Predict Resilient Behaviour of Flexible Pavement by Using Discrete Element Method

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Abstract: - Over the last decade, the rapid development of the computational technology has made a significant impact on the other field of engineering; especially on the method of data analysis. Computational approach has been applied widely to investigate the engineering problem. In the current study, the application of discrete element method (DEM) is examined in simulation of the repeated load triaxial test in pavement engineering. Flexible pavement is complex structure. Under the dynamic traffic loading, the behaviour of pavement can be predicted by using the repeated load triaxial test equipment in the laboratory. However, the nature of the repeated load triaxial testing procedure is considered time-consuming, complicated and expensive, and it is a challenge to carry out as a routine test in the laboratory. Therefore, the current paper proposes a numerical approach to simulate the repeated load triaxial test by employing the discrete element method. A sample with particle size ranging from 2.36 mm to 19.0 mm was constructed. Material properties, which included normal stiffness, shear stiffness, coefficient of friction, maximum dry density and particle density, were used as the input for the simulation. The sample was then subjected to a combination of deviator and confining stress and it was found that the discrete element method is able to simulate the repeated load triaxial test in the laboratory.

Key-Words: - Resilient behaviour, discrete element method, numerical method, dynamic load, pavement, unbound granular.

1 Introduction

Flexible pavement is very complex structure. Under the dynamic traffic loading, the behaviour of pavement can be classified into the resilient and permanent behaviours. In recent decades, extensive research work has been undertaken to characterise the behaviour of flexible pavement [1]. Under moving wheel loads, overstressing the pavement material can produce unacceptable levels of pavement deflection, which, ultimately, affect the pavement performance during the service life [2]. Therefore, a better understanding of the behaviour of flexible pavement under the traffic loading by laboratory tests, through which in-situ stress conditions are adequately considered is strongly required.

2.1 Repeated load triaxial Apparatus

The repeated load triaxial test is the most common testing method wherein the behaviour of the pavement materials during repeated loading is evaluated [3]. Basically, the repeated load triaxial equipment consists of a loading frame that is powered by either a pneumatic or electro-hydraulic loading system. The apparatus can create a loading waveform in different shapes, such as haversine or rectangular. The schematic of a typical repeated load triaxial test apparatus can be seen in Fig. 1:

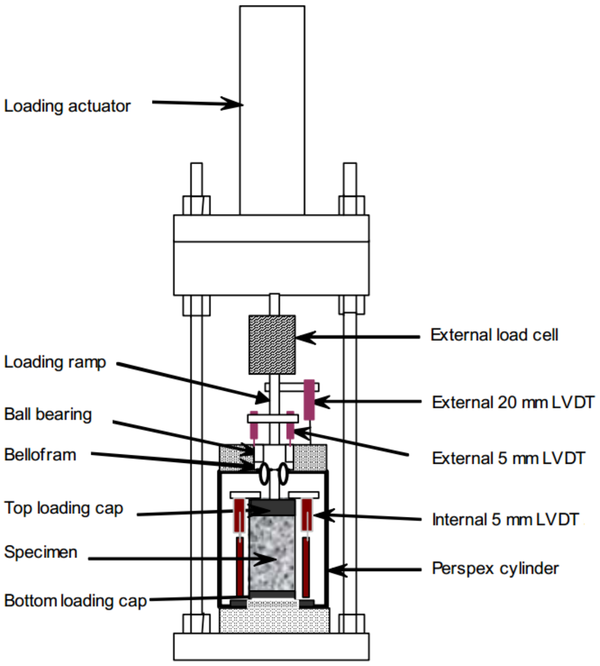

Fig. 1 The schematic of a typical repeated load triaxial test apparatus ([4])

In the test, repeated cyclic axial stress is applied to a cylindrical test specimen. The diameter of the sample is five times larger than the maximum particle size of the tested sample. In addition, the height of the sample is twice that of the diameter for the soil sample having regular platens at both ends. The ratio of the specimen size can be reduced to 1:1 if the frictionless platens are used as reported by Adu-Osei [5]. They also found that the specimens were more stable and practical when the platens were lubricated. The soil specimen can be either undisturbed or compacted fine-grained soil or compacted coarse-grained material. It can be seen from Fig. 1 that the specimen is located inside the triaxial cell and is subjected to a deviator load from the vertical direction, which is measured by the S-shaped load cell. The deviator stress is also referred to as the cyclic stress and is always in a compressive state in the repeated load triaxial test. Besides the deviator stress, the sample is also subjected to the confining stress, which is provided by the confining medium, such as air or water. The sum of the deviator stress and the confining stress is defined as the principle stress, which is applied on the top of the sample in a vertical direction. The main objective of the combination of the deviator stress and confining stress is to simulate traffic loading conditions. The loading values of the deviator stresses and confining stresses are dependent on the relevant testing standards. Moreover, the loading cycle, which consists of the loading and unloading stage, is also pre-determined. For example, in the AASHTO T309 testing standard [6], a loading cycle of 0.1 second of loading and 0.9 second of unloading is suggested in order to simulate a standard vehicle travelling at 60 mph. During the test, the deformation of the sample is also measured by two linear variable differential transformer transducers, which are externally mounted on top of the triaxial cell. In practice, it is a challenge to carry out the repeated load triaxial test as a daily routine test in the laboratory because performing the repeated load triaxial test is a time-consuming and complicated procedure. Furthermore, a skillful operator is also required to run the test with a high quality control procedure in place. Moreover, the repeated load triaxial test is not a common testing apparatus in the laboratory because the testing equipment is considerably expensive, thus making it less affordable.

