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Parameter identification of asphalt pavements subjected to moving loads

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Abstract: Pavements generally demand necessary maintenance and rehabilitation to maintain their service performance in the whole lifespan. The maintenance and rehabilitation strategies are usually formulated based on the results of non-destructive testing, in which the traffic speed deflectometer (TSD) test is an efficient tool for pavement detection at network level. In this paper, the TSD test on asphalt pavements is simulated by a spectral element method-based theoretical model, which is further combined with a nonlinear minimisation algorithm to achieve parameter identification. After conducting parameter sensitivity analysis, a case study is used to demonstrate the ability of the proposed parameter identification technique. The results show that this technique can deal with TSD measurements to identify the structural parameters of asphalt pavements. The presented parameter identification technique is a reliable tool to predict the structural parameters of asphalt pavements by analysing corresponding TSD measurements, which is beneficial to formulate accurate maintenance and rehabilitation strategies.

Keywords: Parameter identification; Asphalt pavement; Moving load; Spectral element method; Traffic speed deflectometer

1 Introduction

The maintenance and rehabilitation of pavements are essential to extend their service life. In order to minimise unnecessary costs, the maintenance and rehabilitation strategies should be accurate enough, which requires reliable techniques for pavement functional and structural evaluation. An elegant method for pavement structural evaluation is the non-destructive testing, in which the falling weight deflectometer (FWD) test is a widely used approach (Li et al., 2017; Elbagalati et al., 2018). In the FWD test, the pavement response caused by an impact load is measured, which can be further analysed to identify structural parameters of pavements (Al-Khoury et al., 2001). However, the FWD test is time consuming and resource intensive for network level structural evaluation because of the stop-and-go testing process (Keenahan and OBrien, 2018). The limitations of the FWD test encourage the development of another non-destructive testing approach, which is called traffic speed deflectometer (TSD) test (Levenberg et al., 2018; Nasimifar et al., 2018). This test can measure the response of pavement surface caused by a wheel loading at normal driving speeds, so it is more suitable for pavement structural evaluation at network level (Maser et al., 2017). Although the TSD vehicle has been well developed, a proper parameter identification technique is still desired to deal with corresponding measurements. Hence, this paper aims to formulate a parameter identification technique suitable for TSD measurement analysis. The presented work is beneficial to the development of engineering techniques for pavement structural evaluation at network level.

2 Model formulation

With the assumptions that the pavement surface is smooth, the driving speed is constant, and the measurements are only caused by the right rear wheel pair of the TSD vehicle, a theoretical model for the TSD test on asphalt pavements is a layered system subjected to a uniformly moving constant surface force, which is evenly distributed over a pair of rectangular areas, as shown in Fig. 1. In order to solve the moving load problem, both a stationary Cartesian coordinate system (*OXYZ*) and a moving Cartesian coordinate system (*oxyz*) are introduced. The stationary coordinate system is stationary with respect to the layered system and its origin is located in the center of the initial loading area, while the moving coordinate system is moving with the load and its origin is located in the center of the moving loading area. The stationary coordinate vector and the moving coordinate vector are notated as $\underline{\mathbf{X}} = \begin{bmatrix} X & Y & Z \end{bmatrix}^{\mathrm{T}}$ and $\underline{\mathbf{x}} = \begin{bmatrix} x & y & z \end{bmatrix}^{\mathrm{T}}$, respectively. If the load moves in the positive direction of the

X-axis with a constant speed c, the relationships between the coordinates of the two coordinate systems are:

$$x = X - ct, \quad y = Y, \quad z = Z \tag{1}$$

where t is time, and these two coordinate systems are coincident when t is zero.

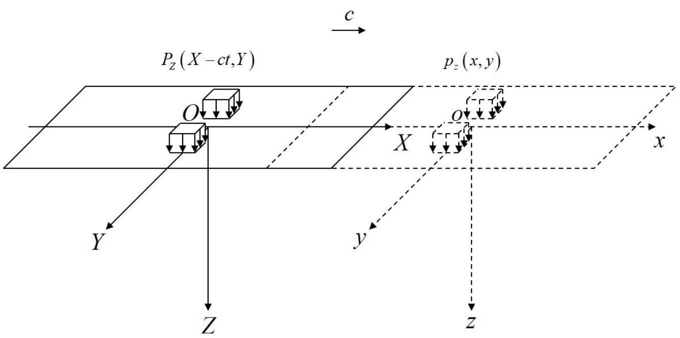

Fig. 1 A theoretical model for the TSD test

2.1 Response of elastic layered systems under moving surface loads

As presented in Sun et al. (2019), a spectral element method-based procedure can be used to calculate the response of elastic layered systems under moving surface loads. In this procedure, a layer spectral element and a semi-infinite spectral element are developed to respectively simulate a layer and a half-space, and the combinations of these two spectral elements can model layered systems with different configurations. For the case of the TSD test, both the loading pressure and loading area are considered to be constant over time. In addition, the contact area between the right rear wheel pair of the TSD vehicle and pavement surface is assumed to be two rectangular areas with a certain distance between them, and the centre of the contact area coincides with the origin of the moving coordinate system. This configuration of the contact area can be described by a spatial distribution function $h_0(x,y)$ defined as follows:

$$h_0(x,y) = H\left(x_0 - |x|\right)\left[H\left(\frac{y_0}{2} - \left|y + \frac{y_0 + d}{2}\right|\right) + H\left(\frac{y_0}{2} - \left|y - \frac{y_0 + d}{2}\right|\right)\right] \tag{2}$$

in which $H(\cdot)$ is the Heaviside step function, $2x_0$ is the length of one rectangular area in x-direction, y_0 is corresponding length in y-direction, and d is the distance between two rectangular areas.

2.2 Simulation of material damping

Numerically, the material damping can be simulated by replacing the Young's modulus with a complex Young's modulus derived from a certain damping model. For the moving loading problem, the complex Young's modulus expressed in the wavenumber-frequency domain related to the moving coordinate system is needed for application. The asphalt layer in asphalt pavements has viscoelastic properties, which are simulated by the Zener model in this study. As shown in Fig. 2, the Zener model consists of a Maxwell component and a Hookean element (spring constant E_0) connected in parallel. The Maxwell component consists of a Hookean element (spring constant E_∞-E_0) and a Newtonian element (viscosity constant η) connected in series. Physically, E_0 is called the static modulus because it corresponds to the complex Young's modulus when loading angular frequency equals zero, E_∞ is called the glassy modulus because it corresponds to the complex Young's modulus when loading angular frequency equals infinity.

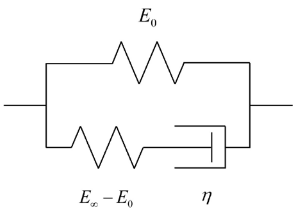

Fig. 2 Schematic representation of the Zener model

In the stationary coordinate system, the stress-strain relationship of the Zener model under uniaxial tension/compression can be expressed as follows:

$$\left[\left(E_\infty - E_0\right) + \eta\partial_t\right]\sigma_0\left(\underline{\mathbf{X}},t\right) = \left[E_0\left(E_\infty - E_0\right) + \eta E_\infty\partial_t\right]\varepsilon_0\left(\underline{\mathbf{X}},t\right) \tag{3}$$

where ∂_t means derivative with respect to t, $\sigma_0(\underline{\mathbf{X}},t)$ and $\varepsilon_0(\underline{\mathbf{X}},t)$ are the tensile/compressive stress and strain in the stationary coordinate system, respectively. According to Eq. (1), the stress-strain relationship of the Zener model has the following form in the moving coordinate system:

$$\left[\left(E_\infty - E_0\right) + \eta\left(\partial_t - c\partial_x\right)\right]\sigma\left(\underline{\mathbf{x}},t\right) = \left[E_0\left(E_\infty - E_0\right) + \eta E_\infty\left(\partial_t - c\partial_x\right)\right]\varepsilon\left(\underline{\mathbf{x}},t\right) \tag{4}$$

in which ∂_x means derivative with respect to x, $\sigma(\underline{\mathbf{x}},t)$ and $\varepsilon(\underline{\mathbf{x}},t)$ are the tensile/compressive stress and strain in the moving coordinate system, respectively.

By following the same Fourier transform convention shown in Sun et al. (2019), the expression of the complex Young's modulus for the Zener model in the wavenumber-frequency domain can be obtained by replacing ∂_t with iω, replacing ∂_x with -ik_x, and using the analogy relation similar to that of linear elasticity:

$$\tilde{E}\left(k_x,\omega\right)=\frac{E_0\left(E_\infty-E_0\right)+\mathrm{i}\eta E_\infty\left(\omega+ck_x\right)}{\left(E_\infty-E_0\right)+\mathrm{i}\eta\left(\omega+ck_x\right)} \tag{5}$$

