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Dynamic response of multi-scale structure in flexible pavement to moving load

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Abstract: In order to study the dynamic responses in the microstructures of the pavement structure, the multi-scale modeling subjected to moving load is analyzed using the discrete element method (DEM). The macro-scale discrete element model of the flexible pavement structure is established. The stress and strain at the bottom of the asphalt concrete layer under moving load are calculated. The DEM model is validated through comparison between DEM predictions and the results from the classical program. Based on the validated macro-scale DEM model, the distribution and the volumetric fraction of coarse aggregate, mastics and air voids at the bottom of the asphalt layer are modeled, and then the multi-scale model is constructed. The dynamic response in the microstructures of the multi-scale model are calculated and compared with the results from the macro model. The influence of mastic stiffness on the distribution of dynamic response in the microstructures is also analyzed. Results show that the average values and the variation coefficient of the tensile stress at the aggregate-mastic interface are far more than those within the mastics. The dynamic response including stress and strain distributes non-uniformly in both mastics and the interface. An increase in mastic stiffness tends to a uniform distribution of tensile stress in asphalt concrete.

Key words: pavement; multi-scale model; moving load; discrete element method; dynamic response

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Responses of layered composite structures subject to traffic loads are important for flexible pavement design. According to the methods employed in the analysis of flexible pavements under traffic loads, the layers are assumed homogeneous and the loads are often considered static[1]. However, asphalt concrete (AC) material is a bonded mixture of aggregates, asphalt binders and air voids. Many studies indicated that the mechanical behavior of AC is anisotropic and heterogeneous[2-4]. Several studies further demonstrated that the mechanical behavior of isotropic and anisotropic materials is rather different[5-6]. Findings of these studies indicate that the pavement design based on isotropic analysis may underestimate both the shear stresses and tensile stresses that are related to the permanent deformation and fatigue cracking assessment. In addition, it is also found that the anisotropic and heterogeneous character of AC is mainly caused by its microstructure, especially the distribution of aggregate particles and air voids. However, the microstructure cannot be desirably controlled in the present pavement design method.

In order to demonstrate the complex morphological features at the micro-scale, namely the distribution of aggregates and air voids, the numerical methods are generally required. Current numerical methods in micro-mechanical engineering can be divided into two groups: the finite element method (FEM) and discrete/distinct element method (DEM). In general, the DEM excels the FEM in the following aspects: 1) The multi-inclusion nature of composites (such as concrete) can be explicitly modeled; 2) The changes of contact and moving of boundary conditions do not pose convergence problems; 3) The deformations and frictional sliding at interfaces and between particles or clustered assemblies can be handled realistically[7-15].

In this paper, a multi-scale DEM model for layered asphalt composite structures is proposed to predict the dynamic response under a moving load. The single-scale macro model of the asphalt pavement structure is first built and validated by the comparison with the classical pavement design software, Bisar 3.0. The multi-scale model is established when the microstructure of AC is complemented in the single-scale model. The distribution of dynamic response in the microstructures of the multi-scale model is calculated and compared with the results from the macro model. The influence of mastic stiffness on the distribution of dynamic response in the microstruc-

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tures is also analyzed and discussed.

1 Single-Scale Macro Model of Flexible Pavement

1.1 DEM model of pavement

A commercial discrete element code called particle flow code in 3-dimensions (PFC3D) is used to build the single-scale macro DEM model according to the typical flexible pavement structure shown in Fig. 1. The DEM model with a length of 5 m and a depth of 1.1 m is constructed by 5.5×10^4 elements. The radius of each element is 5 mm. The thickness of soil is set to be 40 cm in the DEM model. It is well known that the deformation decreases with the increase in the depth of the pavement structure, and thus the vertical displacement of the soil bottom can be ignored. As to the DEM model in this study, the elements at the bottom of the soil are fixed in the vertical direction.

