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FINITE ELEMENT SIMULATION AND MULTI-FACTOR STRESS PREDICTION MODEL FOR CEMENT CONCRETE PAVEMENT CONSIDERING VOID UNDER SLAB

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Abstract

Uneven support as result of voids beneath concrete slabs can lead to high tensile stresses at the corner of the slab and eventually cause many forms of damage, such as cracking or faulting. Three-dimensional (3D) finite element models of the concrete pavement with void are presented. The accuracy of the model is verified by two methods. The analysis shows that the impact of void size and void depth at the slab corner on the slab stress are similar, which result in the change of the position of the maximum tensile stress. The maximum tensile stresses do not increase with the increase of the void size for relatively small void size. The maximum tensile stress increases rapidly with the enlargement in the void size when the size≥0.4m. The increments of maximum tensile stress can reach 183.7% when the void size are 1.0m. The increase of slab thickness can effectively reduce maximum tensile stress. A function is established to calculate the maximum tensile stress of the concrete slab. The function takes into account the void size and the slab thickness. The reliability of the function was verified by comparing the error between the calculated and simulated results.

Keywords: concrete pavement, void underneath the slab, finite element model, predictive function, maximum tensile stress

1 Introduction

Jointed plain concrete pavement (JPCP), known as its significant compressive strength and durability, is designed as one feasible ridged pavement style in those heavy traffic load areas [1]. Thin plate theory is advised as one alternative when doing analysis for cement concrete pavement. This theory is based on a previous assumption which is the foundation (base course or subgrade soil) is regarded as consistently. This opinion is also mentioned by other researchers. It can adequately simplify the mechanical analysis of pavement response. Nevertheless, One main problem is its shortage on illustration the behaviors when some undetermined but natural outcomes occur. Many studies have found that there are voids beneath the cement slab, which are an un-avoidable damage in the pavement service duration particularly near the corner or edge of the slab [2]. The occurrence of voids can result in high tensile stresses at the corner of the slab and eventually cause many forms of potential, such as cracking or faulting [3]. In recent years, most researches on concrete pavement mainly focus on the influence of other factors on the response of pavement structure, such as temperature, dowel bar [4-6]. Foundation is generally considered consistently uniform in their researches. However, the coupling action of void and traffic load remain un-clear and needs to be analyze quantitatively. Furthermore, the void depth is so large that the slab and base can never contact in the void space under traffic loads in their researches. The results of in-situ

coring show that the slab is not completely separated from the base course in the early stage of void development. The slab and base course can still contact in the void area under the traffic load. Few studies have considered the effect of void depth on slab stress, such as the change from non-contact to contact between slab and base in void space under traffic load.
The main purpose of this study is to investigate the effect of void on the maximum tensile stress. In this paper, ABAQUS is selected due to its excellent simulating ability. The reliability of the model was validated by mesh convergence analysis and comparison with the calculation results of the design standards in China. Void size and depth were analysed in the validated FEA model with a single concrete slab. Slab thickness are also considered in the validated model. A stress prediction formula is proposed based on the analysis results. Super computing resources can help to reduce the burden of large problem size.

2 Materials and methods

2.1 FEA model parameters

The analysis model of concrete pavement was worked out in three-dimensional Cartesian coordinate system and corresponded to a selected motorway pavement in China, such as Fig 1. The model consists of two structural layers, which are concrete surface course layer and cement and fly-ash stabilized macadam base course layer. The Winkler foundation is used to simulate the structural layer below the base course layer [7]. There are two methods to build Winkler foundation in ABAQUS. Several studies use spring elements of type SPRING1 to idealize the subgrade [8]. In this study, Interaction of type Elastic Foundation is used.
The surface course of the pavement consists of one concrete slab, which ignore the effect of adjacent slabs on it. Previous studies have indicated that an extended base can effectively decrease the stress of slab, which is more in line with the engineering [9]. Numerous studies have shown that linear elastic constitutive in the model can help to obtain rational results [10], which was used in this paper. The three-dimensional finite model characteristics are shown in Fig 1.

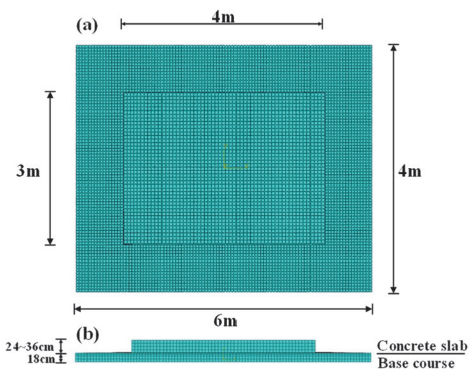

Figure 1 FEA model of concrete pavement structure: a) plane size, b) vertical size

The models were carried out by using eight-node incompatible modes linear hexahedra solid elements (C3D8I--concrete slab) [11] and eight-node reduced-integration linear hexahedra solid elements (C3D8R—base course).The relatively slide behavior between the concrete slab and the base course layer was taken into account, but not the sliding friction, i.e., the friction coefficient is 0 [12]. This can help to get the most unfavorable stress values in the slab. The wheel paths of vehicles were shown in Fig. 2. A boundary condition of the fixed placement in the horizontal direction is applied to the base course. All displacements at nodes on all side faces of the concrete slab are free [13].

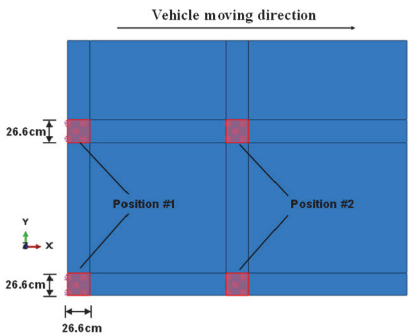

Figure 2 The shape and position of the vehicle load on the slab of FEA model

3 Results and discussion

3.1 Impact of void size at the slab corner

The void depths are provided as 5 cm to ensure that the concrete slab does not contact with the base course under vehicle load. Five sizes of void area are used: 0.02 m^2, 0.08 m^2, 0.18 m^2, 0.32 m^2 and 0.5 m^2. Four slab thicknesses (24 cm, 28 cm, 32 cm and 36 cm) were also analysed. The pressure of vehicle load is provided as 0.8 MPa. In Fig. 3, the stress of the slab remains almost constant with the increase of the void size regardless of the slab thickness for relatively small void size (0 m, 0.2 m and 0.4 m). While the stress of the panel increases rapidly with the enlargement of the void size for relatively large void size (0.6 m, 0.8 m and 1.0 m).

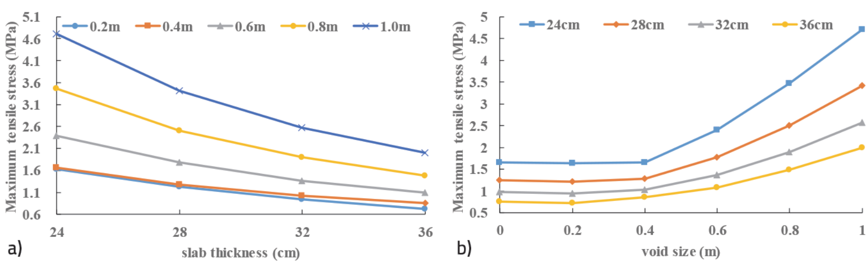

Figure 3 Variation in stress of the slab with slab thickness and void size: (a) slab thickness; and (b) void size

The maximum tensile stress can still be obtained at the bottom of the slab with 0.2 m void size. The point is that the stress at the bottom of the plate decreases slightly while the stress at the top increases rapidly compared to the stress with no void area. Further calculations show that the most unfavorable load is still at position 2. The maximum tensile stress is obtained at the top of the slab (above the edge of the void) with 0.4 m void size. It means that the stress at the slab top exceeds the stress at the slab bottom. The maximum tensile stress when the load is at the slab corner (position #1) is greater than that when the load is at the slab edge (position #2), which means that the most unfavorable load position is at position 1. Both occurred during the increase in the size of the void from 0.2 m to 0.4 m. In the following analysis, the relatively small void sizes (0.2 m and 0.4 m) will not be considered. It can also be obtained from Fig. 3 that the increase of slab thickness can effectively reduce the increase of maximum tensile stress.

