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Seismic analysis of rigid walls retaining a cross-anisotropic poroelastic soil layer over bedrock

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ABSTRACT

The dynamic response of rigid walls retaining a cross-anisotropic poroelastic soil layer over bedrock to seismic horizontal excitation is determined analytically under conditions of plane strain. The problem is treated as a special case of that of a pair of rigid walls with a large separation distance. Use is made of Biot's anisotropic poroelastodynamic theory. Assuming time harmonic excitation, one is able to achieve an exact u-p formulation of the problem in the frequency domain. Expansion of the displacements and the pore-water pressure in terms of Fourier sine and cosine series along the horizontal direction, reduces the partial differential equations of motion in the frequency domain into a system of three ordinary differential equations, which can be easily solved analytically. Thus, closed form expressions for the seismic soil pressure, the distance from the base of the point of application of the resultant seismic pressure and the base shear force and bending moment are obtained. From the above cross-anisotropic poroelastic solution its special cases of isotropic poroelastic solution and cross-anisotropic elastic solution are obtained and compared with the corresponding existing analytical solutions for validation purposes. Finally, parametric studies are performed in order to assess the effect of cross-anisotropy on the seismic response of the wall-soil system.

1. Introduction

Retaining walls are usually constructed to protect transportation arteries (roads and railways), sea ports, bridges and buildings. In high seismicity areas, their seismic design constitutes an essential component of the overall design of these soil-structure systems. This is the reason that seismic analysis and design of retaining walls has received considerable attention in recent years, as this is evident in the review articles of Psarropoulos et al [1], Giarlelis and Mylonakis [2] and Prakash et al [3].

In this work, the seismic analysis of rigid walls retaining a cross-anisotropic fully water saturated poroelastic soil layer on bedrock is done analytically under conditions of plane strain. The importance of "exact" analytical solutions for soil-wall systems assuming linear elastic or poroelastic soil behavior (with or without hysteric damping) has been demonstrated, among others', in the recent publications of Papazafeiropoulos and Psarropoulos [4], Vrettos et al [5] and Papagiannopoulos et al [6], where one can also find a comprehensive literature review.

Very briefly, analytical solutions of retaining wall problems with linear soil constitute conservative upper bounds of the real situation observed in tests and come closer and closer to the test results for increasing wall flexibility and non-homogeneity [5,7–9]. Soils are usually characterized as cross-anisotropic (or transversely isotropic) materials due to sedimentation-consolidation or gravitational deposition [10]. Thus, an assessment of the effect of soil anisotropy on the seismic response of retaining walls in the framework of analytical solutions is certainly needed. This effect for the case of a linear elastic soil has been very recently studied analytically by Beskou et al [11]. In this work, the anisotropy effect on the seismic response of retaining walls is studied analytically for the case of a fully saturated by water poroelastic soil. To the authors' best knowledge this problem has not been studied before and certainly not analytically.

The seismic analysis of rigid walls retaining isotropic poroelastic soil was first studied analytically by Theodorakopoulos et al [12,13], Theodorakopoulos and Beskos [14] and Theodorakopoulos [15] by using the simplifying assumptions of Veletsos and Younan [7]. Following the same simplifying assumptions, Lanzoni et al [16] were able to solve analytically the isotropic poroelastic soil case with flexible massless walls. The exact analytical solution for the case of isotropic poroelastic soil retained by a rigid wall was recently obtained by Papagiannopoulos et al [6], who found that the extension of the simplifying assumptions of [7] from the elastic to the poroelastic case is not correct at least with respect to the pore water pressure, which though

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affects the base shear and moment results.

Extension of the isotropic poroelastodynamics to the anisotropic one is not as easy as it is the corresponding case of isotropic elastodynamics to the anisotropic one. The theory of anisotropic poroelastodynamics has been developed by Biot [17,18] and a very good exposition of that theory can be found in the very recent book of Cheng [19]. The review article of Schanz [20] is also helpful with respect to the literature review on the subject. One can mention here the works of Kazi-Aoual et al [21] and Sahebkar and Eskandari-Ghadi [22], dealing with some wave propagation problems in cross-anisotropic poroelastodynamics involving an infinite and a semi-infinite medium, respectively.

The problem of the seismic response of rigid walls retaining a cross-anisotropic poroelastic soil over bedrock considered here under conditions of plane strain is solved analytically by considering a pair of rigid walls (instead of one), formulating the poroelastodynamic problem in the frequency domain in terms of the displacements and the pore water pressure, expanding these response quantities in sine and cosine Fourier series along the horizontal coordinate and solving the resulting system of three ordinary differential equations to obtain the frequency domain response. The case of one rigid wall is finally obtained by considering a very high value for the separation distance between the two walls. Thus, the horizontal pressure on the wall, the base shear force and bending moment as well as the location of the point of application of the resultant force on the wall are all determined as functions of frequency and the soil material parameters (indices of anisotropy, porosity and permeability). For all the above response quantities the effect of cross-anisotropy is determined and discussed.

