



Seismic isolation foundations with effective attenuation zones



Zhifei Shi*, Zhibao Cheng, Hongjun Xiang

School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, PR China

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ABSTRACT

In this paper, a new configuration of seismic isolation foundation containing several concrete layers and some rubber blocks is proposed. The concrete layers and the rubber blocks are placed periodically to form a periodic foundation. To study the isolation ability of this new configuration of periodic foundation, an equivalent analytical model is established. For practical applications, two very useful formulas are obtained. Using these formulas, the low bound frequency and the width of the first attenuation zone can be directly approximated without the calculation of dispersion structure. This new configuration of seismic isolation foundation enjoys the first attenuation zone between 2.15 Hz and 15.01 Hz, which means that the components of seismic waves with frequencies from 2.15 Hz to 15.01 Hz cannot propagate upward in the foundation. To illustrate the efficiency of this seismic isolation foundation, the seismic responses of a 6-story frame with three different foundations are simulated. Numerical simulations show that the seismic responses of the structure with the periodic foundation are greatly attenuated as compared with those of the structure with no isolation base or with traditional rubber bearings.

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1. Introduction

Base isolation is an effective way to improve structural seismic response and reduce damages that may be caused by earthquakes. In the past several decades, a number of important achievements relating to base isolation have been achieved. Kelly conducted theoretical and experimental work with fiber-reinforced bearings as elastomeric isolators aimed at addressing the shortcomings of conventional isolators [1]. Tsai and Kelly analyzed the buckling load of isolators by solving a cubic equation established using beam theory [2]. Jangid and Datta studied the response of a torsionally coupled base isolated building for two-component random ground motions [3,4]. Kikuchi et al. [5] and Yamamoto et al. [6] studied the response of yielding in seismically isolated structures suggesting that ductility in a seismically isolated structure should be limited contrary to current seismic design philosophies. Warn and his co-workers conducted both experimental and numerical investigations on the critical load capacities of elastomeric and lead-rubber seismic isolation bearings [7,8]. In addition, Warn and Whittaker also investigated the influence of vertical earthquake excitation on the response of a bridge isolated with low-damping rubber and lead-rubber bearings through earthquake simulation testing [9].

By developing the resettable variable stiffness damper and the variable friction damper as well as the leverage-type stiffness controllable damper, Lu et al. studied the performances of the semi-active isolation systems equipped with different dampers [10–12]. The simulated results demonstrated that the sliding isolation system equipped with the resettable variable stiffness damper was able to attenuate the low-frequency resonance behavior of the seismic isolation system induced by long-period ground motions [10]. In order to overcome the limitation of the traditional friction pendulum isolators, Krishnamoorthy developed a variable curvature pendulum isolator and a variable friction pendulum isolator, and studied the effectiveness of these isolation systems through a three-span continuous bridge [13,14]. Replacing the conventional columns by seismic isolation columns, Ribakov and his co-workers developed a hybrid seismic isolation system for protection of structures against near fault earthquakes [15–17]. In order to limit the displacements in the isolating columns, variable friction dampers were added. By mixing shredded rubber tire particles with soil materials and placing the mixtures around building foundations, Tsang et al. proposed a potential seismic isolation method for the protection of low-to-medium-rise buildings [18,19]. Considering the dynamic interaction between soil and structure, Spyarakos et al. investigated the seismic responses of base-isolated structures by formulating the equations of motion in the frequency domain and assuming frequency-independent soil stiffness and damping constants [20,21]. Based on nonlinear regression analysis, Ryan et al. developed the equations to estimate the lateral force distribution in the superstructure and

* Corresponding author. Tel.: +86 10 51688367.
E-mail address: zfshi178@bjtu.edu.cn (Z. Shi).

evaluated an alternative normalized strength characterization against the equivalent linear characterization [22–24]. Their works for evaluation include the ability to effectively account for variations in ground motion intensity and the ability to effectively describe the energy dissipation capacity of the isolation system [24].

Aforementioned seismic isolation systems include elastomeric bearings, frictional/sliding bearings, roller bearings and so on. The mechanisms of these traditional base isolation systems can be ascribed to two points. One is to shift the fundamental frequency of a structure away from the dominant frequencies of earthquake ground motion and fundamental frequency of the fixed base superstructure. Another is to add some preliminary elements to undergo energy dissipation. Different from the above traditional base isolation methods, the method discussed in the present paper is the so-called periodic foundations which are studied in the frequency domain. Periodic foundations have a special dynamic property, named attenuation zones in which waves/vibrations are blocked. It is hoped that the frequency attenuation zone can cover the main frequency region of the seismic vibration and the characteristic frequency of the superstructure. Therefore, it can reduce the seismic energy input and decrease the seismic response of superstructure. Both numerical and experimental investigations show that periodic structures made of common construction materials can greatly reduce the responses of isolated structures [25–30].

