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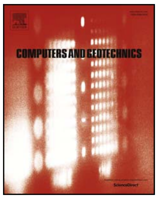

Research Paper

A vehicle-track-tunnel-soil model for evaluating the dynamic response of a double-line metro tunnel in a poroelastic half-space

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ABSTRACT

In this study, a three-dimensional vehicle-track-tunnel-soil model for evaluating the dynamic response of a double-line metro tunnel in a poroelastic half-space is developed. The model development consists of two steps. In the first step, the vehicle-track-tunnel-soil model in a full-space is developed. In the second step, based on the full-space model, the dynamic response of the poroelastic half-space is solved by using the 2.5-dimensional boundary integral equation and the Green's function. The developed vehicle-track-tunnel-soil model is validated against existing tunnel models and is demonstrated through a case study of the dynamic response induced by one-way and two-way train loads.

1. Introduction

The vibration from an underground railway can cause discomfort to residents and disturbance to sensitive equipment in nearby buildings [1]. The cyclic train loadings can also lead to long-term tunnel settlement in soft soil [2,3]. For instance, the maximum cumulative settlement of Shanghai Metro Line 1 reached 60 mm during the first eight-month service, in contrast to the 2–6 mm cumulative settlement that occurred within 27 months after the end of tunnel construction (during that period the metro line was not in service) [4]. The excessive tunnel settlement has damaged the tunnel structure (such as concrete cracks, segment dislocations and water leakage of the lining) in various metro systems [5,6]. There is an imminent need for the engineering practice in urban areas to reasonably evaluate the dynamic response of the tunnel-soil system of underground railways in the environmental vibration control and tunnel serviceability assessment.

The existing approaches to evaluating the dynamic response of underground railways mainly include analytical (or semi-analytical) modelling approaches, numerical modelling approaches, approaches that are experimentally based, or a hybrid of numerical and experimental approaches. The classical analytical or semi-analytical models include the embedded beam model [7] and the Pip in Pip model (PiP model) [8]. The PiP model [8] is computationally efficient but is only suitable for a deep-buried circular tunnel. The PiP model was further enhanced by incorporating a railway track, simulating scenarios such as two parallel circular tunnels, a double-deck circular tunnel and a layered elastic half-space [9–12]. Recently, a closed-form semi-analytical solution to the vibrations due to a moving point load in a tunnel embedded in an elastic half-space was also proposed [13]. The research efforts that focus on developing tunnel models using numerical approaches can be categorized as follows: (1) the finite element method (FEM), including the two-dimensional (2-D) FEM [14,15], modular FEM [16] and 2.5-D FEM [17]; (2) the finite element-boundary element (FE-BE) method, such as the 2.5-D FE-BE model [18,19] and the periodic FE-BE model [20–22]; (3) the finite/infinite element approach [23,24]; and (4) the finite difference method [25,26]. Numerical approaches can account for different forms of tunnel cross-sections (e.g., rectangular tunnels) and refined modeling, but a significant computational effort is required. Considering that the analytical (or semi-analytical) and numerical modelling approaches have model and parameter uncertainty [27], other research efforts in this field focus on vibration measurement and developing empirical methods [28–30]. While the empirical methods can better account for the particularities of the vibration transmission at a given site, they can only be applied in cases for which suitable data and prior experience are available [31]. To overcome these limitations, numerical and experimental hybrid methods for the prediction of railway-induced ground vibration have also been proposed [31,32].

In practice, a large number of metro tunnels are constructed in soft saturated soil, such as the metro systems in the coastal areas of China. Therefore, the actual field conditions will be better simulated if the model for the dynamic response of the tunnel-soil system can consider the saturated soil as a poroelastic medium [33]. In this regard, numerical approaches, including the 2.5-D FEM and the 2.5-D FE–BE

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model, were developed to simulate the dynamic response of a tunnel-saturated soil system [34–36]. Regarding the analytical or semi-analytical approaches, a few research efforts are reported. For example, the dynamic response of a tunnel buried in saturated poroelastic soil induced by a moving point load was investigated using the improved Euler beam model in [37]. The dynamic response of a circular tunnel in saturated soil subjected to axisymmetric ring load was investigated through the Fourier transformation methods [38]. Recently, the improved PiP models were developed to evaluate the dynamic response of a tunnel in a poroelastic full-space subjected to moving harmonic load and train loads [39–41].

