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The particulate interface model for discrete element method

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ABSTRACT

This research proposed a numerical joint model based on discrete element method, which is the particulate interface model (PIM). The characteristic of the PIM is able to simulate joint mechanical behavior exactly with corresponding input parameters under random particle arrangement specimen in discrete element method, which indicates the simulation result is undisturbed by size of particles. The algorithms of PIM contain a user-defined model sandwiched between a prefix subroutine and a suffix subroutine. PIM is developed based on smooth-joint model. The structure of PIM includes four major modification concepts: contact area equalization, stiffness adjustment, exceeded force recapture, and normal force redistribution. Through PIM, the forces of the interface will be correctly calculated based on input joint parameters and provide expected joint macromechanical behavior. Two mechanical model has been provided in the PIM, one is the Mohr-Coulomb failure criterion and another is the Barton-Bandis failure criterion. The former model can simulate shear mechanical behavior under different normal stress based on input cohesion, peak friction angle and residual friction angle, the latter model can simulate cohesion-less joint mechanical behavior with joint roughness, normal stress, joint wall strength and residual friction angle. The shear-displacement curves and the failure envelopes of two models are plotted, and the dilation curves and the closure curves of Barton-Bandis model have also been provided to proof the performance of the PIM. The simulation results show that the PIM can reasonably reflect the mechanical behavior of joint model in discrete element method.

Keywords: Discrete element method, rock joint, smooth-joint model.

1 INTRODUCTION

The strength and deformability of rock mass are heavily influenced by the properties of joints, thus the simulation of interfaces is vital and valuable for engineering design. Various particulate discrete element method software packages, including PFC, EDEM, VEDO, and YADE, are appropriate tools for analyzing the interface problem. Interfaces can be simulated using various method in particulate DEMs, the advanced one is using a smooth-joint contact model to generate the interface. Numerous applications have been derived from the smooth-joint contact model, such as the synthetic rock mass (Mas Ivars et al., 2011) approach and the grain-based model (Potyondy, 2010) and have proof the usefulness of the smooth-joint model for investigating the effects of interfaces in rock mechanics. However, the reference-less input parameters are an unsolved problem that makes the smooth-joint model unreliable and uneconomical in engineering design.

To solve this problem, researchers have investigated the effect of the input parameters of the smooth-joint model through numerical direct shear testing or uniaxial compression testing with a single joint, such as Hu et al.(2018) and Mehranpour and Kulatilake(2017). They provided useful suggestions for simulating interfaces in particulate DEMs; however, the calculation results still contained errors, and the determination of material parameters was time consuming due to the back-analysis.

This paper proposes a new interface model for particulate DEMs, namely the particulate interface model (PIM). The PIM performs highly accurate, stable, and reasonable simulation of specified interface behaviors between particles. The microscopic parameters of the PIM, such as friction angle and cohesion, are consistent with the macroscopic properties. The required parameters are determined through laboratory tests and field investigation; they can be directly entered into the DEM without time-consuming back-analysis. The PIM can faithfully reflect real-world interface behavior.

2 MECHANICAL BASIS OF THE PARTICULATE INTERFACE MODEL

The PIM provides two widely used mechanical model. The first criterion is the Mohr-Coulomb failure criterion (Coulomb, 1776); the second is the Barton-Bandis shear strength criterion (Barton et al., 1985). In the PIM, these failure criteria are adopted for each segment of the interface; whenever the stress state reaches the failure state, the segments transition to sliding state. When all segments are in the sliding state, the apparent interface begins to slide.

