Soil Dynamics and Earthquake Engineering 102 (2017) 25–40

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Response of railway track coupled with a stratified ground consisting of saturated interlayer to high-speed moving train load

Shi-Jin Feng*, Yi-Cheng Li, Zhang-Long Chen, H.X. Chen

Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China

ARTICLE INFO

Keywords:
Track-ground system
Layered ground
Vibration
Poroviscoelastic
Stiffness matrix method

ABSTRACT

A three-dimensional track-ground model is developed to study vibrations induced by high-speed train. The train loads are simplified as a series of moving point loads. The track system consists of rail, pads, sleeper and ballast. The ground consists of a treated soil layer, a crust, a saturated layer and semi-infinite bedrock, which considers the alternate distribution of viscoelastic and poroviscoelastic media. The ground is coupled with the track system according to the continuity conditions between the ballast and ground surface. Fourier transform is applied to solve the governing equations. Some adaptions are made on the basis of classical stiffness matrix method to give solution to the stratified ground. Semi-analytical solution to the coupling system is derived in the wavenumber domain. Solution in spatial and time domains is obtained with the aid of inverse fast Fourier transform (iFFT). The present method is verified against the published analysis results first. Dynamic responses of the coupling system such as displacement, acceleration and pore-water pressure, are then comprehensively investigated. The results indicate that the existence of ground water significantly influences the surface displacement of the ground while the influence on velocity and acceleration is weaker; 'critical speeds' for vertical displacement and acceleration exist for ground but the variations with distance from track center are complicated and depend on soil properties; load speed greatly influences pore-water pressure distribution while the influence of drainage condition is relatively small.

1. Introduction

High speed train has dominated inter-city traffic in many countries. It is fast, comfortable and safe, but also brings a series of problems such as track-ground instability and environmental vibration. For example, intense vibrations of track-ground system induced by high-speed trains have been observed in Europe [1,2]. Moreover, if the train speed approaches the critical speed of track-ground system, a resonant like phenomenon would occur, posing threat to the track system. Great efforts have been made to study the critical speed in recent decades. It was found that the critical speed is closely related to the Rayleigh wave speed of the ground [3–6] and controlled by the minimum phase velocity of the first Rayleigh mode of the embankment-ground system [7]. Further studies [8–11] also indicated that the critical speed is dominated by the surface wave characteristics of the embankment-ground system and bending wave properties of the rail.

Due to vibration problems mentioned above, extensive researches have been conducted to predict track-ground response and help the design of high-speed railway. Existing researches on numerical and analytical vibration prediction models can generally be classified according to the model of superstructures (i.e., embankment, track and vehicles) and subsoil.

To consider the superstructures, an analytical model with a beam lying on an elastic foundation was introduced [12,13]. Analytical models of more comprehensive track system were then proposed [14–16] and applied [17–19]. Dynamic responses of more practical track system were also studied adopting FE or/and BE methodology [20–25]. In these studies, the load from vehicle is taken as constant loads acting on the track system. To consider the dynamic response induced by vehicle-track interaction, random vibration of the track system is investigated [26–30]. The abovementioned models are helpful in understanding the mechanism of wave propagation, but the influence of vehicle structure was not well considered. Thus a multi-body vehicle model was adopted to consider the influence of vehicle structure [31–37].

Ground model is another concern in this field. Vibration problems with moving loads on a homogeneous or layered elastic/viscoelastic half-space were first investigated [38–41]. When train speed is high,

* Corresponding author.
E-mail address: fsjgly@tongji.edu.cn (S.-J. Feng).

http://dx.doi.org/10.1016/j.soildyn.2017.08.018
Received 2 April 2017; Received in revised form 6 July 2017; Accepted 26 August 2017

dynamic strains of the embankment and ground are large and behave nonlinearly [7]. Thus soil non-linearity has been included in some researches since the early twenty-first century [7,42–44], but the existence of ground water was not considered. To consider the existence of ground water, Biot's theory [45] was introduced to model saturated poroelastic/poroviscoelastic soil [46–49]. However, ground can be composed of soils with different water contents and porosities. Soils with low free water content (e.g., bedrock, dense clayed soil) can be modeled as viscoelastic medium while those with higher free water content can be taken as saturated poroviscoelastic medium. Solely one type of material cannot properly describe the variation of soil properties with depth. Hence, great efforts have been made to solve this problem. For example, Sun et al. [50] took the ground as a layered system consisting of an elastic layer (above ground water table) and a saturated poroelastic half-space (below ground water table). The work can well accommodate cases with deep-seated bedrock but was not suitable for cases with shallow bedrock. Recently, Feng et al. [51,52] developed a more practical ground model considering alternate distribution of viscoelastic and poroviscoelastic layers. An 'adapted stiffness matrix method' was proposed to solve this model.

