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A parameter back-calculation technique for pavements under moving loads

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ABSTRACT: Maintenance and rehabilitation strategies of pavements are usually made based on the results of performance evaluation. An efficient tool for pavement structural evaluation at network level is the traffic speed deflectometer (TSD) test. In order to deal with TSD measurements, this paper proposes a parameter back-calculation technique. Firstly, the sensitivity of the surface response for an elastic pavement structure with hysteretic damping to different structural parameters is investigated. Then, the ability of the parameter back-calculation technique is verified by conducting a case study. The results show that the proposed technique is able to back-calculate the structural parameters of pavements by analysing TSD measurements. The presented work contributes to the development of parameter back-calculation techniques for the TSD test.

1 INTRODUCTION

Maintenance and rehabilitation issues are very important in the whole lifespan of pavements. Accurate maintenance and rehabilitation strategies can restore the performance of pavements with minimum costs. In general, the formulation of the strategies are on the basis of functional and structural evaluation of the pavement performance. The pavement structural evaluation is usually achieved by conducting non-destructive tests (Al-Khoury et al. 2001a). A commonly used non-destructive test for pavement structural evaluation is the falling weight deflectometer (FWD) test (Marecos et al. 2017, Rabbi & Mishra 2019). However, the FWD test is quite time and resource consuming because of the stop-and-go measuring process. In addition, this measuring process also results in traffic disruption and safety issues (Liu et al. 2018). These limitations of the FWD test hinder its application at network level. In order to overcome these limitations, the traffic speed deflectometer (TSD) test has been developed recently. The TSD device can measure the pavement surface response at normal driving speeds, so it is a promising tool for pavement structural evaluation at network level (Shrestha et al. 2018). However, the TSD test is not widely used because of the lack of a proper parameter back-calculation technique. To solve this problem, the suitability of a spectral element method-based parameter back-calculation technique to deal with TSD measurements is investigated in this paper.

2 MODEL DESCRIPTION

Theoretically, the TSD test on pavements is modelled as a layered system subjected to a uniformly moving surface load. The load is considered to be a constant force which is evenly distributed over a pair of rectangular areas. The geometry of the loading areas is determined based on the footprint of the TSD wheel. The layered system consists of several layers and a half-space, which are well-defined elastic continua. For the layered system, each layer and the half-space are respectively simulated by a layer spectral element and a semi-infinite spectral element, which are developed by following the spectral element method-based procedure shown in Sun et al. (2019). It is assumed that the layered system has hysteretic damping, which is simulated by replacing the Young's modulus E with a complex Young's modulus $\tilde{E}(k_x,\omega)$ defined in the wavenumber-frequency domain related to a moving coordinate system that follows the load:

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

where i is the imaginary unit satisfying $\mathrm{i}^2=-1$, ξ is the damping ratio, sgn(·) is the signum function, ω is the angular frequency, c is the driving speed of the TSD device, and k_x is the wavenumber in the driving direction.

The origin of the moving coordinate system is consistent with the centre of the loading area, and the positive x-direction is the driving direction. In practice, the TSD device measures the vertical deflection slopes of fixed points in the moving coordinate system. The configuration of the loading area is shown in Figure 1, which can be described by a spatial distribution function $h_0(x,y)$ defined as follows:

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

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

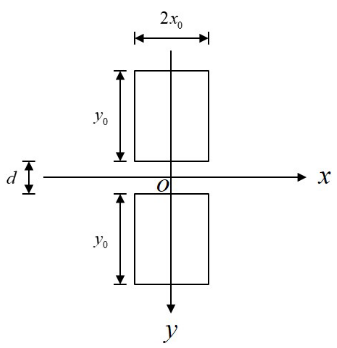

Figure 1. TSD loading configuration used in the simulations.

3 PARAMETER SENSITIVITY ANALYSIS

The accuracy of the back-calculated value for a certain parameter is related to the sensitivity of the response to this parameter. Hence, the parameter sensitivity analysis is necessary to select parameters which can be accurately back-calculated. To well represent the load applied by the TSD device, the following parameters are used:

- The driving speed c of the TSD device is 13.9 m/s (50 km/h);
- The magnitude of the loading pressure p_0 is 707 kPa;
- For the loading area, the parameter x_0 is 0.06316 m, y_0 is 0.27432 m, and d is 0.15 m.

