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A wavenumber domain boundary element method model for the simulation of vibration isolation by periodic pile rows

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ABSTRACT

The wavenumber domain boundary element method (WDBEM) for the interaction between the half-space soil and periodic structures is important for the design of various periodic structures in civil engineering. In this study, a WDBEM model for the half-space soil and periodic pile rows is developed and used in the analysis of the vibration isolation via pile rows. To establish the model, the rigid-body-motion method for the estimation of the Cauchy type singular integrals involved in the WDBEM is established for the first time. In the proposed model, the half-space soil and periodic pile rows are treated as elastic media. Employing the spatial domain boundary integral equations for the half-space soil and pile rows as well as the sequence Fourier transform method, the wavenumber domain boundary integral equations for the soil and pile rows are derived. By using the obtained wavenumber domain boundary integral equations, WDBEM formulations for the half-space soil and periodic pile rows are established. Using the WDBEM formulations as well as the continuity conditions at the pile–soil interfaces, a coupled WDBEM model for the pile–soil system is derived. With the proposed WDBEM model, the influences of the pile length and the shear modulus of the half-space soil on the vibration isolation effect of pile rows are examined. Presented numerical results show that the isolation vibration effect of pile rows is enhanced considerably with increasing length of the piles. Besides, the isolation vibration effect of pile rows is weakened considerably with increasing shear modulus of the half-space soil. Moreover, as expected, multiple pile rows usually produce a better isolation vibration effect than a single pile row.

1. Introduction

Many civil engineering structures can be simplified as periodic structures, for example, railways, tunnels, foundations for long viaducts or bridges, pile breakwaters, piles for roadbeds, pile foundations for high buildings, pile rows used for vibration isolation etc. As a result, dynamic analysis of periodic structures embedded in soil is important for both the academic community and engineering practice. As periodic structures consist of very many identical units, CPU time as well as memory requirement for their analysis will increase tremendously with increasing number of units of the periodic structure. It is thus very difficult to use conventional numerical method, such as, the finite element method (FEM) and boundary element method (BEM) to simulate the interaction between periodic structures and soil. Consequently, few researches have been conducted about the interaction between soil and periodic structures by using common numerical methods so far. To circumvent the above difficulty, the wavenumber domain boundary element method (WDBEM) was proposed for analyzing the interaction between soil and periodic structures [1]. The primary advantage of the WDBEM is that it can reduce a periodic structure with infinite units to a representative unit (generic unit) of the structure, reducing the CPU time and memory requirement for the analysis of the structure substantially. It is noted that the WDBEM proposed in [1] has now been used in many researches concerning the interaction between the soil and periodic structure [2–4].

In this study, a WDBEM model for the half-space soil and periodic pile rows is developed and used in the analysis of the vibration isolation via pile rows. As piles can address high groundwater level and soil instability problems effectively, pile rows or sheet piles are used widely as discrete wave barrier systems. To date, many investigations concerning vibration isolation by piles have been carried out. For example, Aviles and Sanchez-Sesma [5] employed the wave scattering theory to investigate the wave scattering by a pile row or empty hole row for the longitudinal waves and transverse waves. Aviles and Sanchez-Sesma [6] also developed a theoretical model to examine the vibration isolation effect of a pile row when subjected to SV waves and Rayleigh

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waves. Kattis et al. [7,8] used the 3-D frequency domain boundary element method (BEM) to calculate the screening effectiveness of a pile row. Gao et al. [9] studied vibration isolation effect of piles by simplifying the incident waves as plane SH waves. Xu et al. [10] analyzed the vibration isolation effect of a single pile row exposed to plane P waves and plane SH waves using wave function expansion method. Cai et al. [11] investigated the vibration isolation effect of pile rows embedded in a poroelastic medium using the wave function expansion method and also a parametric study was conducted in their research. More recently, Tsai [12] examined the screening effectiveness of four types of circular piles in a row for the vibration caused by a massless square foundation subjected to a harmonic vertical load. Besides, by means of the fictitious pile method and the direct superposition method, Lu et al. [13,14] analyzed the vibration isolation effect of pile rows for a moving load.

It is noted that due to the restriction of the computer capacity, the aforementioned researches using the limited number of piles to investigate vibration isolation effects of pile rows. However, in engineering practice, usually, dozens or even hundreds of piles are used to isolate vibrations. Furthermore, the number of piles used to model pile rows has a significant influence on the effect of vibration isolation [15]. Thus, pile rows are considered to consist of infinite number of piles in this study and a WDBEM model is developed to investigate the vibration isolation effect of pile rows. Compared with previous researches concerning the WDBEM for periodic structures, the main contributions of this study are as follows. Firstly, the rigid-body-motion method for the estimation of the Cauchy type singular integral involved in the WDBEM is established for the first time. For the conventional boundary element method, various methods have been developed to evaluate the Cauchy singular integral and a comprehensive review about the methods is given in [16]. Roughly speaking, there are two methods which can be used to deal with the Cauchy singular integral arising in the boundary element method. The first method is the direct method, which evaluates the Cauchy singular integral directly by means of the analytical or numerical methods [17–19]. The second method is the indirect method, which addresses the Cauchy singular integral indirectly via the rigid-body-motion technique [20–22]. As the indirect method can avoid treating the Cauchy singular integral directly, it has been employed widely to estimate the Cauchy singular integral occurring in the boundary element method. However, for the WDBEM, the rigid-body-motion technique has not been reported in the literature so far. As the evaluation of the Cauchy type singular integral in the WDBEM is crucial for the implementation of the WDBEM, an important task of this study is to establish the rigid-body-motion method for the evaluation of the Cauchy type singular integral in the WDBEM. The second contribution of this study is that a WDBEM model for the analysis of the interaction between the half-space soil and a discrete periodic structure, namely, pile rows, is established for the first time. Note that previous researches about WDBEM model are mainly concerned with the continuous periodic structure.