2.2 Computational approach - discrete element method (DEM)

Pioneered by Cundall and Strack in 1979 [7], DEM was originally developed to investigate the problems in rock mechanics. Since then, it has gained popularity for simulating the dynamics of granular materials. In this method, materials are represented as assemblies of spherical particles (3D) or circular discs (2D). Each of these particles may interact with neighbouring particles or with the boundaries. Newton's equation of motion is employed to characterise these interactions in the translational and rotational directions:

$m_i x_i = F_i + m_i g$
(Translational degrees of freedom) (1)

$I_i w_i = M_i$
(Rotational degrees of freedom) (2)

Where: m_i = mass of the i^{th} particle.

x_i = translational acceleration of the i^{th} particle.

$F_i = \sum_k f_i^k$ = the total force applied on the i^{th} particle due to the k interaction

g = the acceleration of gravity

I_i = the moment of inertia of the i^{th} particle

w_i = the angular of the i^{th} particle

$M_i = \sum_k \left(l_i^k x F_i^k + q_i^k \right)$ = total moment of the i^{th} particle due to the k interaction

q_i^k = the moment of i^{th} particle at the k interaction

Technically, two mathematical techniques are used to characterise the interactions between the particles, as categorised by Walton [8] – hard sphere and soft sphere. In the former technique, the particles are considered as a rigid element. Therefore, no deformation occurs during the collision of the particles. The interaction is mainly controlled by the momentum exchange and is the function of the change in momentum, coefficient of friction, and coefficient of normal and tangential restitution. In simulation, this technique is particularly well conducted for applications in granular material flow [9]. In contrast, the particles are treated as soft during the collision in the soft sphere approach. When two particles collide, the deformation of the contact is represented as the small overlap, which is a function of the particle velocity, normal stiffness and shear stiffness.

Granular materials, such as crushed rock or recycled concrete, are the main materials used in the base and sub-base layers of the flexible pavement. Generally, the granular materials can be viewed as a very large assembly of independent particles. Due to the discontinuous and inhomogeneous nature of these materials, the Discrete Element Method (DEM) is commonly employed to examine the behaviour of the granular materials ([10], [11], [12] and [13]). The current paper uses DEM to simulate the repeated load triaxial test in the laboratory.

2 Computational simulation of repeated load triaxial test

In recent years, with the rapid development in the computing area, there are a significant number of discrete element method software available on the Internet. In general, they can be classified as either commercial or open source software. In the current investigation, the open source ESyS-Particle, which was developed by Stefen Abe et al. [14], is used as the main platform to simulate the repeated load triaxial test. Compared with the other available software on the Internet, the main advantage of the ESyS-Particle is that it is categorised as a high performance computing software. This means that ESyS-Particle is comparable with the other commercial grade software. However, ESyS-Particle has one drawback, which is the lack of the graphic user interface. In order to utilise the ESyS-Particle for their application, a certain level of knowledge and experience in the Python programming language is required. The open source ESyS-Particle can be downloaded from the website https://launchpad.net/esys-particle [15].

In the current simulation, the DEM model was developed in three dimensions with spherical particles. The sample has a diameter of 100 mm and a height of 200 mm. Practically, the granular particle is quite rigid during the repeated load triaxial test. Therefore, in the simulation, the particle is assumed to be rigid. It means that each spherical particle has six degrees of freedom. Moreover, only the translation and rotation of the particle centroids are considered in the equilibrium equations. The input of the DEM model includes the normal stiffness, shear stiffness, coefficient of friction, maximum dry density, particle density and particle size. By taking into consideration the current power of the computer as well as the nature of the granular particle size, the current investigation is limited to the application of only the gravel material. According to the soil classification guide, gravel has a minimum particle size of 2.36 mm and a maximum particle size of 19.0 mm. The values of these input parameters, which are used in the simulation, are illustrated as follows:

