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Investigation of rutting behavior of asphalt pavement in long and steep section of mountainous highway with overloading

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HIGHLIGHTS

- The strain and stress relationship under cyclic haversine load was developed.
- A new operational mode is proposed to obtain the vehicular load characteristics.
- Rut behavior under constant power load in the mountainous highway is gained.
- Sensitivity analysis and parameter fitting of rut impact factor are acquired.
- Restrictions of slope grade and length based on rutting control are conducted.

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ABSTRACT

In order to investigate rutting behavior in long and steep section of mountainous highway, this paper selected generalized Kelvin model as the constitutive relationship for asphalt mixture, proposed a new method for material parameter identification, provided the tangential stiffness matrix for the generalized Kelvin model, and applied the constant power vehicular loads on the finite model. The results show that the overload, operational speed, and the tangential and vertical forces of the vehicle have a significant impact on the rutting of asphalt pavement. Based on rutting sensibility analysis, this paper also develops a confinement method of the slope grade and length in long and steep section of mountainous highway.

1. Introduction

Rutting is one of the most common types of road damage and has a noticeable impact on the performance of pavement in a negative manner in its service life. As the development of the constructions and maintenances of Chinese highways, asphalt pavements are adopted widely in mountainous highway. Compared with behaviors in level and rolling terrain, rutting in the mountainous highway, especially in long and steep section, is much more severe because of the above special terrain and the resulted vehicle's driving behaviors [1]. On one hand, low gear contributes to the crawling ability and reduces the engine damage. On the other hand, the drivers tend to pass through the mountainous terrain with high speed. The above two factors keep the vehicles running with the constant power approximately in a certain section of mountainous highway.

Li [2] thought that the serious rutting in long and steep section was mainly due to the low vehicle speeds uphill whose effect exceeded the one of high temperature on dynamic stability of asphalt mixture. Ma [3] investigated the dynamic response and the failure condition of asphalt pavement under vehicular loading at constant speed with the finite element method (FEM), and as for comparison purpose, the pavement response under static loading is also incorporated into Ma's analysis.

Pei [4] took into account of the effect from the multi-axles of the heavy truck on rutting properties. Hajj [5] investigated the load distribution of semi-trailer on the surface of the urban intersections. Rakha [6] studied the running characteristics of the crawling vehicles with different overload behaviors.

The objective of this paper is to characterize the rutting properties in long and steep section of mountainous highway under the constant power vehicular load. The generalized Kelvin model was

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selected as the constitutive relationship for asphalt mixture whose material parameters was obtained with the cyclic uniaxial test, and to simulate the moving vehicular load of the crawling semi-trailer FORTRAN was used as a platform to program two ABAQUS subroutines called UTRACLOAD and DSLOAD. On the base of the above work, the aim of this paper could be reached.

2. Generalized Kelvin model and the determination of model parameters of asphalt mixture

Asphalt mixture displays strong viscoelastic properties in ambient temperatures. Viscoelastic constitutive laws can be expressed using either a relaxation or creep-based formulation. This paper mainly focuses on the deformation of asphalt pavement, so only the generalized Kelvin model, one kind of creep-based formulation, is employed.

As the vehicular loads pass by the surface of the asphalt pavement, basically it is the process of repeated loading and unloading which can be described as cyclic rectangular, triangular, trapezoidal and haversine waves for a certain point in the above area [7,8]. Barksdale [9] investigated load pulses in different locations of flexible pavement and the results showed that the haversine load would appear to be a reasonable representation. So in this paper, the authors assume that the cylindrical specimens of asphalt mixture done in the laboratory is subjected to the uniaxial cyclic haversine load (MPa) whose first period can been written as:

$$p_t = \begin{cases} \frac{P_0}{2}\left(1-\cos\frac{2\pi}{t_0}t\right) & 0 < t \leqslant t_0 \\ 0 & t_0 \leqslant t < 10t_0 \end{cases} \tag{1}$$

where, P_0 is the peak load, t_0 is the duration of single loading, and t is loading time. In this paper, the selected duration of single loading and rest period is 0.1 and 0.9 s, respectively. The integral representation of Boltzmann superposition principle is as follows:

$$\varepsilon(t) = \sigma_0 J(t) + \int_0^t J(t-\xi)\frac{d\sigma(\xi)}{d\xi}d\xi \tag{2}$$

where, $\varepsilon(t)$ is the strain, σ_0 is the initial strain, $J(t)$ is the creep compliance, and t is the loading time. The stress $\sigma(t)$ shown in Eq. (1) is the piecewise function, so it is inconvenient to differentiate $\sigma(t)$ in relation to t. Integrating the second part of Eq. (2) by parts we have

$$\varepsilon(t) = J(0)\sigma(t) + \int_0^t \sigma(\xi)\frac{dJ(t-\xi)}{d(t-\xi)}d\xi \tag{3}$$

The creep compliance of the generalized Kelvin model is [8,10]

$$J(t) = \sum_{i=1}^{m}\frac{1}{E_i}\left(1-\exp\left(-\frac{t}{\tau_i}\right)\right) \tag{4}$$

where, m is the number of Kelvin unit in parallel, $\tau_i = \eta_i/E_i$, and E_i, η_i are the spring stiffness and dashpot viscosity of Kelvin element i [10,11].