where i is the imaginary unit satisfying $i^2 = -1$, $\tilde{E}(k_x,\omega)$ is the complex Young's modulus in the wavenumber-frequency domain, k_x is the wavenumber in the x-direction, and ω is the angular frequency. It can be concluded that, for a certain damping model, the expression of the complex Young's modulus in the wavenumber-frequency domain related to the moving coordinate system can be obtained from its traditional expression in the frequency domain related to the stationary coordinate system by replacing ω with $\omega+ck_x$. The base layer and subgrade in asphalt pavements are considered to be elastic with hysteretic damping, which corresponds to the following expression of complex Young's modulus in the wavenumber-frequency domain related to the moving coordinate system:

$$\tilde{E}\left(k_x,\omega\right)=E\left[1+2\mathrm{i}\xi\,\mathrm{sgn}\left(\omega+ck_x\right)\right] \tag{6}$$

in which E is the Young's modulus, ξ is the damping ratio, and sgn(·) is the signum function.

3 Parameter sensitivity analysis

The more sensitive the response is to a certain parameter, the easier it is to identify this parameter. Hence, the parameter sensitivity analysis is necessary to have an insight into the feasibility and accuracy of the parameter identification process. In practice, the TSD vehicle measures the vertical deflection slopes of surface points along the midline of right rear wheel pair. Hence, the vertical deflection slope curve along the x-axis observed on the pavement surface is the response of interest. The sensitivity of the slope curve to different structural parameters is investigated based on single factor analysis, in which the variation of a certain parameter is 50% of its reference value. According to the actual loading conditions of the TSD test, the following loading parameters are used for simulation:

- The speed of the moving load c is 13.9 m/s (50 km/h);
- The magnitude of loading pressure p_0 is 707 kPa;
- The distance between two rectangular areas d is 0.15 m;
- The parameters of the loading area are x_0 is 0.06316 m and y_0 is 0.27432 m;
- The dimensions of the space window of interest are 400 m by 400 m.

In addition, the reference structural parameters of the considered asphalt pavement are shown in Table 1. The reference parameters of the Zener model used to simulate the asphalt layer are: E_0 = 6.4 MPa, E_∞ = 19500 MPa, and η = 7000 MPa·s. The response corresponds to the reference structural parameters is shown in solid lines. In order to distinguish the sensitivity to different parameters, the following five levels are used for description: hardly sensitive, slightly sensitive, moderately sensitive, relatively sensitive, and highly sensitive.

Table 1 Reference structural parameters of the asphalt pavement

Layers	E (MPa)	ξ	v	ρ (kg/m^3)	h (m)
Asphalt	–	–	0.3	2300	0.1
Base	110	0.05	0.3	1900	0.3
Subgrade	60	0.05	0.3	1600	Infinite

Note: E is the Young's modulus, ξ is the damping ratio, v is the Poisson's ratio, ρ is the mass density, and h is the layer thickness.

3.1 Sensitivity to parameters of the Zener model

The sensitivity of the vertical deflection slope curve to parameters of the Zener model is shown in Fig. 3. The results indicate that the slope curve is hardly sensitive to the static modulus (E_0), highly sensitive to the glassy modulus (E_∞), and slightly sensitive to the viscosity constant (η).

