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Modeling rock joint behavior using a rough-joint model

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ABSTRACT

This study proposed a rough-joint model to simulate the strength and deformability of rock joint under various loadings. The proposed model adopted the Barton model to consider the roughness effect of joint. To implement the rough-joint model in DEM software, three calculation modifications are performed. Afterward, the proposed model was verified by comparing to theoretical model. The comparisons showed that the proposed model is versatile in simulating the shear displacement, normal closure, and shear dilation of joint. Moreover, this study investigated the influence of particle size on the applicability of rough-joint model, and the results indicate that particle sizes have no significant influence on shear behavior, which indicates the rough-joint model is suitable for different scale simulations. Finally, the proposed model was applied on the simulation of jointed rock mass. The simulation was compared with the experimental data of artificial jointed rock mass. The simulation results reveal that the proposed model reasonably reflects the varying strength and elastic modulus of rock mass under different joint orientations.

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1. Introduction

The term "joint" refers to a weak plane, such as bedding plane, fracture, fault, fissure, and other defect, existing in a rock mass. The presence of joints induces rock mass exhibit high anisotropy and heterogeneity. Under external loading, the fractures developed in the intact rock would interact with the sliding of the existing joint so that the strength and deformability of rock mass are heavily influenced by the properties and the distribution of joints. However, joint behavior is highly non-linear under applied stress and is influenced by surface roughness, interlocking joint surfaces, intact rock properties, and filling properties.[1–6] Therefore, how to evaluate the mechanical properties of joint in rock mass is the major concern in rock engineering.

In recent years, the discrete element method (DEM) has been widely adopted to explore the behavior of rock mass and successfully applied to many engineering areas, such as geotechnical engineering, tunneling, landslide evaluation, and mining engineering.[7–12] Compared with continuum analysis, the DEM has several unique characteristics and advantages, such as the ability to simulate crack propagation, large deformation, post-peak behavior, and sliding.[13–20] The DEM has been implemented in many programs, and this study adopted the software PFC (Particle Flow Code), which is widely used in rock and geotechnical engineering.

To simulate the joint behavior by PFC, the joint generation methods for rock mass can be approximately divided into three categories: (1) bond-eliminated model, (2) band-eliminated model, and (3) smooth-joint model. The bond-eliminated model determines a joint plane through the specimen and eliminates the bonds through the plane, which results in two separate blocks.[21] For the band-eliminated model, a broad-band joint is set through the specimen, and eliminates the bond of particles around the plane to create separate blocks.[22] The smooth-joint model is a new built-in contact model of PFC, and it treats the joint as a fictitious interface regardless of the local particle contact orientations along the interface. The main feature of smooth-joint model is that it can eliminate the roughness resulting from particle arrangement.[23–27] Chiu et al. [28] indicates the bond-eliminated model and the band-eliminated model highly overestimate the shear strength of joint. Strength is overestimated mainly because the roughness caused by the particle arrangement on the joint face, which is severely influenced by the particle size. The smooth-joint model improves the particle influence of the previous two techniques and has better agreement with actual joint behavior. However, since the friction angle of the smooth-joint model is fixed, it is unable to reflect the nonlinearity of failure envelope and provide adequate resistance when the joint slides. The modified smooth-joint model improves the linearity problem but does not consider joint deformation behavior.

Therefore, this study proposed a new joint model, named rough-joint model, to simulate the strength and deformability of joint under various loadings, including the shear displacement,

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shear dilation, and normal closure of joint. The proposed model adopted the Barton theory, which is widely used to predict joint behavior, to consider the effect of roughness,[29–32] and its calculation is based on the numerical structure of the smooth-joint model. All the material parameters of the proposed model can be determined by the Barton suggested procedures. Once the parameters are determined by laboratory tests and field investigation, then they can be directly inputted into the PFC modeling without the time-consuming back analysis. The proposed model provides a more accurate and effective way to consider the nonlinear behavior of joint and is successfully implemented in the DEM software PFC 2D/3D.

2. Rough-joint model

2.1. Background theory of smooth-joint model

The proposed rough-joint model is developed from the smooth-joint model, a build-in model of PFC 2D/3D.[23] The smooth-joint model allows particles at the joint surface that experience relative slip to slide on the specified joint face rather than sliding along the particle surface. The required parameters of smooth-joint model include friction angle ϕ_{sj}, dilation angle i_d, joint normal stiffness $k_{n,sj}$ and joint shear stiffness $k_{s,sj}$.

Based on the smooth-joint model, the force act on joint is calculated as

$$F_{n,sj} := F_{n,sj} + k_{n,sj} A_{sj} \Delta U_n^e \tag{1}$$

$$\mathbf{F}'_{s,sj} := \mathbf{F}_{s,sj} - k_{s,sj} A_{sj} \Delta \mathbf{U}_\mathbf{s}^e \tag{2}$$

where $F_{n,sj}$ is the normal force act on joint plane, ΔU_n^e is the normal displacement in the unbonded part of joint. $\mathbf{F}'_{s,sj}$ is the shear force vector act on joint plane. Bold font means the term is in a vector form. $\Delta\mathbf{U}_\mathbf{s}^e$ is the shear displacement vector of joint, and A_{sj} is the area of SJ (smooth joint) cross section.

