FINITE ELEMENT ANALYSIS OF EFFECTS OF ASPHALT PAVEMENT DISTRESSRS ON FWD DYNAMIC DEFLECTION BASIN

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ABSTRACT

Falling weight deflectometer（FWD） testing has been done extensively in the past to assess structural condition. Utilizing the deflections measured by the FWD, the resilient modulus of layers in the flexible pavement is determined using back calculation software packages. But the pavement distresses influence the validity of FWD dynamic deflection basin. This paper based on the theory of structural dynamics, the three dimensional dynamic finite element model was created. The influence of asphalt pavement distresses such as interlayer contact between surface course and base course, a single transverse pavement cracks, multiple-transverse cracks, longitudinal cracks and block crack on FWD dynamic deflection basin were analyzed using this model.The results show that the interlayer contact mainly affects the dynamic deflection of four surface deflection point. For single transverse cracks , the measured value of FWD is close to that of the pavement structure without cracks when the distance between the load centre of FWD and the cracks is greater than 1.1m. For longitudinal cracks , FWD dynamic deflection basin is not significantly different from that of pavement structure without cracks when the distance between loading and longitudinal cracks is greater than 0.35m.

Keywords: asphalt pavement, falling weight deflectometer, interface condition, cracks

1 INTRODUCTION

Many asphalt pavements appeared a certain degree of distresses in China, such as cracks, rutting, distortion, disintegration, etc. These pavement needs repair immediately, so it is much important to evaluate the performance of pavement before repairing it (XU, 2012).As one of the main non-destructive testing equipment to evaluate pavement strength，Falling weight deflectometer (FWD) is currently used by most highway agencies to determine the structural condition of the highway network. Utilizing the deflections measured by the FWD, the resilient modulus of layers in the flexible pavement is determined using backcalculation software packages. But the pavement distress such as cracks, the layer interface between an AC layer and a base layer can influence the FWD to evaluate the strength. It makes dynamic deflection basin present a significant discontinuity characteristics (WANG, 1999). It also makes the dynamic deflection basin different due to the load position of FWD for the same damage (Hassan, 2007). Many researchers used the data of FWD to determine the modulus of pavement layers (Rada, 1992; Rauhut, 1992; Thompson, 1992; Mehta, 2015). The set of modulus values for pavement layers obtained from the backcalculation process may not be accurate. Because the characteristics of the structure such as damaged layers, a single transverse pavement cracks, multiple-transverse cracks, longitudinal cracks and block crack can overwhelm the deflection data, having a far more significant effect than those induced by structural layer stiffness. So in order to analyze the influence of pavement distresses on dynamic deflection basin of FWD, three-dimensional finite element model is established. The factors of layer interface, transverse single crack, transverse multiple crack, longitudinal crack, block crack to the dynamic deflection basin are analyzed in this paper.

2 THEORY OF DYNAMIC ANALYSIS ON PAVEMENT STRUCTURES

2.1 Dynamic equilibrium equation

Introduce the time coordinates to dynamic analysis of the finite element method, the analyzed objects turn into four dimensions (x, y, z, t), and generally using partial discrete method, only for discrete spatial domain. The motion equation can be expressed as follows (Lin, 2008):

$$\boldsymbol{M}\ddot{\boldsymbol{u}}(\boldsymbol{t})+\boldsymbol{C}\dot{\boldsymbol{u}}(\boldsymbol{t})+\boldsymbol{K}\boldsymbol{u}(\boldsymbol{t})=\boldsymbol{Q}(\boldsymbol{t}) \quad (1)$$

where: $\ddot{\boldsymbol{u}}(\boldsymbol{t})$ and $\dot{\boldsymbol{u}}(\boldsymbol{t})$ are respectively nodes acceleration and velocity vector; $\boldsymbol{M}$ 、$\boldsymbol{C}$ 、 $\boldsymbol{K}$ and $\boldsymbol{Q}(\boldsymbol{t})$ are respectively the system mass matrix, damping matrix, stiffness matrix and nodal load vector.

