Study on the equivalent mechanical parameter model of fractured rock mass based on the numerical test of particle flow code

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Abstract. In order to obtain accurately the equivalent mechanical parameter model of jointed rock mass, in this paper, the numerical test of particle flow code and Hoek-Brown criterion are used to analyse the mechanical parameters of rock mass. First, based on rock sample indoor test, the PFC software is used to check rock block parameters and obtain rock block micromechanics parameters, and the joint elements are added for uniaxial compression and biaxial compression numerical experiments to obtain the mechanical strength parameters of rock mass. Then, these parameters obtained by numerical test are compared with those obtained by Hoek-Brown criterion to comprehensively determine mechanical parameters of rock mass. Finally, the equivalent mechanical parameter model of rock mass is established, and the microscopic parameters of it are obtained by checking the parameters. The research results have certain theoretical significance for joint rock mass modelling.

1. Introduction

At present, China is at the peak of the development of geotechnical engineering when various large-scale water conservancy projects and underground engineering projects are under construction. The construction of these large-scale projects is mostly in jointed rock mass, so reasonable determination of rock mass mechanical parameters is of great significance for engineering design and stability evaluation.

The existence of joint fissure makes it difficult to obtain the mechanical parameters of rock mass accurately, therefore how to obtain the mechanical parameters of rock mass and establish the equivalent mechanical parameter model is an important direction in rock mass engineering. Early researchers obtained the mechanical parameters of rock mass through engineering experience and field in-situ tests or rock mass reduction tests based on geological surveys. For example, Shen studied the mechanical parameters of rock mass in the typical section of the three gorges project lock area. In recent years, machine learning and numerical simulation have gradually been used to estimate rock mechanical parameters. For example, Guo analyzed the rock mass mechanical parameters of the Shuibuya Project through the numerical triaxial test. Based on specific engineering examples, this paper compares the difference between traditional empirical method and numerical test method to obtain the mechanical parameters of rock mass and establishes the equivalent mechanical parameter model of rock mass by numerical test of particle flow code.
2. Profile of particle flow codes software and parameter verification

2.1. PFC software profile
PFC is a commercial numerical simulation software that is used to study the mechanical properties and behaviors of media from the microstructure perspective based on the microscopic discrete element theory proposed by Cundall. It is a simplified discrete element method procedure. The principle of PFC is to use the display center difference method for dynamic relaxation. In the calculation process, Newton's second law and the force-displacement law are used alternately in each step, and each particle body is iteratively traversed by step. The force-displacement law updates the contact force through the relative motion of the contact point and the contact model. Newton's second law determines the motion of particles according to the physical force and the contact force between particles, and then updates the movement speed of particles and the position of particles and particles (or particles and walls).

2.2. Parameter verification process
Since all parameters required for PFC simulation are microscopic parameters, which are different from macroscopic parameters obtained in laboratory tests, it is necessary to check the microscopic parameters through the numerical test to make the macroscopic parameters as close as possible to the laboratory test parameters. For the verification of microcosmic parameters, elasticity moduli $E$, Poisson’s ratio and uniaxial compressive strength are selected as the check basis. The correspondence between microscopic properties and macroscopic behavior has not been clarified, therefore the most effective check method can only be continuous debugging. Itasca recommended the following steps in the PFC user manual to match the micro parameters to reduce the parameter iterative checking process:

First, high strength value is set by changing micro parameters $E_c$ and matching macro young's modulus. And then match Poisson’s ratio by changing $k_n/k_t$ and $k_n/k_s$. Finally, uniaxial compressive strength, internal friction angle and cohesion are matched.

3. Establishment of numerical test model and acquisition of microscopic parameters
The mechanical parameters of rock block are selected from the bank slope project of Zhongliang reservoir in Chongqing, where the lithology is argillaceous limestone of Jialingjiang formation and argillaceous limestone of Daye formation.

3.1. Establishment of numerical test model
According to the biaxial test and uniaxial compression test (figure 1), the parameters such as elastic modulus, Poisson’s ratio, uniaxial compressive strength, cohesion and internal friction angle are matched. Firstly, uniaxial compression is carried out on the particle cluster sample, and the macroscopic parameters of the test are close to the indoor uniaxial compressive strength, elastic modulus and Poisson’s ratio by debugging constantly. Then, a two-axis numerical test is performed, and the values of rock mass $c$ and $\phi$ are obtained according to the generated mole-stress circle envelope (figure 2). A series of micro numerical parameters of dolomite limestone in Jialingjiang formation and argillaceous limestone in Daye formation are obtained through continuous adjustment.
Fig. 1 Biaxial (left) and uniaxial compression (right) test model

Fig. 2. Mohr’s stress circle of dolomite limestone of Jialingjiang formation (a) and argillaceous limestone of Daye formation (b)
3.2. Obtaining of microscopic parameters

The micro-mechanical parameters of rock mass are obtained through a series of numerical tests (Table 1), and the corresponding macroscopic parameters are close to the indoor test (Table 2), which satisfies the numerical simulation calculation of subsequent engineering cases.

