Evaluation of Failure Behavior and Strength of Fractured Rock Sample using in-situ Triaxial Compression Tests and Expanded Distinct Element Method

B. Li[1, a] and Y. Jiang[2,b]

[1] Faculty of Engineering, Nagasaki University, 1-14 Bunkyo-machi, Nagasaki 852-8521, Japan

[2] Faculty of Engineering, Nagasaki University, 1-14 Bunkyo-machi, Nagasaki 852-8521, Japan

[a]libo@nagasaki-u.ac.jp, [b]jiang@nagasaki-u.ac.jp

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Abstract. The in-situ tests have been widely used to directly assess the strength and deformability of rock mass, along with which, various numerical approaches were proposed to give rational interpretations to the mechanical phenomenon happening during these tests. In this study, the so-called potential cracks are introduced into DEM model, leading to expanded DEM (EDEM) approach which is capable of simulating the cracking in intact rocks. The EDEM is applied to an in-situ triaixal compression test on a fractured rock sample. The simulation has well represented the failure mode, peak stress and elastic modulus obtained from tests as well as the cracking phenomenon and the slips on fracture planes during the loading process.

1. Introduction

The design for structures based on rock mass like dam, bridge and nuclear power plant require a comprehensive understanding of the strength and deformation behaviors of the rock masses involved in constructions. In a rock mass, besides the intact rocks, discontinuities play an important role in the mechanical behavior of the rock mass. The in-situ tests have been widely used to directly assess the strength and deformability of the rock mass in concern, along with which, various numerical approaches were proposed to give rational interpretations to the mechanical phenomenon happening during these tests. Many methods have been proposed to account for the crack initiation and growth in rocks under various loading conditions, involving various approaches such as fracture mechanics and micro-cracking (e.g. [1]-[3]). Comparing to other methods, the discrete element method (DEM) represents the rock mass as an assemblage of discrete blocks and the discontinuities as interfaces between blocks, which can realistically model the mechanical behaviors and geometrical properties of discontinuities in a rock mass. The normal discrete element method, however, cannot effectively represent the cracking phenomenon that commonly happens in rock structure constructions, due mainly to the numerical difficulty of setting cracking paths in intact rocks or setting appropriate bonding among meshes/particles. In this study, a new numerical approach capable of simulating crack initiation and propagation was developed based on DEM for the simulations of cracking phenomenon happening during in-situ compression tests on fractured rocks. The failure mechanism and strength of the rock samples were evaluated through test and simulation results.

2. Development of Expanded Distinct Element Method (EDEM)

2.1 Definition of Potential Cracks in Rock Mass. In this study, special treatment in terms of defining the potential cracks in a form of hexagon, which could change to real cracks when satisfying the failure criterions, was applied to the DEM model to accomplish the function of crack initiation [4]. If the size of hexagon is sufficiently small, the model changes to the form similar to that usually adopted in SPH or PFC. By doing so, the direction of cracking is nearly arbitrary, which could help produce realistic cracking paths. The spacing of potential cracks or the size of hexagon applied in the model need to synthetically consider the size of the simulation object and the density of the preexisting discontinuities as well as the computation time in EDEM. A number of simulations by comparing the mechanical behaviors of the models with or without the potential cracks were carried out, with differing mechanical properties of potential cracks. By doing so, the mechanical properties of potential cracks have been carefully chosen to ensure the models with the potential cracks perform reasonable close behavior with the actual rock blocks without potential cracks.

2.2 Failure Criterions for the Potential Cracks. Two failure criterions are adopted according to the principal stresses acting on each potential crack to define the failure modes. Criterions for shear failure f_s and tension failure f_t can be expressed as Eqs. (1) and (2), respectively.

$$f_s = (1.0 - \sin\phi)\sigma_1 - (1.0 + \sin\phi)\sigma_3 - 2.0c\cos\phi = 0\,. \tag{1}$$

$$f_t = \sigma_t - \sigma_3 = 0\,. \tag{2}$$

where c is the cohesion, ϕ is the friction angle of intact rock. σ_t is the tension strength of intact rock. Herein, σ_1 is major, σ_3 is minor principal stresses and compressive stresses are negative. The mechanical properties of the potential cracks satisfying either one of the failure criterions are reduced to that of the preexisting fractures automatically during simulation so that new cracks could subsequently perform the same mechanical behaviors with the preexisting fractures.

2.3 Judgment Procedure of the Crack Generation. The judgment of crack initiation and propagation in the EDEM can be carried out at each calculation step or every *n* steps depending on the limitation of computation time and the required representing accuracy of the cracking process. The process of judgment mainly comprises the following three steps: (a) defining the potential cracks in the intact blocks by generating hexagons; (b) Estimating the stress tensors around the calculation points on each potential crack and judging the propagation direction and magnitude of new cracks by employing the shear and tension failure criterions; (c) Updating the mechanical properties of the newly generated cracks.

3. Simulation of In-situ Triaxial Compression Test

3.1 In-situ Triaxial Compression Test. The rock mass in concern is the construction site for a nuclear power plant located in the western Japan. The ground is covered by cretaceous period sandstone with moderately weathering. The rock sample used in test is 38cm in diameter and 100cm in height with a number of preexisting fractures (see Fig. 1). The loading rate is 50kPa/min and the lateral stress is 0.2MPa in the in-situ test on this rock sample. Another test with lateral stress of 0.55MPa was also carried out on a similar sample. The peak stress is around 1.5MPa for the lateral

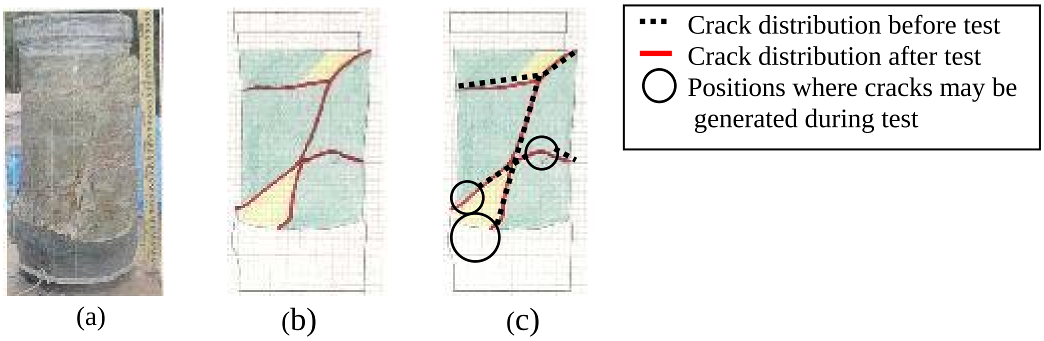

Fig.1 (a) Photo of rock sample, (b) sketch of the main cracks along which failure happens during test, (c) crack distribution before and after test.

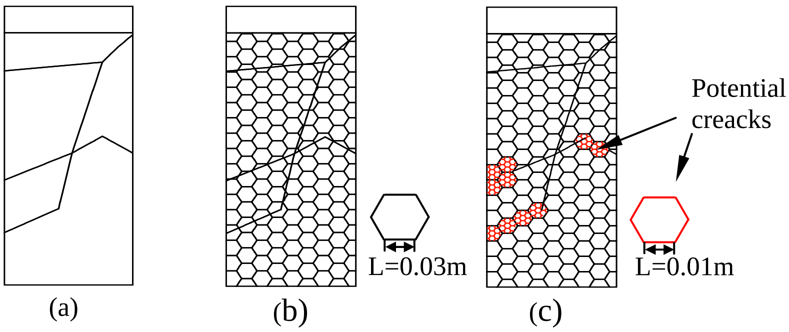

Fig.2 Numerical models for the simulations of triaxial compression test. (a) Basic model based on the crack distribution after test, (b) model considers the micro-cracks existing in the intact part of rock sample, (c) model considers the cracking process by setting potential cracks.

stress of 0.2MPa at a strain of 1.3%. The test results will be demonstrated later together with simulation results.

3.2 Numerical Models. A main fracture plane exists in the sample with a dip angle of 75°, and two other fracture planes with small dip angles (less than 30°) intersect this fracture plane at different positions (Fig. 1). This distribution of rock fractures was extracted from the sketch of sample surface after tests. Therefore, a portion of these fractures can be new cracks generated during the test and they should be treated as potential cracks in the numerical model. These potential cracks are identified by comparing the sketches of the periphery wall and the sample surface after test (see Fig. 1 (c)). Based on this sketch, a few numerical models were constructed with or without considering the cracking as demonstrated in Fig. 2. Model (a) is a basic model using the crack distributions after test and no cracking process is taken into account. The existence of a number of small and thin cracks (smeared cracks) was conformed in the intact part of rock sample with random orientations but with average spacing around 0.03m. To account for their effects to the mechanical behavior of the rock sample, hexagonal rock blocks were generated in the model (b), since the cracks in such a model can in some content represent the random distribution characteristics of the preexisting cracks. Finally, cracking process was considered in model (c) according to the possible positions of cracking as shown in Fig. 2 (c). Totally 6 cases were numerically studied based on these 3 models, among which, case 1 and case 2 correspond to model (a) and model (b) with lateral stress of 0.2MPa, respectively. Case 3 to case 6 correspond to the lateral stresses of 0.2MPa, 0.55MPa, 0MPa and 1.0MPa, respectively based on model (c).

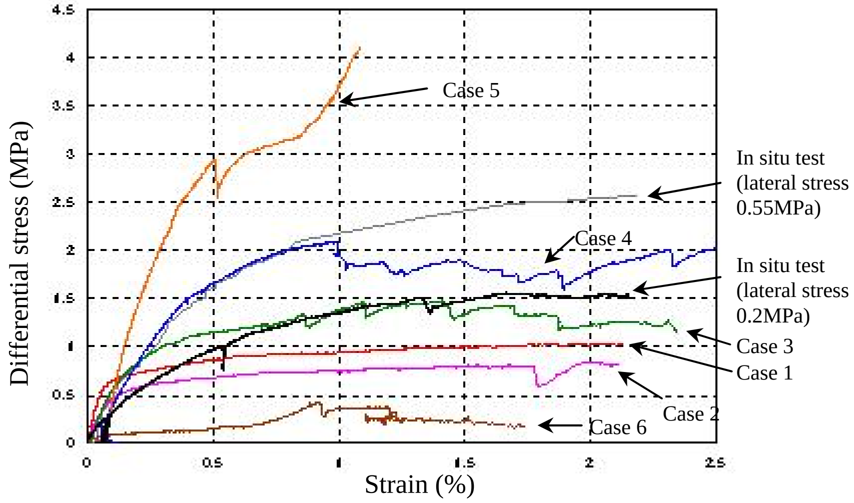

Fig. 3 Comparisons of the differential stress-axial strain curves obtained from tests and simulations.

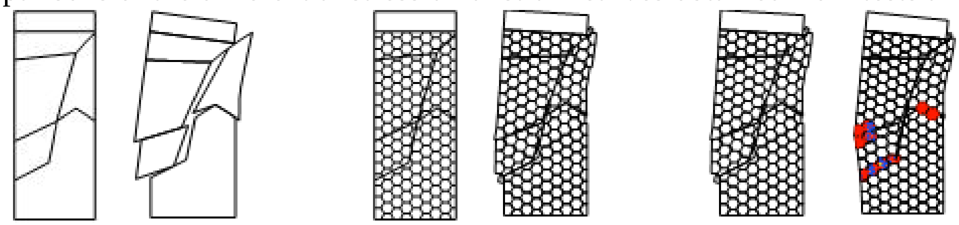

Fig. 4 The forms of different models before (left) and after (right) failure. (a), (b), (c) correspond to cases 1, 2, 3, respectively.

3.3 Test and Simulation Results. The comparisons of the test and simulation results are shown in Fig. 3. In case 1, in the elastic stage of loading, the elastic modulus of simulation is quite larger than the sample behaved in tests. In this model, the stress-strain curve is very smooth, indicating that the deformation happened in the simulation is merely the slips on the preexisting fractures and therefore no obvious peak stress can be observed (Fig. 4 (a)). In case 2, by introducing the small cracks (hexagons) to the intact parts of model (a), the elastic modulus of simulation as well as the differential stress fit better to the test results. Best fit with the test results can be found in case 3, by synthetically considering the preexisting fractures and small cracks as well as the new crack generation at 3 individual positions. As load increases, the closure of preexisting cracks takes place, which reflects the consolidation of pores and micro-cracks in the intact blocks in a compression test. As the new cracks start to initiate approaching the peak stress, failure happens in the areas where failure criterions have been satisfied and slips on main fractures take place (Fig. 4 (c)). In the residual stage, failure zones extend to larger areas accompanied with continuous slip on main fractures. The opening and slips among hexagons also take place especially in the residual stage as can be seen in Figs. 4 (b) and (c), forming a few damaged zones, the positions of which were confirmed identical to that happened on the rock sample after tests. The parameters c and ϕ obtained from test and simulations are 0.16, 36.2° and 0.118, 39.6°, respectively, showing good agreements. Since test conditions such as confining stress of 1.0MPa are difficult to apply in the in-situ tests but can be evaluated by numerical simulations, the proposed numerical simulation approach can be an alternative to help obtain the material properties of rock with preexisting cracks.

Summary

In this study, an expanded DEM approach was used for the simulation of in-situ compression tests on fractured rock. Comparing to conventional DEM program, the proposed approach can simulate the cracking process happening in intact rock, thus can help gain better simulations to the failure phenomenon of rock where micro-cracking plays an important role. The cracking patterns and the stress-axial strain curves of triaxial compression tests obtained from simulations fit well with the test results, showing the possibility of using this numerical approach to assess the failure behavior and strength of fractured rocks, especially in the fields where in-situ test data are insufficient.

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