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Three-dimensional dynamic response of a lined tunnel in a half-space of saturated soil under internal explosive loading

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ABSTRACT

Blast waves have a random direction of propagation with reference to the axis of the tunnel and this renders the problem three-dimensional. Because tunnels are buried in a certain depth, a half-space model is more appropriate than a full space model in the dynamic analysis. In this paper, three-dimensional (3D) dynamic response of a lined tunnel buried in a half-space of soil due to blasting is studied analytically. The lining structure and the surrounding soil are treated as a homogeneous elastic medium and a saturated porous medium, respectively. The 3D solutions for displacement, stress and pore water pressure in the saturated soil and the displacement at the ground surface are derived in time domain by means of the Fourier and Laplace transforms. The effects of buried depth to these various dynamic responses are investigated numerically.

1. Introduction

The study of transient dynamic response of a lined tunnel buried in saturated soil due to internal explosive loading has received considerable interest in recent decades. Senjuntichai and Rajapakse [1] analyzed the dynamic response of a pressurized long cylindrical cavity without lining in an infinite poroelastic medium. Glenn and Kidder [2] obtained solutions of a spherical container surrounded by an infinite elastic medium induced by an explosive loading by using Hooke's law. Osinov [3] focused on the dynamic response of saturated soil subjected to a blast loading inside a tunnel lining. Gao et al. [4] investigated the dynamic response of a cylindrical lined cavity for different parameters of a saturated soil and lining. Wang et al. [5] presented a set of exact solutions for the dynamic response of a lined cavity in a nearly saturated medium and analyzed the effects of the degree of saturation on the dynamic response. Gao et al. [6] presented the three-dimensional dynamic response of a cylindrical lined tunnel in full-space saturated soil due to an internal blast loading. Nevertheless, the tunnel is assumed to be buried in a full-space in all of the above studies.

However, a half-space model is more practical because tunnels always have finite buried depths. Wang et al. [7] obtained the 2-D solutions for the dynamic responses of lined tunnel in saturated soil using a half-space model. Zhang et al. [8] examined the 2-D plane SH waves induced by a non-symmetrical V-shaped canyon by using the wave function expansion method. Kattis et al. [9] obtained numerical solutions for dynamic response of both the unlined and lined tunnels in an infinite saturated soil under a harmonic wave diffraction by BEM. In this paper, to advance the understanding of the dynamic response of lined tunnels, the 3-D dynamic blast response of a lined tunnel in a poroelastic half space is analyzed. Numerical results are compared against those of results obtained for a full-space model.

2. General 3D solutions in a half-space of saturated soil

Consider a long cylindrical tunnel lining of outer and inner radii a_1 and a_2, respectively, and thickness h buried in an infinite half-space of saturated soil medium, as shown in Fig. 1. The inner surface lining is subjected to transient load $P(z,t)$. Assuming that the explosive loading indicates an exponential attenuation along the radial and axial direction of the tunnel, it can be written as:

$$\mathrm{P}(z,\ t) = P_0 e^{-\alpha t} e^{-\beta |z|} \tag{1}$$

where P_0 is the maximum value of explosive load; α and β are the attenuation coefficients of explosive load.

The blast waves show a random direction with respect to the axis of the tunnel and this renders the problem three-dimensional. The blast

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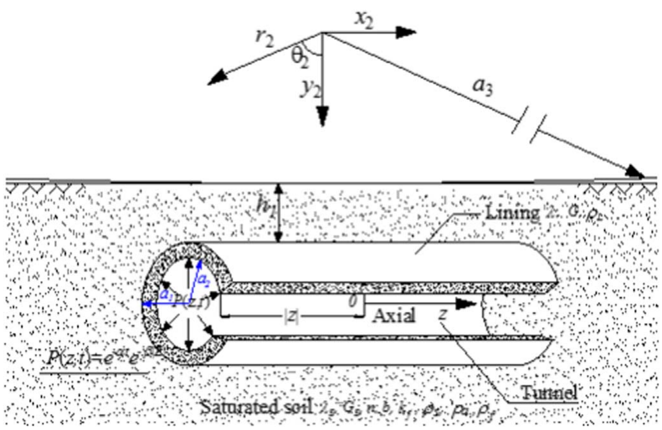

Fig. 1. Analytical model.

loading can be considered as an axisymmetric radial loading acting on the internal surface of the lined tunnel along a certain section, which decays with regard to the axis of the tunnel. Therefore, the problem is effectively reduced to a two dimensional one by the Fourier transformation in coordinate variable z. Then the 3-D solutions are obtained by using inverse Fourier transformation.