It is assumed that the applied load has a rectangular influence area on the pavement surface with a length of 400 m in both x-direction and y-direction, and the centre of this area is the same as that of the loading area. The reference structural parameters of the considered pavement are shown in Table 1. The sensitivity of the slope curve of surface vertical displacement along the x-axis to different structural parameters (Young's modulus, damping ratio, and thickness) is investigated based on single factor analysis, and the result of the reference pavement structure is shown in solid lines. The variation of a certain parameter is set to be 50% of the reference value. In addition, the sensitivity to different parameters is divided into five levels: hardly sensitive, slightly sensitive, moderately sensitive, relatively sensitive, and highly sensitive. For brevity, the surface layer, base layer, and subgrade are represented by subscripts "1", "2", and "3", respectively.

Table 1. Reference structural parameters of the pavement.

Layers	E	ξ	v	ρ	h
	MPa	–	–	kg/m^3	m
Surface	2000	0.05	0.3	2200	0.1
Base	200	0.05	0.3	2000	0.3
Subgrade	50	0.05	0.3	1800	∞

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

3.1 *Sensitivity to Young's modulus*

The slope curves of surface vertical displacement for pavements with different Young's moduli of surface layer, base layer, and subgrade are shown in Figures 2(a), 2(b), and 2(c), respectively. The results show that the slope curve is relatively sensitive to the Young's modulus of the surface layer, and it is highly sensitive to the Young's moduli of the base layer and subgrade. In addition, the results also indicate that the slope of vertical displacement is zero (the vertical displacement is maximum) at a point behind the centre of loading area.

3.2 *Sensitivity to damping ratio*

The slope curves of surface vertical displacement for pavements with different damping ratios of surface layer, base layer, and subgrade are shown in Figures 3(a), 3(b), and 3(c), respectively. The results show that the slope curve is hardly sensitive to the damping ratio of the surface layer, and it is slightly sensitive to the damping ratios of the base layer and subgrade.

3.3 *Sensitivity to thickness*

The slope curves of surface vertical displacement for pavements with different thicknesses of surface layer and base layer are shown in Figures 4(a) and 4(b), respectively. The results show that the slope curve is highly sensitive to the thicknesses of the surface layer and base layer.

4 PARAMETER BACK-CALCULATION

Generally, a parameter back-calculation technique is a combination of a forward calculation model with a minimisation algorithm. In this paper, the proposed spectral element method-based model (Sun et al. 2019) is combined with the Powell hybrid algorithm (Al-Khoury et al. 2001b) to back-calculate the structural parameters of pavements by analysing TSD measurements.

