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Parametric study of smooth joint parameters on the mechanical behavior of transversely isotropic rocks and research on calibration method

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ABSTRACT

This paper aims to study the relationships between microscopic parameters of bedding planes and macroscopic characteristic of transversely isotropic rock using the bonded-particle discrete element models. The bedding planes were simulated by embedding smooth joint models within an area of certain thickness. A macro-microscopic parameters calibration method for transversely isotropic rocks was designed, which was able to adequately capture the essential anisotropic features of transversely isotropic rocks. Verification was conducted by taking Boryeong shale as an example to build the discrete element model and calibrate the parameters. The results were compared, demonstrating the accuracy and superiority of the calibration method.

1. Introduction

Transversely isotropic rocks contain weak planes, such as bedding, foliation, or schistosity, which contribute significantly to the anisotropic behavior of deformation and strength [1–3]. Furthermore, numerous current applications deal with this type of rocks, e.g., exploitation of shale gas [4,5], development of excavation damage that occurs during underground construction and mechanized tunneling [6,7]. Since new techniques and methods have become available for conducting laboratory experiments and numerical simulations, there has been an increasing interest in the behavior of transversely isotropic rock materials.

Many physical experimental studies have been performed in different rock-like and natural materials to investigate the compressive [8,9], shear [4,10] and tensile [11] behavior as well as fracture patterns [12–14] of transversely isotropic rocks. Besides physical experimental studies, numerical simulations are also playing an important role in the research on transversely isotropic rocks [15–19]. As one of the most rapidly developing areas of computational mechanics, the discrete element method (DEM) in particulate and blocky systems has undergone a significant development in the past decades [20]. The bonded-particle model (BPM), which is a distinct element-based model, has been widely used for transversely isotropic rocks [3,18,19]. As a discrete element approach, the major advantage of BPM is that complex empirical constitutive behavior can be replaced by simple particle contact logic [21]. The smooth joint model (SJM) was developed by Cundall [22] to resolve the shortcomings of the bond removal approach [23]. The BPM and the SJM are the two main parts to establish the transversely isotropic model in PFC.

Since the microscopic parameters in DEM did not directly correspond to the macroscopic parameters in real materials, how to choose reasonable microscopic parameters is an unavoidable issue [24]. While there were few studies on the calibration of micro-macroscopic parameters aiming at transversely isotropic models, the objective of this paper is to design the method of calibrating micro-macroscopic parameters of transversely isotropic rocks in PFC^{2D}.

2. Theoretical background

Theoretically, the transversely isotropic model is characterized by five independent elastic constants and one plane of elastic symmetry. Goodman [25] proposed that if the rock was regularly crossed by a set of parallel bedding planes with the same spacing, it was possible to calculate elastic constants for an 'equivalent' continuous material representative of the rock mass. It is assumed that the intact rock itself is isotropy and conforms to the linear elastic constitutive theory. The bedding planes are regularly spaced with a distance δ, defining the term K_n and K_s as the normal and shear stiffness, respectively. The thickness d of bedding planes can be negligible. The analytical solution of the elastic modulus with an inclined angle of θ can be calculated by

$$\frac{1}{E_\theta} = \frac{1}{E} + \cos^2\theta\left(\frac{\cos^2\theta}{K_n\cdot\delta} + \frac{\sin^2\theta}{K_s\cdot\delta}\right) \tag{1}$$

where θ is the angle between the plane of transversely isotropy and the

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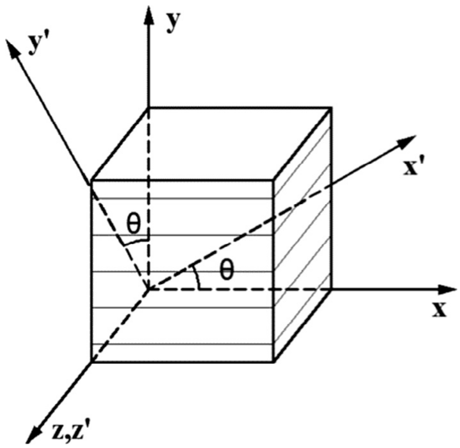

Fig. 1. The model of transversely isotropic rock.

x-axis signifying counterclockwise rotation (Fig. 1).

3. Numerical experiment

3.1. Numerical model

The Particle Flow Code software (PFC^{2D}) was applied in this study to establish the numerical models. Contacts between the particles in the intact rock and bedding planes were assigned by BPM and SJM, respectively. The size of the cylindrical specimens was 76 mm in height and 38 mm in diameter. The particle radius ratio was 1.66. Taking account of the computing time, the minimum particle radius of the numerical model was 0.25 mm in this paper, which made 7481 particles in a single specimen totally. The microscopic parameters of intact rock and smooth joints were shown in Tables 1 and 2, respectively.