2.2 Equation solution method

The traditional solution methods to dynamic equilibrium equations include mode superposition and direct integration. We assume that the solution up to time *t* is known when the direct integration method is used, and the central difference method is used to determine the solution at time $t + \Delta t$. Equation (1) is satisfied at time *t*. The displacement solution, velocity, and acceleration are calculated using the Newton-Raphson iteration algorithm to satisfy the convergence condition. The basic equations used in the analysis are listed as follows:

$$\begin{cases} \dot{\boldsymbol{u}}_{i+1} = \dot{\boldsymbol{u}}_i + (1-\gamma)\Delta t\ddot{\boldsymbol{u}}_i + \gamma\Delta t\ddot{\boldsymbol{u}}_{i+1} \\ \boldsymbol{u}_{i+1} = \boldsymbol{u}_i + \Delta t\dot{\boldsymbol{u}}_i + (\frac{1}{2}-\beta)\Delta t^2\ddot{\boldsymbol{u}}_i + \beta\Delta t^2\ddot{\boldsymbol{u}}_{i+1} \end{cases} \quad (2)$$

where γ and β are the parameters constructed based upon known accuracy and stability. The algorithm is typically stable when $\gamma \geq 0.5$ and $\beta \geq 0.25\ (0.5+\gamma)^2$ based on the Newmark-β algorithm. γ and β are assumed to be 0.505 and 0.2525, respectively, and the time step is limited to less than 1/50 of the basic period time in the analysis.

2.3 Mass and damping matrix

The unit mass matrix is expressed as a consistent mass matrix to correspond with the direct integration Newmark-β solution method. The damping matrix employs the Rayleigh form, as shown in Equation (3).

$$\boldsymbol{C} = \alpha\boldsymbol{M} + \beta\boldsymbol{K} \quad (3)$$

where, α is the viscous damping parameter and β is the structural damping parameter..

3 THREE DIMENSIONAL FINITE ELEMENT MODEL

3.1 Parameters of pavement structure and material

A typical asphalt pavement composed of an asphalt layer (AC), a cement treated base (BC), an unpaved subbase (Sub-BC), and an subgrade(SG) was used as an analysis object (Qiu, 2009). The material properties of various layers are characterized by the elastic dynamic resilience modulus because of the short FWD load time. These properties are enumerated in table 1.

Tab. 1 Material properties of pavement structural Layers

Layer	Thick-ness (cm)	Modulus (MPa)	Poisson ratio	Density ($kg\cdot m^{-3}$)	Damp ratio
AC	16	3 000	0.35	2 200	0.05
BC	40	5 000	0.25	2 100	
Sub-BC	15	250	0.35	1 900	
SG	—	150	0.40	1 800	

3.2 Three dimensional finite element model

The finite element modeling (FEM) used in this study employed three-dimensional 10-node solid elements. The finite element mesh developed has the following dimensions; 30m in x-direction (length), 30m in the y-direction (width), and 10m in the z-direction (height). Fixed constrain was assigned to the model bottom, while normal displacement constrain was applied to the side areas of the model., as shown in figure 1. For this, a transverse crack was placed through the asphalt layer and base layer. Interface elements, namely, TARGE170 and CONTA174 were used to simulate the cracks condition. CONTA174 is an eight-node three-dimensional surface-to-surface contact element, which has three degrees of freedom at each node. TARGE170 is the target surface associated with CONTA174 [ANASYS, 2005].

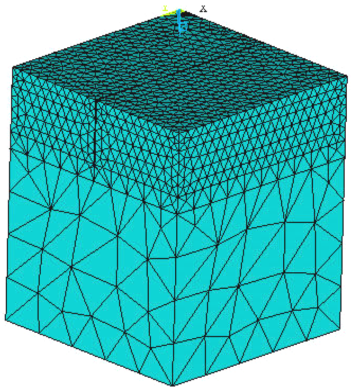


Fig1. Mesh of Pavement Model with Transversal Cracks

3.3 The FWD load model

A haversine FWD load with a peak load of 50 kN was uniformly distributed over a circular area of radius 15 cm for a duration of 30 ms. The corresponding deflections were measured at a distance of 0, 20, 30, 60, 90, 120, 150, 180, and 210 cm from the load center, as shown in table 2. The distance between the applied FWD load center and the crack edge was 16 cm. For measurements, the deflection sensors were placed across the transverse crack.