Based on reference [7], the potential functions of the tunnel and saturated porous medium in Fourier transform domain can be expressed as:

$$\overline{\varphi}(r_2, \theta_2, \omega) = [J_m(\beta_6 r_2) f_m + J_m(\beta_6 r_2) g_m] \cos m\theta_2, \tag{2a}$$

$$\overline{\psi}(r_2, \theta_2, \omega) = [J_m(\beta_7 r_2) h_m + J_m(\beta_7 r_2) i_m] \cos m\theta_2, \tag{2b}$$

$$\overline{\varphi}_1(r_2, \theta_2, \omega) = [J_m(\beta_3 r_2) a_m + J_m(\beta_4 r_2) b_m] \cos m\theta_2, \tag{2c}$$

$$\overline{\varphi}_2(r_2, \theta_2, \omega) = [J_m(\beta_3 r_2) c_m + J_m(\beta_4 r_2) d_m] \cos m\theta_2, \tag{2d}$$

$$\overline{\psi}_1(r_2, \theta_2, \omega) = J_m(\beta_5 r_2) e_m \cos m\theta_2, \tag{2e}$$

$$\overline{\psi}_2(r_2, \theta_2, \omega) = m_7 J_m(\beta_5 r_2) e_m \cos m\theta_2, \tag{2f}$$

in which r_2 and θ_2 are coordinate variables in polar coordinates system; ω is the transform parameter; $\overline{\varphi}(r_2, \theta_2, \omega)$ and $\overline{\psi}(r_2, \theta_2, \omega)$ are potential functions of tunnels; $\overline{\varphi}_1(r_2, \theta_2, \omega)$ and $\overline{\psi}_1(r_2, \theta_2, \omega)$ are potential functions of soil skeleton; $\overline{\varphi}_2(r_2, \theta_2, \omega)$ and $\overline{\psi}_2(r_2, \theta_2, \omega)$ are potential functions of fluid; $J_m(*)$ is the Bessel functions of the first kind of order m; β_3, β_4 and β_5 are the dimensionless wave numbers associated with the two dilatational waves and shear wave; β_6 and β_7 are the dimensionless wave numbers associated with the compression wave and shear wave; and other symbols are as following:

$$\begin{bmatrix} a_m \\ c_m \end{bmatrix} = \sum_{n=-\infty}^{\infty} K_{n+m}(\beta_3 D) \begin{bmatrix} B_3(s) \\ C_3(s) \end{bmatrix}, \begin{bmatrix} b_m \\ d_m \end{bmatrix} = \sum_{n=-\infty}^{\infty} K_{n+m}(\beta_4 D) \begin{bmatrix} B_4(s) \\ C_4(s) \end{bmatrix}, e_m = \sum_{n=-\infty}^{\infty} K_{n+m}(\beta_5 D) D_5(s), \begin{bmatrix} f_m \\ g_m \end{bmatrix} = \sum_{n=-\infty}^{\infty} K_{n+m}(\beta_6 D) \begin{bmatrix} A_6(s) \\ B_6(s) \end{bmatrix}, \begin{bmatrix} h_m \\ i_m \end{bmatrix} = \sum_{n=-\infty}^{\infty} K_{n+m}(\beta_7 D) \begin{bmatrix} A_7(s) \\ B_7(s) \end{bmatrix}, m_7 = \frac{\rho^* s^2}{(m_0^* s^2 + b^* s)}.$$

where $m_0^* = m_0/\rho$, $m_0 = (n\rho_f + \rho_a)/n^2$; K_{n+m} is the modified Bessel functions of the second kind of order $n+m$; m_0, ρ_a, ρ_f are the fluid additional mass density, the mass density induced by fluid coupling and mass density of pore fluid, respectively; $A_6(s)$, $A_7(s)$, $B_3(s)$, $B_4(s)$, $B_6(s)$, $B_7(s)$, $C_3(s)$, $C_4(s)$ and $D_5(s)$ are the undetermined coefficients; D is the distance between two origins of the coordinate systems; b^* is normalized the coefficient related to Darcy's coefficient of permeability; n is the porosity of the soil; s is Laplace transform parameters. Other nomenclatures are the same as Ref. [7].

Based on references [10,11,12], the stress-potentials, displacement-potentials and pore pressure-potentials relations of saturated soil can be expressed in the following forms:

$$\overline{u}_r(r_2, \theta_2, \omega) = \frac{\partial \overline{\varphi}_1}{\partial r_2} + \frac{1}{r_2}\frac{\partial \overline{\psi}_1}{\partial \theta_2}, \overline{u}_\theta(r_2, \theta_2, \omega) = \frac{1}{r_2}\frac{\partial \overline{\varphi}_1}{\partial r_2}\frac{\partial \overline{\psi}_1}{\partial \theta_2}, \overline{w}_r(r_2, \theta_2, \omega) = \frac{\partial \overline{\varphi}_2}{\partial r_2} + \frac{1}{r_2}\frac{\partial \overline{\psi}_2}{\partial \theta_2}, \tag{3a}$$

