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The influence of pore-fluid in the soil on ground vibrations from a tunnel embedded in a layered half-space

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A B S T R A C T

A computationally efficient semi-analytical solution for ground-borne vibrations from underground railways is proposed and used to investigate the influence of hydraulic boundary conditions at the scattering surfaces and the moving ground water table on ground vibrations. The arrangement of a dry soil layer with varying thickness resting on a saturated poroelastic half-space, which includes a circular tunnel subject to a harmonic load at the tunnel invert, creates the scenario of a moving water table for research purposes in this paper. The tunnel is modelled as a hollow cylinder, which is made of visco-elastic material and buried in the half-space below the ground water table. The wave field in the dry soil layer consists of up-going and down-going waves while the wave field in the tunnel wall consists of outgoing and regular cylindrical waves. The complete solution for the saturated half-space with a cylindrical hole is composed of down-going plane waves and outgoing cylindrical waves. By adopting traction-free boundary conditions on the ground surface and continuity conditions at the interfaces of the two soil layers and of the tunnel and the surrounding soil, a set of algebraic equations can be obtained and solved in the transformed domain. Numerical results show that the moving ground water table can cause an uncertainty of up to 20 dB for surface vibrations.

1. Introduction

Underground railways as an important means of mitigating the crowed traffic in densely populated cities can directly affect the living quality of inhabitants who live near railway lines. The ground-borne vibrations and air-borne noise generated by underground moving trains are unlikely to result in severe structural damage but it affects human comfort, disturbs people's sleep and causes much anxiety, which has negative effects on people's mood, activity and health. Also, such disturbances affect the normal function of sensitive equipment, thus it has been generally recognized as an important environmental problem [1–3].

The demand to predict and quantify these vibrations has attracted more and more researchers to examine this issue and many semi-analytical or numerical models have been proposed during the past two decades. Some simple two-dimensional (2D) models [4,5] were proposed to compute the ground-borne vibrations, which have advantage of high computational

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efficiency but cannot account for the wave propagation in the third direction, implying that 2D models can only predict the vibrations in a qualitative way, rather than in a quantitative way [6,7].

By assuming the tunnel as a thin shell or a hollow cylinder embedded in a full-space, a three-dimensional (3D) analytical solution for calculating vibrations from deep underground railways, called the Pipe-in-Pipe (PiP) model, was proposed by Forrest and Hunt [8] and validated with other numerical models [9]. Although the ground surface was not considered in the PiP model, it can easily be coupled with different types of track structures and evaluate the performance of vibration countermeasures in underground tunnels [10,11]. Recently, by assuming that the displacement of the tunnel was not influenced by the ground surface or the soil layer interface, Hussein et al. [12] extended the PiP model to account for a tunnel embedded in a multi-layered half-space and verified it by comparing with 2.5D coupled finite- and boundary-element method (FEM-BEM) calculations. A closed-form analytical solution for vibrations from a point source in a tunnel embedded in a homogeneous visco-elastic or poroelastic half-space was proposed by Yuan et al. [13,14], in which multiple-scattering effects between the ground surface and the tunnel-soil interface can be taken into account. The above analytical model is capable of calculating vibrations from a railway tunnel with a circular cross-section efficiently but is not applicable for more complex geometries.