Tab.2 Layout plan of nine point sensors of FWD

number	d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8	d_9
distance	0	20	30	60	90	120	150	180	210

4 THE INFLUENCE OF LAYER INTERFACE BETWEEN AC AND BC LAYERS ON DEFLECTION

The distress observed in the pavement structure being examined indicates that full bonding between layers does not occur in most situations. A poorly compacted BC layer may result in AC layer slippage because sufficient support is not provided during construction. Thus, the interface between the AC and BC layers varies in condition from full bonding to complete de-bonding (Hu, 2011).The interface condition between the AC and BC layers may be described by Equation (4). Shear stress and displacement are proportional until shear stress equals critical shear stress. A friction model may then be used to represent the interface condition (Romanoschi, 1999)

$$\tau_{crit} = \mu \times P \qquad (4)$$

where τ_{crit} is critical shear strength, P is normal stress, and μ is friction coefficient.
The surface dynamic deflections with different μ values are illustrated in Figure 2, which shows that μ has a strong influence on deflection points close to the load center, such as *d1, d2, d3,* and *d4*, but little influence on other deflection points that are located far from the

load.

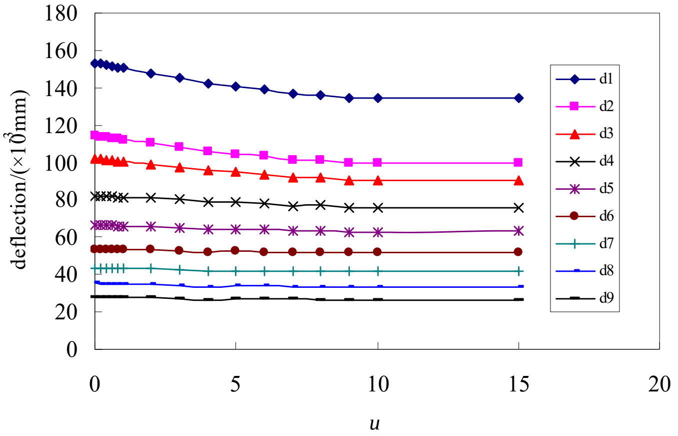


Figure.2 Influence of *μ* on dynamic deflection distribution

The degree of influence decreases with increase of *μ*. When μ is above 15, the various point deflections have a stable phase. When the friction coefficient between the layers is 15, the difference between it and fully continuous is shown in figure 3. Calculation results of deflection value exists significant difference of the former 4 points, and the difference of last 5 points is no more than 2% between them.

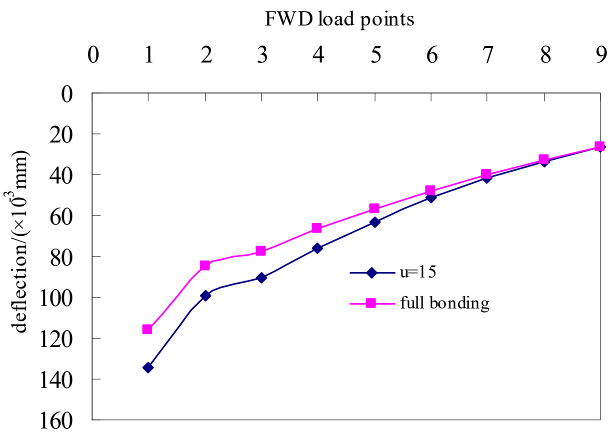
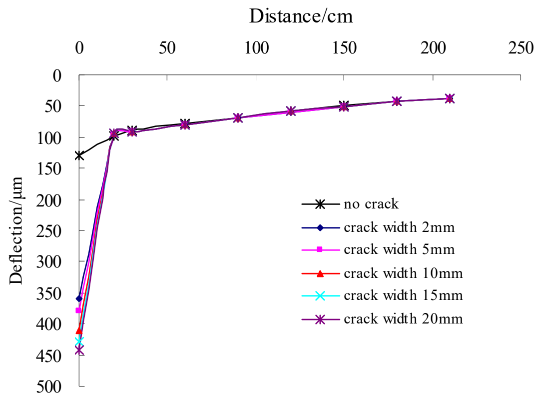