Here the term d means the thickness of bedding planes and defines a specified zone in which all the contacts would be assigned by SJM, as shown in Fig. 2.

Uniaxial compression tests were performed on the numerical specimens with different inclined angles of smooth joints to obtain the macroscopic elastic parameters. The cylindrical specimens with seven different inclined angles were shown in Fig. 3.The obtained macroscopic elastic modulus with different inclined angles were substituted into Eq. (1). The least squares method was adopted to get the macroscopic normal and shear stiffness of bedding planes by Eq. (1).

The test and fitting results with the microscopic parameters in Tables 1 and 2 were listed in Table 3.

3.2. Numerical experiments

The sensitivity analysis of the microscopic parameters of smooth joints is conducted here. The set of microscopic parameters listed in Tables 1 and 2 was regarded as initial parameters. The value range of the six microscopic parameters was shown in Table 4.

In order to facilitate the analysis, the stiffness parameters $k_{n,sj}$ and $k_{s,sj}$ were divided into microscopic deformation parameters, while the

Table 1
Microscopic parameters of intact rock.

Ball parameters		Parallel bond parameters	
Ball density [kg/m^3]	2700	Modulus $\overline{E_c}$ [GPa]	38.0
Modulus E_c [GPa]	38.0	Stiffness ratio $\overline{k_s}/\overline{k_n}$	0.3
Stiffness ratio k_s/k_n	0.3	Mean/SD normal strength [MPa]	65/6.5
Friction coefficient μ	0.8	Mean/SD shear strength [MPa]	65/6.5

SD: standard deviation.

Table 2
Microscopic parameters of smooth joint.

Normal stiffness $k_{n,sj}$ [GPa/m]	Shear stiffness $k_{s,sj}$ [GPa/m]	Friction coefficient μ_{sj}	Normal strength $\sigma_{n,sj}$ [MPa]	Cohesion C_{sj} [MPa]	Thickness d [mm]
3360	960	0.4	10	30	0.6

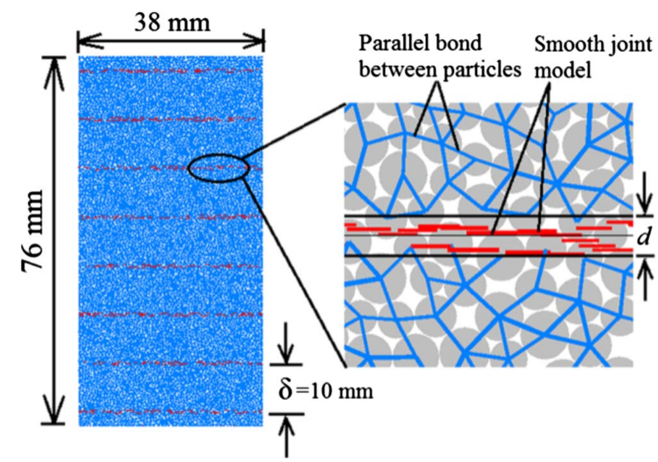

Fig. 2. Numerical model

friction coefficient μ_{sj}, normal strength $\sigma_{n,sj}$ and cohesion C_{sj} were classed as microscopic strength parameters. The parameters d would be discussed separately.

4. Numerical results analysis

4.1. Influence on the deformation characteristics

4.1.1. Influence on the macroscopic normal stiffness K_n and shear stiffness K_s

The macroscopic normal and shear stiffness of bedding planes with each set of microscopic parameters were calculated by the least squares method, and the results were shown in Fig. 4. All the microscopic parameters discussed were standardized in order to display them in a single figure. It showed that the microscopic strength parameters had little effect on neither the K_n nor the K_s. Meanwhile, the K_n and K_s were only associated with the corresponding $k_{n,sj}$ and $k_{s,sj}$ with a linear correlation, as linear fitting in Eq. (2).

$$K_n = 1.8135k_{n,sj} + 312.4R^2 = 99.999\%$$
$$K_s = 1.6895k_{s,sj} + 44.1R^2 = 99.965\% \quad (2)$$

4.1.2. Influence on the elastic modulus Eθ

Fig. 5 showed that both the $k_{n,sj}$ and $k_{s,sj}$ had a significant effect on the trend of elastic modulus with the different inclined angles. As calculated by Eq. (1), there were two main types of the influence of the increasing θ on E_θ of transversely isotropic rocks. Fig. 5a showed that, with the increasing $k_{n,sj}$, the trend of E_θ gradually turned from the incremental type to the shoulder type. And $k_{n,sj}$ mainly affected the elastic modulus at the lower inclined angles. The trend of E_θ with the increasing $k_{s,sj}$ showed in Fig. 5b was completely opposite, which turned from the shoulder type to the incremental type.

4.2. Influence on the strength characteristics

The influence of each microscopic parameter will be analyzed as shown in Fig. 6