However, the track structure is not included in most existing analytical models [37–39,41]. Some numerical models [34–36] and analytical models [40] simplify the track slab and rails as Euler beams, and the track is coupled to the tunnel-soil model with only one-line uniform support. The tunnel models with only one-line support are not adequate for simulating the tangential loads within the cross section of the tunnel. As a result, the existing models with one-line uniform support are only suitable for a single-line tunnel with symmetrical train loading. For large-diameter double-line tunnels in half-space saturated soil, a new computationally efficient tunnel model that can reasonably simulate the asymmetric dynamic response when subjected to one-way or two-way moving train loads is needed in the engineering practice.

In this paper, an improved 3-D vehicle-track-tunnel-soil model for evaluating the dynamic response of a double-line metro tunnel in a poroelastic half-space is developed. The procedure and methodology for the development of this model are illustrated in Fig. 1. The model development consists of two steps. In the first step, the vehicle-track-tunnel-soil model of a full space is developed. In the second step, based on the full-space model, the half-space vehicle-track-tunnel-soil model is developed by using the 2.5-D boundary integral equation and the Green's function for a poroelastic half-space medium. The proposed vehicle-track-tunnel-soil model is based on the semi-analytical solutions; therefore, it is computationally efficient. This new model is capable of (1) considering the actual train loads of multiple carriages, (2) simulating either a one-way moving train load on a single railway line or a two-way moving train load on a double railway line in a tunnel, and (3) modelling the tunnel's surrounding soil either as a saturated poroelastic medium or as a single-phase elastic medium in an infinite medium or a half-space. This developed vehicle-track-tunnel-soil model is validated by comparison with representative existing models and is illustrated through a case study of a double-line metro system in China.

2. Model development for a double-line metro tunnel

2.1. Simulation of a tunnel in a poroelastic full-space

In this study, the tunnel lining and the grouting layer of the shield tunnel are modelled as a double thin cylindrical shell with an infinite longitudinal length. The material of the double cylindrical shell is linear, elastic, homogeneous and isotropic. The saturated soil surrounding the grouting layer are modelled as a three dimensional, homogenous, isotropic porous medium in the form of a thick-wall cylinder with an inner diameter equal to the diameter of the double shell and an outer diameter of infinite extent, as shown in Fig. 2.

To simulate the asymmetric dynamic response when subjected to one-way or two-way moving train loads in a large-diameter double-line tunnel, the tunnel model should be capable of considering both the radial load P^r and the tangential load P^t acting on the tunnel invert (Fig. 2). The periodical load applied to the circular tunnel invert can be represented by a linear summation of sine and cosine components using Fourier series [10]. These cosine and sine components yield two types of loading conditions: load distributions that are symmetrical about one of the tunnel's axes of symmetry in the cross-sectional plane and load distributions that are antisymmetric about the same axis. These two loading conditions are referred to herein as the 'symmetric' and 'antisymmetric' loading cases, respectively.

The solution for the dynamic response of the tunnel-soil system under symmetric load (P^r) was developed in a previous study [41]. In this paper, the solution for the dynamic response of the tunnel-soil system under antisymmetric load (P^t) is systematically developed. For simplification, the coupling of the tunnel-soil system is re-structured and only the key steps are presented here, since the detailed derivation can be obtained in the previous study [41]. Although the displacement and stress of the saturated soil in a full-space model were given in the existing work, in this paper, the expression of average fluid displacement relative to the solid skeleton is implemented in the proposed model for calculating the dynamic response of a half-space using the 2.5-D boundary integral equation and the dynamic Green's function for a poroelastic half-space medium.

