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Structural vibration isolation by rows of piles

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Abstract

Three-dimensional passive structural vibration isolation by rows of piles is studied numerically by the frequency domain boundary element method. The source of soil vibration is assumed to be a vertical force harmonically varying with time. The piles and the soil material behaviour are assumed to be linear elastic or viscoelastic. Coupling between the soil and piles is accomplished through equilibrium and compatibility at their interfaces. Both continuous and discontinuous quadratic quadrilateral elements are employed and advanced direct numerical integration schemes are used for the treatment of the various singular integrals. The full-space dynamic fundamental solution is used and this requires a discretization of not only the substructure interfaces but also a finite portion of the free soil surface around the vibration isolation system. Symmetry and antisymmetry considerations reduce the complexity of the problem considerably. The above methodology is tested for accuracy by solving a problem of active vibration isolation by trenches for which there exist numerical solutions and then applied to the problem of structural vibration isolation by rows of piles and compared with an existing approximate analytical solution.

Introduction

In many situations it is necessary to reduce the level of ground-transmitted vibrations generated by machine foundations, traffic or explosions in order to protect nearby structures. One way of protecting these strucrures is by means of wave barriers isolating them from the source of the disturbance actively or passively (Richart et al. [1]).

Traditionally, the solution to the problem is to introduce an open or infilled trench between the source and the structure. However, for long

Rayleigh wavelengths, the trench depth required is very large and practical construction difficulties arise particularly in very soft ground and high water table level locations. Another option is to employ rows of piles as barriers, which are not limited in terms of depth.

Among the various existing works (experimental and numerical) on vibration isolation by trenches one can mention those of Woods [2], Haupt [3], Segol et al. [4], Beskos et al. [5 - 7], Banerjee et al. [8] and Klein et al. [9].

The use of piles as wave barriers was proposed, without any study, by Richart et al [1]. Subsequently, Woods et al. [10] and Liao and Sangrey [11] investigated the problem experimentally. Aviles and Sanchez-Sesma [12, 13] studied analytically the scattering problem by a row of infinitely long rigid piles in an elastic medium under various type of incident waves. Boroomand and Kaynia [14] proposed an approximate analytical model for studying the screening effectiveness of rigid and elastic piles in the half-space.

Here the structural vibration isolation by rows of piles is studied numerically on the basis of a realistic model by the frequency domain boundary element method (BEM). This method is characterized by its two main advantages, namely the reduction of the spatial dimensions of the problem by one and the high accuracy of the results, especially when the domain of interest is infinite or semi-infinite. Comprehensive reviews on the BEM as applied to elastodynamic problems can be found in Beskos [15, 16], Manolis and Beskos[17] and Dominguez [18]. The present BEM employs quadratic quadrilateral isoparametric elements (continuous and discontinuous), advanced techniques for the direct numerical integration of singular integrals, substructure techniques, geometric symmetry and load decomposition capabilities. The method is first verified by solving an active vibration isolation by trenches problem and then employed for the analysis of vibration isolation by rows of piles.

3-D BEM formulation

It is well known that the displacement u_j of an elastic body with volume V and surface S under zero body forces and initial conditions satisfying the frequency domain equations of motion admit an integral representation of the form [17]

$$c(\mathbf{x})u_j(\mathbf{x},\omega) = -\int_S u_i(\mathbf{y},\omega)T_{ji}(\mathbf{x},\mathbf{y},\omega)dS(\mathbf{y}) + \int_S t_i(\mathbf{y},\omega)U_{ji}(\mathbf{x},\mathbf{y},\omega)dS(\mathbf{y}) \tag{1}$$

where $\mathbf{x} \in$ V or S and $\mathbf{y} \in$ S are the field and source points respectively, $c(\mathbf{x})$ = 1 if $\mathbf{x} \in$ V, $c(\mathbf{x}) = 0.5$ if $\mathbf{x} \in$ S and $c(\mathbf{x}) = 0$ if $\mathbf{x} \notin$ V and S and U_{ij}, T_{ij} are the

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well known singular influence tensors (dynamic fundamental solution) for the infinite space.

Equation (1) with c(**x**) = 0.5 represents a boundary integral expression from which, after discretization of the boundary S into boundary elements, a numerical solution can be derived. Equation (1) can thus be reduced in its discretized form to the matrix equation

$$[\mathbf{H}]\{\mathbf{u}\} = [\mathbf{G}]\{\mathbf{t}\} \tag{2}$$

where $\{\mathbf{u}\}$ and $\{\mathbf{t}\}$ are the displacement and traction vectors, respectively, in the frequency domain and **[H]** and **[G]** are square influence matrices consisting of elemental surface integrals with integrands containing the tensors T_{ij} and U_{ij}, respectively. When $\mathbf{x} \neq \mathbf{y}$, these integrals are regular and integration is accomplished by using standard Gauss quadrature. When $\mathbf{x} \equiv \mathbf{y}$, these integrals become singular due to the O(1/r) and O(1/r^2) singularities of the tensors U_{ij} and T_{ij}, respectively, and they have to be computed in a special way.