Figure.3 Deflection Distribution at the different conditions of layer contact

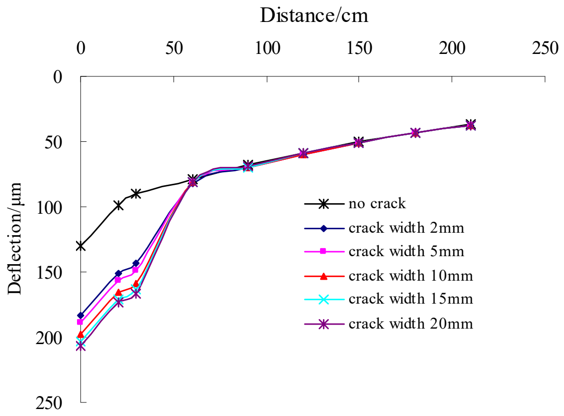
5 THE INFLUENCE OF TRANSVERSE CRACK ON DYNAMIC DEFLECTION BASIN

5.1 Impact of transverse single crack on deflections

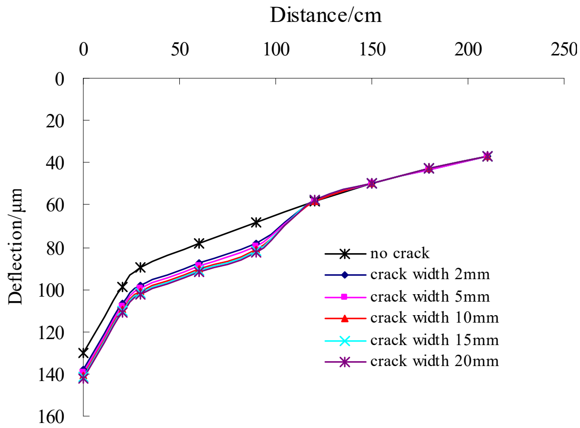
Figure 4 shows the influence of crack width on surface deflections, on changing the distance (d) from the center of FWD load to crack edge. The detailed findings are presented as follows: (1) When d is located between 0 and 150 cm, the shape of deflection basin changes, in addition to the increase in center deflection. The shape appears to be discontinuous. However, with increase in d, the shape of the surface deflection basin remains smooth, which is similar with the deflection form of the intact pavement. (2) When d is assigned to the same value and is less than 150 cm, the surface deflections located on the loading side prominently increases with increase in crack width. However, the other surface deflections remain unchanged.



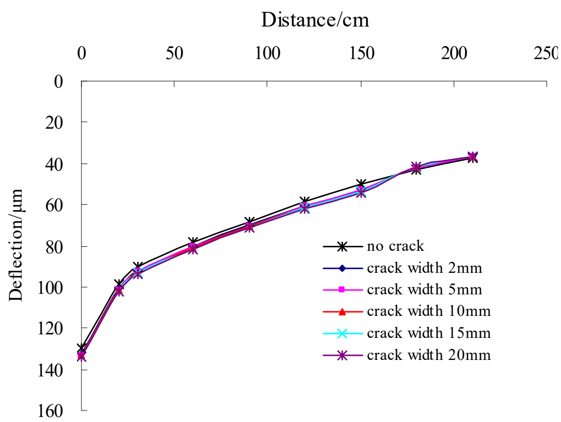
(a) *d*=16cm



(b) *d* = 45 cm



(c) *d* = 110 cm



(d) d = 165 cm

Figure.4 Influence of transverse single crack on deflections

5.2 Impact of transverse multiple cracks on deflections

Furthermore, to analyze the influence of transverse multiple cracks on the deflections, the distance from the center of the applied FWD load to the first crack edge was kept as 16 cm. The other deflection sensors were placed across the first crack. Figure 5 depicts the influence of the transverse crack interval on surface deflections when the crack width is 5 mm.

