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Research Paper

Vibration isolation of row of piles embedded in transverse isotropic multi-layered soils

Zhi Yong Ai*, Zheng Cao

Department of Geotechnical Engineering, Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, China

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ABSTRACT

The analytical layer-element method is used to solve the transverse isotropic multi-layered soils, and the finite element method is used for the piles. Considering the displacement coordination and the equilibrium of the contact force along the pile-soil contact face, the dynamic response equations of the single row of piles under an external circular time-harmonic surface vertical load are achieved. Then, the displacements at the observation point with and without the effect of piles are obtained, respectively. The influences of the soils' transverse isotropy, stratification characteristics and pile spacing on the isolation effect of the single row of piles are investigated.

1. Introduction

The ground vibration caused by the machines, traffic or blasting can do damage to the constructions and structures nearby. Meanwhile it has a bad impact on the people's physical and mental health. Hence, it's of great importance to take measures to reduce the effect of the vibration. Trenches (open or in filled) and rows of piles are the most common methods to protect the structures from the ground vibration in the current engineering practice. Rows of piles are used more widely as the vibration isolation barrier than trenches because of the lower cost and the less disturbance to the soils. Many researchers have studied rows of piles as the vibration isolation barrier with different experimental and theoretical methods. Wood et al. [1] used the holographic technology to study the rows of piles as the vibration isolation barrier through the experimental method. Hasegawa et al. [2] investigated the isolation effect of rows of hollow piles on viaduct bridges with the theoretical and experimental methods. Both Liao and Sangrey [3] and Haupt [4] used the model test to research on the vibration isolation of rows of piles. Avlies and Sanchez-Sesma [5] investigated the vibration isolation effect of the single row of piles subjected to different waves on basis of the wave theory. Boroomand and Kaynia [6,7] used the semi-analytical numerical method to study the vibration isolation effect of rows of piles subjected to Rayleigh wave. Kattis et al. [8] applied the 3D boundary element method (BEM) to research on the vibration isolation effect of rows of concrete piles. To reduce calculation difficulty of the 3D BEM, Kattis et al. [9] made the rows of piles equivalent to the trenches due to mechanics of composite materials. Tsai et al. [10] investigated the vibration isolation effect of rows of piles under the rectangle vertical load with the 3D BEM. Gao et al. [11] studied the ground vibration isolation efficiency of multi-row piles as the barrier embedded in a 3D model of soils with the half-space Green's function. Avoiding the discretization of the entire calculation domain, Xu et al. [12] provided a semi-analytical model to study the vibration isolation effect of rows of piles in the saturated soils. Lu et al. [13] considered the impact of the moving load and studied the effect of the row of piles as barriers on soils.

The natural soils usually have different physical and mechanical properties in horizontal and vertical directions, which can be assumed to be a transverse isotropic model. However, the researches mentioned above seldom took it into account. Therefore, it's necessary to think about the influence of the soil's transverse isotropy on the vibration isolation.

This paper tries to provide a practical and efficient method to study the vibration isolation effect of the single row of piles embedded in the transverse isotropic multi-layered soils under an external circular time-harmonic surface vertical load. The key step for analyzing the vibration isolation effect of the row of piles is to solve the dynamic response solutions for the row of piles. There exist many research findings about the dynamic soil-structure interaction [14–25] which lays a solid foundation for this topic. The paper presents a new coupling method of analytical layer-element and finite element to study the dynamic pile-structure interaction. Specifically, this method utilizes the analytical layer-element solution [26] for the transverse isotropic multi-layered soils subjected to a circular time-harmonic vertical load as the fundamental solution, which costs low computing time and has an advantage on numerical stability owing to the analytical layer-element method (ALEM) only depending on material parameters and negative

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* Corresponding author at: Department of Geotechnical Engineering, Tongji University, 1239 Siping Road, Shanghai 20092, China.
E-mail address: zhiyongai@tongji.edu.cn (Z.Y. Ai).