In the uniaxial cyclic compression test performed in this paper, the measure and record rule of Universal Testing Machine (UTM) is as follows: measuring and recording the strain at the start point of every cycle.

So,

$$\varepsilon(t) = \sum_{i=1}^{m}\frac{1}{E_i}\frac{1}{\tau_i}\exp\left(-\frac{t}{\tau_i}\right)\int_0^t \sigma(\xi)\exp\left(\frac{\xi}{\tau_i}\right)d\xi \tag{5}$$

As mentioned before, $t = 0,\ 10t_0,\ 20t_0\ldots$, and it should be noted that $t_0^2 << 4\pi^2\tau_i^2$, so we have

$$\varepsilon(t) = \frac{P}{20}\sum_{i=1}^{m}\frac{1}{E_i}\left(1-\exp\left(-\frac{t}{\tau_i}\right)\right) \tag{6}$$

Degenerating two Kelvin units into spring and dashpot, respectively, Eq. (6) can be rewritten as

$$\varepsilon(t) = \frac{P_0}{20}\left(\sum_{i=1}^{m}\frac{1}{E_i}\left(1-\exp\left(-\frac{t}{\tau_i}\right)\right) + \frac{t}{\eta_0} + \frac{1}{E_0}\right) \tag{7}$$

Eq. (7) is the strain expression of generalized Kelvin model under uniaxial cyclic haversine load with specified record rule. In this section, a measure and record method (the start point of every cycle) is employed to simplify the strain equation. Others (i.e. the end point of every cycle) also can be used, and different ones will produce different viscoelastic parameters. The selected criteria of various measure and record methods are based on the distinctiveness of every specific research project. Due to limitations of space, the authors only present the start point of every cycle in this paper.

In Eq. (7), the nonlinear relationship between the total strain $\varepsilon(t)$ and the loading time t implies that the initial material parameter estimates have an important effect on the regression models. Below procedure proposes a method to calculate the initial material parameter estimates:

(1) Plotting the scatter diagram of original data (t and $\varepsilon(t)$) in Microsoft EXCEL.
(2) According to the instantaneous elastic strain ε_0, the instantaneous elastic modulus of the generalized Kelvin model can be computed. Removing the instantaneous elastic strain, the residual $\delta(t) = \varepsilon(t) - \varepsilon_0$ can be obtained.
(3) Focusing on the linear part of the diagram of $t \sim \delta(t)$, the initial viscoelastic parameter estimates η_0 and E_1 can be calculated by the equations as follows:

$$\eta_0 = \frac{P_0}{20K_{t\sim\delta(t)}} \quad E_1 = \frac{P_0}{20\delta(0)_{t\to\infty}} \tag{8}$$

where, $K_{t\sim\delta(t)}$ and $\delta(0)_{t\to\infty}$ are the slope and the intercept of the linear part of the diagram $t \sim \delta(t)$, respectively.
(4) Noting $\varphi(t) = \log_{10}[-\delta(t) + P_0/(20\eta_0)t + P_0/(20E_0)]$, the initial viscoelastic parameter estimate η_1 can be obtained by equation below:

$$\eta_1 = -\frac{0.4343}{K_{t\sim\varphi(t)}}E_1 \tag{9}$$

where $K_{t\sim\varphi(t)}$ is the slope of the linear part of the diagram $t \sim \varphi(t)$.
(5) Removing $P_0/(20E_1)$ from the strain $\delta(t)$, we can get the residual $\delta'(t)$ used to calculate the initial viscoelastic parameter estimates E_2 and η_2.
(6) Repeating step (5), we can get the initial estimate values of E_3 and η_3, E_4 and $\eta_4, \cdots, E_m$ and η_m.

Obtained all the initial estimate values, the viscoelastic parameters can be fitted with SPSS. Fig. 1 demonstrates that the above method can get reasonable results and the experimental curve is in good agreement with the fitted one.

3. Constitutive equations and tangent stiffness matrix of three-dimensional generalized Kelvin model

The FEM software ABAQUS is employed to calculate the permanent deformation of asphalt pavement in mountainous terrain. Actually, there are some conventional viscoelastic constitutive models attached in ABAQUS, such as time hardening, strain hardening and hyperbolic sine models. But the above attached models are inconvenient to separate the instantaneous elasticity, recoverable and unrecoverable viscosity from the total strain. Hence, by virtue of the FORTRAN platform, the User Material (UMAT)