The Mohr-Coulomb failure criterion in this PIM uses three parameters to describe the strength of the interface: cohesion, peak friction angle, and residual friction angle. To implement the criterion in the particulate DEM, the calculations use forces rather than stress. The relationship between the peak shear force and normal force of each segment of the interface can be expressed as Eq.(1) :

$$F_{s,max} = cA + F_n \tan\phi_p \tag{1}$$

And the residual shear force can be expressed as:

$$F_{s,max} = F_n \tan\phi_r \tag{2}$$

To ascertain the cohesive-less rock joint characteristics with roughness, the Barton-Bandis shear strength criterion was employed. In addition, Goodman's hyperbolic model was used to describe the closure behavior of a rock joint. The roughness effects of the interface are considered through the joint roughness coefficient. The failure criterion of the Barton-Bandis criterion in the PIM is shown as:

$$F_{s,max} = F_n \tan\phi_p \tag{3}$$

Which the friction angle is:

$$\begin{cases} \phi_p = i_r + \phi_r & \text{if } \phi_p < 70° \\ \phi_p = 70° & \text{if } \phi_p \geq 70° \end{cases} \tag{4}$$

$$i_r = JRC \log_{10}\left(\frac{JCS}{\overline{\sigma_n}}\right) \tag{5}$$

The JRC value during the shear process can be obtained from Fig. 1.

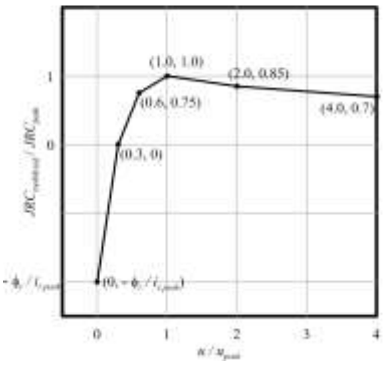


Fig. 1. Variation of mobilized JRC under different shear displacement according to the Barton's model.

The average normal stress acting on the interface, which is the total normal force divided by the summation of the segment areas and can be expressed as:

$$\overline{\sigma_n} = \frac{\sum F_n}{\sum A} \tag{6}$$

The deformability of the Barton-Bandis criterion in the PIM can be described as:

$$k_n = k_{ni}\left(1 - \frac{\sigma_n}{u_n^m k_{ni} + \sigma_n}\right)^{-2} \tag{7}$$

The dilation curve can be controlled by dilation angle, which can be calculated as:

$$i_d = \frac{1}{2} i_r \tag{8}$$

3 NUMERICAL BASIS OF THE PARTICULATE INTERFACE MODEL

The particulate interface model is built from the smooth-joint model, and it fixes the imprecise problem of simulate interface by applies four modifications.

3.1 Smooth-joint model

Smooth-joint model is a contact model developed by Itasca Consulting Group (Itasca Consulting Group, 2014). The characteristic is able to enforce particle direct pass through another particle rather than sliding along particle's circular surface, thus it is proper to simulate joint behavior by place a series of the smooth-joint model on a single plane. The normal force acting on a single smooth-joint can be calculated by:

$$F_n \leftarrow F_n + k_n A U_n \tag{9}$$

k_n, A, and U_n are joint normal stiffness, area and normal displacement increment of a single smooth-joint. The calculation of shear force is similar to normal force and shown as Eq. (10):

$$F_s \leftarrow F_s + k_s A U_s \tag{10}$$

Identically, k_s, A, and U_s are joint shear stiffness, area and shear displacement increment of a single smooth-joint.

3.2 Modification: contact area equalization

The first modification is to correct the area of the particulate interface model. The shear stiffness obtained from the direct shear test is calculated based on a specific area, the relationship is similar to Eq. (10). Thus, if the joint behavior in laboratory test has to be reproduced, the input shear stiffness of the PIM has to be modified because there is the difference between the joint area in the experiment and the summation of the area of the PIM contacts in the simulation (Fig. 2). The modified method is to multiply the input shear stiffness based on the ratio of joint area and summation of the area of the PIM contacts.