The content of this paper is organized as follows. In Section 2, the background as well as the aims and the scope of this paper are presented. The governing equation for shear waves in an infinite layered periodic structure is given in Section 3. The dispersion equation is obtained and two very useful formulas to approximate the low bound frequency and the width of the first attenuation zone are found. A new configuration of layered periodic structures containing several concrete layers and some rubber blocks is proposed and the analytical model is established in Section 4. In Section 5, the seismic responses of a 6-story frame with three different foundations are simulated in order to illustrate the efficiency of this isolation foundation. The present numerical simulations show that the periodic foundation can greatly attenuate the seismic responses of the structure compared with the one with traditional rubber bearings, which indicates that the new configuration of layered periodic structures has a bright future in engineering applications. In addition, detailed discussions about the advantages and disadvantages of the proposed configuration are presented at the end of Section 5. Finally, some conclusions are given in Section 6.

2. Aims and scope

Recently, investigations in the field of solid-state physics have shown that phononic crystals, one kind of periodic materials or periodic structures, enjoy bands of frequency gaps. If the excitation frequencies fall within the range of the gaps, waves cannot propagate in or through the material. This kind of periodic materials has found wide applications in engineering such as frequency filter, noise control, structure isolation, vibration attenuation and so on. Enlightened by the concept of frequency gap existing in phononic crystals, a novel isolation system called 'periodic foundation' was proposed to attenuate seismic waves [25]. Theoretically speaking, periodic foundations can prevent seismic waves coming from all directions if the foundations have periodicity in three dimensions. However, the present paper concentrates on the layered periodic foundations with periodicity only in the vertical direction.

Similar to the property of phononic crystal, different kinds of periodic foundations can be developed according to the periodicity of foundations. In our previous works, foundations with periodicity in

one dimension [26–28], two dimensions [25,29] and three dimensions [30] have been proposed and the feasibility study on seismic isolation of these foundations has been conducted. Different from phononic crystal structures considered in the solid-state-physics, the aforementioned periodic foundations are made of common construction materials such as concrete, rubber, steel and so on. In addition, the size of periodic foundations is much larger than that considered in the solid-state-physics.

Focused on the layered periodic foundation, previous investigations on the dynamic property of the attenuation zone were conducted. Based on the theoretical analysis and numerical simulation, Xiang et al. studied the feasibility of the layered periodic foundation composited of concrete layers and rubber layers [26]. In the work [27,28], a layered periodic foundation was fabricated and shake table tests were performed, in which great attenuations were found when the exciting frequencies fell into the band of frequency gaps.

Though it is demonstrated that layered periodic foundations can greatly reduce seismic responses of isolated structures, further investigations should be conducted to make periodic foundations more applicable in civil engineering. First, originated in the solid-state-physics, it is a hard work for civil engineers to understand the periodic theory, and it wastes a lot of time in determining the region of attenuation zones of periodic foundations. Hence, it is essential to find a simple formula to determine the first attenuation zone, which is one of the major aims of this paper. Given that earthquake is one kind of low-frequency broadband stochastic vibrations, periodic foundations should be designed with low and wide attenuation zones in order to effectively isolate the superstructure from the seismic energy. The second objective of this paper is to develop a new configuration of layered periodic structures in order to produce lower and wider attenuation zones. The present investigation shows that lower and wider attenuation zones could be obtained by replacing rubber layers in the layered periodic foundations [26–28] by rubber blocks. In addition, seismic records with the main frequency falling in the attenuation zones were chosen in our previous studies. In order to consider different site conditions, more seismic records are used to verify the efficiency of the new configuration of layered periodic structures proposed in the present paper.

3. Basic theory

3.1. Dispersion structure

An infinite layered periodic structure as shown in Fig. 1 is considered. Material A and material B are arranged alternatively to form this kind of periodic structure. Due to periodicity, a typical cell as shown in Fig. 1 can be drawn to study the property of this periodic structure. The thickness of every layer of material A and material B is denoted by h_A and h_B , respectively. Therefore, the thickness of the typical cell is $H = h_A + h_B$.

Let $u(z, t)$ be the component of displacement in the x direction. Under the assumption of continuous, isotropic, perfectly elastic and small deformation as well as without consideration of damping, the governing equation for shear wave (S_x) can be given as:

$$G \frac{\partial^2 u}{\partial z^2} = \rho \frac{\partial^2 u}{\partial t^2} \quad (1)$$

where G is the shear modulus and ρ is the mass density. The solution of Eq. (1) is assumed as:

$$u(z, t) = U(z)e^{i\omega t} \quad (2)$$

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