration mitigation method by optimal insertion of concrete WBs in the soil domain around the structure considering the body waves generated by an earthquake event as the major source of excitation. In this context, the soil medium in the vicinity of the structure and the inserted WBs are treated as a large-scale composite material. In fact, the soil medium behaves as an elastic matrix, with the constant material damping, in which the WBs are buried as the sources of inhomogeneity. Due to the lack of gradient information, a heuristic adaptive optimization methodology is adopted for optimal design of the WBs. This approach is based on genetic algorithm (GA) method and is coupled to a FE solver for analyzing the wave propagation response of the medium. It should be pointed out that this study should be regarded as a preliminary evaluation for finding the optimal spatial distribution of the wave barriers for mitigating the effects of seismic waves and further studies are needed to be conducted by considering soil nonlinearity.

2. Problem definition

One of the major objectives of the vibration control of the structures is mitigating the elastic demands. Elastic demands of a structure can be defined by calculating the structure's drift. In this paper, three different structures with the height of 10 m and the natural frequencies of 1, 2, and 3 Hz are placed on the top of a horizontally infinite soil layer. These structures are selected to represent the medium to very stiff structures. To consider soil-structure interaction effect, a SDOF, as utilized in many of the previous papers [20–24], is used.

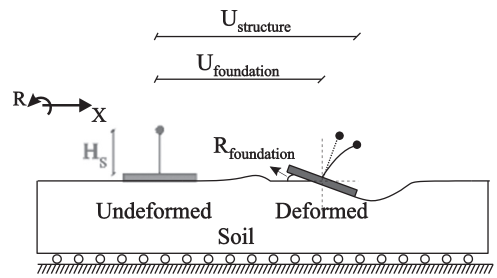

Fig. 1. Deformed shape of foundation and structure under bedrock motion.

According to Fig. 1 the drift of a SDOF can be defined as:

$$Drift \quad (\%) = 100\left(\frac{U_{\text{structre}} - U_{\text{foundation}} + H_S R_{\text{foundation}}}{H_S}\right) \tag{1}$$

where H_S is the height of the SDOF structure, U_{structre} and $U_{\text{foundation}}$ are the horizontal displacement of the structure's tip and foundation, respectively. $R_{\text{foundation}}$ is the rotation of the foundation.

Consequently, by applying the acceleration records of an earthquake at the base of the soil layer, reaction forces and the demands of the structure can be calculated during the earthquake phenomenon. In order to mitigate the structure's drift shown in Fig. 1, it is assumed that some parts of a specific domain of the finite soil medium, which is called manipulated zone (Fig. 2), can be replaced by concrete WBs. Concrete is used for the barriers materials due to two major reasons. Firstly, concrete provides a significant amount of impedance mismatch as the waves enter the WBs from the soil or vice versa. Secondly, it is practical to insert some concrete WBs in the soil domain using jet grouting techniques [25].

The wave propagation phenomenon in a soil matrix containing haphazardly distributed concrete WBs is quite complex and it is required to position the WBs appropriately within the domain in order to prevent the seismic waves from reaching the structure. The results show that if the WBs are not well situated, it is highly possible to get higher elastic demands, even if some stiffer materials are inserted in the soil. Thus, it is needed to develop a robust procedure for finding the optimal position of the WBs within the manipulated zone. To tackle this issue, an appropriate optimization methodology should be utilized, which suits the nature of the problem. The analyses are performed in the frequency domain and the efficiency of the WBs is examined under the real earthquake loadings in the time domain. The theory of the study and the details of the coupled GA-FE methodology are explained comprehensively in the subsequent sections.

3. Finite element modeling

In this paper, the propagation of waves through the manipulated zone is investigated using FE analysis, which is performed using ABAQUS [26] commercial software. Fig. 2 shows different parts of the model developed using ABAQUS software. The finite element model is comprised of four parts: soil medium, a strip foundation, a SDOF structure and the free-field boundaries. It is assumed that the infinite (in the horizontal direction) soil medium has the depth of 50 m and the strip foundation has the width and height of 10 m and 1 m, respectively. Owing to the assumption that the thickness of the model is large in the out-of-plane direction (i.e. $\varepsilon_{yy} = 0$), four-node plane strain elements with reduced integration (element CPE4R from ABAQUS element library) is used for modeling the soil medium and the strip foundation.