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A nondestructive evaluation method for semi-rigid base cracking condition of asphalt pavement

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HIGHLIGHTS

- A model was developed to nondestructively evaluate the semi-rigid base cracking condition.
- The normalized base modulus ($\bar{E}_b/E_0$) was selected as the discriminant indicator in the model.
- $\bar{E}_b/E_0$ and PCI_B have a good linear relationship on log-log scales.
- The model is robust to the fixed value of the subgrade modulus.

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ABSTRACT

The evaluation of semi-rigid base cracking condition is one of the most important elements of project-level pavement evaluation, and has been a key challenge facing pavement engineers for many years. This is because that the semi-rigid base cracking condition cannot be obtained through visual surveys unless the asphalt course is milled off, therefore the nondestructive detection and evaluation method is a better choice. This paper develops a nondestructive FWD-based evaluation model to evaluate the semi-rigid base cracking condition. It was found that the normalized base modulus (ratio between back-calculated and initial modulus) and the semi-rigid base cracking condition had good relationship on log-log scales, therefore the normalized base modulus was considered to be a reasonable indicator for the evaluation of semi-rigid base damage (cracking) condition. Based on the comparison of measured data and back-calculated modulus in freeway pavements, the evaluation criterion is established.

1. Introduction

The base courses of approximately 95% expressway pavement structures in China were constructed with cement-treated material to reduce effectively the vertical compressive strain on the subgrade [1]. This base course with a higher cement content is known as semi-rigid base course. The main disadvantage of the semi-rigid base course is that it is very often to induce cracks, which will further induce the reflective cracks in asphalt course [2–4]. Many freeways, which were built early, have reached or been close to their service lives, therefore been facing rehabilitation or overlay. In determining whether or not to renovate the semi-rigid bases of these existing pavements in the rehabilitation design, a key challenge facing pavement engineers is how to accurately evaluate the cracking condition of semi-rigid base.

The semi-rigid base course is hidden beneath the asphalt layer, so that its cracking condition is invisible and cannot be evaluated by the routine methods such as visual surveys or image identification [5]. Usually, the resilient deflection on the pavement surface were used for the evaluation of structural bearing capacity, but not for the evaluation of distress condition of the semi-rigid base course. In this case, the nondestructive detection based on FWD and evaluation method would be a better choice.

FWD is believed to be the most popular nondestructive test procedures for the evaluation of the structural condition of pavements [6]. Typically, the pavement deflection bowl measured by FWD is used to back-calculate a set of layer properties through searching the best matches between theoretical deflection bowl and the measured data. Based on this back-calculation principle, many back-calculation procedures have been developed [1,6].

Pavement response analysis (production of deflections) can be considered as either static or dynamic. The methods that can incorporate dynamic effects usually assume a damped elastic or elastodynamic system, which is analyzed using the finite element

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method (FEM) [7] or the spectral element method [8]. Dynamic response analysis can be performed either in the time domain [9] or the frequency domain [10]. Although dynamic analysis can predict the viscoelastic properties of the asphalt surface course, it is complex and computationally expensive. Therefore, static inverse analysis is extensively used in pavement-related design and research [11].

The Young's modulus is an important back-calculated parameter, also a widely-used indicator of material properties, and will be gradually reduced with the development of material damage. Therefore, the objective of this paper is to develop a nondestructive evaluation method for the semi-rigid base damage (cracking) condition based on the back-calculated modulus of base course.

2. Data profile

2.1. Test site characteristics

The test sites selected for this project were two freeways (FREEWAY CZ and FREEWAY CT) with semi-rigid pavements (Table 1) in southern China. These two freeways were under maintenance, and all the existing asphalt layers and part of the semi-rigid base would be milled off. These two freeways both had a passing lane and a driving lane in each direction.

2.2. Test program

The deflection measurements were made on the pavement surface by FWD at regular 20 m intervals on both sides of the wheel track in each lane. The load level was 50 kN, and nine deflections were measured at radial distances of 0, 203, 305, 457, 610, 914, 1219, 1524, and 1829 mm from the center of the loaded area. Then the existing asphalt layers were completely milled off, and the semi-rigid base surface was cleaned. The surveys of semi-rigid base cracking condition were performed.