For an unbonded joint, if $\left|\mathbf{F}'_{s,sj}\right| \le \left(F^*_{s,sj} = \mu F_{n,sj}\right)$, then the resistant shear force $\left|\mathbf{F}_{s,sj}\right|$ is

$$\left|\mathbf{F}_{s,sj}\right| = \left|\mathbf{F}'_{s,sj}\right| \tag{3}$$

where μ is the coefficient of friction.

Otherwise, sliding is assumed to occur, and the resistant shear force is limited by

$$\left|\mathbf{F}_{s,sj}\right| = \left(F^*_{s,sj} = \mu F_{n,sj}\right) \tag{4}$$

Once sliding occurs, and the dilation effect increases normal force due to shear displacement can be obtained from

$$\begin{aligned} F_{n,sj} &:= F_{n,sj} + \left[\Delta U^*_{s,sj} \tan\psi\right] k_{n,sj} A_{sj} \\ &= F_{n,sj} + \left(\frac{\left|\mathbf{F}'_{s,sj}\right| - F^*_{s,sj}}{k_{s,sj}}\right) k_{n,sj} \tan\psi \end{aligned} \tag{5}$$

where ψ is the dilation angle.

In contrast, the original smooth-joint model allows just one fixed value for the friction and the dilation angle, and it neglects the friction variations due to the effect of different normal stress stages on the varying roughness along the joint surface.

2.2. Shear strength

The rough-joint model applies the Barton criterion for shear strength.[29] Compared with Coulomb friction law whose friction angle is a constant, the characteristic of Barton criterion is that the friction angle varies with the magnitude of normal stress on joint surface, which effectively reflects the effect of roughness on joint surface. For a cohesive-less joint surface, the peak friction angle $\phi_{rj,peak}$ can be expressed as

$$\tau_s^p = \sigma_n \tan\phi_{rj,peak}$$

$$\begin{cases} \phi_{rj,peak} = JRC_{peak}\log_{10}\left(\dfrac{JCS}{\sigma_n}\right) + \phi_{residual} & ,if\ \phi_{rj,peak} < 70^\circ \\ \phi_{rj,peak} = 70^\circ & ,if\ \phi_{rj,peak} \ge 70^\circ \end{cases} \tag{6}$$

where JRC_{peak} is peak joint roughness coefficient; JCS is joint wall compressive strength; σ_n is normal stress acting on joint surface; and $\phi_{residual}$ is the residual friction angle of the joint surface. The JRC_{peak} can be obtained by back analysis of direct shear test through the Barton criterion; JCS is approximately equal to uniaxial compressive strength; $\phi_{residual}$ is related to the basic friction angle and weather condition of joint surface, and can be obtained by Eq. (7):

$$\phi_{residual} = 10^\circ + r/R\left(\phi_b - 10^\circ\right) \tag{7}$$

where r/R is the ratio of rebound values for a weathered joint surface and fresh joint surface, ϕ_b is the basic friction angle of rock material. In this study, the joint surface are assumed unweathered, thus $\phi_{residual}$ is equal to ϕ_b. Due to the discrete characteristic of PFC, the normal stress σ_n can be calculated by

$$\sigma_n = \frac{\sum_{i=1}^{m} F^i_{n,sj}}{A_{joint}} \tag{8}$$

where $F^i_{n,sj}$ is the normal force acted on ith joint, A_{joint} is the area of joint surface, which is length times width of shear box of direct shear test, and m is the total number of joints.

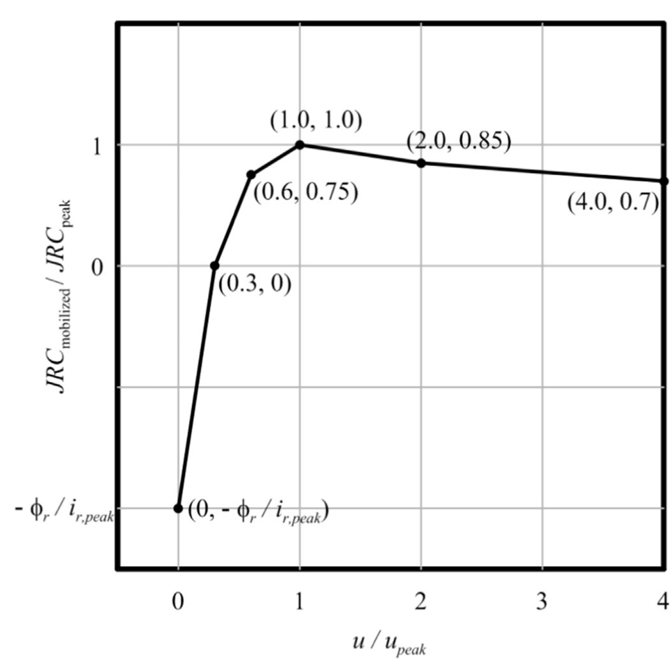

Fig. 1. Variation of mobilized JRC ($JRC_{mobilized}$) under different shear displacement according to the Barton model.[30]

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