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An efficient method for predicting train-induced vibrations from a tunnel in a poroelastic half-space

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ABSTRACT

This paper presents an efficient method for the prediction of vibrations induced by underground railways in a poroelastic half-space. The proposed method accounts for both the saturated porous characteristic of the soil and the free surface effect. An analytical tunnel model, which is coupled with a train-track system, is firstly developed to calculate the dynamic response of the tunnel–soil interface in a poroelastic full-space. By assuming that the near field response of the tunnel is not affected by the existence of the free surface, vibrations of the poroelastic half-space is then calculated by the two-and-a-half-dimensional (2.5-D) boundary integral equation for saturated porous media along with the Green's function for a poroelastic half-space. Soil vibrations generated by the quasi-static and dynamic train load are presented. It is found that an increase of the soil permeability leads to a decrease of the soil displacement. A saturated soil model may be more suitable for calculating the train-induced vibration in water-rich region. Isolation effectiveness of a float slab is also investigated. The simulation results show that floating the track slab can moderately induces the ground vibration, but also causes more transmission of vibration under certain conditions.

1. Introduction

Metro tunnels are usually located in densely populated downtown area with crowded buildings. The ground vibration induced by railway traffic in tunnels may cause some environmental impact such as malfunction of sensitive equipment and annoyance to inhabitants. The problem is more significant for shallow tunnels in close proximity to foundations of nearby buildings.

Modelling of the dynamic response of a tunnel–soil system is gaining more interest to meet the need for quick tools to design vibration countermeasures for both existing and newly constructed tunnels. Several models have been established to simulate the dynamic response of a tunnel–soil system. Metrikine and Vrouwenvelder [1] and Haak [2] proposed an embedded beam model to study the ground vibrations induced by moving train loads, in which the tunnel is modelled as an embedded Euler beam. Although this analytical model is convenient for parametric analysis, the accuracy of vibration prediction is limited owing to oversimplification. The Pipe in Pipe (PiP) model [3] is a three-dimensional analytical model for predicting the vibration from a tunnel buried in a full-space. The tunnel and the soil are conceptualized as two concentric pipes in the PiP model. The inner pipe, which represents the tunnel, is modelled using thin shell theory. The outer pipe with infinite radius, which represents the surrounding soil, is simulated by elastodynamics. The PiP model was further improved by Forrest and Hunt [4] and Hussein and Hunt [5], who incorporated a floating slab track of the metro tunnel. By using the Green's functions for a layered half-space, the PiP model is extended to predict vibrations from underground railways that allows for the incorporation of a multi-layered half-space geometry [6]. The PiP model is computationally efficient and is suitable for tunnels with circular cross-section.

The coupled finite element–boundary element (FE–BE) model is a numerical approach, where the tunnel is modelled using the FE method and the surrounding soil is modelled using the BE method. In order to reduce the computational cost, the tunnel geometry is in some cases assumed to be periodic or invariant in the longitudinal direction. For periodic structures, a periodic FE–BE model can be used to determine the structural response and the radiated wave field [7–11]. The Floquet transform of the longitudinal coordinate allows the three-dimensional (3-D) response to be represented on a single-bounded reference mesh. In the case of longitudinally invariant structures, a two-and-a-half-dimensional (2.5-D) coupled FE–BE model was presented by Sheng et al. [12,13]. By applying the Fourier transform of the longitudinal coordinate, only a two-dimensional (2-D) mesh is required to obtain 3-D responses of the structure and the surrounding soil. François et al. [14] and Galvín

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et al. [15] introduced the regularized 2.5-D boundary integral equation and Green's function for a layered elastodynamic half-space to improve the computational efficiency of the model. In addition, Yang and Hung [16] proposed a 2.5-D finite/infinite element method to analyse wave propagation problems caused by underground moving trains. Even with these recent developments, numerical modelling for dynamic responses of a tunnel–soil system still requires significant computational efforts.

It should be noted that the aforementioned models for evaluating the vibration induced by underground railway traffic do not consider the effect of pore-water in soil. In practice, a large number of metros are constructed in saturated soft soils and many tunnels are located below ground water level. According to Biot's theory [17,18], the propagation of elastic waves in a saturated porous medium is different from that in a single-phase medium, and some special wave motion phenomena have also been verified by experiments [19]. Therefore, it is expected that a model considering surrounding soils as saturated porous media will provide more rational results for the dynamic response of a tunnel–soil system. Among the numerical approaches, the train-induced vibrations from a tunnel in saturated soils were investigated using 2.5-D FEM [20]. A 2.5-D coupled FE–BE model for the dynamic interaction between saturated soils and longitudinally invariant structures was also proposed [21]. However, the numerical models require a significant computational effort and are still computationally too expensive to be used as a design tool. Regarding the analytical approaches, Hasheminejad and Komeili [22] proposed a method to calculate the axisymmetric elastodynamic response of a lined circular tunnel in the saturated soil. Yuan et al. [23] and Di et al. [24] developed an analytical model for vibration prediction of a tunnel embedded in a saturated full-space to a radial harmonic point load applied at the tunnel invert. However, the existing analytical approaches for saturated soils [22–24] are established in a poroelastic full-space without considering the effect of free surface for real engineering systems. In addition, the effect of track is not considered in these analytical models.

In this paper, an efficient method for calculating the vibration from a tunnel embedded in poroelastic half-space is presented. The proposed method is able to account for both the saturated porous characteristic of soils and the free surface effect. An analytical tunnel model, which is coupled with the train-track system, is firstly developed to calculate the dynamic response of a tunnel embedded in a poroelastic full-space. The rail and track slab are formulated as Euler beams and the slabs are coupled to the tunnel via three lines of uniform supports. The train load is divided into the quasi-static and dynamic components. Next, by assuming that the near field response of the tunnel is not affected by the existence of a free surface, the dynamic responses of the poroelastic half-space are calculated by the 2.5-D boundary integral equation for saturated porous media along with the Green's function for a poroelastic half-space.