3. Methodology

3.1. Back-calculation of semi-rigid base moduli

3.1.1. Back-calculation algorithm

In back-calculation analysis of pavement-layer moduli, the objective is to identify a set of pavement layer moduli that would produce a deflection basin matching the measured deflection basin. Modulus back-calculation is an optimization process that can be performed by many algorithms such as the gradient descent method, the least-squares method, genetic algorithms, and database search [6]. A major problem faced by this process is that the multidimensional surface represented by the objective function may have many local minima [12].

A potentially good back-calculation procedure should have a strong global search capability to overcome the problem of local minima. The simulated annealing-particle swarm optimization (SA-PSO) algorithm was proposed by Chaojun and Zulian [13].

Table 1
Properties of pavement structures.

Pavement layer	Material	Thickness (cm)	
		FREEWAY CZ	FREEWAY CT
Surface course	Asphalt concrete	19	16
Base	Crushed stone (with 4% cement)	23	58
Subbase	Granular stone	30	–

The basic idea of PSO algorithm came from research on the behavior of bird swarms looking for food. For example, it is assumed that there are m particles in a swarm, and the ith particle's position and flit speed is $\mathbf{X}_i$ and $\mathbf{V}_i$ respectively. Until now the best position of the ith particle and the whole swarm is $\mathbf{P}_i$ and $\mathbf{P}_g$ respectively. Every particle always follows two best positions – the best position in the whole swarm and for itself – in iterative computation. The PSO algorithm is shown in Eqs. (1) and (2). It is obvious that the PSO algorithm is very simple, but the algorithm itself includes the principles of sociology, psychology and bionomics, which is the main reason that many peoples are sure that the PSO algorithm has a good foreground.

$$\mathbf{X}_i = \mathbf{X}_i + \mathbf{V}_i \tag{1}$$

$$\mathbf{V}_i = \mathbf{V}_i + c_1\gamma_1(\mathbf{P}_i - \mathbf{X}_i) + c_2\gamma_2(\mathbf{P}_g - \mathbf{X}_i) \tag{2}$$

where, $i = 1, 2, \cdots, m$, c_1 and c_2 are, respectively, the study coefficients of cognizing and society. γ_1 and γ_2 are both random numbers between 0 and 1.

The PSO algorithm converges very fast, but easily gets stuck in local minima. So the Metropolis law used in the SA algorithm is introduced into PSO to make SA-PSO become a global optimal algorithm. The Metropolis law is that the hypo-best point is accepted at a certain extent probability. The accepted probability function was got from the extent Boltzman-Gibbs distributing, shown blow:

$$p = \exp(-\Delta f / T_k) \tag{3}$$

where, $\Delta f = f(\mathbf{X}_i) - f(\mathbf{P}_i)$, $f(\mathbf{X}_i)$ and $f(\mathbf{P}_i)$ is the ith particle solution and the historical best solution respectively. $T_k = T_0\alpha^k$, $T_k$and T_0 is the anneal temperature at the kth annealing-time and the initialized temperature, α is rate of cooling.

The performance evaluation of the SA-PSO algorithm is presented here by solving the back-calculation problems analyzed by Harichandran et al. [12], and compared with two well-known algorithms, namely, MODULUS, and MICHBACK. The detailed material properties and deflections can be found in the reference [12]. The maximum percentage error in the back-calculated modulus for each pavement layer is given in Table 2. The results show that SA-PSO produced the best estimates of layer moduli in Problems A and B. Therefore, the SA-PSO algorithm was used in this paper to analyze the deflection basins measured by FWD.

The number of pavement layers in the two freeways was reduced to a three-layer system: surface course, semi-rigid base, and subgrade. The granular subbase was incorporated into the subgrade in modulus back-calculation for FREEWAY CZ. Poisson's ratios were assumed to be 0.35, 0.2, and 0.35 for the surface course, the base course layer, and the subgrade respectively. And Eq. (4) was used in this paper as the objective function for estimating the layer moduli:

$$\text{Minimize } f = \sum_{i=1}^{m} (d_i - D_i)^2, \tag{4}$$

where, m is the number of deflection-measurement points, d_i is the calculated deflection at point i, and D_i is the measured deflection at point i.

3.1.2. Subgrade modulus treatment

With the objective function shown in Eq. (4) and SA-PSO algorithm, the subgrade moduli were back-calculated. Table 3 shows the spatial variation of back-calculated subgrade moduli. The coefficients of variation (CV) of FREEWAY CZ and CT were 34.3% and 37.9% respectively. The spatial variation of the back-calculated subgrade moduli was larger than measured results. The spatial variation may result from the modulus back-calculation algorithm

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