$$\frac{\overline{\sigma}_r(r_2, \theta_2, \omega)}{G_s} = (\lambda_s^* + 2)\frac{\partial^2 \overline{\varphi}_1}{\partial r_2^2} + \lambda_s^* \frac{\partial^2 \overline{\varphi}_1}{\partial \theta_2^2} + 2\frac{\partial^2 \overline{\psi}_1}{\partial r_2 \partial \theta_2} + \alpha^2 M^* \nabla^2 \overline{\varphi}_1 + \alpha M^* \nabla^2 \overline{\varphi}_2, \tag{3b}$$

$$\frac{\overline{\sigma}_\theta(r_2, \theta_2, \omega)}{G_s} = (\lambda_s^* + 2)\frac{\partial^2 \overline{\varphi}_1}{\partial \theta_2^2} + \lambda_s^* \frac{\partial^2 \overline{\varphi}_1}{\partial r_2^2} + 2\frac{\partial^2 \overline{\psi}_1}{\partial r_2 \partial \theta_2} + \alpha^2 M^* \nabla^2 \overline{\varphi}_1 + \alpha M^* \nabla^2 \overline{\varphi}_2, \tag{3c}$$

$$\frac{\overline{\sigma}_f(r_2, \theta_2, \omega)}{G_s} = \alpha M^* \nabla^2 \overline{\varphi}_1 - M^* \nabla^2 \overline{\varphi}_2. \tag{3d}$$

where $\overline{u}_r(r_2, \theta_2, \omega)$, $\overline{u}_\theta(r_2, \theta_2, \omega)$ and $\overline{w}_r(r_2, \theta_2, \omega)$ are the radial, hoop displacement of soil skeleton and displacement of fluid relative to solid in Fourier and Laplace transform domain, respectively; $\overline{\sigma}_r(r_2, \theta_2, \omega)$, $\overline{\sigma}_\theta(r_2, \theta_2, \omega)$ and $\overline{\sigma}_f(r_2, \theta_2, \omega)$ are the radial, hoop stress of soil skeleton and pore pressure of fluid in Fourier and Laplace transform domain, respectively.

Substituting Eqs. (2c)–(2f) into (3a)–(3d) yields:

$$\overline{u}_r(r_2, \theta_2, \omega) = \frac{\beta_3}{2}[J_{m-1}(\beta_3 r_2) - J_{m+1}(\beta_3 r_2)] a_m \cos m\theta_2 + \frac{\beta_4}{2}[J_{m-1}(\beta_4 r_2) - J_{m+1}(\beta_4 r_2)] b_m \cos m\theta_2 - \frac{m}{r_2} J_m(\beta_5 r_2) e_m \sin m\theta_2 \tag{4a}$$

$$\overline{u}_\theta(r_2, \theta_2, \omega) = \frac{\beta_3}{2r_2}[J_{m-1}(\beta_3 r_2) - J_{m+1}(\beta_3 r_2)] a_m \cos m\theta_2 + \frac{\beta_4}{2r_2}[J_{m-1}(\beta_4 r_2) - J_{m+1}(\beta_4 r_2)] b_m \cos m\theta_2 + m J_m(\beta_5 r_2) e_m \sin m\theta_2 \tag{4b}$$

$$\overline{w}_r(r_2, \theta_2, \omega) = \frac{\beta_3}{2}[J_{m-1}(\beta_3 r_2) - J_{m+1}(\beta_3 r_2)] c_m \cos m\theta_2 + \frac{\beta_4}{2}[J_{m-1}(\beta_4 r_2) - J_{m+1}(\beta_4 r_2)] d_m \cos m\theta_2 - \frac{m_7 m}{r_2} J_m(\beta_5 r_2) e_m \sin m\theta_2 \tag{4c}$$

$$\frac{\overline{\sigma}_r(r_2, \theta_2, \omega)}{G_s} = \frac{\beta_3^2}{4}[(\lambda_s^* + 2 + \alpha^2 M^*) a_m + \alpha^2 M^* c_m][J_{m-2}(\beta_3 r_2) - 2J_m(\beta_3 r_2) + J_{m+2}(\beta_3 r_2)] \cos m\theta_2 + \frac{\beta_4^2}{4}[(\lambda_s^* + 2 + \alpha^2 M^*) b_m + \alpha^2 M^* d_m][J_{m-2}(\beta_4 r_2) - 2J_m(\beta_4 r_2) + J_{m+2}(\beta_4 r_2)] \cos m\theta_2 - m^2[(\lambda_s^* + \alpha^2 M^*) a_m + \alpha^2 M^* c_m] J_m(\beta_3 r_2) \cos m\theta_2 - m^2[(\lambda_s^* + \alpha^2 M^*) b_m + \alpha^2 M^* d_m] J_m(\beta_4 r_2) \cos m\theta_2 - \beta_5 m [J_{m-1}(\beta_5 r_2) - J_{m+1}(\beta_5 r_2)] e_m \sin m\theta_2 \tag{4d}$$