2. Statement of the problem

Consider the system of Fig. 1 consisting of two rigid cantilever walls retaining a homogeneous and transversely isotropic (or cross-anisotropic) fully saturated poroelastic soil layer over bedrock under the action of a uniform, horizontal seismic acceleration $\ddot{x}_g = \ddot{x}_g(t)$, where overdots denote differentiation with respect to time t. The above soil layer has a length L and height H, is considered to be under conditions of plane strain and with reference to a rectangular coordinate system x,y, as shown in Fig. 1, has a behavior governed by the equations of motion [17–19]

$$c_{11}\frac{\partial^2 u}{\partial x^2} + c_{44}\frac{\partial^2 u}{\partial y^2} + (c_{13} + c_{44})\frac{\partial^2 v}{\partial x \partial y} - a_1\frac{\partial p}{\partial x} = \rho\ddot{u} + \rho_f\ddot{r}_x + \rho\ddot{x}_g \tag{1}$$

$$c_{33}\frac{\partial^2 \upsilon}{\partial y^2} + (c_{13} + c_{44})\frac{\partial^2 u}{\partial x \partial y} + c_{44}\frac{\partial^2 \upsilon}{\partial x^2} - a_3\frac{\partial p}{\partial y} = \rho\ddot{\upsilon} + \rho_f\ddot{r}_y \tag{2}$$

$$-\frac{\partial p}{\partial x} - \rho_f\ddot{u} = \frac{\eta}{k_x}\dot{r}_x + m^*\ddot{r}_x \tag{3}$$

$$-\frac{\partial p}{\partial y} - \rho_f\ddot{\upsilon} = \frac{\eta}{k_y}\dot{r}_y + m^*\ddot{r}_y \tag{4}$$

where $u = u(x,y,t)$ and $\upsilon = \upsilon(x,y,t)$ are the displacements of the soil skeleton along the x and y directions, respectively, $p = p(x,y,t)$ is the porewater pressure, r_x and r_y are defined as

$$r_x = \varphi(u^f - u) \quad , \quad r_y = \varphi(\upsilon^f - \upsilon) \tag{5}$$

η is the dynamic viscosity of the fluid, k_x and k_y are the permeabilities along the x and y directions, respectively, φ is the porosity, $\rho = \varphi\rho_f + (1-\varphi)\rho_s$ with ρ_f and ρ_s being the actual mass densities of the fluid and the solid, respectively, subscript or superscript f denotes fluid, $m^* \simeq \rho_f/\varphi$ is a mass coefficient and c_{11},c_{13},c_{33} and c_{44} are the four elastic constants of the cross-anisotropic (or transversely isotropic) solid medium. The vertical y axis is the axis of symmetry of the solid material and thus its behavior to any plane orthogonal to this axis is isotropic.

The elastic constants c_{ij} (i,j = 1–4) are given by the expressions [19]

$$c_{11} = \frac{E_h(E_V - E_h\nu^2)}{(1+\nu)(E_V - E_V\nu - 2E_h\nu^2)} \tag{6}$$

$$c_{13} = \frac{E_h E_V \nu}{E_V - E_V\nu - 2E_h\nu^2} \tag{7}$$

$$c_{33} = \frac{E_V{}^2(1-\nu)}{E_V - E_V\nu - 2E_h\nu^2} \tag{9}$$

$$c_{44} = G_V \tag{10}$$

in terms of the engineering constants E_h, E_v (Young's moduli), G_v (shear modulus) and ν (Poisson's ratio) with the indices h and v denoting horizontal and vertical direction, respectively. Thus, in this case there are 4 independent elastic constants (c_{11}, c_{13}, c_{33}, c_{44} or E_v, E_h, G_v, ν) instead of 2 (E,ν) as in the isotropic case.

The total stresses in the anisotropic poroelastic medium σ_{xx}, σ_{yy} and σ_{xy} are expressed in terms of displacements and porowater pressure as [17–19]

$$\sigma_{xx} = c_{11}\frac{\partial u}{\partial x} + c_{13}\frac{\partial \upsilon}{\partial y} - \alpha_1 p \tag{10}$$

$$\sigma_{yy} = c_{13}\frac{\partial u}{\partial x} + c_{33}\frac{\partial \upsilon}{\partial y} - \alpha_3 p \tag{11}$$

$$\sigma_{xy} = c_{44}\left(\frac{\partial u}{\partial y} + \frac{\partial \upsilon}{\partial x}\right) \tag{12}$$

while the porewater pressure is expressed as [17–19]

$$p = -M\left(a_1\frac{\partial u}{\partial x} + a_3\frac{\partial \upsilon}{\partial y} + \frac{\partial r_x}{\partial x} + \frac{\partial r_y}{\partial y}\right) \tag{13}$$

where the modulus M is given by [19]

$$M = {}^{K_s}\Big/\left[\left(1 - \frac{K^*}{K_s}\right) - \varphi\left(1 - \frac{K_s}{K_f}\right)\right] \tag{14}$$

with K* and K_s being the bulk modulus for the skeleton and the grains, respectively, K_f being the fluid bulk modulus and α_1 and α_3 being the Biot effective stress coefficients.

The boundary conditions of the problem with reference to Fig. 1 are the following:

At the free soil surface (y = H)

$$\sigma_{yy} = 0 \quad , \quad \sigma_{xy} = 0 \quad , \quad p = 0 \tag{15}$$

At the soil-wall interfaces (x = 0, x = L) on the assumption of smooth contact

$$\sigma_{xy} = 0 \quad , \quad u = 0 \tag{16}$$

At the soil-bedrock interface (y = 0) on the assumption of rough contact and impervious bedrock

$$u = 0 \quad , \quad \upsilon = 0 \quad , \quad \frac{\partial p}{\partial y} = 0 \tag{17}$$

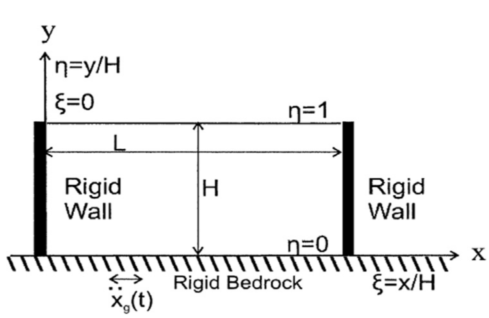

Fig. 1. A system of two rigid walls retaining a linear cross-anisotropic poroelastic soil layer under horizontal seismic motion.