TABLE I
THE VALUES OF THE INPUT PARAMETERS FOR THE MODEL

Input parameter	**Value**
Normal stiffness (kN/m)	1000
Shear stiffness (kN/m)	1000
Coefficient of friction (rad)	0.5
Maximum dry density (kg/m^3)	2,200
Particle density (kg/m^3)	2,700
Minimum particle size (mm)	2.36
Maximum particle size (mm)	19.0

After the trial and error process, a total of 24,317 particles were found to be required to construct the sample. The density of the sample after the fabrication process is 1,925 kg/m^3, which is approximately 88% of the input value of the maximum dry density of 2,200 kg/m^3. The 3 dimensional visualisation of the sample after the fabrication, which is produced by the ParaView open source software [16], is illustrated as follows:

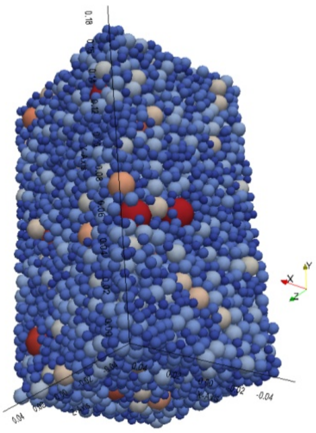

Fig. 2 The three dimensional visualisation of the sample after the fabrication

In the next stage, when the sample fabrication is completed, the contact list for all the particles is created by taking a single sphere and searching in the immediate neighbourhood for other objects that are overlapping with it. Practically, the searching procedure starts from the 1st sphere to the last sphere.

The next step is force calculation. The contact between particles in granular materials consists of normal and tangential components of forces. Fig. 3 illustrates the schematic diagram of the contact model used in the current investigation. One spring with normal stiffness k_n models the normal component of the contact and the other, with the shear stiffness k_s, models the tangential component. The friction between two contact components has an inter-particle coefficient of friction μ.

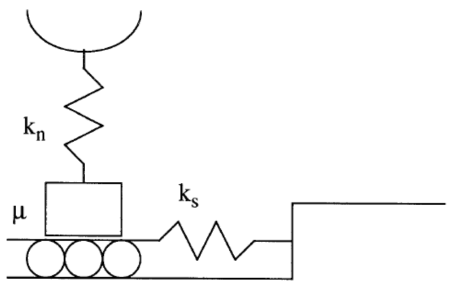

Fig. 3 The schematic diagram of the contact model (modified from [17])

Subsequently, the explicit first order finite difference time integration scheme is used to yield the velocities and position of the sphere at the next time step. In the current simulation, only the compressive state of contact is considered. The neighbouring particle search algorithm implemented in the model is the Verlet list neighbour [18].

As mentioned earlier, the repeated load triaxial test involves applying a different deviator and confining stress stage to the sample. The stress level during the current simulation is controlled by the boundary loading conditions. Technically, there are four types of boundary: rigid, period, membrane and asymmetrical. The current simulation employed the rigid boundary, which is the most widely used. This type of boundary is described as a planar surface and is well suited to simulate the triaxial or direct shear test [19]. Generally, a total of six servo-controlled rigid walls are used. One wall is located at the top of the sample and works as an actuator to provide the cyclic axial load on the sample. One fixed wall is located at the bottom of the sample and works as a pedestal. The other four planar walls are around the sample to provide the confining pressure.

The testing standard, which is used to determine the resilient modulus for the current investigation, is the Protocol P46: “Resilient modulus of unbound granular, base/sub-base materials and subgrade soils” [20]. The Protocol P46 was developed by the U.S. Department of Transportation in 1996 and is partially based on the AASHTO T292-91 test standard: “Resilient modulus of subgrade soils and untreated base/sub-base materials” (1991). Compared with other testing standards, such as the Australian testing procedure AG:PT/T053 [4], a new loading parameter contact stress is introduced. The main purpose of the contact stress is to keep the sample in position during the unloading cycle. The value of the contact stress is normally selected as 10 per cent of the maximum axial stress, which is the sum of the cyclic stress and the contact stress. In the protocol P46, the loading cycle comprises 0.1 second of loading and 0.9 second of resting in order to simulate the loading conditions of a vehicle travelling at 60 mph, for the road base and sub-base granular layers. More details about the loading waveform can be seen as follows:

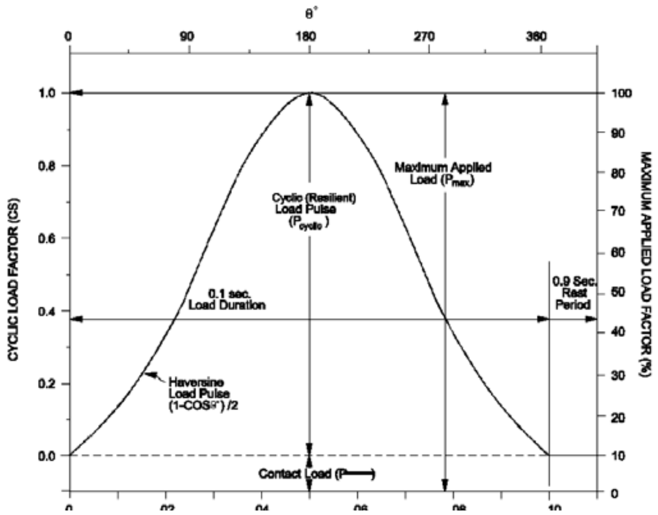

Fig. 4 The loading cycle waveform ([20])

Obviously, from the above figure, the loading waveform, as recommended by the standard, is in haversine shape. The individual loading cycle increases from zero per cent to one hundred per cent of the maximum applied. The loading value at any time of the loading cycle can be determined from the following equation:

$$S_{pulse} = \left[\frac{1-\cos(\theta)}{2}\right] x S_{max} \quad (3)$$

Where:

S_{pulse} = Loading value at any time of the loading cycle (kPa)

θ = loading degree (rad)

S_{max} = Maximum axial stress (kPa)

In the current study, for the stress level, the deviator is 90 kPa, the confining stress is 50 kPa and the contact stress is 10 kPa. In order to examine the performance of the repeated load triaxial test simulation, the stress-strain curve is first investigated. The recoverable and permanent strain of the sample reposed to the cyclic loading of the first sequence is illustrated in Fig. 5

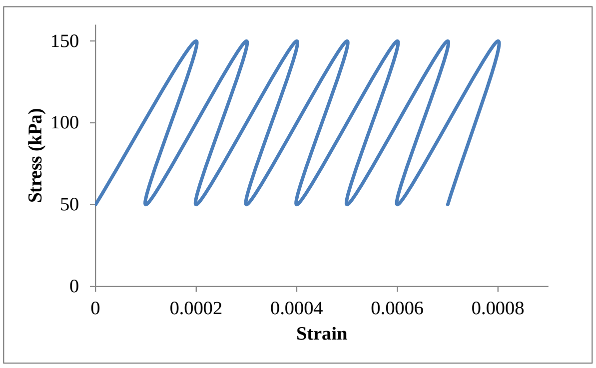

Fig. 5 The illustration of stress-strain curve in the first sequence of cyclic loading

It can be seen from the Fig. 5 that the strain increases when the deviator stress is applied on the top of the sample. In addition, when the deviator stress is released, the sample almost returns back to its previous state. This behaviour is literally defined as the resilient behaviour of the pavement materials under the repeated load triaxial test. In addition, the increase in the strain reading between two loading cycles presents the permanent deformation of the sample. The typical stress-strain curve for the repeated load triaxial test in the laboratory is illustrated as follows:

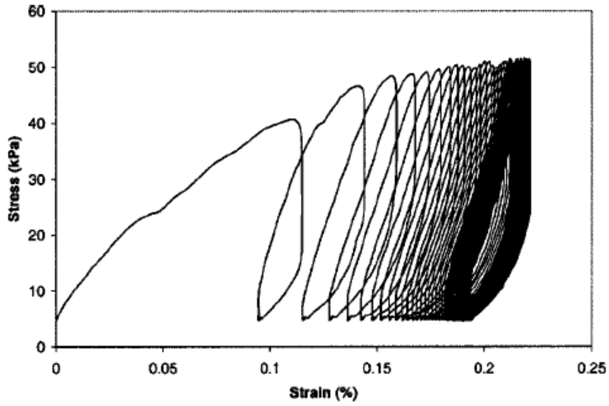

Fig. 6 The typical laboratory stress-strain curve [21]

Clearly, the stress-strain response from the discrete element method simulation conforms to the data for a typical experiment in the laboratory. This means that the numerical method is capable of replicating the resilient behaviour of unbound granular materials under cyclic loading.

4 Conclusion

In the current study, the application of computational approach (discrete element method - DEM) in pavement engineering was investigated. DEM was employed to simulate the repeated load triaxial test for the granular materials. The sample comprised 24,317 particles with the particle size ranging from 2.36 mm to 19.0 mm. The simulation was then carried out by applying a combination of 16 different stress levels to the sample according to the testing protocol P46: "Resilient modulus of unbound granular, base/sub-base materials and subgrade soils". Based on the observations obtained from the simulation, it is shown that the discrete element method is able to replicate the repeated load triaxial test in the laboratory. The stress-strain response from the discrete element method simulation conforms to the data for a typical experiment in the laboratory. However, due to the complexity of the input parameters, such as normal and shear stiffness, the currently developed DEM model is not capable of simulating the repeated load triaxial test independently. Further research works are required in order to improve the application of the proposed DEM model.

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