Soil Dynamics and Earthquake Engineering 115 (2018) 319–323

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Study on dynamic responses of unsaturated railway subgrade subjected to moving train load

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ARTICLE INFO

Keywords:
Unsaturated subgrade
Moving load
Railway track
Matrix method
Fourier transform
Dynamic responses

ABSTRACT

A new track-multilayer ground model was established to investigate railway subgrade dynamic responses induced by moving train load in this paper. The ground structure was modeled by an elastic layer overlying an unsaturated porous elastic half space. The dynamic governing equations of the three-phase porous medium, which are easy to be degraded to Biot's theory, were derived with consideration of both viscous drag and inertial coupling between pore fluids and soil skeleton as well as capillary pressure. The model solutions were obtained based on dynamic stiffness matrix method and Fourier transform and introducing corresponding boundary condition. The vertical displacement on the subgrade top surface and the pore water pressure along the depth were studied. The numerical results show that the effects of saturation, vehicle speed, train axle load and subgrade bed material properties on the subgrade responses are significant.

1. Introduction

As the safety, comfort and stability demands of moving high speed train improve, the problem of railway subgrade dynamic responses caused by moving train load has attracted a lot of attention in recent few decades. The high speed train not only has a more serious impact on people's life but also makes greater damages for railway structures than a normal-speed train does [1]. The unsaturated property of subgrade soil greatly affects the dynamic analysis of subgrade itself [2]. Thus, studying this dynamic response subject with consideration of these effects is significant.

The multilayer soil model is widely used to investigate the dynamic responses of the ground structure. Sheng et al. [3] analytically investigated the vibration generated by a moving harmonic load for three different velocities along the track resting on the ground. Beskou et al. [4] also studied the dynamic response of an plate on a cross-anisotropic elastic half-plane based on analytical method. By means of numerical simulation, Beskou et al. [5] and Ruiz et al. [6] respectively analyzed vehicle-induced flexible pavement responses and traffic-induced railway ground vibrations using commercial programs ANSYS and PLAXIS. However, the effect of pore water cannot be considered in their studies. By taking the impact of this important parameter into consideration, under the plane-strain condition, Chen et al. [7] employed full Biot's equations of motion to solve the dynamic problem of an elastic plate on a cross-anisotropic poroelastic half-space. Treating the ground as a multilayered structure, Lefeuve-Mesgouez and Mesgouez [8] and Yao et al. [9] conducted the dynamic analysis by their presented models, of which the difference is that one ground was modeled as a poroviscoelastic multilayered soil and the other one was denoted by two elastic layers overlying a poroelastic half-space. While in practical engineering, the subgrade is unsaturated and Fredlund and Rahardjo [10] repeatedly emphasized that the air phase had a significant impact on the analysis of deformation and stress in unsaturated soils. Therefore, it is much necessary to treat some ground structures as unsaturated layers to carry out dynamic analysis.

In this paper, a railway track-elastic subgrade bed-unsaturated porous subgrade model was built to obtain the train-load-induced subgrade dynamic responses. Based on the dynamic stiffness matrix method and Fourier transformation, the solutions for the track-ground system were obtained and finally a parameter study was conducted by numerical calculation.

2. Solutions for the railway track-ground system

2.1. For the track and elastic layer

A 3D track-multilayer ground coupling model is considered in this study, as shown in Fig. 1. The track model and its solutions and some

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https://doi.org/10.1016/j.soildyn.2018.08.037
Received 16 August 2018; Received in revised form 29 August 2018; Accepted 29 August 2018
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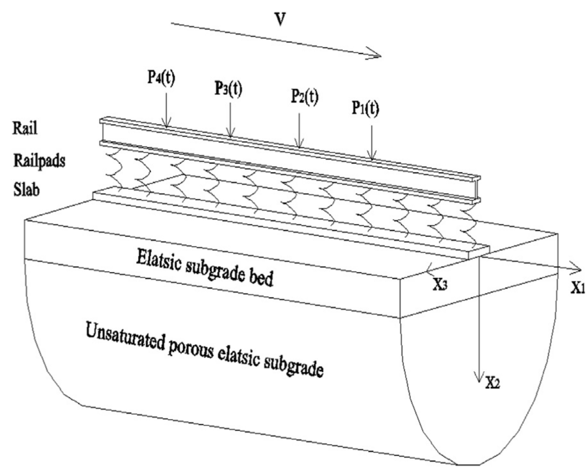

