Soil Dynamics and Earthquake Engineering 69 (2015) 172–181

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Dynamic responses of a saturated poroelastic half-space generated by a moving truck on the uneven pavement

Yuanqiang Cai [a,b], Yao Chen [a], Zhigang Cao [a,*], Honglei Sun [c], Lin Guo [b]

[a] Research Center of Coastal and Urban Geotechnical Engineering, Zhejiang University, Hangzhou 310058, PR China
[b] College of Civil Engineering and Architecture, Wenzhou University, Wenzhou 325035, PR China
[c] Institute of Disaster Prevention Engineering, Zhejiang University, Hangzhou 310058, PR China

ARTICLE INFO

Article history:
Received 1 July 2014
Received in revised form
11 October 2014
Accepted 13 October 2014

Keywords:
Moving load
Poroelastic half-space
Biot's theory
Pavement roughness
Stress path

ABSTRACT

A truck–pavement–ground coupling model was established to study the dynamic responses of a saturated poroelastic half-space generated by a moving heavy truck on the uneven pavement. The ground was simulated as a fully saturated poroelastic half-space governed by Biot's theory. The overlying pavement was simplified as a Kirchhoff thin plate. With the assumption of a sinusoidal pavement surface, the dynamic wheel–pavement force was obtained through a linear Hertizian contact model. The numerical results showed that this dynamic load could make considerable contributions to the stress and excess pore water pressure responses in the ground. Furthermore, the effective stress path of the soil unit beneath the pavement caused by the moving truck was firstly calculated and presented. It was found that the differences between the total stress path and the effective stress path became significant as the truck speed increased, thus the effective stress path was more suitable than total stress path to reflect the stress history of soil elements in the saturated ground during the passage of high-speed traffics.

1. Introduction

As trucks become heavier and run faster on the road, increasing pavement damages are caused by moving heavy trucks. Ground vibration will also be caused by moving traffics which may do harm to the dwelling environment along the traffic lines [1,2] and even cause liquefaction in the ground [3]. The pavement damages and ground vibrations caused by moving traffics usually become intensified when the roughness exists on pavement surface. Therefore, it is of significance to investigate the dynamic responses of pavement and ground generated by moving traffics on an uneven pavement.

In many existing studies, the pavement is usually modeled as a plate or a beam resting on the ground. Kim and McCullough [4] investigated the dynamic displacements and stress responses of an infinite thin plate on a viscous Winkler foundation subjected to moving tandem-axle loads. Huang and Thambiratnam [5] discussed the effects of moving velocity, elastic foundation stiffness and moving path on the dynamic behavior of plate structure resting on an elastic Winkler foundation. Utilizing the Bessel and Hankel functions, Sun [6] derived a closed-form analytical solution of a Kirchhoff plate on a visco-elastic foundation subjected to harmonic circular loads with Fourier transform. Andersen et al. [7] dealt with the problem of loads moving uniformly along an infinite Euler beam supported by a visco-elastic Kelvin foundation by the finite element method (FEM). Fang et al. [8] studied the vertical displacement response of thin rigid and flexible plates resting on a layered poroelastic half-space under a moving traffic load. Auersch [9] investigated the dynamic response of an infinite or finite plate on a homogeneous or layered ground generated by a harmonic point load. Lombaert et al. [10] investigated the influence of the soil stratification on the free field vibrations generated by the passage of a vehicle on an uneven road and a horizontally layered linear elastic half-space was used for the soil. Kim and Tutumluer [11] presented stress path and the principal stress rotation of the soil elements caused by moving wheel loads. Powrie et al. [12] presented a finite element analysis to investigate the stress path of a soil unit beneath a ballasted railway track during train passage, and the stress paths were simulated in a cyclic hollow cylinder apparatus later. Liu et al. [13] used the 3-dimensional finite element method to study the stress path of soil elements at different positions beneath railway embankment during the passages of train loads. In the above mentioned literatures, the grounds were all modeled as a single-phase elastic or visco-elastic medium. However, the excess pore water pressure in the saturated ground, which cannot be considered with the single-phase elastic soil model, is generated during the passage of traffic load, thus the saturated poroelastic soil model is superior to the single-phase elastic soil model in this

---

* Corresponding author.
E-mail address: caozhigang2011@zju.edu.cn (Z. Cao).

http://dx.doi.org/10.1016/j.soildyn.2014.10.014
0267-7261/© 2014 Elsevier Ltd. All rights reserved.

simulation. Existing studies only focus on the total stresses and total stress paths of soil element in the ground generated by moving traffic, the effective stresses and the effective stress paths, which relate directly to the soil deformation properties, deserve more attention.

