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Attenuation zones of periodic pile barriers with initial stress

Xinnan Liu [a], Zhifei Shi [a,*], Hongjun Xiang [a], Y.L. Mo [b]

[a] School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, PR China
[b] Department of Civil and Environmental Engineering, University of Houston, Houston, TX 77004, USA

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ABSTRACT

Periodic pile barriers exhibit unique dynamic property, i.e., the frequency attenuation zones. When wave frequencies fall in the attenuation zones, the amplitude of the elastic waves could be reduced by the periodic pile barriers. In the present paper, out-of-plane waves propagating in two-dimensional periodic pile barriers are investigated. A novel numerical approach based on the weak form quadrature element method (WFQEM) is developed to study the effect of initial stress on the attenuation zones of the pile barriers. The proposed method is verified to be with significant advantages in both accuracy and convergence with regard to the lumped-mass method (LMM) in particular cases. The theoretical results show that the initial stress significantly alters the position and width of the attenuation zones, however, it does not affect the maximum attenuation coefficient. In addition, elastic waves propagating in periodic pile barriers with finite number of unit cells is simulated at the end of this paper. The results obtained in the present paper are very useful for the design and application of periodic pile barriers in ambient vibration reduction.

1. Introduction

Pile barriers have been commonly utilized to filter the ambient vibrations caused by urban traffic, construction blasting and heavy equipment [1–4]. Recently, studies in the solid-state physics show that waves in specific frequency ranges are unable to transmit through periodic structures, which consist of scatters periodically embedded in matrix. Based on the studies in the field of solid-state physics, Huang and Shi [5] introduced periodic pile barriers theory in the study of multi-row pile barriers. Periodic pile barriers are assumed to be formed by embedding piles with infinite-periodicity in soil. The periodic pile barriers exhibit unique property called frequency attenuation zones (AZs), i.e., frequency ranges within which the elastic waves are attenuated irrespective of the directions of their propagation in space [6,7]. Further, Huang and Shi [8] investigated the filtering effectiveness of periodic hollow pile barriers by the plane wave expansion method (PWE). Their investigations show that larger difference of material properties between the piles and soil is helpful for obtaining wider AZs.

On the other hand, the existence of initial stresses in piles/soil structures has long been known [9,10]. The initial stress can result from not only the pile penetration, but also soil reconsolidation after the installation of piles [11,12]. The importance of initial stress in interpreting the stress distribution in pile load test has been recognized [13]. However, the effect of initial stress on the dynamic behavior of periodic piles has not been examined. Recently, several investigations have been conducted to study the effect of initial stress on wave propagation in periodic structures. Using the transfer matrix method, Gei et al. [14,15] explored the AZs of 1D periodic beams with axial initial stress. Their investigations show that the AZs of periodic beams shift toward lower frequencies for compressive initial stress and toward higher frequencies for tensile initial stress, respectively. Feng and Liu [16] experimentally studied the dynamic properties of 1D finite periodic steel/epoxy and aluminum/epoxy rods with initial stress. The experimental results show that the isolation of longitudinal waves in the AZs becomes more obvious when the compressive initial stress increases. Recently, Zhou and Chen [17] investigated the effect of external electric field and initial stress on the AZs of 2D periodic locally resonant electroactive composites. Similar to the findings in 1D periodic beams, the results in [17] also show that the tensile initial stress shifts up the AZs while compressive initial stress shifts down the AZs. However, the aforementioned studies focus on the AZs at high frequency range from 400 to 2400 Hz, which do not reflect the dominant frequency contents (3–40 Hz) of ambient vibrations and strong ground motions [5]. Since the effect of initial stress on the dynamic behavior of periodic pile barriers has not yet been examined, a systematic investigation is needed.

Several methods have been used to study the AZs of periodic structures, such as the PWE [18–20], multiple scattering theory (MST) [21,22] and finite difference time domain method (FDTD)

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

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[23,24]. However, the PWE method encounters convergence problems when there is a large elastic difference between components of the periodic structures [25]. In addition, the PWE method fails in handling mixed solid-fluid systems. The MST can only handle specific arrays of spheres or cylinders with complicated deductions. The FDTD method requires a very strong reduction of the discrete time parameter in order to ensure the stability in the calculation involving large elastic difference. Given the disadvantages of the methods mentioned above, it is of significant importance to introduce new methods for the analysis of periodic pile barriers.

Fortunately, there are some methods such as lumped mass method (LMM) and finite element method (FEM) which overcome these difficulties. Wang et al. [26] firstly introduced the LMM to study the propagation of elastic waves in 2D periodic structures. Their study found that the convergence of LMM is insensitive to sharp variation of the elastic constants at the interfaces inside the periodic structures. Further, Wang et al. [27] improved the LMM to discretize the unit cell with arbitrary triangular lumped mass cells. Subsequently, using the improved LMM, Wen et al. [28] studied the directional behavior of wave propagation in 2D periodic plates. In addition, the FEM has been also extensively employed by a number of researchers to study periodic structures. Cheng et al. [29] investigated the AZs and the corresponding vibration modes of locally resonant periodic structures using FEM. Liu et al. [30] investigated the in-plane wave motion in 2D periodic chiral lattice and determined its effective dynamic mass and modulus by the commercial package ANSYS.

