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Research Paper

Two-dimensional numerical approach for the vibration isolation analysis of thin walled wave barriers in poroelastic soils

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ABSTRACT

This paper is concerned with the vibration isolation efficiency analysis of total or partially buried thin walled wave barriers in poroelastic soils. A two-dimensional time harmonic model that treats soils and structures in a direct way by combining appropriately the conventional Boundary Element Method (BEM), the Dual BEM (DBEM) and the Finite Element Method (FEM) is developed to this aim. The wave barriers are impinged by Rayleigh waves obtained from Biot's poroelasticity equations assuming a permeable free-surface. The suitability of the proposed model is justified by comparison with available previous results. The vibration isolation efficiency of three kinds of wave barriers (open trench, simple wall, open trench-wall) in poroelastic soils is studied by varying their geometry, the soil properties and the frequency. It is found that the efficiency of these wave barriers behaves similarly to these in elastic soils, except for high porosities and small dissipation coefficients. The efficiency of open trench-wall barriers can be evaluated neglecting their walls if they are typical sheet piles. This does not happen with walls of bigger cross-sections, leading in general to efficiency losses. Likewise, increasing the burial depth to trench depth ratio has a negative impact on the efficiency.

1. Introduction

The vibrations induced by machinery or vehicles can travel through the soil to nearby constructions, which can annoy people or cause the malfunction of devices located inside of these. In order to reduce the vibrations, a wave barrier can be installed at a point of the transmission path. The design of each vibration isolation system depends on the source of vibrations, the properties of the transmission path, and the isolation requirements. An open trench is a very efficient system because its stress-free boundaries act as perfect reflectors of elastic waves. Its efficiency greatly depends on the ratio between the Rayleigh wavelength and the trench depth. However, for soil stability reasons, especially in water saturated soils, a pure open trench cannot be excavated to any desired depth. Thus, other systems such as in-filled trenches, or the installation of sheet piles or rows of piles, are often used. Another option is reinforcing the open trench by installing retaining sheet piles or concrete walls on both sides of the trench. This type of wave barrier is called an open trench-wall.

There exist a vast literature about the design and analysis of wave barriers. Before the numerical computing era, only experimental studies were performed in order to assess these problems, where the works by Barkan [1] and Woods [2] blazed a trail. Nowadays, analytical, semi-analytical and numerical methods, mainly the Boundary Element Method (BEM), are being used, although experimental methods are still being used to confirm and/or parametrize mathematical models, e.g. [3]. Three kinds of wave barriers in elastic soils have been extensively studied: open and in-filled trenches, and rows of piles. The open and in-filled trenches have been studied through two-dimensional BEM models by Emad et al. [4], Beskos et al. [5,6], and even formulas for a simplified design have been given by Ahmad et al. [7]. They were studied in three-dimensional problems using BEM models by Banerjee et al. [8] and Dasgupta et al. [9]. The vibration isolation produced by rows of piles have been studied by Avilés et al. [10] analytically, and by Kattis et al. [11] using a three-dimensional BEM model. The open trench-wall systems have been rarely studied, to the authors' knowledge only Tsai et al. [12] using a two-dimensional multidomain BEM model. When compared with elastic soils, much less works dealing with the efficiency of wave barriers in poroelastic soils exist. Cai et al. [13,14] and Xu et al. [15] studied the isolation efficiency of rows of piles in poroelastic soils using

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semi-analytical methods, and Cao et al. [16] did the same for open trenches under a moving load. As it is seen, the BEM has been widely applied to study these types of problems because of its own capability to deal with unbounded regions. The Finite Element Method (FEM) has been used also, but mainly in combination with the BEM, being the FEM used for structural parts of the problem. Among other coupled BEM–FEM models used in this field, those developed for the study of the isolation of vibrations produced by moving loads (trains) are of great interest nowadays. To this end, the models developed by Andersen et al. [17] and François et al. [18] are great exponents.

The aim of this paper is twofold. Firstly, to present a two-dimensional BEM–FEM dynamic model for soil-structure interaction analyses, where the structures are thin, and one or both of their faces can interact with the surrounding media. The initial idea of this model for fluid–structure analyses has already been presented [19]. Here, the model is expanded by considering a Biot's poroelastic surrounding medium. Secondly, to apply the proposed model to study a problem of interest where there are clear advantages of its use: the efficiency of thin walled wave barriers buried in this medium. For this study, three kinds of wave barriers are considered: open trench, simple barrier (thin in-filled trench), and open trench-wall; which are impinged by a Rayleigh incident wave field assuming a permeable free-surface.

