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Research on macro-meso relationship of geological materials based on Discrete Element Method: Review and prospect

Recherche sur la relation macro-méso des matériaux géologiques basée sur la Méthode des Éléments Discrets: Revue et perspective

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ABSTRACT: The discrete element method has been widely adopted in the geotechnical engineering. In this paper, the discrete element study on the soil-rock mixtures, and the crushing as well as creep properties of rockfill materials, are reviewed. The development trend of discrete element method in geotechnical engineering is introduced, and the main issue is the determination of meso-parameters in the model. In addition, by combining the large amount of discrete element data and machine learning technology, it seems that the intelligent constitutive models can be reasonably established.

RÉSUMÉ: La méthode des éléments discrets a été largement adoptée dans l'ingénierie géotechnique. Dans cet article, l'étude des éléments discrets sur les mélanges sol-roche, ainsi que les propriétés de concassage et de fluage des matériaux d'enrochement, sont passées en revue. La tendance de développement de la méthode des éléments discrets dans l'ingénierie géotechnique est introduite, et le problème principal est la détermination des méso-paramètres dans le modèle. De plus, en combinant la grande quantité de données sur les éléments discrets et la technologie d'apprentissage automatique, il semble que les modèles constitutifs intelligents puissent être raisonnablement établis.

Keywords: Macro-micro analysis; discrete element method; constitutive relationship; data-driven predictions

1 INTRODUCTION

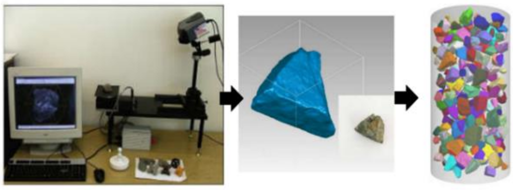
Although soil is often treated as a continuous medium in theoretical or numerical methods (Luo and Yao, 2010; Liu et al., 2015), it is actually a bulk material with complex structures in the mesoscopic scale, especially for soil-rock materials and rockfill materials. As a numerical method suitable for bulk materials, DEM has been widely applied in geotechnical engineering (Xu et al., 2003). DEM can reproduce the soil characteristics in laboratory tests with multi-stress path and are capable of preparing soil materials with different meso-structures, thus it is very suitable for macro-meso mechanism study. In addition, DEM is a suitable method to study the failure process of geotechnical engineering for its capability of large deformation problems and macro-meso mechanisim. This article will review the current state of discrete element simulations of soil-rock mixtures and crushing creep properties of rockfill, as well as its application prospects of engineering simulation and consititutive construction.

2 MESO BEHAVIOR SIMULATION OF SOIL-ROCK MIXTURES

The soil-rock mixture is a special engineering geological material, which is mainly adopted in the geotechnical slope and subgrade engineering. The soil-rock mixture is formed by the accumulation of rock blocks with a certain size and high elastic modulus, as well as the soil with low elastic modulus, thus its physical and mechanical properties are between the soil mass and the fractured rock mass. Numerical methods such as DEM, particle flow (PFC) and finite element-based discrete element method (CDEM) are playing an increasingly important role.

It is a potential method to analyze and predict the deformation and failure behavior of soil-rock mixture based on its structural model. Most of the structural models of soil-rock mixtures are based on macroscopic statistical laws, which mostly use regular geometric shapes, such as rectangles, circles, triangles and ellipses, to represent rock blocks. There is a large gap from the actual structure (Huang et al., 2013). Recently, the structural model generated based on digital images can accurately reflect the actual distribution of blocks and soil in the mixed body (Figure 1) (Xu and Wang, 2016; Jia et al., 2022). However, it is still not suitable for large-scale engineering problems due to the limitation of the ability of acquisition and recognition equipment.

The deformation and failure of soil-rock mixture is not only related to the geometric characteristics, strength and deformation properties of the soil or Rock, but also closely related to the motion state, the contact property, friction characteristics and other factors. At present, there is a lack of quantitative experimental research and analysis methods for this internal meso-mechanism.