Meanwhile, in the field of computational mechanics, it has been shown that the quadrature element method (QEM), a numerical method based on the differential quadrature (DQ) technique and domain decomposition, is superior to the traditional FEM in terms of the efficiency and accuracy [31,32]. Additionally, different from the traditional finite element method, no shape functions and trial solutions are needed for the QEM. The QEM includes two distinct methods, namely the strong form QEM [31,33] based on the differential governing equations and the weak form QEM (WFQEM) [34–37] based on the energy principle. By combining the energy principle and QEM, the WFQEM works more powerfully.

In this paper, the WFQEM is incorporated into the Bloch analysis method, which leads to a new approach to study the AZs and the attenuation coefficient of periodic pile barriers for out-of-plane vibrations. The basic equations and solving method are given in Section 2. In Section 3, the efficiency and accuracy of the present method are validated with results available in literature. The effects of initial stress on the AZs and attenuation coefficient of the periodic pile barriers are studied in Section 4. Furthermore, elastic waves propagating in periodic pile barriers with a finite number of unit cells are simulated. Finally, some conclusions are given in Section 5.

2. Basic equations of out-of-plane waves propagating in periodic pile barriers

2.1. Configuration and simplification

Fig. 1 shows the cross section of periodic square pile barriers, where the black parts are concrete piles periodically embedded in soil. The piles in practical engineering are finite along the z direction. However, in some cases such as in the in-plane (x–y) mode and the out-of-plane (z) mode, the piles are assumed to be infinite by many researchers in order to simplify the analysis [4,38,39]. In the present paper, only the out-of-plane wave is considered. The z axis is assumed to be perpendicular to the cross section and the length of piles is assumed to be infinite. In addition, the number of periodic unit cells is also assumed to be infinite both in the x and y directions, so that the Bloch–Floquet theorem could be used. Furthermore, both the piles and soil are assumed to be isotropic and homogeneous. For simplicity, length-independent biaxial initial stress state $\sigma^0_{xx} = \sigma^0_{yy}$ is assumed in the periodic pile barriers. With these assumptions, wave propagation can be evaluated through the dynamic analysis of a typical unit cell by using the Bloch–Floquet theorem. The typical unit cell is shown in Fig. 1, where the side length of square piles is denoted as l, and the periodic constant is denoted as a.

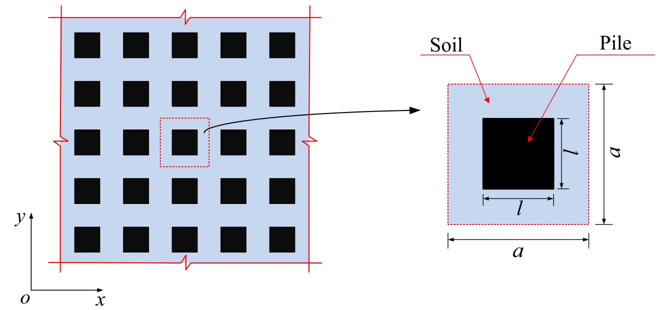

Fig. 1. Cross section of periodic pile barriers and a typical unit cell.

2.2. Governing equations

In the present paper, the waves propagating in the x–y plane are considered. The governing equations for the out-of-plane motion and the solving method are presented below.

First, the unit cell is divided into 3×3 subdomains as shown in Fig. 2(a). By employing Hamilton's principle and the WFQEM, the following dynamic equations of the unit cell can be obtained:

$$M\ddot{\mathbf{d}} + \left(\mathbf{K} + \mathbf{K}^0\right)\mathbf{d} = \mathbf{F}, \tag{1}$$

where $\mathbf{d}$, $\mathbf{F}$, $\mathbf{M}$, $\mathbf{K}$ and $\mathbf{K}^0$ are the nodal displacement vector, nodal load vector, assembled mass matrix, stiffness matrix and geometric stiffness matrix of the whole unit cell, respectively. The detailed derivation of the above governing equations is given in Appendix A.

2.3. Bloch analysis method

According to the location of the nodes within the unit cell as shown in Fig. 2(a), the nodal displacement vector $\mathbf{d}$ and the nodal load vector $\mathbf{F}$ can be rearranged as

$$\mathbf{d} = \begin{bmatrix} \mathbf{d}_i & \mathbf{d}_l & \mathbf{d}_b & \mathbf{d}_r & \mathbf{d}_t \end{bmatrix}^T, \quad \mathbf{F} = \begin{bmatrix} \mathbf{0} & \mathbf{F}_l & \mathbf{F}_b & \mathbf{F}_r & \mathbf{F}_t \end{bmatrix}^T, \tag{2}$$

where the subscripts i, l, b, r and t denote the nodes in the interior, and on the left, bottom, right and top boundaries of the unit cell, respectively.

A harmonic wave with an angular frequency ω and a Bloch wave vector $\mathbf{k} = k_x\mathbf{e}_x + k_y\mathbf{e}_y$ is considered. According to the Bloch–Floquet theorem [40], the boundary conditions satisfy the following equations:

$$\mathbf{d}_r = \mathrm{e}^{\mathrm{i}k_x a}\mathbf{d}_l\ , \quad \mathbf{d}_t = \mathrm{e}^{\mathrm{i}k_y a}\mathbf{d}_b,$$

$$\mathbf{F}_r = -\mathrm{e}^{\mathrm{i}k_x a}\mathbf{F}_l\ , \quad \mathbf{F}_t = -\mathrm{e}^{\mathrm{i}k_y a}\mathbf{F}_b. \tag{3}$$

Substituting Eqs. (2) and (3) into Eq. (1) yields a standard complex