| Table 1 | Rock mass micromechanical parameters |
| --- | --- |
| | Formation | Minimum grain size | Maximum grain size | Particle contact modulus | Particle stiffness ratio of particle | Particle Friction coefficient | Parallel bond modulus | Parallel bond Stiffness ratio | Normal strength | Tangential strength | Rubbing angle |
| | mm | mm | GPa | GPa | MPa | MPa | ° |
| T1j | 0.5 | 1.0 | 4.6 | 1.1 | 0.3 | 4.6 | 1.1 | 50.0 | 10.0 | 35.0 |
| T1d | 0.5 | 1.0 | 2.1 | 1.9 | 0.2 | 2.3 | 3.1 | 25.0 | 5.0 | 30.0 |

| Table 2 | Comparison of rock mass microcosmic and macroscopic parameters |
| --- | --- |
| | Types | Young’s modulus E / GPa | Poisson’s ratio ν | Uniaxial compressive strength σc / MPa | Internal friction angle ϕ° | Cohesion c / MPa |
| | | | | | |
| T1j | laboratory test | 10.563 | 0.15 | 47.69 | 40.61 | 5.02 |
| | PFC model | 10.717 | 0.150 | 48.78 | 39.83 | 10.87 |
| T1d | laboratory test | 4.375 | 0.27 | 23.30 | 37.53 | 3.32 |
| | PFC model | 4.378 | 0.275 | 22.94 | 36.57 | 5.98 |

4. Study of rock mass parameters

4.1. Estimation of rock mass parameters based on Hoek-brown criterion

Hoek-brown intensity criterion was proposed by Hoek and Brown in the early stage based on RMR classification and field in-situ tests, which can be used to estimate rock mass strength and deformation parameters by rock block parameters and RMR classification results. This criterion has been improved and perfected in the engineering application, therefore Hoek E published the latest research results of Hoek-Brown strength criterion (Generalized Hoek-Brown Criterion) in his paper in 2002. It is failure criteria of rock mass which is based on a statistical analysis results of a large number of in-situ tests of rock mass and of indoor triaxial tests, and integrates the influence of many aspects, such as rock mass structure characteristics, joint development characteristics, ground stress, rock block strength and so on.

The expression is as follows:

\[
\sigma'_1 = \sigma'_3 + \sigma'_{ci} \left( m_b \frac{\sigma'_3}{\sigma'_{ci}} + s \right)^a
\]

\[
m_b = m_i \exp \left( \frac{GSI - 100}{28 - 14D} \right)
\]

\[
s = \exp \left( \frac{GSI - 100}{9 - 3D} \right)
\]

\[
a = \frac{1}{2} + \frac{1}{6} \left( e^{-GSI/15} - e^{-20/3} \right)
\]
Where: \( \sigma'_{\text{max}} \) -- maximum effective principal stress (MPa) at rock mass failure;
\( \sigma'_{\text{min}} \) - minimum effective principal stress (MPa) at rock mass failure;
\( \sigma'_{\text{uniax}} \) - uniaxial compressive strength of rock blocks (MPa);

\( m_i \) -- rock mass material constants, which can be obtained by fitting the triaxial test data of rock blocks or determined by rock type;
D -- disturbance coefficient, which is Geological Strength Index proposed by GSI—Hoek et al.

When \( \sigma'_{\text{min}} = 0 \), the formula (1) can be written:
\[
\sigma_c = \sigma_{ci} \cdot S^a
\]  

When \( \sigma'_{\text{min}} = \sigma'_{\text{max}} \), the formula (1) can be written:
\[
\sigma'_i = \frac{s\sigma_{ci}^a}{m_b}
\]

When the generalized Hoek-Brown criterion is used to estimate rock body parameters, only the parameters such as \( \sigma'_{\text{uniax}} \), \( m_i \), D and GSI need be obtained. The first two parameters can be obtained by indoor triaxial test, the disturbance coefficient D can be determined by the method suggested in the literature such as Hoek E and GSI can be determined according to GSI rock mass classification system. Based on the geological survey in the field area, combined with indoor tests, in-situ tests and borehole camera data, the Hoek-Brown criterion is adopted to estimate the rock mass parameters within the impact depth (50m-110m) of toppling deformation on the bank slope (Table 3).

**Table 3** Estimation results of rock mass parameters based on Hoek-Brown criterion

| Formation | Lithology | \( \sigma_{ci} \)/mpa | GSI | \( m_i \) | D | Mb | s | a | \( \sigma_{\text{min}} \)/mpa | C/mpa | \( \phi \)/° |
|-----------|-----------|---------------------|-----|-------|---|----|---|---|-----------------|-------|--------|
| T1j       |           | 47.69               | 66  | 12    | 0.7 | 1.853 | 0.0072 | 0.502 | -0.186            | 1.843 | 35.71  |
| T1d       |           | 23.30               | 54  | 10    | 0.7 | 0.799  | 0.0013 | 0.504 | -0.037            | 1.003 | 23.18  |

4.2. Obtain rock mass parameters based on numerical test

Numerical model of rock mass is in the rock model with three groups of 80° (with axial angle is 80°) rock formation (Figure 3), assigning the value of rock mass and joint and obtaining the mechanical strength parameters of rock mass through uniaxial compression and biaxial compression tests.