(a) Blocks based on computer 3D scanning

(b) Soil-rock mixture model

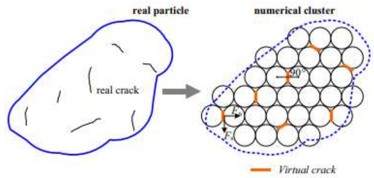
Figure 1. Reconstruction of a real soil-rock mixture (Zhang et al., 2019).

3 CRUSHING & CREEP SIMULATION OF ROCKFILL

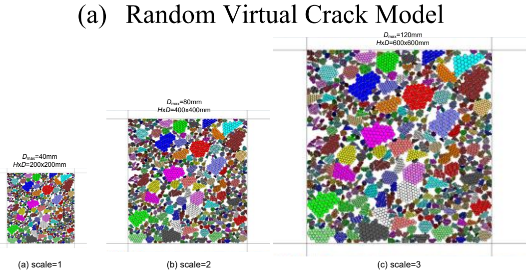
Particle breakage and its size effect are the typical properties of rockfill material due to its irregular shapes and large particle size. In the engineering of dams and high filled foundations, the quantitative law of size effects is one of the main technical difficulty to predict the in-situ settlement due to the limitation of test scale. Numerical simulation of the test considering particle breakage is regarded as one of the solutions (Alonso et al., 2012).

Among many DEM models reported in literature, the bonded-particle model (BPM), which is formed by bonding small balls together, is one of the most popular models for particle breakage simulation. Recently, Wu & Wang (2020) demonstrated the capability of reproducing the realistic particle breakage behaviors of BPM by generating initial flaws based on the realistic fracture surfaces obtained from the experiment. Cil et al. (2020) & Zhou (2021) adopted random and size-dependent bond strength in BPM and showed at both particle and assembly scale that the proposed modelling strategy can be a viable approach to capture the mechanics of size-dependent granular matter.

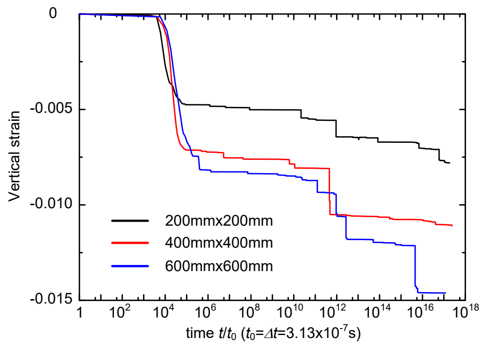
To establish the bridge between grain-scale phenomena and continuum-scale processes, the more accurate DEM model as well as the summary of the law of test results are the future study plan, in which photo elastic test, X-ray technology and DIC technology provide the possibility. In addition, compared to the modelling of particle breakage, the simulation of creep gained relatively less attention. Soil creep may be caused by delayed grain breakage and reorientation or time-delayed sliding of particles (Figure 2) (Zhou and Song, 2016).



(a) Random Virtual Crack Model



(b) Models of different test sizes



(c) Size effects of creep properties

Figure 2. Discrete element study of the size effect of creep behaviour for rockfill material (Zhou and Song, 2016).

4 THE FAILURE PROCESS SIMULATION OF GEOTECHNICAL ENGINEERING

Discrete elements not only have good applicability in the mechanism study at material mesoscale, but also are suitable to the study of large deformation problems with obvious block properties at the engineering scale. For geotechnical and hydraulic engineering, the DEM shows strong superiority in numerical simulation problems such as landslide, rockfall motion, seepage field analysis and so on. Zhang et al. (2010) and Hu (2010) established the discrete element theory for three-dimensional modal deformation body and simulated the dam failure process of the Meihua arch dam. Pekau et al. (2004) and Hou (2005) combined the finite element method, discrete element method and fracture mechanics to analyze the failure process of Koyna concrete gravity dam. Su et al. (2019) simulated the embankment engineering by DEM, analyzed the influence of particle scale parameters on the macro-mechanical parameters of the embankment, and simulated the process from local failure to overall instability. It is found that, in recent years, the application of DEM to solve practical problems of engineering scale structures is in a rapid development stage, and good progress has been made in phenomenon reproduction and structural simulation, but the above research also has problems such as difficulties in the calibration of discrete element mesoscopic parameters.

