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Dynamic Stress Responses of Rough Pavement Resting on Layered Poroelastic Half-Space under Moving Traffic Load

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Abstract

To investigate the influence of pavement roughness on the dynamic stresses under traffic vehicles, a pavement resting on a layered poroelastic half-space is studied. The shape of pavement roughness is treated as a sine function of irregularity while the vehicle is modeled as a quarter-vehicle vibration system with two degrees of freedom (DOF). Based on the Biot's dynamic poroelastic theory, the time domain solutions of the homogeneous poroelastic half-space are obtained by Fourier transforms and inverse Fourier transforms. The time domain solutions of the layered poroelastic half-space are then presented using the transfer-matrix method. By regarding the top layer as a thin-plate and using the Kirchhoff's hypotheses, the vertical displacement and stress of the thin plate are calculated. The time domain solutions of the rigid pavement-layered poroelastic ground system are obtained based on the compatibility condition at the interface of the pavement-ground system. The dynamic effects of the load velocity, the wave length and the thickness of the plate are discussed, respectively. It is found that the roughness of the top plate significantly affects the dynamic stress response in the poroelastic layers when the vehicle velocity is below a critical value. In addition, the dynamic impact coefficient depends on the wave length of the roughness as well as the amplitude. The dynamic stress response caused by the roughness of pavement is evident and different from the dynamic stress response caused by vehicle weight. This study is intended to provide potential guidance for the design of a rigid pavement system.

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Keywords: rigid pavement, roughness, layered poroelastic half-space, moving vehicle load, dynamic stress response

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1. Introduction

With the rapid development of mechanical technology, many high-speed transportation systems have been developed and their speeds normally reach about 200-500km/h. As a result, the high-speed traffic load may do harm to the transportation systems [1] and even cause permanent settlement in the ground in China's eastern coastal areas [2]. The dynamic component of traffic load caused by the roughness of pavement usually 0.3~0.4 times of the vehicle weight [3]. To decrease the harms, it is necessary to predict the dynamic stress response of a rough pavement resting on layered ground under moving traffic load.

In most existing studies, the soil media under pavement was usually simplified as a single-phased elastic or viscoelastic model, rather than a water-filled elastic porous model (i.e. two-phased) devoted by Biot [4]. Based on Biot's theory, many researchers [5,6] extended the theoretical analysis in various dynamic problems and studied the dynamic response of saturated poroelastic soil media induced by different kinds of loads. In the past years, the rigid pavement was usually simplified as a plate or a beam resting on the single-phased elastic or viscoelastic soil media [7,8] or the saturated poroelastic soil media [9,10]. Considering the soil media consists of one or more layers, Xu [11] adopted the transmission and reflection matrix method to solve a layered poroelastic half-space. Fang et al. investigated the dynamic response of pavement-layered soil systems subjected to moving traffic load [12]. Cai et al. [13] have discussed the dynamic response of a saturated poroelastic half-space generated by a moving truck on the uneven pavement. However, these studies mainly focused on the displacement and acceleration responses. The dynamic stress response of the vehicles-rigid pavement-layered ground system subjected to moving traffic load needs to be further investigated.

In this paper, the vehicles-rigid pavement-layered soil media system is established. To consider the roughness of the pavement, its shape is treated as a sine function of irregularity while the vehicle is modeled as a quarter-vehicle vibration system. The dynamic component of traffic load caused by the pavement roughness is calculated. Based on the Biot's dynamic poroelastic theory, analytical solutions of stresses in a saturated poroelastic ground subjected to a harmonic rectangular moving load are obtained by four scalar potential functions and Helmholtz decomposition theorem, Fourier transform and inverse Fourier transform technique. Furthermore, based on the transfer matrix method and Kirchhoff's hypotheses, the time domain solutions of the rigid pavement system are gained by the compatibility condition at the interface of the pavement and the soil. The effects of the traffic velocity, frequency, the wave length of the roughness and the thickness of the plate on the dynamic stress response are discussed.

2. The dynamic component of traffic load caused by pavement roughness

2.1. Mathematical model

According to the theoretical analysis [14], the moving traffic load consists of the dynamic component caused by the roughness of pavement and the vehicle weight. The total moving traffic load can express as:

$$Q = Q_1 + Q_2 e^{i\omega_0 t} = Q_1 + Q_2 e^{i(2\pi c/\lambda_t)t} \tag{1}$$

where Q_1 is the vehicle weight, and $Q_2 e^{i\omega_0 t}$ is the dynamic component. $\omega_0 = 2\pi c/\lambda_t$ is the circular frequency of the dynamic component, where c is the vehicle speed and λ_t is the wavelength of the pavement roughness.

Vehicles are a multi-particle vibration system. Kuo [15] simplified vehicles as a quarter-vehicle vibration system with two degrees of freedom, and found that this system can accurately simulate the acceleration of vehicles. In this paper, the vehicle vibration system established in Fig.1, in which m_2, k_2, c_2, y_2 are the mass, suspension spring stiffness, suspension damping, and displacement of the carbody, m_1 is the mass of wheel axle, k_1 and c_1 are the spring stiffness and the damping of quarter-car wheel, y_0 is the pavement roughness function.

The motion equations for the vehicle vibration system are given as:

$$\begin{cases} \ddot{z}_1 + 2\xi_1\omega_1\dot{z}_1 + \omega_1^2 z_1 - 2\mu\xi_2\omega_2\dot{z}_2 - \mu\omega_2^2 z_2 = -\ddot{y}_0 \\ \ddot{z}_1 + \ddot{z}_2 + 2\xi_2\omega_2\dot{z}_2 + \omega_2^2 z_2 = -\ddot{y}_0 \end{cases} \tag{2}$$

where $z_1 = y_1 - y_0$; $z_2 = y_2 - y_1$; $\omega_1^2 = k_1/m_1$; $\omega_2^2 = k_2/m_2$; $\xi_1 = c_1/2\sqrt{m_1 k_1}$; $\xi_2 = c_2/2\sqrt{m_2 k_2}$; $\mu = m_2/m_1$.

The initial position of vehicle is assumed at the origin of coordinate, and the shape of pavement roughness is treated as a sine function of irregularity. As a result, the pavement roughness function can be expressed as: