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Fast determination of meso-level mechanical parameters of PFC models

Guo Jianwei [a,b], Xu Guoan [c,d,*], Jing Hongwen [c,d], Kuang Tiejun [e]

[a] School of Safety Engineering, China University of Mining & Technology, Xuzhou 221116,China
[b] Energy and Chemical Research Institute of Zhong Ping Shen Ma Group, Pingdingshan 467000, China
[c] State Key Laboratory of Geomechanics and Deep Underground Engineering, China University of Mining & Technology, Xuzhou 221008, China
[d] School of Mechanics and Civil Engineering, China University of Mining & Technology, Xuzhou 221116, China
[e] Sitai Coal Mine, Datong Coal Mine Group, Datong 037016, China

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ABSTRACT

To solve the problems of blindness and inefficiency existing in the determination of meso-level mechanical parameters of particle flow code (PFC) models, we firstly designed and numerically carried out orthogonal tests on rock samples to investigate the correlations between macro- and meso-level mechanical parameters of rock-like bonded granular materials. Then based on the artificial intelligent technology, the intelligent prediction systems for nine meso-level mechanical parameters of PFC models were obtained by creating, training and testing the prediction models with the set of data got from the orthogonal tests. Lastly the prediction systems were used to predict the meso-level mechanical parameters of one kind of sandy mudstone, and according to the predicted results the macroscopic properties of the rock were obtained by numerical tests. The maximum relative error between the numerical test results and real rock properties is 3.28% which satisfies the precision requirement in engineering. It shows that this paper provides a fast and accurate method for the determination of meso-level mechanical parameters of PFC models.

1. Introduction

Particle flow code (PFC) is powerful numerical simulation software advanced by Peter Cundall, which is based on meso-level discrete element theory [1]. It can reproduce the physical and mechanical properties of rock by simulating its meso-level structure and mechanical behavior. The PFC has many advantages compared with other numerical simulation software and physical simulation tests [2]. It has been applied to various fields of geotechnical engineering in recent years [3–8].

The complex macroscopic mechanical behaviors of a material in PFC are reflected by its meso-level constitution and elementary mechanical relations. The basic composition of rock includes particles and bonds whose geometrical and mechanical properties determine the macroscopic properties of rock (e.g., constitutive relation), which is different from other numerical simulation software [9]. The macroscopic mechanical behaviors of rocks can be reproduced by rock models in PFC provided that the appropriate values of meso-level parameters are set for the models.

The primary difficulty in the application of PFC is to determine the appropriate values of meso-level parameters because the values cannot be directly obtained by laboratory test, field measurement or theoretical calculation. The determination of PFC model parameters generally includes three steps. First the macroscopic mechanical properties of rock are tested in laboratory. Then numerical rock models are created with the same dimension as real rock samples. Last, the rock models are numerically tested by trial and adjusting the values of meso-level parameters until the test results accord with those of real rock samples. A large number of simulations are generally needed due to the blindness and chanciness of the "trial and error" method. In order to determine the right values of meso-level parameters quickly and efficiently, we studied the influence of meso-level parameters on the macroscopic mechanical properties of rock by orthogonal numerical tests, and predicted the values of meso-level parameters using artificial intelligent techniques.

It should be noted that the influence of meso-level geometric parameters (i.e., dimension and distribution of particles) on macroscopic rock properties is omitted for the sake of simplicity. According to the calculation capacity of personal computer, the average radius of particles, the radius ratio of largest to smallest particles and the porosity of rocks are set as 1 mm, 1.66 and 0.2 respectively.

2. Influence of meso-level mechanical parameters on rock macroscopic properties

In order to deeply understand the relationship between macroscopic mechanical behaviors and meso-level mechanical parameters of rock, so as to provide guidance for the values determination

* Corresponding author. Tel.: +86 13685170778.
E-mail address: xgacumt@cumt.edu.cn (G. Xu).

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of meso-level parameters of PFC models, we investigated the influence of meso-level mechanical parameters on macroscopic properties of rock by orthogonal numerical tests.

2.1. Design of orthogonal test

Rock is a typical bonded granular material. The meso-level mechanical parameters of rock in PFC^{3D} includes the Young's modulus at each particle-particle contact E_c, the normal to shear stiffness ratio of particle k_n/k_s, the friction coefficient between particles μ, the Young's modulus of parallel bond E_{pc}, the normal to shear stiffness ratio of parallel-bond k_{pn}/k_{ps}, the average normal strength of parallel-bond σ_{pnm}, the average shear strength of parallel-bond σ_{psm}, the standard deviation of parallel-bond normal strength σ_{pndev} and the standard deviation of parallel-bond shear strength σ_{psdev}.

The number of levels of each meso-level mechanical parameter in orthogonal test design should be as many as possible to get enough data that can sufficiently reflect the intrinsic relation between macroscopic and meso-level mechanical parameters of rock. On the other hand, the number of levels is limited by orthogonal table and calculation time. By taking all these factors into consideration, the number of levels of each meso-level mechanical parameter is set as four. Besides, to provide ideal data for the subsequent intelligent prediction, the assignment domain (i.e., the range from minimum to maximum values) of each meso-level mechanical parameter should cover the expected appropriate value corresponding to a certain rock which is to be investigated. However, the expected appropriate values cannot be truly foreseen. Based on a large amount of numerical simulations, the assignment domain of main meso-level mechanical parameters can be approximately determined by the macroscopic properties such as elastic modulus and compressive strength of rock. Table 1 shows the values of meso-level mechanical parameters determined on the basis of common rocks' properties. According to Table 1 and the orthogonal table of nine factors with four levels, we obtained 32 sets of meso-level parameters listed in Table 2.

The numerical tests were conducted with the method proposed by International Society for Rock Mechanics [10]. First, the geometric models of standard rock samples were built with the meso-level geometric parameters given above. Then each set of meso-level parameters in Table 2 were assigned to the geometric models to get the corresponding calculation models. Last, the Brazilian tests and compressive tests were numerically made on standard rock

Table 1
Values of meso-level mechanical parameters of rocks

Test level	Meso-level mechanical parameter								
	E_c (GPa)	E_{pc} (GPa)	$\frac{k_n}{k_s}$	$\frac{k_{pn}}{k_{ps}}$	μ	σ_{pnm} (MPa)	σ_{pndev} (MPa)	σ_{psm} (MPa)	σ_{psdev} (MPa)
1	10	10	1	1	0.1	15	0	15	0
2	30	30	2	2	0.3	40	5	40	5
3	50	50	3	3	0.5	65	10	65	10
4	70	70	4	4	0.7	90	15	90	15

Table 2
Rock models for orthogonal tests in PFC^{3D}

No. of model	Meso-level mechanical parameter								
	E_c (GPa)	E_{pc} (GPa)	$\frac{k_n}{k_s}$	$\frac{k_{pn}}{k_{ps}}$	μ	σ_{pnm} (MPa)	σ_{pndev} (MPa)	σ_{psm} (MPa)	σ_{psdev} (MPa)
1	10	10	1	1	0.1	15	0	15	0
2	10	30	2	2	0.3	40	5	40	5
3	10	50	3	3	0.5	65	10	65	10
4	10	70	4	4	0.7	90	15	90	15
5	30	10	1	2	0.3	65	10	90	15
6	30	30	2	1	0.1	90	15	65	10
7	30	50	3	4	0.7	15	0	40	5
8	30	70	4	3	0.5	40	5	15	0
9	50	10	2	3	0.7	15	5	65	15
10	50	30	1	4	0.5	40	0	90	10
11	50	50	4	1	0.3	65	15	15	5
12	50	70	3	2	0.1	90	10	40	0
13	70	10	2	4	0.5	65	15	40	0
14	70	30	1	3	0.7	90	10	15	5
15	70	50	4	2	0.1	15	5	90	10
16	70	70	3	1	0.3	40	0	65	15
17	10	10	4	1	0.7	40	10	40	10
18	10	30	3	2	0.5	15	15	15	15
19	10	50	2	3	0.3	90	0	90	0
20	10	70	1	4	0.1	65	5	65	5
21	30	10	4	2	0.5	90	0	65	5
22	30	30	3	1	0.7	65	5	90	0
23	30	50	2	4	0.1	40	10	15	15
24	30	70	1	3	0.3	15	15	40	10
25	50	10	3	3	0.1	40	15	90	5
26	50	30	4	4	0.3	15	10	65	0
27	50	50	1	1	0.5	90	5	40	15
28	50	70	2	2	0.7	65	0	15	10
29	70	10	3	4	0.3	90	5	15	10
30	70	30	4	3	0.1	65	0	40	15
31	70	50	1	2	0.7	40	15	65	0
32	70	70	2	1	0.5	15	10	90	5