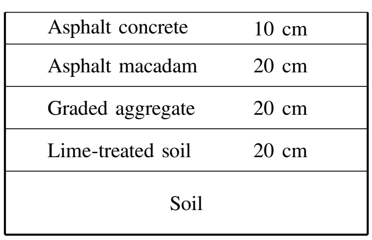

Fig. 1 Typical flexible pavement structure

1.2 Micro-parameters of the DEM model

There are five levels containing different materials in the DEM model, including AC, AM, graded aggregate, lime-treated soil and soil. In this study, the DEM model will be validated by the SHELL pavement design software Bisar 3.0, in which materials are assumed to be elastic. Therefore, the spring element is used to represent the elastic behavior of the five materials in the DEM model. The contact-bond model with the normal stiffness k_n and the shear stiffness k_s is used for unbounded graded aggregate, lime-treated soil and soil. The parallel-bond model is employed for AC and AM.

Tab. 1 gives the empirical macro-parameters of the five materials at 15 ℃. Normal micro-stiffness k_n in contact bond of the three elastic materials and normal stiffness $\bar{k}_n$ in parallel bond of the two materials are determined based on the following equations[16]:

$$k_n = 4ER \tag{1}$$

$$\bar{k}_n = \frac{E}{2R} \tag{2}$$

where E is the apparent Young's modulus and R is the radius of the discrete element in the DEM model.

Tab. 1 Micro-parameters of the five materials

Layer	E/MPa	γ	k_n/(N · m^{-1})	$\bar{k}_n$/(Pa · m^{-1})
AC	1 800	0.25		3.6×10^{11}
AM	1 200	0.25		2.4×10^{11}
Graded aggregate	400	0.25	8×10^6	
Lime-treated soil	400	0.30	8×10^6	
Soil	50	0.35	2×10^6	

Micro-parameters in the contact-bond model and the parallel-bond model are calculated by solving the above equations and listed in Tab. 1. The shear contact stiffness k_s of the five materials is then expressed as

$$k_s = \frac{k_n}{1+\gamma} \tag{3}$$

where γ is the Poisson ratio and it is shown in Tab. 1.

1.3 Simulation of the moving load

A wheel load of 25 kN with a tire pressure of 0.7 MPa is assumed to be uniformly distributed over a square contact area between the tire and the pavement. The side length of the square contact is 18.9 cm.

The load moving with a velocity of 100 km/h is simulated, and the moving distance of the wheel load is set to be 3 m, as shown in Fig. 2. Since the diameter of each element in the DEM model is 1 cm, the wheel load is uniformly distributed on 18 elements in the developed model. First, a load is placed on the leftmost 18 elements within a moving range of 3 m. Then the load moves rightward with a speed of one element every 3.6×10^{-4} s until it reaches the rightmost of the moving range.

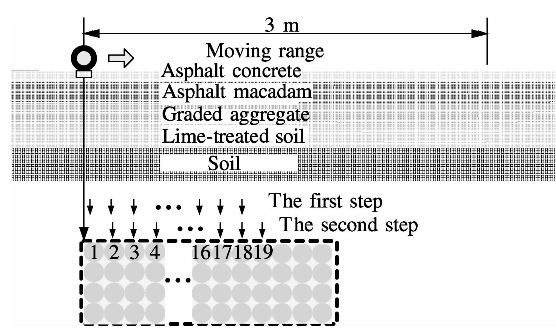

Fig. 2 Simulation of the moving load

2 Validation of the DEM Model

The middle point of the DEM model is selected as the measuring point of dynamic response, which is 1.5 m distance from the leftmost element in a moving range of 3 m. Fig. 3 illustrates the dynamic response of the measuring point when the load moves from leftmost to rightmost within the moving range of 3 m. It can be seen from Fig. 3 that all the predictions are well consistent with results from previous studies[17], which preliminarily validates the developed DEM model.

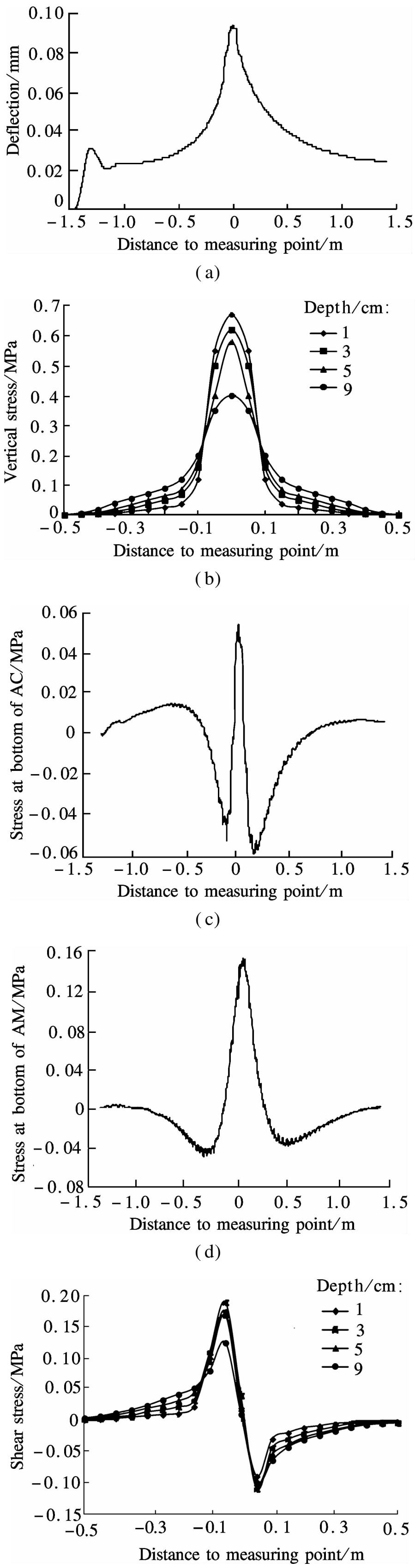

Fig. 3 Dynamic response in layered structures. (a) Surface deflection; (b) Vertical compressive stress at different depths; (c) Horizontal stress at the bottom of AC; (d) Horizontal stress at the bottom of AM; (e) Shear stress at different depths along the moving direction

The developed DEM model is further validated using predictions from the Shell pavement design software Bisar 3.0. Tab. 2 gives the maximum tensile stress at the bottom of AC surface and AM course from the DEM model and Bisar 3.0.

Tab. 2 Comparisons of the results from DEM model and Bisar

Calculation method	Maximum tensile stress at the bottom of the following layers/MPa	
	AC	AM
DEM model	0.059	0.153
Bisar 3.0	0.078	0.181

Although there is no obvious difference in tensile stress of AM course between the DEM model and Bisar 3.0, the tensile stress of the AC layer from the DEM model is about 50% less than that from the Bisar program. Several possible reasons for different results are as follows: 1) The DEM model in this study is two-dimensional (2D), while the calculation within Bisar software is based on the 3D system; 2) The thickness of soil in the DEM model is assumed to be 40 cm, while the soil is infinite in Bisar 3.0; 3) Unlike the moving load in the DEM model, the load in Bisar is assumed to be static. As various assumptions are made in the present prediction methods, including Bisar, FEM models and DEM models, it is extremely difficult to make an absolutely accurate prediction for the response in the pavement structure. From this point of view, the developed DEM model is competent for the following simulations.

3 Multi-Scale Model of Flexible Pavement under Moving Load

3.1 Multi-scale model

The beam of AM with a nominal maximum aggregate size of 19 mm was prepared in laboratory with an asphalt content of around 4.3%. The image of the structure in the compacted AM beam was captured using a high-resolution digital camera and image processing techniques. Fig. 4 shows the 2D image of the AM beam with a length of 30 cm and a width of 5 cm. The image is composed of coarse aggregates and homogeneous sand-asphalt mastics including binder and fine aggregates. The dividing line between coarse aggregates and fine aggregates placed in the homogeneous mastic is 2.36 mm.

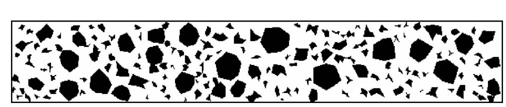

Fig. 4 2D image of AM beam

The multi-scale model of the flexible pavement is constructed when the 2D microstructure image is placed at the bottom of the AM layer. Fig. 5 shows the multi-scale DEM model. It is realized that too large an element size for the 2D beam will result in low computing efficiency, while too small an element size will bring stress concentration at the edge of the beam. A particle radius of 1 mm is selected for the discrete element in the AM beam, so that an accurate morphological representation can be achieved. Other elements with a diameter of 1 cm in the multi-scale model are the same as those in the single-scale model.

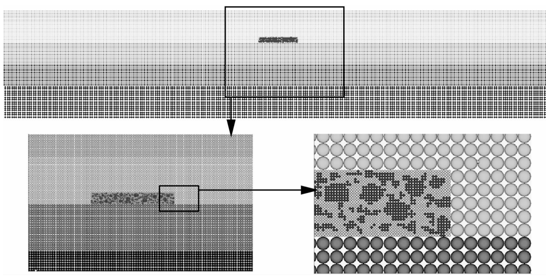

Fig. 5 Multi-scale model of the layer structure

3.2 Dynamic response to moving load

Because the horizontal stress and strain in asphalt layers are commonly used for pavement design, the horizontal tensile stress and strain in the microstructures of the multi-scale model are chosen to investigate the dynamic response in this study. In addition, previous studies have found that fatigue cracks are generally observed within mastics and/or the aggregate-mastic interface, rather than aggregate particles[18]. Therefore, the dynamic responses within mastics bonds and the aggregate-mastics interface are monitored in every time step. Considering the temperature insensitive behavior of aggregate, a typical value of 55.5 GPa is used as aggregate stiffness[12, 18]. The mastics stiffness at 15 ℃ is assumed to be 750 MPa in this section. The influence of the mastic stiffness on dynamic response will be investigated in the following section.

In the microstructure of the AM beam, there are 2 069 and 716 bonds in mastics and the interface, respectively. The average values and variation coefficients of these bonds in mastics and the interface are calculated and listed in Tab. 3. As shown in Tab. 3, the average value of the tensile stress within the aggregate-mastic interface is about 1.7 times more than that within mastics. Unlike the tensile stress, the strain at the mastic-aggregate interface is less than that within mastics to a slight degree. From Tab. 3, it can be seen that the dynamic response is unevenly divided between mastics and the interface. A reasonable explanation for this phenomenon is that the stiffness of aggregate is more than that of mastics, and the stiffness difference of two comprised materials in AM will cause the stress concentration at the aggregate-mastic interface.

Moreover, when comparing Tab. 3 with Tab. 2, it is clear that the average value of the tensile stress in the mastics of the multi-scale model is less than that in the macro model, while the average value of the tensile stress at the aggregate-mastic interface of the multi-scale model is much more than that in the macro model. This phenomenon implies that the present pavement design based on macro models may underestimate the tensile stress at the aggregate-mastic interface and overestimate the tensile stress in mastics.

Tab. 3 Dynamic response of the microstructure in pavement

Location	Bonds number	Tensile stress		Tensile strain	
		Average value/MPa	Variation coefficient/%	Average value/10^{-6}	Variation coefficient/%
Mastics	2 069	0.104	11	114	10
Interface	716	0.287	27	132	19

Tab. 3 also presents the variation coefficients of dynamic response in both mastics and the interface. Although mastics and aggregates are homogeneous, the dynamic response including stress and strain distributes non-uniformly in both mastics and the interface from the micro-structural perspective. Moreover, it is observed that the dynamic response at the mastic-aggregate interface exhibits higher variation than that in mastics. By summarizing the analysis above, there are two types of non-uniform distribution related to dynamic response: one is uneven distribution between mastics and the interface and the other is non-uniform distribution within mastics and the interface.

3.3 Influence of mastic stiffness on dynamic response

Considering that the mastic stiffness is very sensitive to the temperature, the influence of the mastics stiffness on dynamic response is also investigated in this study. The comparisons of dynamic response predicted between different mastic stiffnesses are shown in Tab. 4.

Tab. 4 Dynamic response at different mastic stiffnesses

Mastic stiffness/MPa	Average value of tensile stress/MPa	
	Within mastics	At mastic-aggregate interface
250	0.023	0.152
500	0.059	0.243
750	0.104	0.287
1 000	0.153	0.318
1 250	0.198	0.331

The increase in the mastic stiffness can result in an increase in the tensile stress in both mastics and the interface; nevertheless, the average of the tensile stress at the interface is more than that in mastics when the mastic stiffness is fixed. Fig. 6 gives the ratio of the tensile stress at the aggregate-mastic interface to that in mastic for the five different mastics stiffnesses. As the mastic stiffness decreases, the stress ratio of interfaces to mastic increases rapidly. It is implied that an increase in mastic stiffness tends to a uniform distribution of the tensile stress. However, even when the mastic stiffness increases to 1 250 MPa (equivalent to the mastic stiffness at 0 to 15 ℃)[12], the ratio still reaches as high as 1.7. Therefore, the non-uniform distribution should be properly considered in the analysis of pavement responses and complemented in pavement design procedures as well.

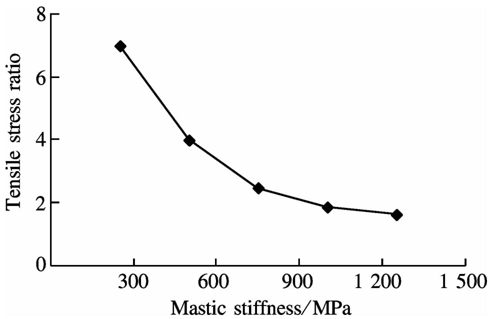

Fig. 6 Tensile stress ratio of interface to mastic at different mastic stiffnesses

4 Conclusions

1) A single-scale macro discrete element model of a typical flexible pavement is developed in PFC3D. The dynamic response of pavement structures is predicted after the discrete element simulation of the moving load is performed. The favorable agreement between the DEM predictions and results from the SHELL pavement design software Bisar 3.0 indicates that the discrete element model developed in this study is capable of predicting dynamic response subject to a moving load.

2) Based on the single-scale discrete element model, the multi-scale model of the pavement structure is constructed when the 2D AM image is placed on the bottom of the AM layer. The dynamic response to a moving load exhibits significantly non-uniform distribution in the AM microstructure. It is noteworthy that the non-uniform distribution is found not only between mastics and the interface but also within the homogeneous materials, mastics.

3) The average and variation coefficient of the tensile stress at the aggregate-mastic interface is far more than that within mastics. The non-uniform distribution decreases with the increase in the mastics stiffness.

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移动荷载作用下柔性路面多尺度结构的响应

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摘要:为了研究移动荷载下路面结构内部细观结构的响应,采用离散元方法进行了多尺度路面结构移动荷载响应的分析.建立了柔性基层沥青路面典型结构的离散元模型,并计算了移动荷载作用下沥青层底的应力和应变,通过与已有经典计算程序荷载响应计算结果的比较,验证了所建立的离散元模型.以该离散元模型为基础,在沥青混凝土结构层的底部,采用尺度较小的离散单元描述粗集料的体积含量、分布特征以及空隙大小等细观结构,以此建立路面结构的多尺度模型.对路面结构宏观响应与细观结构的荷载响应进行了比较分析,并分析了沥青砂浆劲度对细观结构处荷载响应的影响.结果表明:粗集料与沥青砂浆界面位置的拉应力均值和离散系数均大于沥青砂浆内部;荷载引起的应力和应变在沥青砂浆内部和界面内部均存在不均匀分布;沥青砂浆的劲度越大,沥青混凝土内部的荷载响应分布越趋于均匀.

关键词:路面;多尺度模型;移动荷载;离散元方法;动态响应

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