The above works have made great contribution to understanding the dynamic response of track-ground system. However, problem still remains. Although Feng et al. [51,52] have developed ground model considering alternate distribution of viscoelastic and poroviscoelastic layers, dynamic responses of this ground model coupled with track system are still unclear, such as displacement, acceleration and pore-water pressure. In this study, a semi-analytical coupling track-ground system is developed. The ground model is composed of treated layer, crust, saturated soil, and bedrock. The ground model is coupled with the track system [15] by adopting the continuity conditions at the interface between the ballast and the ground surface. Dynamic responses of the coupling system to high-speed train loads are then comprehensively investigated.

2. Track-ground system under study

A schematic diagram of train operation is shown in Fig. 1a. A high speed train with sixteen axles runs along a railway track on a stratified ground. The simplified model is illustrated in Fig. 1b. Loads from train-rail interaction are simplified as a series of constant point loads, determined by train geometry, moving at a constant speed, c. The magnitude and coordinate of theses loads are P_i and a_i ($i = 1, 2, 3,\ldots,n$), respectively. The adopted track system follows Sheng et al. [15]. The rails are taken as Euler-Bernoulli beams. The mass of pads is neglected and pads are considered as springs. The sleepers are modeled as continuous mass. The ballast is governed by Cosserat theory. The subgrade consists of treated soil, dry crust, ground water table, saturated soil and semi-infinite bedrock from top to bottom. Above the ground water table, soils (i.e., treated soil and crust) are of low free water content and modeled as two viscoelastic layers. Below the ground water table, the saturated soil is taken as poroviscoelastic layer. Under the saturated layer lies semi-infinite bedrock which is considered as a viscoelastic half-space. The thicknesses of the top three layers are h_1, h_2, h_3, respectively (Fig. 1b).

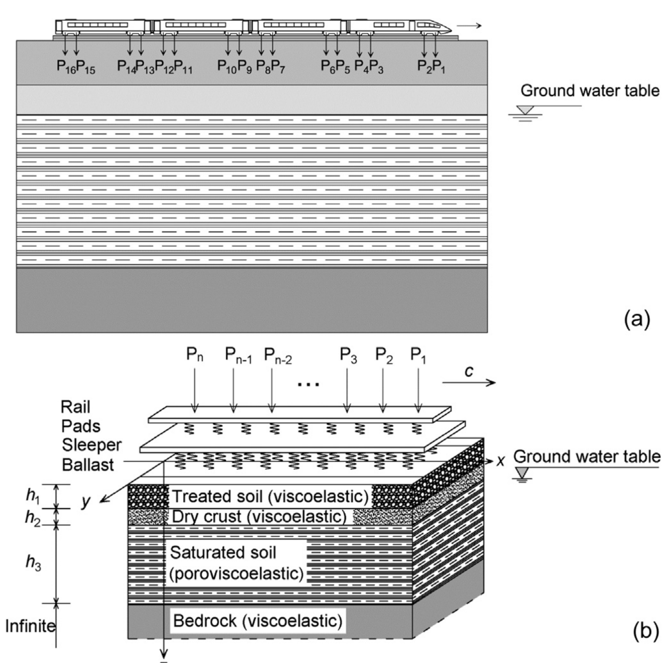

Fig. 1. (a) Schematic diagram of the problem; (b) simplified model in this study.

3. Governing equations and solutions

In this section, solution to the ground with alternately distributed different types of layers is proposed first. Afterwards, solution to the track system is introduced. Finally, solution to the whole track-ground system is derived.

3.1. Solution to the ground

Governing equations of top soil, crust and bedrock can be listed as follows:

$$(\lambda^{e} + \mu^{e})\nabla(\nabla\cdot\mathbf{u}^{\mathbf{e}}) + \mu^{e}\nabla^{2}\mathbf{u}^{\mathbf{e}} = \rho^{e}\ddot{\mathbf{u}}^{\mathbf{e}} \tag{1}$$

$$\boldsymbol{\sigma}^{\mathbf{e}} = \lambda^{e}(\nabla\cdot\mathbf{u}^{\mathbf{e}})\mathbf{I} + \mu^{e}(\mathbf{u}^{\mathbf{e}}\nabla + \nabla\mathbf{u}^{\mathbf{e}}) \tag{2}$$

where $\mathbf{u}^{\mathbf{e}}$ is the displacement vector; $\boldsymbol{\sigma}^{\mathbf{e}}$ is the stress tensor of elastic medium; λ^{e} and μ^{e} are the Lamé constants; ρ^{e} is the density; $\mathbf{I}$ represents unit second order tensor; ∇ is the Hamiltonian operator. The double dots denote the second order time derivative.

