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Surface-wave attenuation zone of layered periodic structures and feasible application in ground vibration reduction

Jiankun Huang [a,*], Wen Liu [a], Zhifei Shi [b]

[a] Department of Civil Engineering, Beijing Forestry University, Beijing 100083, China
[b] School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China

HIGHLIGHTS

- A layered periodic wave barrier is proposed to reduce ground vibrations.
- The influence of material and geometrical parameters on the surface-wave attenuation zone are investigated.
- The link between the infinite periodic structure and a realistic finite case is discussed.
- The feasible application of layered periodic wave barriers is illustrated using 3D FEM.

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ABSTRACT

A layered periodic structure is proposed to construct a periodic wave barrier, which is defined by extended typical cells consisting of two different components. The periodic structure with reasonable design has attenuation zones (AZs) which can block wave propagation. The surface-wave dispersion curves and material/geometric parameters of layered periodic structures were investigated using finite element method. A typical three-dimensional simulation model was applied to verify the efficiency of the proposed periodic wave barrier in terms of ground vibration isolation. The results showed that simulated frequency zones of vibration reduction are consistent with the theoretical surface-wave AZs, and that periodic wave barriers can greatly reduce train-induced vibrations.

1. Introduction

Ground vibrations caused by mechanical operation, traffic load, pile driving, and blasting introduce serious problems to the adjacent structures. These ground vibrations also cause high-precision instruments to malfunction, and represent a source of continuous vexation to the occupants of said structures. Therefore, it is necessary to develop techniques for mitigating vibration propagation.

Vibration energy propagates in the half-space in the forms of body waves (P-waves and S-waves) and surface waves (R-waves). Surface waves, which propagate exclusively along the surface, attenuate with distance much slower than body waves. Constructing barriers between vibration sources and protected structures is useful for mitigating ground vibrations. These barriers can be divided into two categories: continuous barriers (e.g., open and in-filled trenches) and discontinuous barriers (e.g., pile barriers and rows of holes). Open and in-filled trenches are popular vibration reduction methods due to several advantages, including simplicity and cost-effectiveness.

A great deal of research has already been conducted on the screening effectiveness of wave barriers on ground vibration reduction. Woods [1] experimentally investigated the screening effectiveness of surface waves by open trenches. Celebi et al. [2] conducted a field experiment on wave propagation and vibration isolation by investigating different types of wave barriers, as well as the amplitude reduction factor as a function of excited frequencies for active and passive isolation. Sivakumar Babu et al. [3] conducted a field vibration test and performed a corresponding two-dimensional (2D) numerical analysis. Alzawi and El Naggar [4] carried out a full-scale experiment on open and GeoFoam filled trenches. From their research, the numerical results obtained by 2D finite element method (FEM) fit well with the full-scale experiment results.

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* Corresponding author.
E-mail addresses: jiankunhuang@yahoo.com (J. Huang), liuwen@bjfu.edu.cn (W. Liu), zfshi178@bjtu.edu.cn (Z. Shi).

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The boundary element method (BEM) and FEM are two highly effective numerical approaches for studying the performance of wave barriers. Based on 2D and three-dimensional (3D) BEM, Beskos et al. [5] and Dasgupta et al. [6] conducted non-dimensional parametric studies in a homogeneous half-space. Tsai and Chang [7] investigated the effect of trenches with sheet piles and diaphragm walls on both sides, and analyzed the screening effectiveness of these trenches with 2D BEM. El Naggar and Chehab [8] used 2D FEM to investigate the effectiveness of concrete, gas-cushion, and bentonite trenches for shock-producing equipment and further conducted parametric analyses on the soil layer depth, trench location, and embedment of the foundation. Saikia and Das [9] analyzed open trenches in screening steady-state surface vibrations by 2D FEM, and Celebi and Kırtel [10] applied a non-linear 2D finite element (FE) model to predict the screening performance of in-filled trenches in the reduction of train-induced ground vibrations. Zoccali et al. [11] used a 3D FE model to study the mutual influence between the trench length and in-filled material type, and found that the isolation effect is strongly influenced by the type of backfill material being used. Ju [12] explored three different approaches for reducing train-induced ground vibrations: open trenches, in-filled trenches, and ground improvement. Ju and Li [13] later studied the isolation effectiveness of trenches filled with water by using 3D FEM.