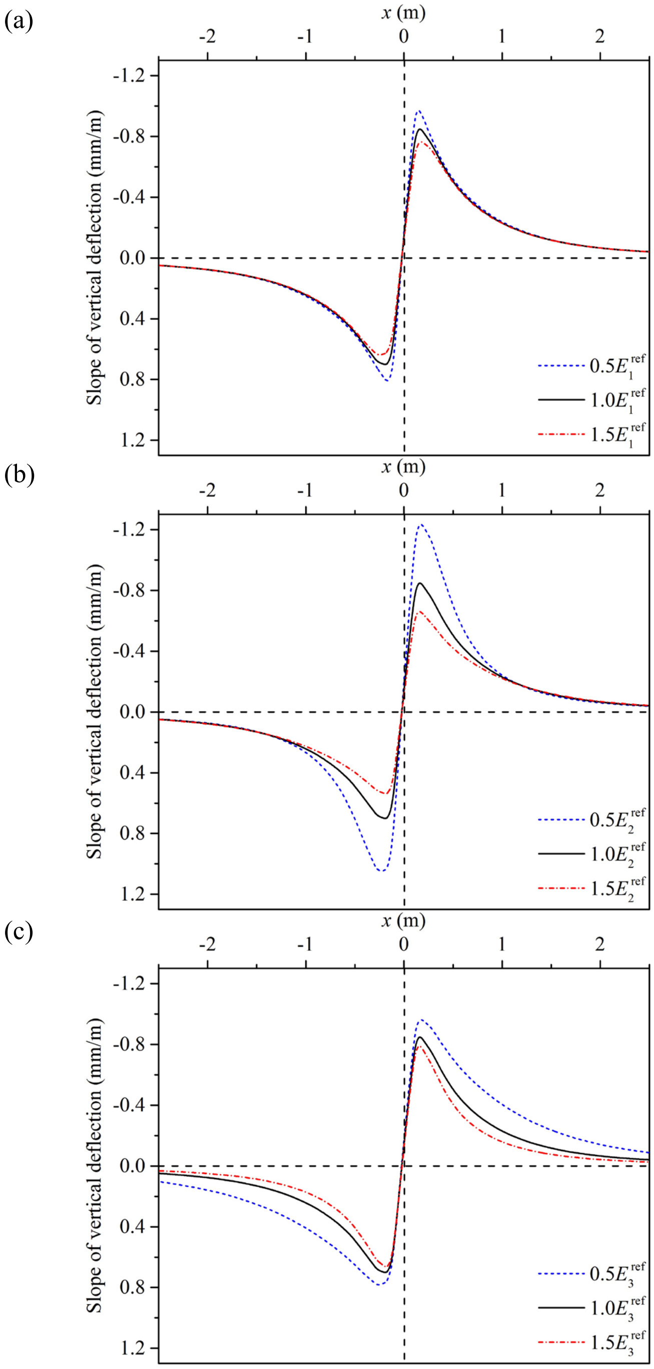

Figure 2. Sensitivity of the slope curve to the Young's modulus of: (a) surface layer, (b) base layer, and (c) subgrade.

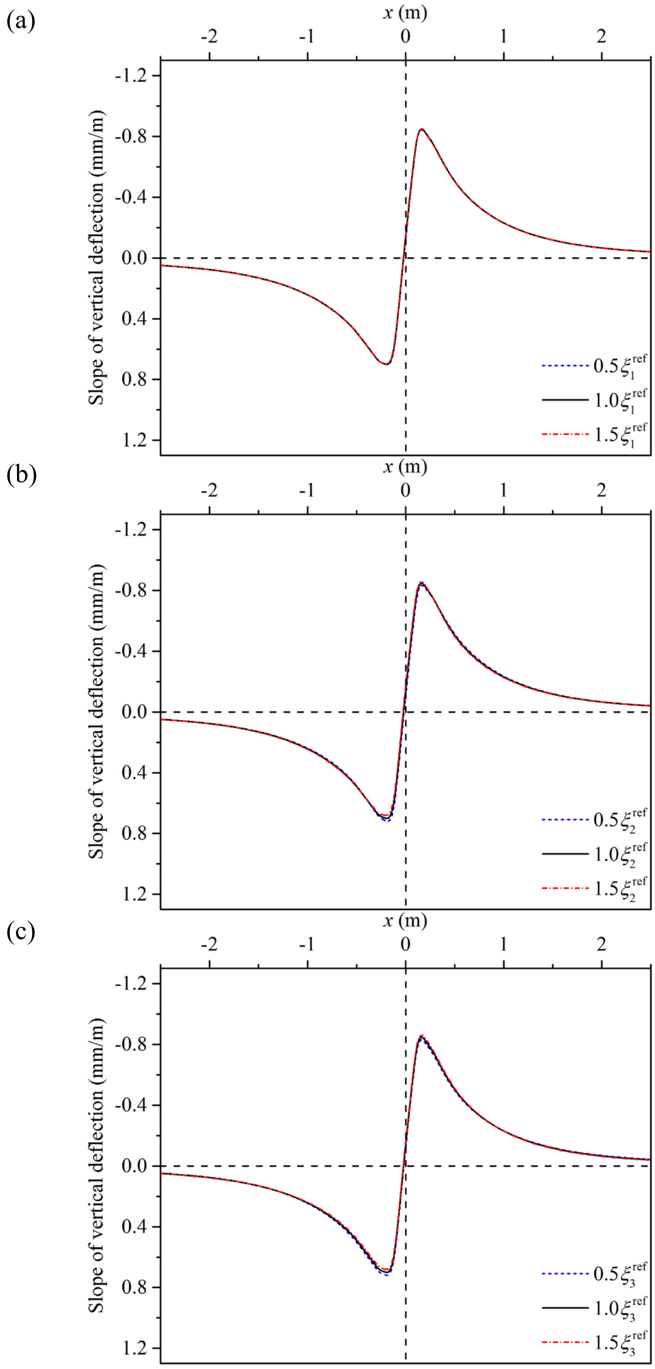

Figure 3. Sensitivity of the slope curve to the damping ratio of: (a) surface layer, (b) base layer, and (c) subgrade.

The objective function for the minimisation algorithm is:

$$f\left(\underline{\mathbf{p}}\right)=\sqrt{\sum_{m=1}^{M}\left[\frac{s^{\text{modelled}}\left(x_m, y_m;\underline{\mathbf{p}}\right)}{s^{\text{measured}}\left(x_m, y_m\right)}-1\right]^2} \tag{3}$$

where $f(\underline{\mathbf{p}})$ is the objective function, $\underline{\mathbf{p}}$ is a vector that contains the parameters to be back-calculated, (x_m, y_m) are the coordinates of the m-th measuring point, M is the total number of measuring points, $s^{\text{modelled}}(x_m, y_m;\underline{\mathbf{p}})$ is the modelled slope of vertical displacement at the m-th measuring point, and $s^{\text{measured}}(x_m, y_m)$ is the corresponding measured slope.