The rest of the paper is organized as follows. The Biot's poroelasticity model is briefly described in Section 2.1. In Section 2.2, the Rayleigh waves on a permeable free-surface are discussed for this model. In Section 2.3, the conventional BEM and the Dual BEM for the Biot's poroelasticity are presented. The soil-structure coupling conditions are described in Section 2.4. In Section 3.1, results obtained from the proposed model are compared with published results. In Section 3.2, a study of the previously mentioned wave barriers under incident Rayleigh waves is presented.

2. Methodology

2.1. Biot's poroelasticity

A very general representation of soils can be done by the Biot's poroelasticity model [20]. This model is able to represent a two-phase medium consisting of a solid frame saturated by a fluid. Let u_i and τ_{ij} be the displacements and stresses of the solid phase, U_i and τ the displacements and equivalent stress of the fluid phase, and $i,j \in [1,2]$. The governing equations in the time domain can be written as:

$$\mu\nabla^2\mathbf{u} + \nabla[N(\nabla\cdot\mathbf{u}) + Q(\nabla\cdot\mathbf{U})] + \mathbf{X} = \rho_{11}\ddot{\mathbf{u}} + \rho_{12}\ddot{\mathbf{U}} + b\left(\dot{\mathbf{u}} - \dot{\mathbf{U}}\right) \quad (1)$$

$$\nabla[Q(\nabla\cdot\mathbf{u}) + R(\nabla\cdot\mathbf{U})] + \mathbf{X}' = \rho_{12}\ddot{\mathbf{u}} + \rho_{22}\ddot{\mathbf{U}} - b\left(\dot{\mathbf{u}} - \dot{\mathbf{U}}\right) \quad (2)$$

and the stress–strain relationships as:

$$\tau_{ij} = \delta_{ij}\left[\left(\lambda + Q^2/R\right)(\nabla\cdot\mathbf{u}) + Q(\nabla\cdot\mathbf{U})\right] + \mu(u_{i,j} + u_{j,i}) \quad (3)$$

$$\tau = Q(\nabla\cdot\mathbf{u}) + R(\nabla\cdot\mathbf{U}) \quad (4)$$

where $N = \lambda + \mu + Q^2/R$, $\mathbf{X}$ and $\mathbf{X}'$ are the body forces of the solid and fluid phases, respectively, λ and μ are the Lamé's parameters of the solid phase, Q and R are the Biot's coupling parameters, b is the dissipation constant, and $\rho_{11} = (1-\phi)\rho_s + \rho_a$, $\rho_{12} = -\rho_a$, $\rho_{22} = \phi\rho_f + \rho_a$, being ϕ the porosity, ρ_s the solid phase density, ρ_f the fluid phase density, and ρ_a the additional aparent density. In the following, in order to avoid confusion, the subscripts 1 and 2 are used to denote solid phase and fluid phase variables, respectively, while x, y are used to denote coordinates.

Using the Helmholtz decomposition:

$$\begin{aligned} u_x &= \frac{\partial\varphi_1}{\partial x} + \frac{\partial\psi_1}{\partial y}, \quad u_y = \frac{\partial\varphi_1}{\partial y} - \frac{\partial\psi_1}{\partial x} \\ U_x &= \frac{\partial\varphi_2}{\partial x} + \frac{\partial\psi_2}{\partial y}, \quad U_y = \frac{\partial\varphi_2}{\partial y} - \frac{\partial\psi_2}{\partial x} \end{aligned} \quad (5)$$

and considering null body forces, two decoupled sets of two equations are obtained from Eqs. (1) and (2):

$$\varphi_1, \varphi_2 \begin{cases} (N+\mu)\nabla^2\varphi_1 + Q\nabla^2\varphi_2 = \rho_{11}\ddot{\varphi}_1 + \rho_{12}\ddot{\varphi}_2 + b(\dot{\varphi}_1 - \dot{\varphi}_2) & \text{(a)} \\ Q\nabla^2\varphi_1 + R\nabla^2\varphi_2 = \rho_{12}\ddot{\varphi}_1 + \rho_{22}\ddot{\varphi}_2 - b(\dot{\varphi}_1 - \dot{\varphi}_2) & \text{(b)} \end{cases} \quad (6)$$

$$\psi_1, \psi_2 \begin{cases} \mu\nabla^2\psi_1 = \rho_{11}\ddot{\psi}_1 + \rho_{12}\ddot{\psi}_2 + b\left(\dot{\psi}_1 - \dot{\psi}_2\right) & \text{(a)} \\ 0 = \rho_{12}\ddot{\psi}_1 + \rho_{22}\ddot{\psi}_2 - b\left(\dot{\psi}_1 - \dot{\psi}_2\right) & \text{(b)} \end{cases} \quad (7)$$