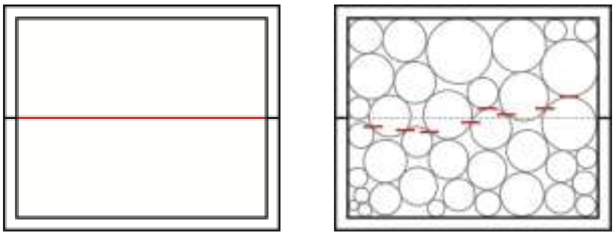


Fig. 2. The difference of interface area between mechanical model and numerical model.

3.3 Modification: stiffness adjustment

The second modification is to correct the shear stiffness based on the sliding state of the PIM contacts. In the simulation, the shear state of the PIM contacts will different due to its normal force, shear displacement and joint area, thus some contact will reach "sliding state" and some will not. At this moment, those contacts with "sliding state" will not generate shear force anymore and the shear force will keep at a stable value. This situation will cause the decreasing of the slope of the shear-displacement curve because increment of shear force is decreased. This problem is solved by modifying the shear stiffness based on the sliding state, the shear stiffness will multiply the value of the ratio between the area of all PIM contacts and un-sliding PIM contacts.

3.4 Modification: exceeded force recapture

The modification is to collect exceeded shear force. In the DEM simulation, the calculation of force-displacement and motion is step by step, so the increment of force is also discretization. When shear force reaches to the capacity of the PIM contact, it will set to capacity rather than the original value plus increment. In this situation, the difference between original value plus shear force increment and shear force capacity (which is the surplus shear force) will be ignored, and causes the shear-displacement curve to decrease and cannot shows a constant trend before peak shear stress (Fig. 3). The solution is to collect those surplus shear force and redistribute into those un-sliding PIM contacts. The modification can ensure that the shear stress incremental ratio will be constant and gives a stable and straight shear-displacement curve before reaches peak shear stress.

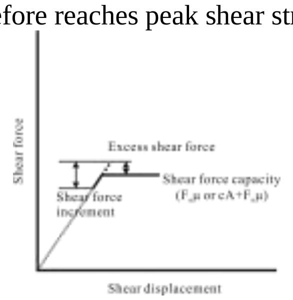


Fig. 3. Modification based on exceeded force recapture.

3.5 Modification: normal force redistribution

This modification is intended to modify the normal force distribution when part of interface begins to separate. In the particulate DEM interface simulation, the interface is discretized into a series of segments. When the interface begins to slide, some segments detach and the forces are dissipated. Thus, the apparent shear-displacement curve simultaneously exhibits an unreasonable stress drop. The stress drop is related to the shapes of the particulate elements, and it causes the simulation to underestimate the shear force during the shearing process. To avoid the drop of the force of the incompletely separated interface, the normal force of slightly separated particles should be transferred to other particles.

4 MODEL SETTINGS AND VALIDATIONS

4.1 Model settings

In this study, numerical direct shear test is prepared to show the performance of the particulate interface model (Fig. 4). The geometry of the direct shear box is 8 cm height with 10 cm width. The particle radius is 5 mm; the shear box contains 86 particles; shear velocity is 10^{-4} m/s; The interface parameters of the Mohr-Coulomb criterion were as follows: k_n was 3 GPa/m, k_s was 3 GPa/m, c was 0.5 MPa, ϕ_p was 45˚, and ϕ_r was 30˚. The interface parameters of the Barton-Bandis criterion were as follows: *JRC* was 14.4, *JCS* was 7.86 MPa, ϕ_r was 31˚, k_{ni} was 0.3 GPa/m, and $u_m{}^n$ was 0.18 mm. Various normal stress states, ranging from the tensile state (−0.5 MPa) to compressive state (1.5 MPa), were applied in the simulation of direct shear testing. In the PIM, any calibration method is unnecessary because all input parameters are obtained by laboratory direct shear test. The bottom box and rock (green particles) are fixed, and the upper box and rock (red particles) are moved servo-controlled based constant normal stress and shear velocity. The PIM contacts are placed between green and red particles and correct parameters are given in each time step by the PIM. To prevent the stress transfer error between the shear box and joint surface, the basis of monitoring normal stress is from the summation of all PIM contacts rather than the top shear box. This practice also prevents the interference of crack generation of rock specimen.