In case one has to study the dynamic behaviour of a system of interconnected elastic bodies, he can employ equation (2) for every body and then combine them through equilibrium and compatibility at their interfaces. The above formulation assumes linear elastic material behaviour. However, it is also valid for linear viscoelastic material behaviour provided that the elastic moduli are replaced by their complex counterparts λ' and μ'

$$\lambda' = \lambda(1 + i2\beta) \quad , \quad \mu' = \mu(1 + i2\beta) \tag{3}$$

where the damping factor β is usually taken to be independent of frequency (hysteretic material).

In the following, the general structure and the main components of a general 3-D frequency domain BEM code developed by the authors [19] and used in this work is briefly described. This code is designed for solving elastodynamic problems involving : i) elastic and viscoelastic material behavior, ii) external harmonic loads and plane harmonic waves and iii) finite and infinite bodies (alone or being parts of a multibody system). The quantities that can be evaluated are the displacements, the tractions and the stresses on the boundary and the displacements and the stresses in the interior, in a pointwise fashion.

More specifically the program consists of the following main components :

- Input of model characteristics (geometry, boundary conditions, etc).
- Automatic generation of modeling details (selection of continuous or discontinuous elements, reconstruction of the input mesh, etc.).
- Construction of influence matrices by a collocation scheme and performance of numerical integrations (regular and singular integrals)

- Construction of total system equations by assembling subregion influence matrices and employing boundary conditions.
- Solution of the total system equations for boundary displacements and tractions.
- Calculation of stresses on the boundary.
- Calculation of interior domain quantities.

Special features of program are mainly :

- the treatment of corners, edges, interfaces and discontinuities in the boundary conditions, using both continuous, discontinuous and partially discontinuous elements [20], in order to combine the advantages of all types of elements.
- the accurate computation of singular and hypersingular integrals using an accurate and efficient direct method [21].
- the use of geometric symmerty properties and decomposition of loads into a sum of symmetric and antisymmetric load cases [22], reducing the size of the problem.
- the use of an out-of-core complex solver for the large matrices appearing in BEM [23].

Code verification

The accuracy and the effectiveness of the presviously described BEM formulation and implemantion is tested in this section by solving a problem of active vibration isolation by trenches. This problem was analysed using direct BEM by Beskos et al. [7], Banerjee et al. [8] and Klein et al. [9]. The difference between these works is in the type of the elements, the extension of the discretized area and the treatment of singular element.

The isolation system consists of a rigid, massless, square foundation of side $w = 0.2\ L_R$, surrounded by a rectangular open trench of depth $t = 0.5\ L_R$ and width $b = 0.06\ L_R$. The distance from the center of foundation to the centerline of trench is $r = 0.4\ L_R$. In the above, L_R is the Rayleigh wave length. The soil properties are shear modulus $G = 132\ MN / m^2$, Poisson's ratio $\nu = 0.25$, mass density $\rho = 17.5\ kN / m^3$ and hysteretic damping $2\beta = 6\%$. The magnitude of the applied force on the foundation is $P_o = 1$ kN and the excitation frequency $\omega = 50$ Hz.

Due to the quadrant symmetry of the problem, only one quarter of the area needs discretization, as shown in Figure 1. The side of the square area of discretized soil is 19 m.

Figure 2 presents the contour diagram of amplitude reduction factor (ARF) as obtained by Beskos et al. [7], Banerjee et al. [8] and the present method. The (ARF) is defined as the ratio of the vertical displacement amplitude in the presence of the trench to the vertical displacement amplitude in the absence of the trench.

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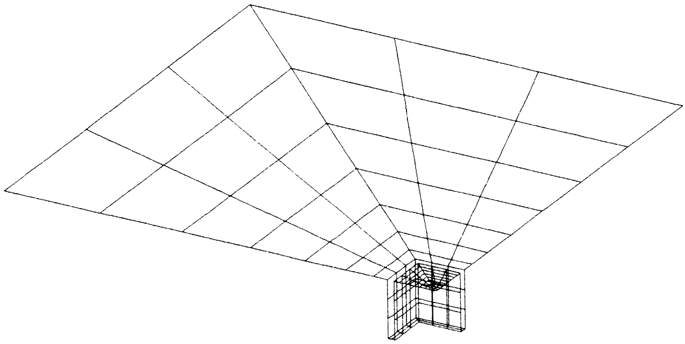

Figure 1 : Discretization for active vibration isolation by trench.