The first set is related with a rotational-free (P) displacement field due to scalar potentials φ_1 and φ_2, and the second set with a divergence-free (S) displacement field due to scalar potentials ψ_1 and ψ_2. In the time harmonic regime, these equations lead to the three well known bulk modes of wave propagation in Biot's poroelasticity. Onwards, the circular frequency is denoted as ω, and the assumed time harmonic term is $\exp(i\omega t)$, which is omitted for brevity. If only the time harmonic potentials $\varphi_i = P_i\exp(-ik_P x)$ are considered, then the bulk P mode is obtained from:

$$P_1, P_2 \begin{cases} \left[\omega^2\hat{\rho}_{11} - k_P^2(N+\mu)\right]P_1 + \left[\omega^2\hat{\rho}_{12} - k_P^2 Q\right]P_2 = 0 & \text{(a)} \\ \left[\omega^2\hat{\rho}_{12} - k_P^2 Q\right]P_1 + \left[\omega^2\hat{\rho}_{22} - k_P^2 R\right]P_2 = 0 & \text{(b)} \end{cases} \quad (8)$$

where $\hat{\rho}_{11} = \rho_{11} - ib/\omega$, $\hat{\rho}_{22} = \rho_{22} - ib/\omega$ and $\hat{\rho}_{12} = \rho_{12} + ib/\omega$. The wavenumbers k_P are obtained from its characteristic equation:

$$\begin{aligned} k_P &= \pm\tfrac{1}{\sqrt{2}}\left(a_1 \pm \left(a_1^2 - 4a_0\right)^{1/2}\right)^{1/2}, \quad a_0 = \omega^4\frac{\hat{\rho}_{11}\hat{\rho}_{22} - \hat{\rho}_{12}^2}{R(\lambda+2\mu)} \\ a_1 &= \omega^2\left(\frac{\hat{\rho}_{22}}{R} + \frac{\hat{\rho}_{11} + \hat{\rho}_{22}Q^2/R^2 - \hat{\rho}_{12}2Q/R}{\lambda + 2\mu}\right) \end{aligned} \quad (9)$$

where two of the solutions are relevant incoming waves ($\mathrm{Re}(k_P) > 0$). Hence, two P modes exist: the wavenumber associated with the fastest wave speed is k_{P1}, while the wavenumber associated with the slowest wave speed is k_{P2}. If only the time harmonic potentials $\psi_i = S_i\exp(-ik_S x)$ are considered, then the bulk S mode is obtained from:

$$S_1, S_2 \begin{cases} \left[\omega^2\hat{\rho}_{11} - k_S^2\mu\right]S_1 + \omega^2\hat{\rho}_{12}S_2 = 0 & \text{(a)} \\ \omega^2\hat{\rho}_{12}S_1 + \omega^2\hat{\rho}_{22}S_2 = 0 & \text{(b)} \end{cases} \quad (10)$$

and the wavenumber k_S is obtained from its characteristic equation:

$$k_S = \pm\omega\left(\frac{\hat{\rho}_{11} - \hat{\rho}_{12}^2/\hat{\rho}_{22}}{\mu}\right)^{1/2} \quad (11)$$

where only one solution is a relevant incoming wave ($\mathrm{Re}(k_S) > 0$).

2.2. Rayleigh waves on a permeable free-surface

The Rayleigh waves are surface waves that exist when a half-space is in contact with the vacuum through its free-surface. For a half-space $y \le 0$, three different cases can be considered at the free-surface $y = 0$: permeable ($\tau_{ij}n_j = 0, \tau = 0$), impermeable ($(\tau_{ij} + \tau\delta_{ij})n_j = 0, (U_j - u_j)n_j = 0$) or partially permeable. In this paper, only the permeable case is considered.