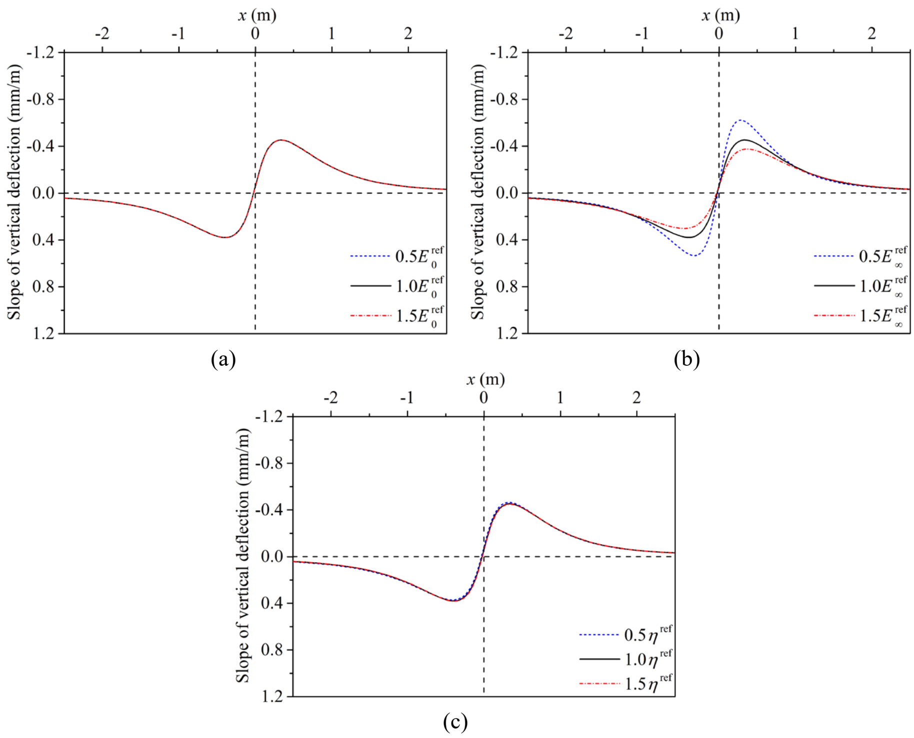

Fig. 3 Sensitivity of vertical deflection slope curve to parameters of the Zener model: (a) static modulus, (b) glassy modulus, and (c) viscosity constant

3.2 *Sensitivity to Young's modulus*

The sensitivity of the vertical deflection slope curve to the Young's moduli of base layer (E_2) and subgrade (E_3) is shown in Fig. 4. The results indicate that the slope curve is relatively sensitive to the Young's modulus of base layer and highly sensitive to the Young's modulus of subgrade.

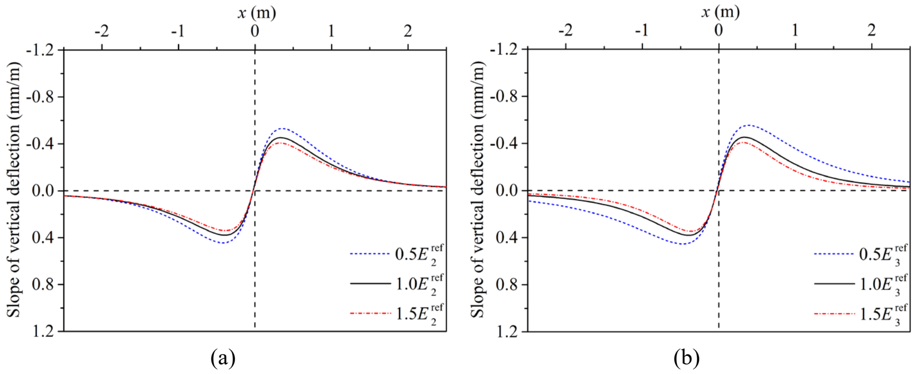

Fig. 4 Sensitivity of vertical deflection slope curve to Young's moduli of: (a) base layer and (b) subgrade

3.3 *Sensitivity to damping ratio*

The sensitivity of the vertical deflection slope curve to the damping ratios of base layer (ξ_2) and subgrade (ξ_3) is shown in Fig. 5. The results indicate that the slope curve is slightly sensitive to the damping ratios of base layer and subgrade.

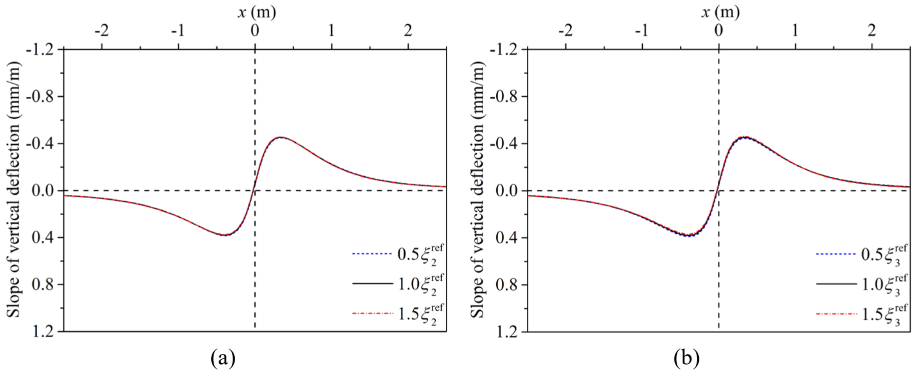

Fig. 5 Sensitivity of vertical deflection slope curve to damping ratios of: (a) base layer and (b) subgrade

3.4 Sensitivity to thickness

The sensitivity of the vertical deflection slope curve to the thicknesses of asphalt layer (h_1) and base layer (h_2) is shown in Fig. 6. The results indicate that the slope curve is highly sensitive to the thickness of asphalt layer and moderately sensitive to the thickness of base layer.