There are relatively few studies on the correlation between cross-scale parameters of rockfill materials and meso-parameter calibration methods. Ma (2020) proposed a new parameter calibration method for rockfill meso-contact model based on the dam structure monitoring data and machine learning technology. The multiple data samples related to the meso-contact model parameters in DEM and the engineering scale dam deformation are first established based on the DEM simulation of stress-strain curves of rockfill material, parameter determination of macroscopic constitutive models and finite element analysis of dam structures. Then the machine learning is adopted to train and propose a fast-prediction model for the cross-scale relationship between meso-contact model parameters in DEM and the engineering scale dam deformation. Finally, the quantum genetic algorithm is used to find the minimum error between predicted and measured dam deformation, and the DEM meso parameters are determined.

5 DATA-DRIVEN INTELLIGENT CONSTITUTIVE PREDICTION

Meso-scale DEM simulation has been shown to be effective in simulating the constitutive behavior of granular materials. Compared with laboratory triaxial tests of granular materials, DEM virtual triaxial tests are less expensive, more efficient, and more convenient to consider various loading conditions. The constitutive model based on deep learning uses neural networks to establish the mapping relationship between stress and strain. Usually the input parameter is the strain tensor, and the output parameter is the stress tensor. The stress response of granular materials has obvious characteristics of strain history and strain path dependence, and a material constitutive response model that can reflect complex stress-strain path conditions must have the ability to "remember" the stress or strain history, so the constitutive model is essentially a time series model or process model (Figure 3).

Yu (2021) used the DEM to establish a particle material model sample, and carried out a total of 96 sets of triaxial compression simulations with different groups of confining pressure, strain rate, and loading/unloading conditions. The stress-strain relationship curve obtained by numerical simulation and the internal variable data such as porosity, coordination number, and composition tensor were used as the training and verification datasets, and the constitutive relationship was proposed and verified by deep autonomous reinforcement learning algorithm. Qu et al. (2021) proposed a deep learning strategy guided by mechanical knowledge by adopting the small strain theory of granular materials based on the homogenization assumption of Vogit. DEM simulation of triaxial experiments were used to generate stress-strain data. The results show that the trained deep learning model can effectively capture the stress-strain response relationship under complex multiaxial loading conditions, with good interpolation and extrapolation prediction capabilities.

Based on experimental data and deep learning model, the key constitutive parameters or complete stress-strain relationship of rockfill material can be predicted, and the strength parameters or stress-strain relationship are directly obtained from the basic physical parameters of rockfill. At present, the research on rockfill constitutive model based on machine learning/deep learning method is still in its infancy. The DEM, as a powerful means to expand datasets and provide key information such as internal variables, has initially demonstrated its advantages in considering different loading paths. There is still a lot of work to be done to consider the different gradings, initial state and particle crushing.

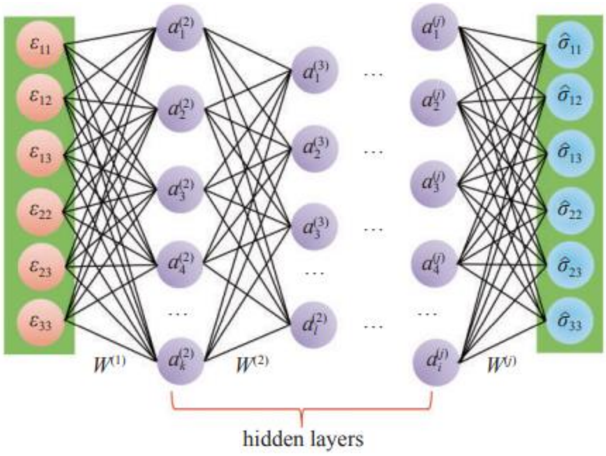


Figure3. Schematic diagram of a constitutive model based on deep learning (Qu et al., 2021).

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