Fourier transform with respect to x, y coordinates and time t are defined as follows:

$$\bar{f}(\xi) = \int_{-\infty}^{\infty} f(x)e^{-\mathrm{i}\xi x}dx, \quad \tilde{g}(\eta) = \int_{-\infty}^{\infty} g(y)e^{-\mathrm{i}\eta y}dy, \quad \hat{h}(\omega) = \int_{-\infty}^{\infty} h(t)e^{-\mathrm{i}\omega t}dt \tag{3}$$

Perform Fourier transform with respect to time t and x, y coordinates in Eqs. (1) and (2). General solutions to Eqs. (1) and (2) can be expressed as

$$\underbrace{\begin{bmatrix} \mathbf{S}_{\mathbf{e}}^{\mathbf{D}} & \mathbf{S}_{\mathbf{e}}^{\mathbf{U}}\mathbf{Z}_{\mathbf{e}}^{\mathbf{D}} \\ -\mathbf{S}_{\mathbf{e}}^{\mathbf{D}}\mathbf{Z}_{\mathbf{e}}^{\mathbf{D}} & -\mathbf{S}_{\mathbf{e}}^{\mathbf{U}} \end{bmatrix}\begin{bmatrix} \mathbf{D}_{\mathbf{e}}^{\mathbf{D}} & \mathbf{D}_{\mathbf{e}}^{\mathbf{U}}\mathbf{Z}_{\mathbf{e}}^{\mathbf{D}} \\ \mathbf{D}_{\mathbf{e}}^{\mathbf{D}}\mathbf{Z}_{\mathbf{e}}^{\mathbf{D}} & \mathbf{D}_{\mathbf{e}}^{\mathbf{U}} \end{bmatrix}^{-1}}_{\mathbf{K}_{(n)}(\xi,\eta,h_n,\omega)_{6\times6}} \begin{Bmatrix} \hat{\tilde{\bar{u}}}_{\mathbf{e}|\mathbf{up}}(\xi, \eta, z_{n-1}, \omega) \\ \hat{\tilde{\bar{u}}}_{\mathbf{e}|\mathbf{lo}}(\xi, \eta, z_{n}, \omega) \end{Bmatrix} = \begin{Bmatrix} \hat{\tilde{\bar{\Sigma}}}_{\mathbf{e}|\mathbf{up}}(\xi, \eta, z_{n-1}, \omega) \\ -\hat{\tilde{\bar{\Sigma}}}_{\mathbf{e}|\mathbf{lo}}(\xi, \eta, z_{n}, \omega) \end{Bmatrix} \tag{4}$$

where $\hat{\tilde{\bar{u}}}_{\mathbf{e}|\mathbf{up}}(\xi, \eta, z_{n-1}, \omega)$, $\hat{\tilde{\bar{u}}}_{\mathbf{e}|\mathbf{lo}}(\xi, \eta, z_{n}, \omega)$ and $\hat{\tilde{\bar{\Sigma}}}_{\mathbf{e}|\mathbf{up}}(\xi, \eta, z_{n-1}, \omega)$, $\hat{\tilde{\bar{\Sigma}}}_{\mathbf{e}|\mathbf{lo}}(\xi, \eta, z_{n-1}, \omega)$ are the displacement and stress vectors of upper and lower boundaries of an viscoelastic layer, respectively. The hats '-, ~, ^' denote Fourier transform with respect to x, y, and t, respectively. The subscript 'n' denotes the n-th layer ($n = 1, 2$ for viscoelastic layers in this study); h_n is the thickness of the n-th layer; z_n is the depth of the lower boundary of the n-th layer as well as upper boundary of the (n + 1)-th layer ($z_0 = 0$ m). Expressions of the other matrices in Eq. (4) are presented in Appendix A.

According to Biot's theory [45], the governing equations of saturated soil are as follows:

$$\boldsymbol{\sigma} = [\lambda(\nabla\cdot\mathbf{u}) - \beta p]\mathbf{I} + \mu(\mathbf{u}\nabla + \nabla\mathbf{u}) \tag{5}$$