Fully 3D numerical discretization methods can solve more practical situations and adapt to arbitrary geometries, but high the computational cost restricts its application [7]. To reduce the computation time, the 2.5D methodology was proposed by assuming the geometrical and material properties along the tunnel direction to be invariant or periodical. With the aid of a Fourier or Floquet transform, the space domain in the tunnel direction is transformed to the wavenumber domain which gives the possibility to obtain the 3D response of the tunnel-soil system with a 2D discretized mesh [15,16]. As the 2.5D approach achieves a compromise between the computational efficiency and the ability to solve complex situations, during the past decades it is successfully applied with FEM, BEM and coupled FEM-BEM. In the 2.5D methodology, the finite near-field structure is modelled using FEM while the infinite far-field is simulated using the BEM or various artificial absorbing boundaries, for instance the viscous boundary [17], the infinite element [18], the thin layer element [19] or the perfectly matched layer (PML) [20], to ensure that no wave is reflected from infinity. Sheng et al. [21] used a 2.5D wavenumber FE-BE method to model ground vibrations from a railway tunnel and compared two alternative tunnel designs for a double-track line, a single double-track tunnel and a pair of single-track tunnels, in terms of vibration on the ground surface. Hung and Yang [22] analyzed the wave propagation due to underground moving loads using the 2.5D FEM with infinite elements to model the far-field extending to infinity. Lopes et al. [23] used a similar 2.5D formulation to model the track-tunnel-soil interaction with PML as the artificial boundary absorbing outgoing waves. Instead of assuming the tunnel-soil system invariant in the longitudinal direction, Degrande et al. [24,25] considered it as a periodical structure and proposed a periodic 2.5D FEM-BEM by the Floquet transform, restricting the discretization to a single reference cell rather than 2D slices in the standard 2.5D methodology. This model was successfully used for the prediction of vibrations induced by underground railways in London, Groene Hart and Beijing [26–28]. It is worth noting that Müller et al. [29] presented a coupled method for modelling vibrations from an underground tunnel of arbitrary shape, which has some characteristics of the 2.5D FEM as well as the semi-analytical method. A fictitious cylindrical surface that encloses the tunnel divides the tunnel-soil system into two parts: one part is the tunnel of arbitrary shape and a portion of the surrounding soil within the fictitious surface discretized by the 2.5D FEM and another part is the half-space with a cylindrical cavity whose approximate solution is found using the solutions for a uniform half-space and a full-space with a cylindrical cavity.

Based on the computationally efficient PiP model, some uncertainty analysis associated with simplifying assumptions used to reduce the complexity of vibration prediction models were performed to investigate the effect of the inclusion of ground surface [30], twin tunnel interaction [31], voids between the tunnel-soil interface [32] and the tunnel-soil-pile interaction [33] on ground-borne vibrations from underground moving trains. Similarly, the level of vibration prediction uncertainty due to soil inhomogeneity, inclined soil layers and source-receiver interaction was also analyzed [34–36]. Another assumption usually made in the majority of vibration prediction models is to regard the soil medium as a single-phase material and neglect coupling effects between the solid skeleton and the pore fluid. However, investigations for ground-borne vibrations induced by surface moving trains have shown that the water presence in the soil medium cannot be ignored and the equivalent one-phase model for the two-phase material leads to inaccuracy in vibration calculations, especially when the soil permeability or the load velocity is high [37,38]. If the soil medium is modelled as a two-phase material, the influences of pore-fluid related parameters and hydraulic boundary conditions at scattering surfaces can be studied [39,40]. Besides, the effect of the seasonal variation of the ground water table on the wave propagation can also be investigated [41,42].

This paper presents a semi-analytical solution for vibrations from a tunnel embedded in a layered half-space to assess the influence of the pore-fluid in the soil medium and to determine the level of uncertainty associated with the hydraulic boundary condition at the scattering surfaces and the variation of the ground water table. The moving ground water table is simulated by a dry soil layer with varying thickness resting on the underlying poroelastic saturated half-space. If the ground water table rises, the submerged part becomes water-saturated and will be taken as the poroelastic medium. The tunnel is modelled as a hollow cylinder, which is buried in the half-space below the ground water table. The wave field in the dry soil layer (or in the tunnel wall) consists of up-going and down-going plane (or outgoing and regular cylindrical) waves. The wave field in the saturated half-space with a cylindrical hole is composed of down-going plane waves from the free surface and outgoing cylindrical waves from the hole, as follows from the surface integral representation for the elastodynamic field with the free space Green's tensor expanded in terms of plane waves and cylindrical waves on the respective surface. Some