The remainder of this paper is organized as follows. In Section 2, the definition for the sequence Fourier transform is introduced. In Section 3, wavenumber domain boundary element method for the half-space soil and periodic pile rows are developed. In Section 4, a coupled WDBEM model for the half-space soil and periodic pile rows is established. In Section 5, the treatment of the Cauchy-type singular integral occurring in the wavenumber domain boundary element method is discussed in detail. In Section 6, based on the proposed model, some numerical results and corresponding analysis are presented. Finally, based on the investigation of this paper, some conclusions are drawn in Section 7.

2. Definition for the sequence Fourier transform

As the wavenumber domain boundary element method in this study involves the sequence Fourier transform, the definition of the sequence Fourier transform will be introduced in this section. Since the pile rows considered here only shows periodicity in one direction, it is sufficient to introduce the definition for the one-dimensional sequence Fourier transform only. Note that the sequence Fourier transform in this study is referred to as the Fourier transform applied to a discrete sequence. It is worth stressing that the sequence Fourier transform is also referred to as the Floquet transform by some researchers [1–4], while it is named as the discrete-time Fourier transform in [23].

Supposing that the separation between two neighboring lattice points in a one-dimensional Bravais lattice is L [24], then, the one-dimensional position vector for the Bravais lattice is $\mathbf{R}=nL\mathbf{e}$, in which $\mathbf{e}$ is the base vector along the longitudinal direction of the lattices and n is an arbitrary integer number. The position vector for the corresponding reciprocal lattice is $\mathbf{G}=n(2\pi/L)\mathbf{e}$. Note that the volumes for the primitive cells of the one-dimensional Bravais lattice and its reciprocal lattice are L and $2\pi/L$, respectively. If $f(\mathbf{R})(f(nL))$ is a discrete spatial function defined on the aforementioned one-dimensional Bravais lattice, then the one-dimensional forward and inverse sequence Fourier transforms are defined as follows [23,25]:

$$\tilde{f}(\boldsymbol{\kappa})=\tilde{f}(\kappa)=\sum_{\mathbf{R}} f(\mathbf{R})e^{i\boldsymbol{\kappa}\cdot\mathbf{R}}=\sum_{n=-\infty}^{+\infty} f(nL)e^{in\kappa L},$$
$$f(\mathbf{R})=f(nL)=\frac{1}{V_b}\int_{V_b}\tilde{f}(\boldsymbol{\kappa})e^{-i\boldsymbol{\kappa}\cdot\mathbf{R}}\,d\boldsymbol{\kappa}=\frac{L}{2\pi}\int_{-\pi/L}^{\pi/L}\tilde{f}(\kappa)e^{-in\kappa L}\,d\kappa \quad (1)$$

in which the wavenumber $\boldsymbol{\kappa}=\kappa\mathbf{e}$. The convolution of two discrete spatial functions defined on the same one-dimensional Bravais lattice and its corresponding sequence Fourier transform are as follows [23]:

$$f*g=\sum_{n_r} f(n_rL)g[(n_q-n_r)L],$$
$$Ff*g=\sum_{n_q}\sum_{n_r} f(n_rL)g[(n_q-n_r)L]e^{in_q\kappa L}=\tilde{f}(\kappa)\tilde{g}(\kappa) \quad (2)$$

where the symbol F denote the sequence Fourier transform.

As this paper is concerned with the dynamic analysis of the pile rows in the frequency domain, the Fourier transform for the time is also involved. In this study, the Fourier transform for the time is defined as follows [25]:

$$\hat{f}(\omega)=\int_{-\infty}^{+\infty} f(t)e^{-i\omega t}\,dt,\quad f(t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\hat{f}(\omega)e^{i\omega t}\,d\omega \quad (3)$$

in which ω and t represent the angular frequency and time, respectively, the variable with a caret denotes the frequency domain variable, while the variable without a caret represents the time domain variable. Note that as this study is restricted to the frequency domain analysis of the pile rows, for brevity, the caret denoting the frequency domain variable will be dropped for all forthcoming frequency domain variables.

Using Eq. (1), it is straightforward to derive the sequence Fourier transform for the sequence $f[(n+m)L]$, where m is an arbitrary integer

$$Ff[(n+m)L]=\tilde{f}_m(\boldsymbol{\kappa})=\sum_{n=-\infty}^{+\infty} f[(n+m)L]e^{in\kappa L}=e^{-im\kappa L}\tilde{f}(\kappa) \quad (4)$$

in which the subscript m denotes the mth lattice centered sequence Fourier transform. Eq. (4) suggests that the phase difference between the 0th lattice centered sequence Fourier transform $\tilde{f}(\kappa)$ and the mth lattice centered sequence Fourier transform $\tilde{f}_m(\boldsymbol{\kappa})$ is $e^{-im\kappa L}$. If combining the phase difference $e^{-im\kappa L}$ with the time factor $e^{i\omega t}$ of the Fourier transform in Eq. (3), it