Fig. 1. Geometry of the track-ground model.

railway parameters are based on the research of Sheng et al. [3]. The subgrade bed is modeled by an elastic layer with thickness H_b, of which solutions can be given by six constants and a relation between displacement and stress can be derived by [9]

$$\{\overline{\Sigma}_b\} = [S^b][D^b]^{-1}\{\overline{U}_b\} = [K^b]\{\overline{U}_b\} \tag{1}$$

where $[D^b]$ and $[S^b]$ denote displacement and stress matrixes, $[K^b]$ is dynamic stiffness matrix.

2.2. For the unsaturated half-space

In terms of the subgrade, for an unsaturated half-space, the behavior law is given by

$$\tau_{ij}^s = \lambda_s\theta_s\delta_{ij} + 2\mu_s\varepsilon_{ij}^s - \delta_{ij}ap \tag{2}$$

where $\boldsymbol{\tau}^s$, $\boldsymbol{\varepsilon}^s$ are stress and strain vectors, respectively; λ_s, μ_s are Lame constants and δ_{ij} denotes Kronecker delta; θ_s represents volumetric strain; the coefficient $a = 1\text{-}K_b/K_s$, K_b, K_s respectively represent compressive modulus of soil skeleton and solid grain and $K_b \ll K_s$; the equivalent pore fluid pressure $p = \chi p^w + (1\text{-}\chi)p^a$, p^w, p^a denote pore pressures of water and air, χ is an effective stress parameter, of which value is equal to that of saturation.

By introducing the relative displacement vectors $\mathbf{w} = nS_r(\mathbf{u}^w\text{-}\mathbf{u}^s)$, $\mathbf{v} = n(1\text{-}S_r)(\mathbf{u}^a\text{-}\mathbf{u}^s)$ and neglecting body force as well as dissipation, the motion equation can be derived

$$\tau_{ij,j}^s = \rho\ddot{u}_i^s + \rho_w\ddot{w}_i + \rho_a\ddot{v}_i \tag{3}$$

where $\mathbf{u}^s$, $\mathbf{u}^w$ and $\mathbf{u}^a$ denote displacement vectors of solid grain, pore water and air; the total density $\rho = (1-n)\rho_s + nS_r\rho_w + n(1-S_r)\rho_a$, ρ_s, ρ_w and ρ_a are absolute mass densities of each individual phases, S_r is saturation, n represents soil porosity; ($\dot{}$) denotes time derivative.

Based on generalized Darcy's law, the seepage equations of motion can be written as

$$-p^w{}_{,i} = \rho_w\ddot{u}_i^s + \rho_w\ddot{w}_i/(nS_r) + \rho_w g\dot{w}_i/k_w,\ \ -p^a{}_{,i} = \rho_a\ddot{u}_i^s + \rho_a\ddot{v}_i/[n(1-S_r)] + \rho_a g\dot{v}_i/k_a \tag{4}$$

in which g represents gravity acceleration; k_w, k_a are permeability coefficients, according to Fredlund and Rahardjo [10] $k_w = \rho_w g\kappa k_{rw}/\eta_w$, $k_a = \rho_a g\kappa k_{ra}/\eta_a$, where η_w, η_a are dynamic viscosities, κ denotes intrinsic permeability, the relative permeability coefficients k_{rw}, k_{ra} are obtained based on theoretical pore size distribution model [11].

From Eqs. (2)–(4), the following equation can be derived

$$\mu_s\nabla^2\mathbf{u}^s + (\lambda_s + \mu_s)\nabla(\nabla\cdot\mathbf{u}^s) - a\chi\nabla p^w - a(1-\chi)\nabla p^a = \rho\ddot{\mathbf{u}}^s + \rho_w\ddot{\mathbf{w}} + \rho_a\ddot{\mathbf{v}} \tag{5}$$

Rewriting Eq. (2) based on space average method and using the constitutive equation for solid grain deformation due to stress component exerted on solid skeleton $\boldsymbol{\tau}^{ss}$ given by $d\rho_s/(\rho_s dt) = -d\tau_{ii}^{ss}/(3K_s dt)$ then gives

$$d\rho_s/(\rho_s dt) = \{(a\chi - nS_r)\dot{p}^w + [a(1-\chi) - n(1-S_r)]\dot{p}^a - K_b\nabla\cdot\dot{\mathbf{u}}^s\}/[(1-n)K_s] \tag{6}$$

Likewise, similar relations exist for deformations of pore water and air

$$d\rho_w/(\rho_w dt) = dp^w/(K_w dt),\ \ d\rho_a/(\rho_a dt) = dp^a/(K_a dt) \tag{7}$$

where K_w, K_a denote bulk compression modulus.