3.2 Impact of void depth at the slab corner

Three void sizes (0.6 m, 0.8 m and 1.0 m) and four slab thicknesses (24 cm, 28 cm, 32 cm and 36 cm) are considered in this section. The initial height of the void area was 0.2mm and increase 0.2 mm each time until the slab stress no longer changes. The stress of different positions of concrete slab under 0.7 MPa load is recorded. The compressive stress at the bottom of the slab corner is the contact stress between concrete slab and base course. It can be seen that the stresses at the bottom and top of the slab do not change when the compressive stress at the slab corner is reduced to zero in Fig. 4. This means that the depth of voiding has been increased sufficiently so that the slab never contacts the base course and the slab stress is independent of the void depth.

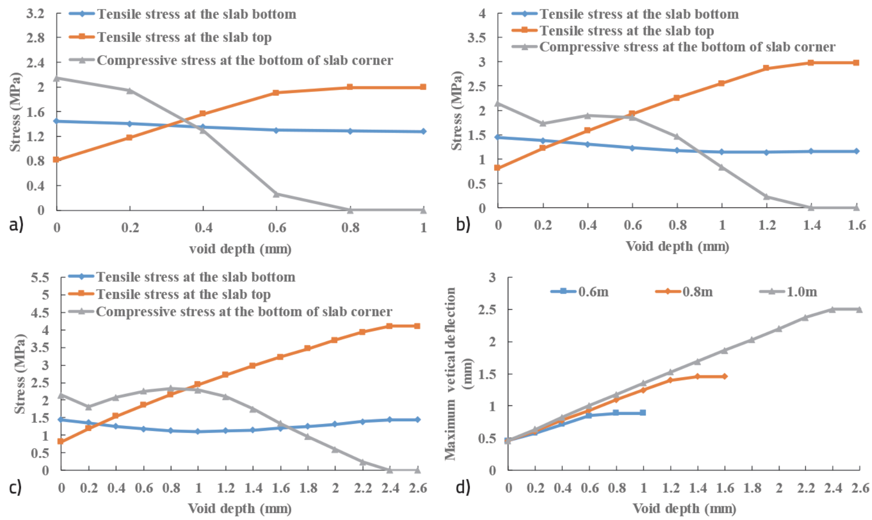

Figure 4 Stress variation of 24 cm thick slab with void depth: a) void size is 0.6m, b) void size is 0.8m, c) void size is 1.0m, d) vertical deflection

In Fig. 5, the stress at the bottom of the slab decreases first and then increases with the increase of the void depth. However, the variation is very small, which is within 20 %. The stress on the top of the slab increases with the increase of the void depth until the cement slab no longer contacts the base course. There is approximately a secondary correlation between the slab top stress and void depth. The stress of slab top gradually exceeds the stress of slab bottom when the void depth increase from 0.2 to 0.4 mm. This law is similar to that of the variation of slab stress with the void size.

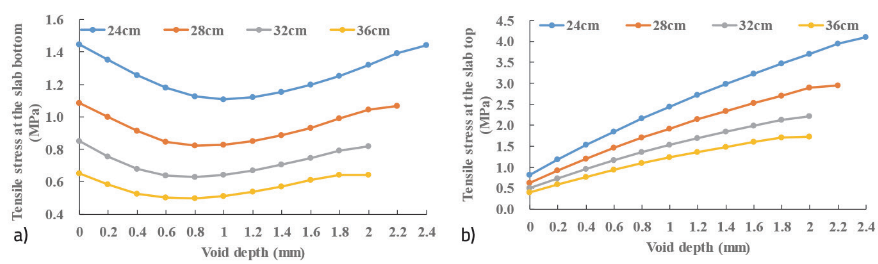

Figure 5 Tensile stress variation of 1.0m void size with void depth: (a) stress at the slab bottom and (b) stress at the slab top

3.3 Regression analysis of maximum tensile stress

In Section 3.1, the effects of slab thickness, void size and vehicle load on the maximum tensile stress of slab are analyzed. In this section, the function for obtaining the maximum tensile stress through these three factors is presented. Since the most unfavorable load position of the slab is always at the edge of the slab (position #2) when the void size is small (0.2 m), this function only considers the case when the void size is large (0.4 m, 0.6 m, 0.8 m and 1.0 m).

