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Transient responses of porous media under moving surface impulses

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ABSTRACT

Three-dimensional transient responses of porous media under moving surface impulses of finite frequency components are theoretically studied. We discuss three free-surface stiffness conditions, such as fully permeable—'open pore', fully impermeable—'closed pore', and partially permeable boundaries, that are not explicitly discussed before. The transient responses of the solid vertical displacement and the pore fluid pressure triggered by the moving impulses on the surface are particularly investigated in different typical surface stiffness, moving impulse velocities, material permeabilities and impulse peak frequencies. It is concluded that the $R1$ surface wave carries the strongest energy as that for stationary source configurations. Moreover, it is more sensitive to surface stiffness condition than body waves represented in the responses of the corresponding wave forms of obvious different amplitudes and arrival time. Furthermore, the apparent velocity of the moving impulse pointing toward the fixed receiver may cause 'blue shift' in frequency. The higher velocity triggers more obvious frequency shift. For the moving impulse of low peak frequency, this shift becomes much serious. The lateral velocity of the moving impulse to the receiver may also twist the received wave forms, especially for the impulse of low peak frequency.

1. Introduction

The transient dynamic responses of soil media under moving surface impulses are of significance for civil engineering, geotechnique and earthquake engineering, etc. Propagating waves are usually measured to reflect the transient responses of the media. For most engineering cases under stationary sources, the time and spectrum responses of waves may characterize the dynamic characteristics of the rocks subsurface. For some soft foundations, however, the surface waves propagate at pretty low velocities. Therefore, the moving velocities of the source impulse have to be considered in order to obtain the transient responses to represent the ground truth.

Vibrated responses were first noted by Sneddon (1951, 1952), who discussed a line steady load at a subsonic velocity moving on the surface of an elastic medium, and obtained the 2D solutions by using integral transform method. This problem was extended by Eason (1965) into 3D elastic half-space. He derived the general solutions of the responses by using double Fourier transformations. Payton (1967) considered the transient responses of a line load applied suddenly and then moving with a constant velocity, and analyzed the acceleration process of the source in the solutions. Apsel (1979) and de Barros and Luco (1994) developed a theory of dealing with multilayered viscoelastic half-space. Lefeuve-Mesgouez et al. (2000, 2002) investigated the transmission of the vibrations on the surface of 2D and 3D elastic soils, under the vertical harmonic strip and rectangular loads moving at high-velocities. These achievements refer to the dynamic responses of single phase media under moving impulses.

However, the solids near surface are filled with fluids due to general hydrogeological conditions. The interaction between a moving impulse and the porous media attracted plenty of attentions. Based on the Biot theory of fluid saturated porous media (Biot, 1956, 1962), Burke and Kingsbury (1984) presented an analytical solution of poroelastic material responses under the traveling surface pressure. Siddharthan et al. (1993) analyzed the dynamic responses of a layered poroelastic half-space under a moving load in the plane strain case. They approximated the solutions of Biot's wave equations by neglecting the solid and fluid coupling. Jin et al. (2004) obtained a semi-analytical expression of 2D half-plane porous media under a surface steady moving line load. Theodorakopoulos and his coworkers (2003, 2004) studied the responses of a poroelastic half-plane soil medium under moving line loads by analytical and approximated numerical methods. Lu and Jeng (2007) firstly derived the 3D porous medium responses under constantly moving point loads. Xu et al. (2008) extended

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these solutions to the layered porous media. Cai et al. (2007, 2008) studied the 3D saturated poroelastic medium steady responses, assuming the solid incompressible, under a finite rectangular load, and simulated the case of rail track system on the surface. Cao and Boström (2013) studied the accelerating and decelerating moving trains loading on a poroelastic half space. Lefeuve-Mesgouez and Mesgouez (2008, 2012) studied the ground vibration transmission due to a high-velocity moving harmonic rectangular load on a poroviscoelastic homogeneous and multilayered half-space by wave-mode analysis. Li et al. (2012) analyzed several approximated formulations of porous media in wavenumber domain for modeling the responses of a poroelastic half-space under a moving harmonic point load. Beskou and Theodorakopoulos (2011) comprehensively reviewed the moving load problems. Although many problems involving in the responses of porous media under moving loads have been considered, to the best of our knowledge, the studies dealing with the transient responses of porous media under a moving impulse of finite frequency components are rather limited. Especially, lack discussions on the different surface stiffness conditions, which are often encountered in pavement maintenance engineering, make the thorough investigation on dynamic response of porous media has still to be suggested.

In the present work, we analyze the near surface transient responses in space domain under the moving surface impulses. We classify surface stiffness conditions into three types, fully drained permeable, fully undrained impermeable and partially permeable free surface boundary conditions (Deresiewicz and Skalak, 1963; Bourbié et al., 1987). In most engineering cases, the different surface stiffness can represent different surface conditions for fluid drainage, such as the loose overlap, the bituminous pavement and the general conditions between the two extreme conditions. In fact, partially permeable conditions are more often encountered, since all fluids in subsurface pores are not fully drained or fully plugged simultaneously on the surface. Unfortunately, the partially permeable boundary has not been explicitly analyzed. Focusing on this issue, we firstly introduce the formalism of a fluid-saturated Biot's model to analyze the expressions of 3D transient responses. Then the transient solutions for different free surface stiffness conditions will be derived. The partial differential wave equations corresponding to these three possible surfaces are solved in frequency–wavenumber domain. The extended PTAM (Peak and Trough Average Method, Zhang et al., 2003) method is employed in 2D wavenumber domain to handle the oscillatory inverse integrals, and inverse Fourier transform is implemented in the frequency domain. The numerical experiments of transient responses represented in solid displacements and the pore fluid pressures are conducted to show the modal characteristics of the wave propagation. The displacement and pressure responses in typical cases of material and moving impulse configurations are plotted to reflect their similarities and differences of the transient characteristics.

