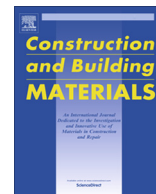




Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

More accurate modulus back-calculation by reducing noise information from in situ-measured asphalt pavement deflection basin using regression model

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HIGHLIGHTS

- Quintic polynomial regression model best for fitting theoretical deflection basin.
- Theoretical basin used to remove noise within in situ-measured basin.
- Partial validation provided by comparison to measured core splitting moduli.

ARTICLE INFO

Article history:

Received 19 June 2017

Received in revised form 2 October 2017

Accepted 4 October 2017

Available online xxxx

Keywords:

Noise information

Back-calculation modulus

Theoretical deflected basin

Measured deflection basin

Mathematical regression model

Probability density

ABSTRACT

The noise in in-situ measured asphalt pavement deflection basin is the primary cause for the difference between the theoretical deflection basin in back-calculating software and measured basin, which affects the accuracy of the modulus back-calculation. The influence of noise, including the pavement surface condition and internal anomalies, on the deflection basin was studied. The optimum mathematical regression model for the theoretical deflection basin without interference was analysed using the probabilistic density method, which was then applied to remove the noise information of the in-situ measured deflection basin. The back-calculated moduli (with and without deflection basin correction) were compared, and splitting moduli from coring samples of the surface asphalt layer were additionally compared for partial validation. The results show that the quintic polynomial is effective at eliminating the noise information of deflection basin. The corrected back-calculation moduli are reasonable and close to the splitting moduli, and its data variation is smaller than that of the uncorrected back-calculation moduli.

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1. Introduction

The back-calculation of the layer moduli of asphalt pavement is an important methodology for evaluating the mechanical strength, bearing capacity, material durability, and residual life of each layer of asphalt pavement [1–4]. Layer moduli back-calculation is based on simulated theoretical deflection basin using numeric hypothesis model and in-situ measured deflection basin using the falling weight deflectometer (FWD).

Efforts have been made to develop some generalized modulus back-calculating approaches such as the database-searching

method, multi-layered elastic system cyclic iterative algorithm, homotopic algorithm, genetic algorithm, artificial neural network method, and particle swarm optimization algorithm [5–8]. However, there are some inevitable reasons for a poor uniform back-calculated modulus and a result deviating from the in-situ measured pavement modulus [9].

The falling weight deflectometer (FWD) is a device that applies an impulsive load to the pavement surface and records the deflection response from sensors. The level of impact load, loading duration, and area are adjusted to correspond to the actual loading by a standard truck moving on in-service asphalt pavement [10]. However, the theoretical deflection basin is simulated using simplified numerical hypothesis model without completely considering the actually deflection collecting condition [11,12]. The difference between the in-situ measured and the theoretical deflection basin

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is one of the main reasons for the low accuracy of the back-calculated modulus [13].

Factors affecting the difference mainly include the temperature, humidity, layer modulus ranges, thickness ranges, Poisson's ratio, bonding condition and loading characteristics [14–23]. These factors are relevant to the pavement structure and mechanism, which can be adjusted to make the theoretical structure be in line with the in-situ structure and the difference of theoretical deflection basin and in-situ measured deflection basin can be reduced to a minimum [24–26]. However, some other factors affecting the difference are random, uncertain and not easy to quantify. They are concluded as multiple potential sources of useless information, named noise or noise information herein, generation in in-situ measured deflection basin [27,28]. Firstly, the movement of nearby heavy traffic may interfere with the stress wave produced by FWD loading and therefore produce noise information in the FWD basin. Secondly, the pavement surface condition (i.e. debris, roughness, and potholes) may result in poor sensor-pavement contact and some sensor of the sensor array may get unsatisfactory data. Thirdly, one or more sensor may be invalid and their response data may be error. Lastly, pavement anomalies (i.e. voids, rigid stones, macro cracking, and micro cracking) underneath the pavement could result in deviation of layered elastic system hypothesis and induce the variation of the whole collected deflection basin.

Finding a way to reduce the difference between the theoretical and in-situ measured deflection basin due to the noise information has theoretical and practical significance for improving the accuracy of modulus back-calculation. The objective of this paper is to systematically study the noise information affecting the in-situ measured deflection basin and find how to eliminate the noise information and thereby reducing the difference between measured and theoretical results. The following aspects were studied:

- 1) Analysis of the theoretical deflection basin and development of the optimum regression model;
- 2) Analysis of the effect of pavement condition (i.e. surface condition and pavement anomalies) and nearby heavy moving traffic on the in-situ measured deflection basin;
- 3) Introduction and validation of the deflection basin correction method presented in this paper.

2. Theoretical methodology

The theoretical asphalt pavement deflection basin is established under the ideal condition, which completely eliminates the influence of the disturbance factors resulting in noise information in measured deflection basin. Thus, research the theoretical basin under ideal condition and find the optimum mathematical regression curve which fits the interesting deflection basin perfectly can effectively guide the removal of noise information from the measured deflection basin.

2.1. Typical regression models

Scholars have researched the geometric shape of the deflection basin for many years. The consensus is that the asphalt pavement deflection basin curve can be best described with some typical regression models [29,30]. These regression models are summarized in Table 1.

2.2. Evaluation index for descriptive effect

In order to assess the descriptive effectiveness of the regression models, the root mean square error (RMSE) has been adopted in this research [31]. The mathematical explanation of root mean square error (RMSE) is as Eq. (1):

Table 1
Typical regression models of deflection basin curve.

Model No.	Type	Regression models
1	Normal probability	$y = ae^{-bx^2}$
2	Quadratic fractional	$y = a/(1 + bx^2)$
3	Sinusoidal	$y = a \sin(bx + 2/\pi)$
4	Parabola	$y = a + bx + cx^2$
5	Cubic polynomial	$y = a + bx + cx^2 + dx^3$
6	Quartic polynomial	$y = a + bx + cx^2 + dx^3 + ex^4$
7	Quintic polynomial	$y = a + bx + cx^2 + dx^3 + ex^4 + fx^5$
8	Exponential	$y = ae^{bx}$
9	Sigmoid	$y = a/(1 + e^{-b(x-c)})$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n \left(\frac{d(r_i) - y(r_i)}{y(r_i)} \right)^2} \times 100\%. \quad (1)$$

where, $d(r_i)$ is the in-situ measured deflection at different distances (r_i) from the load centre. $y(r_i)$ is the calculated deflection at corresponding distance (r_i) using the fitted regression model based on theoretical or in-situ measured deflection. n is the amount of response points of deflection basin.

In order to more vivid demonstrate the descriptive effectiveness of the regression models using RMSE index. One in-situ measured deflection basin is selected in Table 2. The measured deflection basin are fitted using Quintic polynomial and Exponential respectively. Deflections at response points are calculated using the fitted basin curve showed in Table 3. Fig. 1 shows the descriptive effectiveness of the Quintic polynomial and Exponential.

According to Table 3 and Fig. 1, it is apparent that the fitted basin 1 is closer to the measured basin than the fitted basin 2. As for the fitted basin 2, deflections are different or deviated from that of measured basin except for the fifth response point. The fitted basin 1 is almost coincided with the measured one. The RMSE of fitted basin 1 is 1.94% and the RMSE of fitted basin 2 is 8.21%. A larger RMSE indicates that the difference (deviation) between the regression model and theoretical or between the regression model and in-situ measured deflection basin is more apparent and the descriptive effect is worse, vice versa.

2.3. Development of theoretical pavement structures and theoretical deflection basin

Based on the typical four-layer asphalt pavement structure of an expressway (especially in China), the basic ranges of the parameters of each structural layer are determined (Table 4) according to the asphalt pavement design specification [32]. The Poisson's ratio and bonding condition have a relatively small impact on the surface deflection [33]. Thus, the Poisson's ratio is assumed to be a constant for each corresponding layer, and the bonding conditions are assumed to be completely continuous to simplify variations.

Using the modulus and thickness ranges of each structural layer in Table 4, 10000 sets of pavement structures were randomly combined. The statistical data of each structural layer are shown in Table 5.

The 10000 sets theoretical deflection basins of 10000 random pavement structures under the standard load (50 kN) are solved with pavement mechanics calculation software based on a layered elastic system. The sensor arrangement and response points of the deflection basin are shown in Table 6.

2.4. Statistical geometrical analysis of theoretical deflection basin

Based on the nine different regression models presented in this paper, 10000 theoretical deflection basins were fitted, and the

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