The most likely parameters which give good match between modelled and measured slopes can be obtained by minimising the value of the objective function. According to the results of the sensitivity analysis, the Young's moduli (E_1, E_2, and E_3) of all layers and the thicknesses (h_1 and h_2) of surface layer and base layer are chosen as unknown parameters to be back-calculated. The modelled slopes at five points on the surface of the reference pavement structure are set as synthetic measurements, which are used to back-calculate the unknown parameters by the proposed technique. The true values of these parameters are the values shown in Table 1.

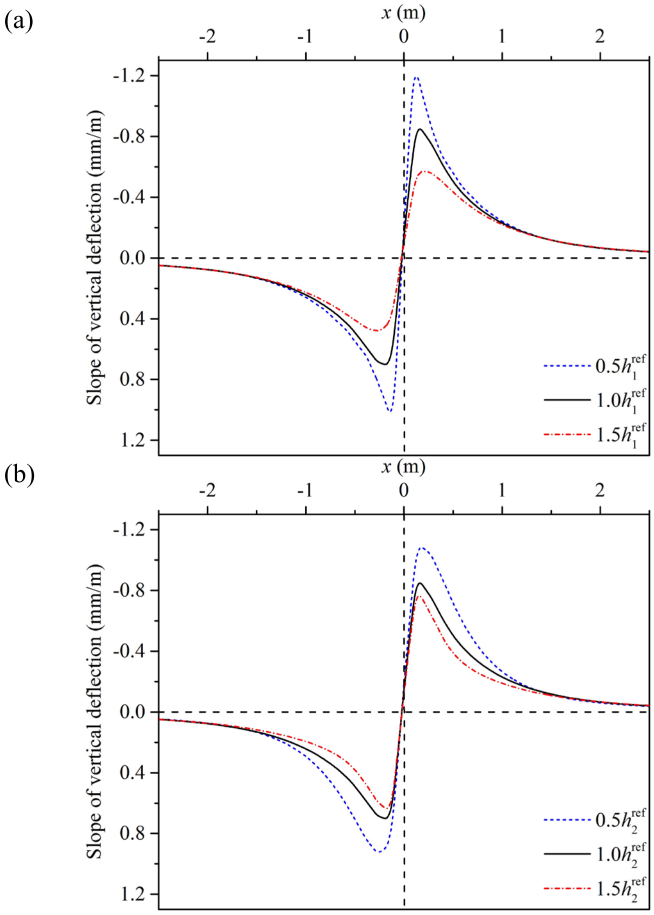

Figure 4. Sensitivity of the slope curve to the thickness of: (a) surface layer and (b) base layer.

In the back-calculation process, it is found that the initial guesses of the unknown parameters affect both the accuracy of the back-calculated results and the computational time. Hence, some auxiliary methods are recommended to be used to find a good set of initial guesses, such as referring to the design data of pavements. In this paper, the following initial guesses of the unknown parameters are used: E_1 = 2500 MPa, E_2 = 150 MPa, E_3 = 40 MPa, h_1 = 0.07 m, and h_2 = 0.4 m. The back-calculated parameters are: E_1 = 2001.2 MPa, E_2 = 205.5 MPa, E_3 = 50.2 MPa, h_1 = 0.099 m, and h_2 = 0.30 m. The relatively good agreement between the back-calculated and the true parameter values confirms the ability of the proposed technique to deal with TSD measurements.

5 CONCLUSIONS

A spectral element method-based parameter back-calculation technique for the traffic speed deflectometer (TSD) test is proposed in this paper. Firstly, the sensitivity of the slope curve of pavement surface vertical displacement to different structural parameters is investigated. Then, the ability of the proposed parameter back-calculation technique is verified via a case study. On the basis of the results and discussions above, the following conclusions can be drawn:

- The slope curve is relatively sensitive to the Young's modulus of the surface layer, and it is highly sensitive to the Young's moduli of the base layer and subgrade.
- The slope curve is hardly sensitive to the damping ratio of the surface layer, and it is slightly sensitive to the damping ratios of the base layer and subgrade.
- The slope curve is highly sensitive to the thicknesses of the surface layer and base layer.
- The combination of the spectral element method-based pavement model and the Powell hybrid algorithm may become a promising parameter back-calculation technique for the TSD test.

The work presented in this paper promotes the development of parameter back-calculation techniques based on TSD measurements.

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