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Dynamic response of a tunnel buried in a saturated poroelastic soil layer to a moving point load

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ABSTRACT

The dynamic response of a tunnel buried in a two-dimensional poroelastic soil layer subjected to a moving point load was investigated theoretically. The tunnel was simplified as an infinite long Euler–Bernoulli beam, which was placed parallel to the traction-free ground surface. The saturated layer was governed by Biot's theory. Combined with the specified boundary conditions along the beam and saturated poroelastic layer, the coupled equations of the system were solved analytically in the frequency–wavenumber domain based on Fourier transform. The time domain responses were obtained by the fast inverse Fourier transform. The critical velocity of the considered structure was determined from the dispersion curves. The different dynamic characteristics of the elastic soil medium and the saturated poroelastic medium subjected to the underground moving load were investigated. It is concluded that, for coarse materials or fine materials subjected to the high-velocity loading, models ignoring the coupling effects between the pore fluid and the soil skeleton may cause errors. The shear modulus and the permeability coefficients of the saturated soil as well as the load moving velocity had significant influence on the displacement and pore pressure responses.

1. Introduction

The environmental impacts caused by railway traffic become a very important issue in recent years with the increasing train running speed, and have drawn much attention in the transportation engineering and environmental engineering fields [1–6]. A comprehensive literature review on the subject of moving loads applied on pavements was presented by Beskou and Theodorakopoulos [7].

For the study on the ground vibration caused by trains moving in underground tunnels, different approaches were also well developed. Metrikine and Vrouwenvelder. [8] established a two dimensional model by considering the tunnel as an Euler beam embedded in a viscoelastic soil layer with a rigid base. The vibrations at the ground surface were investigated for constant, harmonic, and random loads moving along the beam, respectively. Koziol et al. [9] modified Metrikine's model by introducing a half-space ground beneath the beam and using the wavelet approach to accomplish the inverse Fourier transform. Forrest and Hunt [10] described an analytical three-dimensional model called "Pipe in Pipe" for a deep underground railway tunnel of circular cross-section. By using discrete wavenumber method, Sheng et al. [11] studied the dynamic response of ground under harmonic loads moving in a circular tunnel. The effect of the tunnel on vibration responses at the ground surface and the difference between lined tunnel and unlined tunnel were presented. In order to simulate the wave propagation in the longitudinal direction of the tunnel, the so-called 2.5D (two point five dimensional) analysis concept was proposed in 2001 by Yang and Hung [12]. By using the 2.5D finite element method, Yang and Hung [13] performed a parametric study on soil vibrations caused by underground moving trains. Bian et al. [14,15] presented an efficient 2.5D formulation with artificial boundaries to study the ground-borne vibrations due to dynamic loadings from moving trains. Recently, a numerical model for predicting vibrations induced by railway traffics in tunnels was proposed by Lopes et al. [16] with a 2.5D version of a PML (Perfectly Matched Layers) formulation. Müller et al. [17] proposed a similar approach by coupling the finite element and integral transform method to study the problem of vehicle–slab–track–tunnel–soil interaction. By assuming the geometry to be periodic instead of invariant in the tunnel direction, Degrande et al. [18] proposed a coupled finite/boundary element model based on the Floquet transform.

For all the works above, the soil was all treated as a single-phase elastic or visco-elastic medium. However, underground water often exists in the soil medium, which affects the wave propagation apparently. Thus, the fully saturated poroelastic soil

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model is closer to the actual situation. Biot [19] pioneered the development of an elastodynamic theory for a fluid-filled poroelastic medium. Some studies [20,25,26,28] have shown that significant differences exist between the saturated poroelastic soil model and the elastic one. Based on Biot's theory, dynamic response of a poroelastic half-plane or half-space subjected to loads moving on its surface have been widely studied [20–28]. However, there are few studies on the dynamic response of poroelastic medium caused by underground moving load. Lu et al. [29,30] employed Biot's theory to obtain a closed-form general solution for the dynamic response of an unlined circular tunnel, which is embedded in a full-space porous medium and subjected to a moving axisymmetric ring load. Hasheminejad et al. [31] studied the effect of imperfect bounding on axisymmetric elastodynamic response of a lined circular tunnel in poroelastic soil due to a moving ring load. The limitation of these works is that the soil was treated as a full-space, thus it cannot model the wave reflections at the ground surface. Currently, no study was presented to investigate the dynamic response of tunnel buried in a saturated poroelastic half-space.

This paper theoretically investigated the dynamic response of the ground induced by a point load moving uniformly along an infinite long beam inside a two-dimensional soil layer. The soil layer was modeled as saturated poroelastic medium, which was more realistic than the single-phase elastic medium. Biot's theory was adopted to describe the poroelastic layer. The beam was described by the Euler–Bernoulli model and located parallel to both the surface and the bottom of the layer. Using the stress and displacement compatibility conditions along the beam and poroelastic layer, the expressions for displacement and pore pressure were solved analytically in the frequency–wavenumber domain. The time domain results were obtained by the fast inverse Fourier transform. The critical velocity of the considered structure was analyzed. The different dynamic characteristics of the elastic soil medium and the saturated poroelastic medium subjected to underground moving loads were investigated. In addition, a parametric analysis including the shear modulus of the solid skeleton, the permeability of the saturated soil and the load moving velocity, on displacement and pore pressure responses was presented. The proposed model can identify the different performance of the elastic soil medium and the poroelastic soil medium subjected to underground moving loads. It can also serve as the benchmark for comparison to other solutions obtained by strictly numerical or asymptotic approach from the theoretical viewpoint.