The paper is organized as follows. Section 2 describes the methodology used in this paper, where a distinction is made between the two steps for the calculation of vibrations from a tunnel in a poroelastic half-space. Section 3 assesses the performance and accuracy of the proposed method via comparison with the existing numerical model. Section 4 presents a numerical study to investigate soil vibrations generated by the harmonic load and train load applied at the rails.

2. Methodology development for a poroelastic half-space

This section presents the methodology for the calculation of vibrations induced by underground railways in a poroelastic half-space. Based on the assumption that the near field response of a tunnel is not affected by the existence of a free surface, the methodology consists of two steps, as outlined in Fig. 1. In the first step, an analytical tunnel model, which is coupled with a train-track system, is developed to calculate the dynamic response of a tunnel embedded in a poroelastic full-space, as shown in Fig. 1(a). The assumption that the tunnel is embedded in a full-space allows for a fast evaluation of the dynamic response on the tunnel–soil interface. In the second step, a model of the poroelastic half-space with a cylindrical cavity is considered, as shown in Fig. 1(b). The vibration of the soil is calculated by the 2.5-D boundary integral equation for saturated porous media along with a Green's function for a poroelastic half-space. The displacements, stresses and pore-water pressure on the tunnel–soil interface calculated in the first step are treated as known boundary conditions in this model. The two steps of calculation are discussed in more details in the following subsections.

2.1. Step 1: calculation of dynamic responses on the tunnel–soil interface

In this step, an analytical tunnel model is developed to determine the displacements, stresses, and pore-water pressure on the tunnel–soil interface induced by underground railways. This model consists of four interrelated components:

(1) The tunnel that is modelled as a cylindrical shell of infinite length.
(2) The soil that is modelled as a poroelastic full-space.
(3) The track slab and rails that are formulated as Euler–Bernoulli beams, of which the slab is coupled to the tunnel via three lines of uniform supports. Generally the track slab is constructed in segment and not a continuous structure. It is illustrated in Ref. [27] that the dynamic response for a discontinuous slab has a good match with that for a continuous slab except at the resonance frequencies of the slab, at which a slab track with a discontinuous slab tends to result in more vibrations. Therefore, if the ground vibration under the resonance frequencies of the slab is concerned, a track model with the discontinuous slab should be considered. The theoretical derivation of a track model with the discontinuous slab can be found in Ref. [27].
(4) The wheel/rail force can be decoupled into two components: quasi-static and dynamic. The quasi-static component is due to the movement of static axle loads of the train and the dynamic component arises from inertial forces generated by vehicle/track interaction. Therefore, a series of axle loads moving at a constant velocity is used to model the quasi-static force. The dynamic excitation generated by vehicle/track interaction is further considered by coupling a vehicle dynamics model to the analytical model in the frequency domain.

To derive the solution of this model in the frequency–wavenumber domain, two types of Fourier transform are involved: (1) the Fourier transform with respect to time t to frequency ω, and (2) the Fourier transform with respect to coordinate z (along the tunnel axis) to wavenumber k_z [25]:

$$\hat{f}(\omega) = \int_{-\infty}^{+\infty} f(t)e^{-i\omega t}\mathrm{d}t, \quad f(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \hat{f}(\omega)e^{i\omega t}\mathrm{d}\omega \tag{1a}$$

$$\bar{f}(k_z) = \int_{-\infty}^{+\infty} f(z)e^{ik_z z}\mathrm{d}z, \quad f(z) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \bar{f}(k_z)e^{-ik_z z}\mathrm{d}k_z \tag{1b}$$

2.1.1. Wave propagation in the tunnel

The tunnel is modelled as a cylindrical shell of infinite length. Performing the Fourier transforms in Eqs. (1a) and (1b), the displacement vector $\tilde{\mathbf{u}}_T = \{\tilde{u}_{Tz}(r,\theta,k_z,\omega),\ \tilde{u}_{T\theta}(r,\theta,k_z,\omega),\ \tilde{u}_{Tr}(r,\theta,k_z,\omega)\}^{\mathrm{T}}$ and the stress vector $\tilde{\mathbf{q}}_T = \{\tilde{q}_{Tz}(r,\theta,k_z,\omega),\ \tilde{q}_{T\theta}(r,\theta,k_z,\omega),\ \tilde{q}_{Tr}(r,\theta,k_z,\omega)\}^{\mathrm{T}}$ of the shell can be expressed as a Fourier series expansion in the circumferential direction θ. For the case of a symmetrical load applied radially to the inside of tunnel

$$\tilde{\mathbf{u}}_T^1 = \sum_{n=0}^{\infty} \mathbf{S}_n^1 \tilde{\mathbf{U}}_{Tn}^1, \quad \tilde{\mathbf{q}}_T^1 = \sum_{n=0}^{\infty} \mathbf{S}_n^1 \tilde{\mathbf{Q}}_{Tn}^1 \tag{2}$$

And for the case of an antisymmetric load applied tangentially to the inside of tunnel

$$\tilde{\mathbf{u}}_T^2 = \sum_{n=0}^{\infty} \mathbf{S}_n^2 \tilde{\mathbf{U}}_{Tn}^2, \quad \tilde{\mathbf{q}}_T^2 = \sum_{n=0}^{\infty} \mathbf{S}_n^2 \tilde{\mathbf{Q}}_{Tn}^2 \tag{3}$$