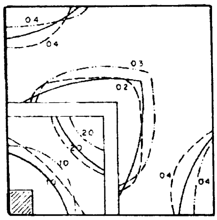

Figure 2 : Contour of amplitude reduction factor (ARF) for active vibration isolation by trench and comparisons.
---: Beskos et al. [7], -..-..-: Banerjee et al. [8], ___: Present results

Vibration isolation by a row of piles

The effectiveness of a row of piles as a wave barrier to ground-transmitted waves produced by an external source is studied numerically in this section. This problem was analysed using an approximate analytical solution by Boroomand and Kaynia [14].

A row of 8 piles of diameter $d = 0.5$ m, length $L_p = 20$ d and spacing $s = 2$ d is constructed to protect structures from waves generated by a vertical harmonic force of magnidute $P_o = 1$kN located at a distance $l = 10$ d from the row of piles. The soil properties are shear modulus $G_s = 132$ MN / m^2 , Poisson's ratio $\nu_s = 0.3$, mass density $\rho_s = 17.5$ kN / m^3 and hysteretic damping $2\beta_s = 5\%$. The piles properties are shear modulus $G_p = 100\ G_s$, Poisson's ratio $\nu_p = \nu_s$, mass density $\rho_p = \rho_s / 0.7$ and hysteretic damping $2\beta_p = 2\beta_s$. The results are obtained for a value of the dimensionless frequency $a = \omega d / C_s = 1.5$ where ω is the excitation frequency and C_s the shear wave velocity.

Only one quarter of the area needs discretization, as shown in Figure 3, because a decomposition of the load into a symmetric and an antisymmetric part is utilized.

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Figure 4 presents the contour diagram of amplitude reduction factor (ARF) as obtained by the present method. The (ARF) is defined as the ratio of the vertical displacement amplitude in the presence of piles to the vertical displacement amplitude in the absence of piles. The results of Figure 4 show some differences from those of Boroomand and Kaynia [14] but the trends are similar.

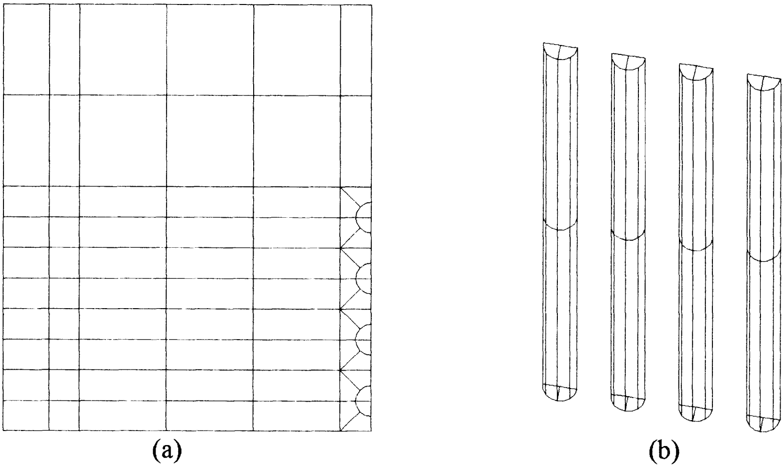

Figure 3 : Discretization for passive vibration isolation by a row of piles. (a) for the soil area (b) for each pile.

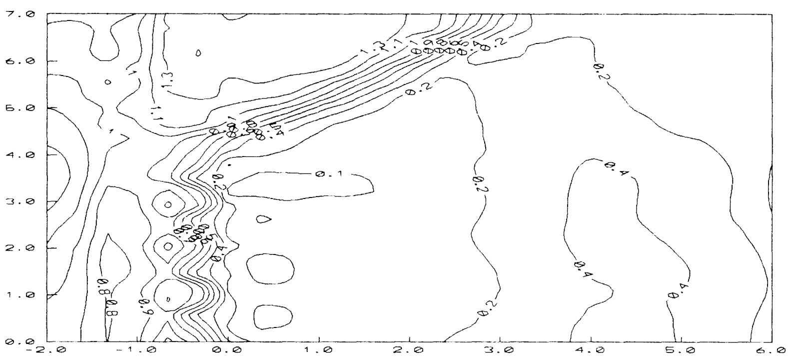

Figure 4 : Contour of amplitude reduction factor (ARF) for passive vibration isolation by a row of piles.

Conclusions

A general and advanced frequency domain BEM for analyzing 3-D harmonic elastodynamic systems encountered in vibration isolation problems has been presented. The accuracy of the method has been verified by comparing its results against those of others for the case of a problem of active vibration isolation by trenches. The problem of vibration isolation by a row of piles has been successfully solved by the above method and the advantages of the method have been demonstrated.

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