The mass conservation equations are written as [12]

$$\partial\overline{\rho}_m/\partial t + (\overline{\rho}_m\dot{u}_i^m)_{,i} = 0,\ \ m = s, w, a \tag{8}$$

in which $\overline{\rho}_m$ (the subscripts $m = s$, w, a corresponding to solid grain, water and air) stand for apparent densities, which are denoted by $\overline{\rho}_s = (1-n)\rho_s$, $\overline{\rho}_w = nS_r\rho_w$ and $\overline{\rho}_a = n(1-S_r)\rho_a$.

Supposing that the change rates of n, ρ_m and S_r in space are far less than that regarding time, combining Eq. (6) and Eq. (8) (m = s), the porosity time derivative is obtained

$$\dot{n} = (1 - n - K_b/K_s)\nabla\cdot\dot{\mathbf{u}}^s + (a\chi - nS_r)\dot{p}^w/K_s + [a(1-\chi) - n(1-S_r)]\dot{p}^a/K_s \tag{9}$$

In order to obtain saturation time derivative, the soil water characteristic curve model proposed by Genuchten [13] $S_e = [1-(\alpha p_c)^d]^{-m}$ is introduced, thus gives

$$\dot{S}_r = -\alpha md(1 - S_{w0})(S_e)^{\frac{m+1}{m}}\left[(S_e)^{-\frac{1}{m}} - 1\right]^{\frac{d-1}{d}}(\dot{p}^a - \dot{p}^w) \tag{10}$$

where the matrix suction $p_c = p^a\text{-}p^w$, α, m and d are fitting parameters and usually $m = 1-1/d$, here $m = 0.5$, $d = 2$; the effective saturation $S_e = (S_r\text{-}S_{w0})/(1\text{-}S_{w0})$, S_{w0} is irreducible saturation. The variation of shear modulus, which was influenced by saturation, was considered in this study. Based on V-G model, the relationship between these two parameters is given by [14]

$$\mu_s = \mu + 2200\ln\left(\sqrt{(S_e)^{-2} - 1} + (S_e)^{-1}\right)\tan\varphi'/\alpha \tag{11}$$

where μ denotes shear modulus in the saturated case, φ' is internal friction angle.

Putting Eqs. (7)–(10) into Eq. (8) (m = w, a) obtains

$$A_{11}\dot{p}^w + A_{12}\dot{p}^a + A_{13}\nabla\cdot\dot{\mathbf{u}}^s + A_{14}\nabla\cdot\dot{\mathbf{v}} = 0,\ \ A_{21}\dot{p}^w + A_{22}\dot{p}^a + A_{23}\nabla\cdot\dot{\mathbf{u}}^s + A_{24}\nabla\cdot\dot{\mathbf{w}} = 0 \tag{12}$$

where the coefficients A_{11}-A_{24} and the related solutions can refer to reference [14], then gives

$$\{\overline{\Sigma}_s\} = [S^s][D^s]^{-1}\{\overline{U}_s\} = [K^s]\{\overline{U}_s\} \tag{13}$$

2.3. Boundary conditions and corresponding solutions

The displacement and stress are assumed to be continuous at the ground interface, which is also considered to be fully permeable. Combining these assumptions with Eqs. (1) and (13), the relationship between displacements and stresses at each layer interface can be obtained

$$\{\overline{U}\} = [B]\{\overline{\Sigma}\} = [K]^{-1}\{\overline{\Sigma}\} \tag{14}$$

where $[B]$ denotes inverse stiffness matrix of which size is 8×8 for multilayer ground.

Four vertical plane contact forces $P_1(t)$, $P_2(t)$, $P_3(t)$, $P_4(t)$ with a moving speed V along x direction are considered, as shown in Fig. 1. According to results in studies [3,9], the vertical force induced by slab can be obtained, therefore, the boundary conditions are given by