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Notation

superscript — variables in the Hankel transform domain

$\bar{u}_r, \bar{u}_z$	displacements of soils in the r and z directions, respectively
$\bar{\tau}_{zr}, \bar{\sigma}_z$	radial shear stress and vertical normal stress of soils, respectively
ξ	Hankel transform parameter
$\bar{\mathbf{U}}(\xi,z)$	displacement vector at the depth of z, defined as $\bar{\mathbf{U}}(\xi,z) = [\bar{u}_r,\bar{u}_z]^{\mathrm{T}}$
$\bar{\mathbf{T}}(\xi,z)$	stress vector at the depth of z, defined as $\bar{\mathbf{T}}(\xi,z) = [\bar{\tau}_{zr},\bar{\sigma}_z]^{\mathrm{T}}$
$P_0(r,H_i)e^{i\omega t}$	circular time-harmonic uniform load applied at $z = H_i$
P_0, ω, R	amplitude, frequency and radius of load, respectively
$J_m()$	Bessel function of the first kind for the m th order
$\bar{\mathbf{F}}(\xi,H_i)$	load vector when $z = H_i$, defined as $\bar{\mathbf{F}}(\xi,H_i) = \left[0, \frac{P_0 \cdot R \cdot J_1(\xi R)}{\xi}\right]^{\mathrm{T}}$
$\mathbf{K}, \mathbf{K}_1$	stiffness matrices for a single layer and a half space, respectively
H_i, H_{i-1}	depths from surface to bottom and top of the i th layer, respectively
ΔH_i	thickness of the i th layer defined as $\Delta H_i = H_i - H_{i-1}$
G_{svj}, ρ_{sj}	shear modulus and mass density of the j th soil layer, respectively
E_{svj}, E_{shj}	vertical and horizontal Young's modulus of the j th soil layer, respectively
μ_{svj}, μ_{shj}	Poisson's ratio of the j th soil layer characterizing the lateral strain response in the plane of transverse isotropy to a stress acting normal and parallel to it, respectively
d, L, s	diameter, length and spacing of piles, respectively
b	distance from excitation to row of piles
E_p, ρ_p	Young's modulus and mass density of piles, respectively
D_t, W_t, L_t	length, width and depth of in-filled trench, respectively
u^t_{spj}	displacement of the t th pile on the j th pile-soil node
F^o_{si}	vertical traction of the o th pile on the i th pile-soil node
F^o_{pi}	vertical nodal force of the o th pile on the i th pile-soil node
F^o_{top}	vertical external force applied on top of the o th pile
A^t_{j1}	flexibility coefficient representing displacement of the t th pile on the j th pile-soil node produced by unit external load
B^{to}_{ji}	flexibility coefficient representing displacement of the t th pile on the j th pile-soil node produced by vertical unit traction of the o th pile on the i th pile-soil node
$\mathbf{U}_{sp}$	vector of vertical pile-soil nodal displacements
$\mathbf{F}_s$	vector of vertical tractions from the pile-soil interaction
$\mathbf{F}_p$	vector of vertical nodal forces for row of piles
$\mathbf{F}_{top}$	vector of vertical external force applied on top of piles
$\mathbf{A}, \mathbf{B}, \mathbf{E}$	flexibility matrices of soils subjected to an circular time-harmonic vertical load, respectively
$\mathbf{K}, \mathbf{M}$	global stiffness and mass matrices of row of piles, respectively
$\mathbf{K}_p, \mathbf{M}_p$	global stiffness and mass matrices of single pile
$\mathbf{C}$	vector that transforms nodal vertical traction to equivalent vertical nodal forces between row of piles and soils
$\mathbf{C}_p$	vector that transforms nodal vertical traction to equivalent vertical nodal forces between single pile and soils
A_p	area of piles defined as $A_p = \pi d^2/4$
ΔL	length of pile element
$u_A(x,y,0)$	amplitude of observation point A before vibration isolation
$u_{AF}(x,y,0)$	amplitude of observation point A after vibration isolation
A_{rv}	average amplitude reduction ratio on whole viewing zone
A_r	amplitude reduction ratio of viewing point
ξ_s	damping ratio of soils
ω^*	dimensionless frequency defined as $\omega^* = 0.5d\omega\sqrt{\rho_v/G_v}$
f^*_{soi}	dimensionless vertical pile-soil traction of the o th pile on the i th pile-soil node defined as $f^*_{soi} = F^o_{si}/P_0$
f^*_{poi}	dimensionless vertical nodal force of the o th pile on the i th pile-soil node defined as $f^*_{poi} = F^o_{pi}/P_0$
E^*	pile-soil modulus ratio defined as $E^* = E_p/E_{sv}$
ρ^*_i	pile-soil mass density ratio defined as $\rho^*_i = \rho_p/\rho_{si}$
β_{1i}, β_{2i}	dimensionless transverse isotropic parameters defined as $\beta_{1i} = E_{shi}/E_{svi}$ and $\beta_{2i} = G_{svi}/E_{svi}$, respectively
d^*, L^*, s^*, b^*	diameter, length, pile spacing and source distance ratio defined as $d^* = d/\lambda_R$, $L^* = L/\lambda_R$, $s^* = s/\lambda_R$, $b^* = b/\lambda_R$, respectively
λ_R	calculated length of Rayleigh wave for the first layer soil

exponential. Since the length-diameter ratio of pile is usually far more than 1 in engineering practice and the pile can be considered as a 1D rod. Hence, the paper neglects the influence of the radial deformation to simplify the establishment of model by referring to the reasonable assumption of Butterfield and Banerjee [27]. According to 1D FEM, we can set up a dynamic model of a single row of piles in the transverse isotropic multi-layered soils. It is worth mentioning that this paper models the piles using Euler-Bernoulli beam element [28,29] with the FEM, and only considers the vertical load. In fact, the element can be considered as, in essence, 3-node rod element, which has a high precision. By coupling the ALEM for the soils and the FEM for the piles, the dynamic model of the single row of piles embedded in transverse isotropic multi-layered soils subjected to the external load outside the piles is established by considering the displacement coordination condition and the equilibrium of the contact force along the pile-soil contact face. Thus, the displacements at the observation point induced by the vibration of the single row of piles and external loads outside the piles are achieved through solving the dynamic model. Finally, the accuracy and efficiency of the presented method are examined through the comparison with the existing solutions, and the influences of the soils' transverse isotropy, stratification characteristics and pile spacing on the vibration isolation of the row of piles are studied.

2. Analytical layer-element solutions for the soil model

In order to make the method in the paper easy to understand, the derivation of the global stiffness matrix of the transverse isotropic multi-layered soils subjected to an external circular time-harmonic vertical load is showed briefly referring to the work of Ai et al. [26]. Taking the inverse of the stiffness matrix, we can easily achieve the flexibility matrix required by the method in Section 3.

2.1. Establishment of a single analytical layer element

Firstly, to obtain the single analytical layer element of the transverse isotropic soils, we establish the relationship between the stresses and displacements for a single layer of soils in Fig. 1, where $\bar{u}_r$ and $\bar{u}_z$ are the displacements of soils in directions r and z, respectively; $\bar{\tau}_{zr}$ and $\bar{\sigma}_z$ are the radial shear stress and vertical normal stress, respectively; ξ is

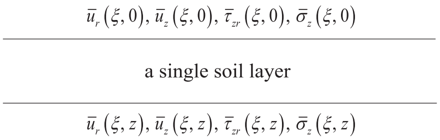

Fig. 1. Stresses and displacements for a single soil layer in the Hankel transform domain.

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