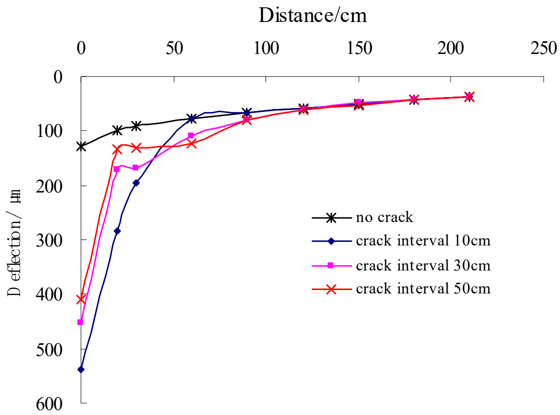


Figure. 5 Influence of transverse multiple crack on deflection

The results indicate that the crack interval is a prime determinant to change the distribution feature of surface deflection basins of asphalt pavements. With decrease in crack interval, the distribution shape becomes gradually different between intact pavements and crack pavements.

6 THE INFLUENCE OF LONGITUDINAL CRACKS ON DYNAMIC DEFLECTION BASIN

6.1 Impact of Longitudinal single crack on deflections

All deflection sensors were placed in parallel, along with the longitudinal crack side. The two variable parameters analyzed were the distance from FWD load center to crack edge and the crack width. Figure 6 illustrates the influence of the FWD load center to crack edge distance on surface deflections, when the crack width is 10 mm. The results indicate that the center deflections continuously decrease and tend to the deflection value of the intact pavement with increase in the FWD load center to crack edge distance.

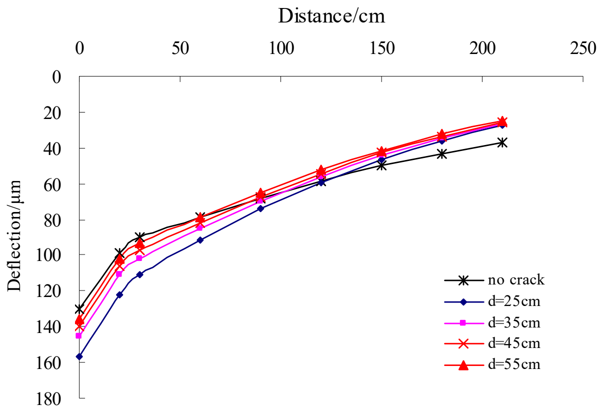


Figure.6 Loading Position and Dynamic Deflection Basin

Figure 7 shows the influence of the crack width on surface deflections, when the FWD load center to crack edge distance is 35 cm. It could be realized that, under different crack width values, the deflection distribution characteristics of distressed asphalt pavements are similar to each other, however, they are clearly different from that of the intact pavement.

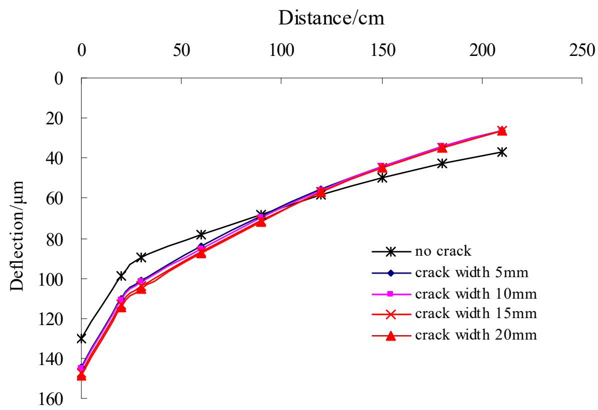


Figure.7 Cracks Gap and Dynamic Deflection Basin

6.2 Block cracks

In reality, the shape of block cracks is quite irregular and cannot be described completely. Therefore, a kind of "idealized" block crack model was established by multiple cross transverse and longitudinal cracks to magnify the discontinuity effect that would occur in the field. The FWD load center was located at the middle of block cracks, while the other sensors were place across the cracks. Figure 8 illustrates the FEM model of the pavement with block cracks.