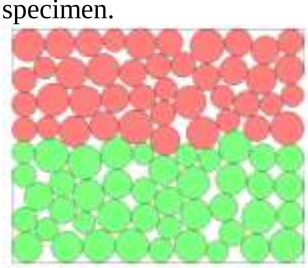
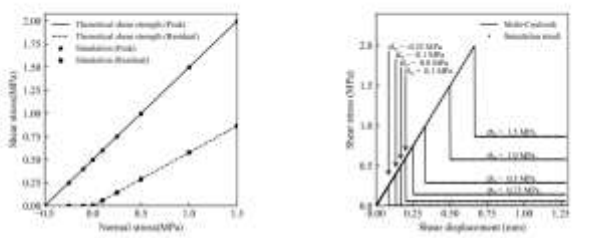


Fig. 4. The model of direct shear test simulation.

4.2 Simulation results

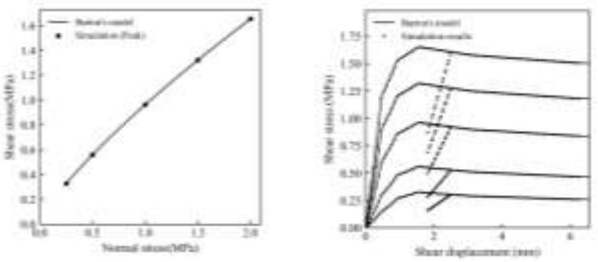
Fig. 5 is the comparison of failure envelope and the shear-displacement curve between theoretical value and simulation results. The black dots are the simulation data of the PIM, and the black line is the theoretical value of the Mohr-Coulomb failure criterion. The simulation results show the PIM is able to reflect the peak shear strength and the shear-displacement curve of rock joint under various normal loadings. This characteristic is important and useful in rock engineering problems, help us to predict the strength of jointed rock mass and make an economic design.



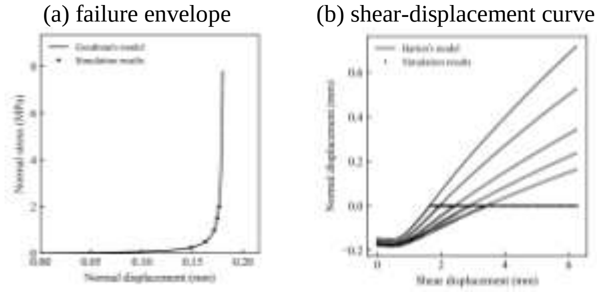
(a) failure envelope (b) shear-displacement curve

Fig. 5. The performance of the PIM to simulate the Mohr-Coulomb failure criterion.

Fig. 6 is the comparison of failure envelope, the shear-displacement curve, the closure curve and the dilation curve between theoretical value and simulation results. The black dots are the simulation data of the PIM, and the black line is the theoretical value of the Barton-Bandis shear strength criterion. The values of simulation data are apropos located on the theoretical line, means the PIM has a good performance to reflect the behavior of cohesive-less rough joint.



(a) failure envelope (b) shear-displacement curve



(c) Closure curve (d) Dilation curve

Fig. 6. The performance of the PIM to simulate the Barton-Bandis shear strength criterion.

6 CONCLUSION

This research provides a new method in discrete element method to simulate rock joint behavior predicted by the Mohr-Coulomb failure criterion and the Barton-Bandis shear strength criterion. The calibration of input parameters is based on experimental data, and the simulation results can be controlled through the PIM. The failure envelope, the shear-displacement curve, the closure curve and the dilation curve are captured well. The simulation results are precise and stable, which is extremely important for predicting the mechanical behavior of rock joint. The next step of this research is to improve the efficiency and convenience of the PIM and popularize to more researchers and engineers.

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