Treating the ground as a saturated poroelastic medium, Biot [14,15] pioneered a dynamic theory for a fully saturated poroelastic medium. Siddharthan et al. [16] studied the dynamic response of a layered poroelastic half-space under a moving line load by solving Biot's equations approximately. Theodorakopoulos [17] used Biot's theory to study the dynamic response of a poroelastic half-plane soil medium subjected to moving loads analytically/numerically, under conditions of plane strain. Cai et al. [18] employed the Biot's theory to calculate soil vertical displacements, accelerations and pore water pressures induced by moving load in a poroelastic half-space soil medium. Sun et al. [19] investigated the dynamic responses of a track system and the poroelastic half-space soil medium subjected to a moving point load under three-dimensional condition. Considering the rail surface irregularities, Cao et al. [20] investigated the dynamic responses of the poroelastic half-space soil medium due to quasi-static and dynamic loads from a moving train semi-analytically, based on Biot's theory. Cao et al. [21] investigated the vibrations of railway tracks on a poroelastic half-space generated by moving trains through a vehicle–track–ground coupling model. Cao et al. [22] presented an investigation of the dynamic responses of the pavement systems on a saturated poroelastic half-space analytically based on Fourier transforms, with simulating the vehicle load as four constant rectangular pressures, and the vibration velocities and dynamic stresses of the pavement–ground system were obtained. In practical engineering, the dynamic loads can be induced by pavement surface roughness, which will cause additional damage to the pavement structures and intensify the ground vibrations. Also the pavement roughness may lead to many other problems. Kuo et al. [23] developed a quarter car–pavement coupling model to investigate the influences of roadway roughness on pavement stresses. Cantisani and Loprencipe [24] and Yildirim [25] presented models of the vehicle to control the vehicle vibrations due to pavement roughness and road irregularities. However, there is no study presented to consider the effect of pavement roughness on the traffic-induced ground vibrations. Therefore, a truck–pavement–ground coupling model is essential for investigating the dynamic responses of the saturated poroelastic half-space generated by a moving truck on the uneven pavement. Furthermore, no researches have been presented on the effective soil stress paths in the saturated ground during the passage of moving traffic load.

In this paper, a truck–pavement–saturated ground coupling model was established to investigate the dynamic responses of the saturated poroelastic half-space. The loading from the heavy truck on the pavement consisted of the axle load and the dynamic wheel–pavement force, which was resulted from the uneven pavement surface. The pavement was simplified as a Kirchhoff thin plate and the ground was modeled as a fully saturated poroelastic half-space governed by Biot's theory. The governing equations of the pavement–ground system were solved by the Fourier transform and the time-domain results were got by applying the inverse fast Fourier transform. The stresses and excess pore water pressures generated by the axle load and the dynamic wheel–pavement force were calculated at different speeds and different ground depths. The effective stress path of the soil element in the ground, which was generated by moving heavy truck, was presented.

2. Governing equations of the saturated poroelastic half-space

The established theoretical model is shown in Fig. 1. The soil medium was modeled as a fully saturated poroelastic half-space. The asphalt mixture in the flexible pavement system was modeled as a thin plate which extended to infinity in the horizontal directions. The heavy truck was modeled as a rigid body system connected with springs and dampers [26]. Ignoring the compressibility and the apparent mass density of soil grains, the governing equations of the saturated poroelastic soil were presented by Biot [15] as:

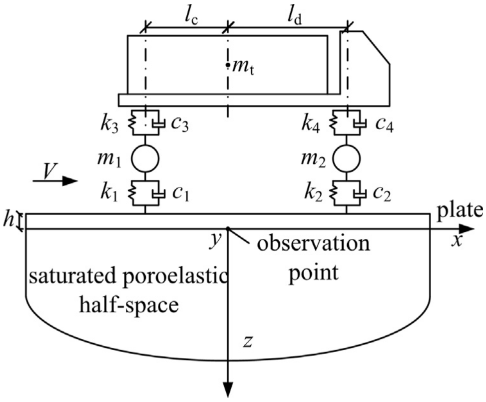

Fig. 1. The heavy truck–pavement–ground coupling model.

$$\mu u_{i,jj}+(\lambda+\alpha^2M+\mu)u_{j,ji}+\alpha M w_{j,ji}=\rho\ddot{u}_i+\rho_f\ddot{w}_i \tag{1}$$

$$\alpha M u_{j,ji}+M w_{j,ji}=\rho_f\ddot{u}_i+m\ddot{w}_i+b\dot{w}_i \tag{2}$$

The constitutive relations of the saturated soil medium were written as

$$\sigma_{ij}=\lambda\delta_{ij}u_{i,i}+\mu(u_{i,j}+u_{j,i})-\alpha\delta_{ij}p_f \tag{3}$$

$$p_f=-\alpha M u_{i,i}-M w_{i,i} \tag{4}$$

where μ and λ were Lame constants; u_i and w_i $(i=x,y,z)$ denoted the solid framework displacement and the infiltration displacement of the pore fluid in the x, y and z directions, respectively, the points above them meant derivatives with respect to time; α and M were parameters which denoted the compressibility of the soil grain and the excess pore water, respectively. $\rho=(1-n)\rho_s+n\rho_f$, where n was the porosity, ρ_s and ρ_f were densities of the solid and fluid, respectively; $m=\rho_f/n$; b was the ratio between the fluid viscosity and the intrinsic permeability of the soil medium; σ_{ij} was the total stress for bulk soil medium; $\delta_{ij}=\begin{cases}1 & i=j\\ 0 & i\neq j\end{cases}$; p_f was the excess pore water pressure.

The Fourier transformation pairs for the time t, x, y were defined as [27]:

$$\tilde{f}(x,y,z,\Omega)=\int_{-\infty}^{+\infty}f(x,y,z,t)e^{-i\Omega t}dt \tag{5}$$

$$f(x,y,z,t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\tilde{f}(x,y,z,\Omega)e^{i\Omega t}d\Omega \tag{6}$$

$$\bar{f}(\xi,y,z,t)=\int_{-\infty}^{+\infty}f(x,y,z,t)e^{-i\xi x}dx \tag{7}$$

$$f(x,y,z,t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\bar{f}(\xi,y,z,t)e^{i\xi x}\,d\xi \tag{8}$$

$$\bar{f}(x,\eta,z,t)=\int_{-\infty}^{+\infty}f(x,y,z,t)e^{-i\eta y}\,dy \tag{9}$$

$$f(x,y,z,t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\bar{f}(x,\eta,z,t)e^{i\eta y}\,d\eta \tag{10}$$