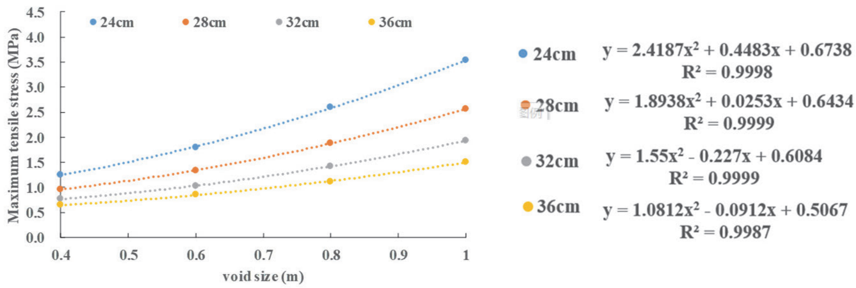

Figure 6 Regression relationship between maximum tensile stress and void size under 0.6MPa load

It can be seen from Fig. 6 that the error between the curve obtained by quadratic regression and the simulation calculation result is within 2 %. When the panel thickness is 24 cm, 28 cm, 32 cm and 36 cm, the relationship between the panel stress function and the void size as the independent variable is as follows:

$$\sigma = 2.4187X^2+0.4483X+0.6738 \tag{1}$$

$$\sigma = 1.8938X^2+0.0253X+0.6434 \tag{2}$$

$$\sigma = 1.55X^2+0.227X+0.6084 \tag{3}$$

$$\sigma = 1.0812X^2+0.0912X+0.5067 \tag{4}$$

Where σ is maximum tensile stress; X is the void size and X ≥ 0.4 m. The quadratic term, primary term and constant term of X are regressed respectively in Fig. 7 and the stress calculation function considering both void size and slab thickness is obtained:

$$\sigma =(-0.1089h+5.0032)x^2+(0.0087h^2-0.5706h+9.1255)x+(-0.0011h^2+0.0534h+0.0299) \tag{5}$$

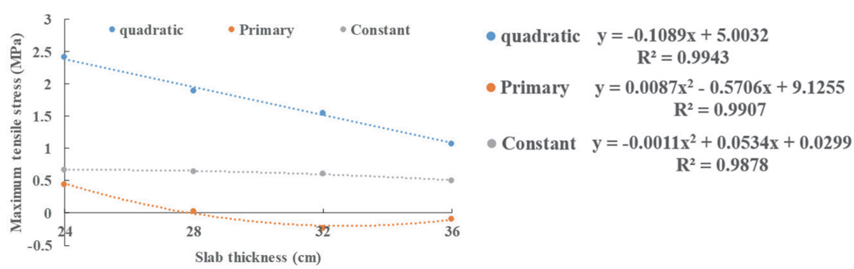

Figure 7 Regression relationship between maximum tensile stress and slab thickness under 0.6MPa load

Five void sizes (0.6 m, 0.7 m, 0.8 m, 0.9 m, 1.0 m) and three panel thicknesses (26 cm, 30 cm, 34 cm) are considered. 15 examples are additionally calculated for validation. The results are presented in Table 3. The maximum error between the results of the formula calculations and the model calculations is 2.36 %. The results show that the use of this function to predict slab stress is reliable.

4 Conclusions

In this paper, the impact of void parameters on concrete slab stress is investigated, which is supported by numerical simulation. The location, shape, and size of voids underneath slabs are indicated to have a significant effect on panel stresses. Finally, a function is established to calculate the maximum tensile stress of the concrete slab. The major findings are summarized as follows:

- Impact of void size and void depth at the slab corner on the slab stress are similar. With the increase of both, the stress at the bottom of the slab decreases slightly and the stress at the top of the slab increases rapidly. When the void size is greater than 0.4m and the void depth is greater than 0.4mm, the stress at the top of the slab exceed that at the bottom.
- A function is established to calculate the maximum tensile stress of the concrete slab. The function takes into account the void size, the slab thickness and the vehicle load. The reliability of the function was verified by comparing the error between the calculated and simulated results

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