Periodic structures have a wave-forbidding feature – in other words, elastic waves with frequencies in particular frequency bands, which are called attenuation zones (AZs), cannot propagate in periodic structures. In recent years, several researchers have proposed various applications of periodic structures as novel materials and structures in the civil engineering field [14]. By utilizing the wave-forbidding feature, periodic structures can be extended to seismic isolation [15–17], vibration reduction [18–21], and noise control [22,23] applications. It is feasible to design a layered periodic structure for the use of its surface-wave attenuation zones (SWAZs) to isolate the dominant frequencies of vibrations. Djafari-Rouhani et al. [24] applied the Rayleigh wave theory to a layered periodic structure; dispersion curves for a Rayleigh wave on two media were obtained by Fourier analysis, which is also called the plane wave expansion (PWE) method. Hu et al. [25] computed the dispersion curves of surface waves for layered periodic structures with two materials. Meanwhile, the Rayleigh-Ritz variation method was applied to demonstrate the existence of SWAZs. Maznev and Every [26] calculated the dispersion curves of surface waves in a supported film with periodic mass loading at the surface by the use of PWE method, and found that AZ width is determined by particle motion ellipticity. On the basis of a laser-induced transient grating technique, Maznev [27] experimentally studied the surface modes of a periodic array of copper and SiO_2 lining on a silicon substrate. Westafer [28] investigated surface-wave dispersion curves in periodically patterned layered structures with FE analysis in COMSOL Multiphysics software. A post-processing method was proposed to rank the wave modes and the numerical results were consistent with experimental data in his study.

Based on the above review, research on trenches for vibration reduction appears to have mainly focused on open trenches and in-filled trenches. Previous researchers have also investigated open trenches with sheet piles and diaphragm walls [7]. “Pure” open trenches have better screening effectiveness than in-filled trenches, however, they are generally unstable past a certain depth. In-filled trenches, sheet piles, and diaphragm walls do not have the limitations of open trenches, accordingly.

Typically, backfill is comprised of only a single material such as concrete, GeoFoam, water, or bentonite. Previous research on periodic structures in civil engineering has been mostly focused on periodic pile barriers. The focus of the present study, conversely, is bulk-wave attenuation zones (BWAZs) [18,21]. Layered periodic structures, which have been used to tune beams and elastic waves in applied physics studies, have not yet been applied to ground vibration reduction. The surface wave is the main composition of wave energy in ground vibration, so the use of layered periodic structure SWAZs to mitigate ground vibrations is a scientific problem which merits further research.

In this study, the SWAZs of layered periodic structures with two different engineering materials were systematically investigated. First, we employed a post-processing method based on the FE technique to calculate the surface-wave dispersion curves of the layered periodic structures. Second, the SWAZs features were analyzed by varying the material and geometric parameters of the periodic structures. Third, a layered periodic structure was transformed into a periodic wave barrier and a typical 3D FE model was used to validate the effectiveness of the proposed periodic wave barrier in terms of ground vibration reduction. Finally, the conclusions of this study were presented based on these analyses.

2. Mathematical formulation

The geometry of the layered periodic structure studied in this paper is depicted in Fig. 1. The layered periodic structure consists of a series of typical cells (marked by dots in Fig. 1), which are infinitely extended in the x direction. Each typical cell includes two different materials, which are denoted by subscripts 1 and 2. The widths of the components and the total width of the typical cell are defined as a_1, a_2, and a, respectively. The width of the typical cell is also referred to as the periodic constant. The typical cells are completely invariant along the z direction, so a 2D plane strain problem was established to calculate the dispersion curves of the periodic structures. As indicated in Fig. 1, the free surface is perpendicular to the y direction and the surface wave propagates along the x direction.

2.1. Governing equation

Due to its advantageous periodicity, a typical cell is commonly used to analyze the dynamic characteristics of infinitely extended periodic structures. Both layers in the typical cell are assumed to be homogeneous, isotropic, and perfectly bonded at the interface. Ignoring the body force, the harmonic motion of a 2D plane strain typical cell can be drawn as follows [29]:

$$\frac{1}{\rho(\mathbf{r})}\left\{\frac{\partial}{\partial x_i}\left(\lambda(\mathbf{r})\frac{\partial u_j}{\partial x_j}\right)+\frac{\partial}{\partial x_j}\left[\mu(\mathbf{r})\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]\right\}=-\omega^2 u_i^2 \quad (i,j=x,y) \tag{1}$$

where u, ρ, λ, and μ are displacement, density, and two Lame’s constants of the mediums, respectively; $\mathbf{r}$ is the displacement vector and ω is the circular frequency. As mentioned above, the FE technique was employed to study the elastodynamic properties of the

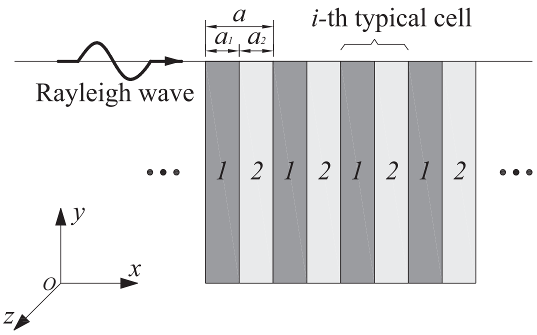

Fig. 1. Schematic diagram of a layered periodic structure.