2. A fluid-saturated porous model

A framework of solid grains and a connected pore space filled entirely by fluid comprise the fluid-saturated porous medium. The volume ratio of the pore space is defined as porosity, ϕ. Two displacement vectors, $\mathbf{u}$ and $\mathbf{U}$, describe the motions of the multiphases of the solid and fluid, respectively. Usually, $\mathbf{w} = \phi(\mathbf{U} - \mathbf{u})$ characterizes the relative fluid-solid displacement (Biot, 1962). The stress tensor for porous media has a volume average effect of the solid frame and the pore fluid. For a general isotropic case, the equations governing the motion of porous media are written by Biot (1962).

$$\mu\nabla^2\mathbf{u} + (\lambda_C + \mu)\nabla(\nabla\cdot\mathbf{u}) + \alpha M\nabla(\nabla\cdot\mathbf{w}) = \partial_{tt}(\rho\mathbf{u} + \rho_f\mathbf{w}),$$

and

$$\alpha M\nabla(\nabla\cdot\mathbf{u}) + M\nabla(\nabla\cdot\mathbf{w}) = \partial_{tt}(\rho_f\mathbf{u} + m\mathbf{w}) + b\partial_t\mathbf{w}, \qquad (1)$$

where $\rho = (1-\phi)\rho_s + \phi\rho_f$ is the bulk density of the fluid saturated medium, ρ_s and ρ_f are the densities of the solid grains and fluid, respectively. The parameter $\lambda_C = \lambda + \alpha^2 M$ is the Lame coefficient of the medium on undrained condition, while λ and μ are the Lame constants of the solid skeleton. The parameters α (Biot–Wills coefficient) and M are given by

$$\alpha = 1 - \frac{K_m}{K_s},$$

and

$$\frac{1}{M} = \frac{\alpha-\phi}{K_s} + \frac{\phi}{K_f}, \qquad (2)$$

respectively, where $K_m = \lambda + \frac{4}{3}\mu$ is the solid skeleton bulk modulus, K_s and K_f are the solid grain bulk modulus and fluid modulus, respectively. The parameter m is a mass-like coefficient in terms of $m = C\rho_f/\phi$, and C denotes tortuosity. Berryman (1980) gives an estimated value of tortuosity as a function of porosity, $C = \frac{1}{2}(1 + 1/\phi)$ for uniform spherical grains. The drag force coupling damping coefficient b_0 is formulated by $b_0 = \frac{\eta}{\kappa}$, where η is dynamic fluid viscosity, and κ represents macroscopic permeability. And $b = b_0F_r$, where F_r is the viscous correction factor, Johnson et al. (1987) gave an expression of $F_r(f) = \left(1 + \frac{i}{2}M_s f/f_C\right)^{1/2}$, where M_s is the shape factor (always equal to 1). The reference critical frequency is defined as $f_c = \frac{\eta\phi}{2\pi\rho_f\kappa}$.

3. Generation of transient responses

We consider a three-dimensional configuration of the half space, $z > 0$ represents the porous media, shown in Fig. 1a. Assuming the dynamic response in three-dimensional media, we introduce a Cartesian coordinate system (x, y, z). When deriving

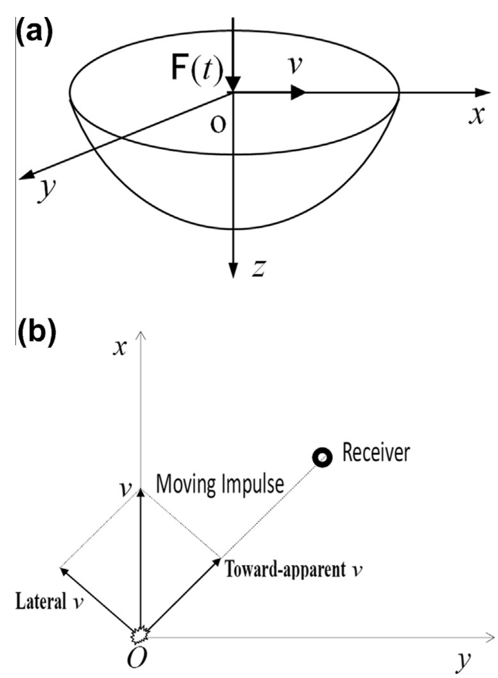

Fig. 1. A three-dimensional Cartesian coordinate system for the moving surface impulse problems. (a) A moving surface impulse along the x axis of time dependent $F(t)$, and velocity v; (b) The decomposition of the velocity of the moving impulse related to the receiver on the xy plane.