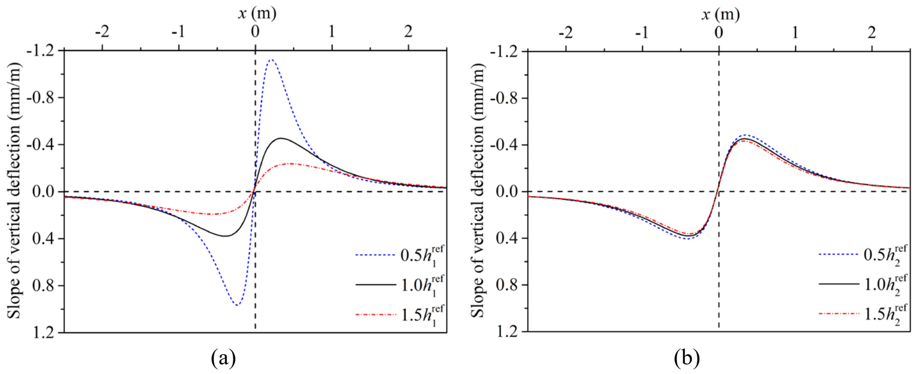

Fig. 6 Sensitivity of vertical deflection slope curve to thicknesses of: (a) asphalt layer and (b) base layer

4 Structural parameter identification

The response of a structure is determined by the loading conditions and structural parameters. Theoretically, if the response and loading conditions are known, it should be possible to identify the structural parameters. This parameter identification process is normally achieved by combining a forward calculation model with a proper nonlinear minimisation algorithm. A set of most likely parameters can be sought by minimising the difference between the modelled and measured response. In the case of the TSD test, the objective function $f(\underline{\mathbf{p}})$ used for the nonlinear minimisation algorithm can be defined as follows:

$$f\left(\underline{\mathbf{p}}\right)=\sum_{n=1}^{N}\left|\frac{s^{\mathrm{modelled}}\left(x_n,y_n;\underline{\mathbf{p}}\right)}{s^{\mathrm{measured}}\left(x_n,y_n\right)}-1\right| \tag{7}$$

where $\underline{\mathbf{p}}$ is a vector contains all the unknown parameters, N is the total number of measuring points, $s^{\mathrm{modelled}}(x_n,y_n;\underline{\mathbf{p}})$ and $s^{\mathrm{measured}}(x_n,y_n)$ are the modelled and measured vertical deflection slopes at measuring point (x_n,y_n), respectively. In general, a smaller value of the objective function corresponds to a better match between the modelled and measured response. Hence, for a set of specific measured response, the most likely parameters can be identified by minimising the objective function.

The nonlinear minimisation algorithm used in this paper is the Powell hybrid algorithm, which can solve a non-constrained system of nonlinear simultaneous equations via a finite-difference Jacobian. One feature of the Powell hybrid algorithm is that the number of unknowns equals to the number of equations. Hence, in the case of the TSD test, the number of unknown parameters should be no more than the number of measuring points. In reality, the TSD vehicle can only measure the slopes of about 9 points. Hence, some parameters should be fixed to make the problem solvable. With considering the results of sensitivity analysis, the following parameters are chosen for identification: E_∞, E_2, E_3, η, ξ_2, ξ_3, h_1, and h_2. For the reference asphalt pavement structure shown in the previous section, the slopes of eight points along the x-axis on the pavement surface calculated by the forward model are taken as synthetic measurements. Then, the unknown parameters are identified by using the proposed parameter identification technique. It is found that good initial guesses of the unknown parameters are important to improve the accuracy and efficiency of the parameter identification process. The initial guesses used in this case are: E_∞ = 18000 MPa, E_2 = 60 MPa, E_3 = 40 MPa, η = 6000 MPa·s, ξ_2 = 0.04, ξ_3 = 0.04, h_1 = 0.05 m, and h_2 = 0.2 m. Correspondingly, the identified parameters are: E_∞ = 19500.5 MPa, E_2 = 110.0 MPa, E_3 = 60.0 MPa, η = 6996.3 MPa·s, ξ_2 = 0.050, ξ_3 = 0.050, h_1 = 0.10 m, and h_2 = 0.30 m. These identified parameters have reasonably good agreement with true values (i.e. reference parameters), which confirms the ability of the proposed technique.

5 Conclusions

This paper proposes a parameter identification technique for asphalt pavements subjected to moving loads, which can be used to deal with traffic speed deflectometer (TSD) measurements to identify pavement structural parameters. The proposed TSD test associated parameter identification technique may become a promising tool for pavement structural evaluation at network level, which is beneficial to the formulation of accurate maintenance and rehabilitation strategies. In the future work, more case studies will be conducted to verify the robustness of the proposed parameter identification technique.

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