2. Model description

The model consists of an infinite long beam buried in a two-dimensional poroelastic layer and a uniformly moving load as shown in Fig. 1. The upper layer has a thickness h and the lower layer has a thickness H in z direction. It should be noted that the goal of current study is to determine the critical velocity of the considered structure, identify the different performance of the elastic soil medium and the poroelastic soil medium and perform a parametric analysis on displacement and pore pressure responses induced by underground moving loads. According to the research done by Andersen et al. [32], a simplified 2D model can give qualitatively the same results with the 3D model of the vibrations induced by underground moving loads. Consequently, for current study which the qualitative behavior rather than the quantitative behavior is of primary concern, a 2D model is considered sufficient. Moreover, results obtained by this model can be treated as an upper estimate of ground vibration level generated by a metro line which is of significance in the practical vibration control.

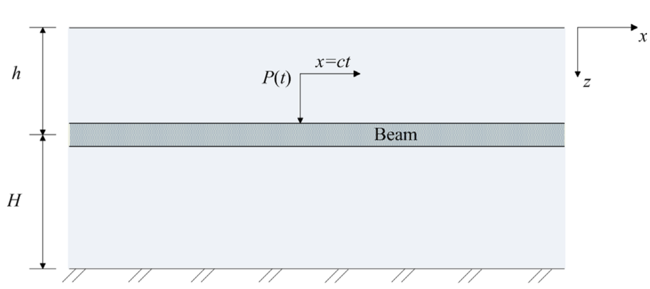

Fig. 1. Geometry of the problem model.

The equation of the Euler beam vertical motion is given as:

$$EI\frac{\partial^4 W}{\partial x^4}+\rho_B\frac{\partial^2 W}{\partial t^2}=P(t)\delta(x-ct)+a[\sigma_{zz}(x,h^-,t)-\sigma_{zz}(x,h^+,t)] \quad (1)$$

where $\sigma_{zz}(x, z)$ is the vertical stress; $W(x,t)$ is the beam vertical displacement; ρ_B and EI are the mass per unit length and the bending stiffness of the beam, respectively; $P(t)$ is the vertical point load acting on the beam at the point $x=ct$; c is the moving load velocity; $\delta(.)$ is the Dirac delta function; a is a characteristic length associated with the length of the structure in the y direction; h is the thickness of the upper layer.

Neglecting the apparent mass density, the linearized dynamic equations of motion for fully saturated poroelastic are given by Biot [19] as:

$$\mu u_{i,jj}+(\lambda+\alpha^2 M+\mu)u_{j,ji}+\alpha M w_{j,ji}=\rho\ddot{u}_i+\rho_f\ddot{w}_i \quad (2)$$

$$\alpha M u_{j,ji}+M w_{j,ji}=\rho_f\ddot{u}_i+m\ddot{w}_i+b\dot{w}_i \quad (3)$$

where u_i, w_i ($i=x$, z) are the solid displacement components and fluid displacement relative to solid displacement along the x, z directions; the subscript i,jj and j,ji are symbols of tensor and the summation convention is applied; dots on u_i and w_i indicate the derivatives with respect to time t; λ and μ are Lame constants; α and M are Biot's parameters accounting for the compressibility of the two-phase material; $\rho=n\rho_f+(1-n)\rho_s$, where ρ_f and ρ_s are the mass densities of the fluid and solid and n is the porosity; m is a density-like parameter that depends on ρ_f and the geometry of the pores; b is a parameter accounting for the internal friction due to the relative motion between the solid and the pore fluid. The parameter b equals to the ratio between the fluid viscosity and the intrinsic permeability of the medium ($b=0$ for zero internal friction). The hysteretic material damping in the soil skeleton can be accounted for by using complex Lame constants as $\lambda=\lambda(1+2i\beta)$ and $\mu=\mu(1+2i\beta)$, where $i=\sqrt{-1}$ is the imaginary unit and β is the hysteretic material damping ratio.

The constitutive relations can be expressed as:

$$\sigma_{ij}=\lambda\theta\delta_{ij}+\mu(u_{i,j}+u_{j,i})-\alpha\delta_{ij}p \quad (4)$$

$$p=-Mw_{i,i}-\alpha M\theta \quad (5)$$

where $\theta=u_{i,i}$ is solid strain; σ_{ij} is the total stress component of bulk material; p is the pore water pressure.

The boundary and interface conditions are given as:

$$u_x(x,h^+,t)=0,\ u_x(x,h^-,t)=0, \quad (6a)$$

$$u_z(x,h^-,t)=W(x,t),\ u_z(x,h^+,t)=W(x,t), \quad (6b)$$

$$\sigma_{zz}(x,0,t)=0,\ \sigma_{xz}(x,0,t)=0,\ p_f(x,0,t)=0, \quad (6c)$$

$$w_z(x,h^-,t)=0,\ w_z(x,h^+,t)=0, \quad (6d)$$

$$u_x(x,h+H,t)=0,\ u_z(x,h+H,t)=0,\ w_z(x,h+H,t)=0. \quad (6e)$$

The physical interpretation of these conditions are: the beam does not move horizontally (6a), the beam displacement and the