To derive the solution to wave propagation in the track-tunnel-soil system in the frequency and wavenumber domain, the double Fourier transform with respect to time t and coordinate z (along the tunnel axis) are adopted, expressed as [8]

$$\begin{cases} \widetilde{f}(\xi,\omega) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(z,t)\mathrm{e}^{-i(\xi z+\omega t)}dzdt \\ f(z,t) = \frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\widetilde{f}(\xi,\omega)\mathrm{e}^{i(\xi z+\omega t)}d\xi d\omega \end{cases} \tag{1}$$

where $i = \sqrt{-1}$, and the tilde "$\sim$" on the uppercase coefficients indicates that the quantities are in the frequency-wavenumber domain.

The equations of motion for the double cylindrical shell are partial differential equations and can be solved using the method of separation of variables. The modal displacements of the double cylindrical shell, as shown in Fig. 2, are denoted by the vector $\{\widetilde{U}_{zn},\widetilde{U}_{\theta n},\widetilde{U}_{rn}\}^T|_{tunnel}$ at the mean radius R of the cylinder in the longitudinal, tangential and radial directions. The subscript n represents the circumferential mode number. These displacements $\{\widetilde{U}_{zn},\widetilde{U}_{\theta n},\widetilde{U}_{rn}\}^T|_{tunnel}$ result from the net stresses, denoted by the vector $\{\widetilde{Q}_{zn},\widetilde{Q}_{\theta n},\widetilde{Q}_{rn}\}^T|_{tunnel}$, acting on the shell surface in the longitudinal, tangential and radial directions. The expression for the motion of the double shell can be written in matrix form as

$$\left.\begin{Bmatrix} \widetilde{U}_{zn} \\ \widetilde{U}_{\theta n} \\ \widetilde{U}_{rn} \end{Bmatrix}\right|_{tunnel} = [\widetilde{\mathbf{A}}']^{-1}\left.\begin{Bmatrix} \widetilde{Q}_{zn} \\ \widetilde{Q}_{\theta n} \\ \widetilde{Q}_{rn} \end{Bmatrix}\right|_{tunnel} \tag{2}$$

where the elements of matrix $[\widetilde{\mathbf{A}}']$ are given in Appendix A.

Similarly, the relationship between load and displacement can be obtained for the soil represented by a thick-walled cylinder. The modal displacements of the inner surface of the soil skeleton cylinder $\{\widetilde{U}_n\} = \{\widetilde{U}_{zn},\widetilde{U}_{\theta n},\widetilde{U}_{rn}\}^T$ are correlated with the tractions related to the same surface $\{\widetilde{T}_{rzn},\widetilde{T}_{r\theta n},\widetilde{T}_{rrn}\}^T$ obtained by solving the wave equation of motion in a poroelastic medium, expressed as

$$\{\widetilde{U}_n\} = \begin{Bmatrix} \widetilde{U}_{zn} \\ \widetilde{U}_{\theta n} \\ \widetilde{U}_{rn} \end{Bmatrix} = [\mathbf{U}_{\infty}]\cdot\quad[\mathbf{T}_{\infty}]^{-1}\begin{Bmatrix} \widetilde{T}_{rzn} \\ \widetilde{T}_{r\theta n} \\ \widetilde{T}_{rrn} \end{Bmatrix} = [\mathbf{U}_{\infty}]\begin{Bmatrix} B_1 \\ B_2 \\ B_r \\ B_z \end{Bmatrix} \tag{3-1}$$

The average fluid displacement relative to the solid skeleton $\{\widetilde{W}_n\}$ can be written as

$$\{\widetilde{W}_n\} = \begin{Bmatrix} \widetilde{W}_{zn} \\ \widetilde{W}_{\theta n} \\ \widetilde{W}_{rn} \end{Bmatrix} = [\mathbf{W}_{\infty}]\begin{Bmatrix} B_1 \\ B_2 \\ B_r \\ B_z \end{Bmatrix} \tag{3-2}$$

where the elements of matrices $[\mathbf{U}_{\infty}]$,$[\mathbf{T}_{\infty}]$ and $[\mathbf{W}_{\infty}]$ are given in