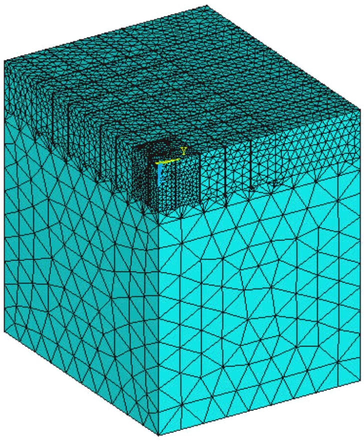


Figure. 8 Finite element modeling of pavement with a transverse crack

When the crack width is 5mm, the effect of block crack spacing on road surface dynamic deflection basin distribution, as shown in figure 9.

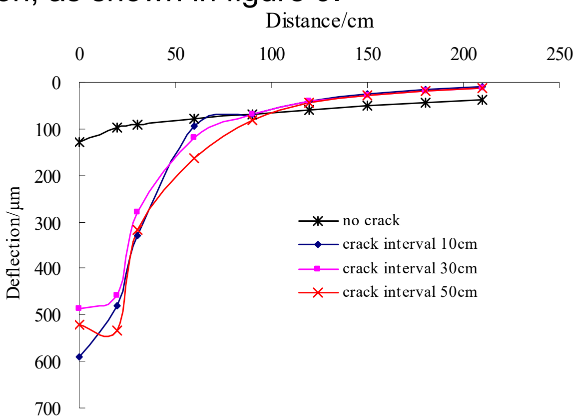


Figure.9 Net-shaped Area and Dynamic Deflection Basin

Figure 9 shows the influence of block cracks on surface deflections, when the crack width is 5 mm. The results indicate that the distribution characteristic has an increasing discrepancy between intact pavements and distressed pavements with increase in crack interval.

7 CONCLUSION

A number of conclusions can be drawn from this study. The influence of pavement distresses on deflections was analyzed using a 3D-FE program. The main findings of this analysis are as follows.

(1)There are obvious differences in distribution of deflection when the layer interface between AC and BC layers is different. The layer interface has a strong influence on deflection points close to the load center, such as *d1, d2, d3,* and *d4*, but little influence on the other deflection points that are located far from the load. When the friction coefficient between the layers is greater than 15, the difference of the last 5 points is no more than 2%. So it can use the outermost deflection to backcalculation the subgrade modulus

(2)For the transverse single crack, when the distance between the FWD load point and crack is greater than 110cm, the deflection is the same between the crack pavement and non-crack pavement. Influence of crack width on the deflection is increasing with the increase of the distance from the load center. But the impact of different crack width is not obvious.

(3)For the transverse multiple crack, the wider the crack width is, the fewer difference of deflection between transverse multiple crack and non-crack pavement. The impact of crack width on the deflection of the last 5 points such as d_5, d_6, d_7, d_8, d_9 is not obvious.
(4)When loading point distance from longitudinal cracks is greater than 35 cm, the dynamic deflection is not obvious between longitudinal crack pavement and non-crack pavement. With the space increase of block, there have great difference of the deflection for the first four point, but to the last 5 points, the deflection is not obvious between longitudinal crack pavement and non-crack pavement.
This cracks can influence the results of the resilient modulus of layers in the flexible pavement using backcalculation software packages. Future research should be carried out on other aspects, e.g. how to perform data filtering to backcalculate the resilient modulus. how crack can influence the resilient modulus of layers in the flexible pavement when using the backcalculation software packages.

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