**Fig.3** Numerical test model of rock mass
By comparing the failure forms of two types of rock masses under uniaxial compression test (FIG. 4), the number of dolomite limestone cracks in Jialingjiang formation is more than that in Daye formation, and the former crack distribution is more concentrated near the joint.

The Mohr's stress circle of the two types of rock masses are obtained by the biaxial test under different confining pressures (Fig.5), then mechanical strength parameter of them are obtained through the envelope of the Mohr’s stress circle.
Fig. 5 Mohr’s stress circle of rock mass in the Jialing river formation (a) and Daye formation (b)

Table 4 Calculation results of rock mass parameters based on numerical test

| Formation lithology | Young’s modulus (E)/GPa | Poisson’s ratio (ν) | Uniaxial compressive strength (σ_c)/MPa | Cohesion (c)/MPa | Internal friction angle (φ)° |
|---------------------|-------------------------|-------------------|----------------------------------------|-----------------|-----------------------------|
| T1j                 | 5.540                   | 0.245             | 18.15                                  | 5.445           | 29.74                       |
| T1d                 | 2.254                   | 0.297             | 10.16                                  | 3.805           | 20.33                       |

5. Study on mechanical parameters of equivalent rock blocks

5.1. Comprehensive value of rock mass parameters

Comparing the results in table 3 and table 4, the overall mechanical strength parameters of rock mass obtained by PFC numerical test are stronger than those estimated by Hoek-Brown. This is because the empirical formula obtained by the latter is based on numerous engineering cases, therefore various internal and external factors, such as weathering and ground stress, are integrated. The former is the ideal condition, only considering the combination of rock blocks and bedding, so the mechanical parameters estimated by the latter are more in line with the actual engineering. However, the parameters of rock mass obtained by Hoek-Brown criteria are not as complete as those obtained by numerical tests. Therefore, Hoek-Brown criteria and numerical test results are integrated in this section to obtain rock mass parameters (Table 5).

Table 5 Comprehensive values of rock mass parameters

| Formation lithology | Young’s modulus (E)/GPa | Poisson’s ratio (ν) | Uniaxial compressive strength (σ_c)/MPa | Tensile strength (σ_t)/MPa | Cohesion (c)/MPa | Internal friction angle (φ)° |
|---------------------|-------------------------|-------------------|----------------------------------------|-----------------|----------------|-----------------------------|
| T1j                 | 5.540                   | 0.245             | 18.15                                  | -0.186          | 1.843          | 29.74                       |
| T1d                 | 2.254                   | 0.297             | 10.16                                  | -0.037          | 1.003          | 20.33                       |
5.2. Obtaining the micro parameters of equivalent rock blocks

Based on obtaining rock mass parameters, the microscopic parameters of rock mass are checked according to the above PFC parameter checking method, and the micromechanical parameters of two types of rock masses in the field were obtained by numerical test (table 6).

**Table 6** Rock mass micro-mechanical parameters

| Formation | Minimum grain size (m) | Maximum grain size (m) | Particle contact modulus (GPa) | Particle friction coefficient (MPa) | Parallel bond modulus (MPa) | Parallel bond Stiffness ratio | Normal strength (MPa) | Tangential strength (MPa) | Friction angle (°) |
|-----------|------------------------|------------------------|---------------------------|-----------------|-----------------------------|-----------------------------|---------------------|------------------------|------------------|
| T1j       | 0.5                    | 1.0                    | 2.5                       | 1.8             | 0.15                        | 2.5                        | 1.8                 | 10.0                   | 5.0              |
| T1d       | 0.5                    | 1.0                    | 1.2                       | 2.2             | 0.05                        | 1.2                        | 2.2                 | 6.0                    | 3.0              |

By comparing table 1 and table 6, it can be seen that the mechanical parameters of equivalent rock blocks are reduced in the microscopic parameters such as particle contact modulus, particle friction coefficient, parallel bonding modulus, normal strength, tangential strength and friction angle, while the particle stiffness ratio parameter increases, and the parallel bond stiffness ratio parameter can both increase and decrease.

6. Conclusion

In this paper, based on the checking of rock block micro-parameters, the mechanical strength parameters of rock mass are determined by the Hoek-Brown criterion and the numerical test, and the equivalent rock blocks numerical model is established. The following conclusions are obtained through research:

1. Less external factors are considered in numerical tests, making the overall mechanical strength parameters of rock mass obtained by PFC numerical tests stronger than those estimated by Hoek-Brown.
2. The mechanical parameters of equivalent rock blocks are reduced in the microscopic parameters such as particle contact modulus, particle friction coefficient, parallel bonding modulus, normal strength, tangential strength and friction angle, while the particle stiffness ratio parameter increases, and the parallel bond stiffness ratio parameter can both increase and decrease.

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