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Expanded distinct element model for stability analysis of deep underground opening in jointed rock masses

Extension du modèle d'éléments distincts à l'analyse de la stabilité des ouvrages souterrains profonds dans un massif fracturé

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ABSTRACT: A numerical approach for simulation of generation and progress of new cracks due to shear and tension failure in the matrix blocks of jointed rock masses is proposed by using distinct element method (DEM). As the application of the proposed approach, changing the depth of opening and geometrical distribution of the existing discontinuities carries out excavation simulations of deep underground opening in the jointed rock masses. Furthermore, the effects of cable bolts on controlling deformational behaviour of opening and movements of key blocks are also discussed.

RÉSUMÉ: Une approche numérique utilisant la méthode des éléments distincts (DEM) est proposée pour étudier la rupture au cisaillement et à la traction d'un massif rocheux fracturé. Cette méthode est utilisée pour simuler l'excavation dans un massif fracturé dont la profondeur et la loi de distribution géométrique des discontinuités varient. Par ailleurs, les effets du boulonnage sur le contrôle des déformations et du mouvement des blocs clefs sont analysés.

1 INTRODUCTION

A rock mass of a site is not continuum and its mechanical behaviour is strongly affected by the behaviour of the existing discontinuities, such as bedding, joints, faults and fractures. Several experimental and numerical investigations have demonstrated the influence of discontinuities on mechanical, thermal and hydraulic behaviour of jointed rock masses. It has also been indicated based on the experimental and *in-situ* investigations that deformational mechanism and stability of rock structures in the discontinuous rock masses extremely depend on not only the existing discontinuities but also new cracks, which are generated and progress due to loading and/or excavation.

For modeling the shear behaviour of the existing rock joints under both conditions of the constant normal loading (CNL) and the constant normal stiffness (CNS), Jiang et al (1999 and 2001) presented a new constitutive formulation based on the results of laboratory shear tests of the natural and artificial rock joints by using the newly developed shear test apparatus and set up it in the numerical program of the distinct element method (DEM).

This study is to develop an expanded distinct element method (EDEM) for simulation of generation and progress of new cracks due to shear and tension failure in the matrix blocks. The proposed method is a powerful discontinuum modeling tool for simulating the behaviour of jointed rock masses subjected to quasi-static or dynamic conditions. As the applications, changing the depth of opening and geometrical distributions of the existing discontinuities carries out excavation simulations of deep underground opening. For the verification of the proposed approach, scale model experiments by using the base friction experiment apparatus are also carried out. Finally, effects of cable bolts on controlling deformations of the rock masses surrounding opening and movements of key blocks are discussed.

2 MODELING GENERATION AND PROGRESS OF NEW CRACKS BY USING DEM

The rock masses in DEM are regarded as an assembly of deformable blocks interacting through discontinuities, and the discontinuities are regarded as boundary interactions between blocks. Large displacements and rotations are permitted based on the use of an explicit time step algorithm. Due to redistribution

and concentration of stresses in the nearby region to underground opening, shear failure or tension failure in the deformational matrix are caused easily. The principles and procedure for modeling the generation and progress of new cracks are presented below.

2.1 Setting Potential Joints in Matrix

Based on the elasto-plastic calculation with a continuum numerical approach before carrying out the discontinuum simulation, directions of principle stresses and extent of plastic regions can be indicated. Next step is to set the initial potential planes that have the same mechanical properties (i.e. strength and stiffness) with the intact rock (Jiang, 2000). Generation location and progress direction, distribution frequency of the potential planes in the deformational blocks are defined carefully according to the distribution directions of the principle stresses in each element of the DEM model. In the shear failure zone, the application of slip angle, $45^\circ + \phi/2$, as the direction of generation of new cracks is thought to be appropriate. The potential joints show the same behavior with the surrounding intact rock before satisfied the failure criterions, and its properties are reduced automatically to the values of the existing discontinuities when the stresses acting on a potential plane reached at the limitation of shear strength or tension strength.

2.2 Failure Criterions for the Potential Cracks

In order to define the failure modes for each potential plane, two failure criterions are applied based on the calculations of principle stresses acted on each potential plane. Criterion functions for shear failure and tension failure can be expressed as equations (1) and (2).

$$f_s = (1.0 - \sin \phi) \sigma_1 - (1.0 + \sin \phi) \sigma_3 - 2.0C \cos \phi \quad (1)$$

$$f_t = \sigma_1 - \sigma_3 \quad (2)$$

here C is the cohesion force, ϕ is the friction angle of intact rock. σ_1 means the tension strength of intact rock.

Principle stresses on a potential plane can be evaluated by using the Airy stress function. Judgment of generation and prog-

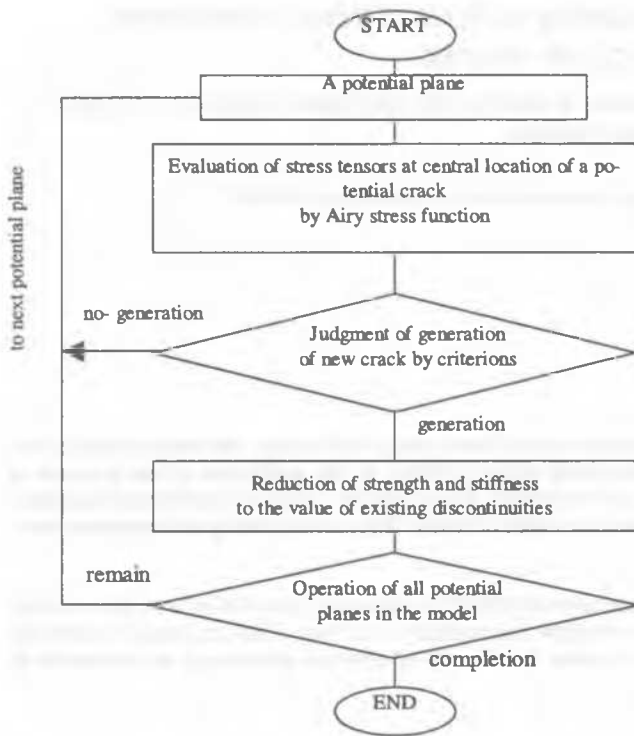


Figure 1. Judgment procedure of generation of new cracks.

ress of new cracks in DEM model are carried out based on two failure criterions for each calculation cycle. Judgment process is executed only for the prior defined potential planes and is finished when all of the potential cracks have been evaluated. The mechanical properties (i.e. strength and stiffness) of the potential planes satisfied one of both failure conditions are decreased as ones of the existing joints automatically so as to that the potential plane shows the same deformational behavior with the existing joints.

2.3 Judgment procedure of generation of new cracks

As shown in Figure 1, generation simulation involved progress direction and distribution frequency of new cracks due to loading and/or excavation can be realized in three steps:

- (a) objective definition of the potential planes in deformational blocks according to the distribution features of principle stresses in jointed rock masses, and estimation of stress tensor at the central location of each potential plane;
- (b) judgment of generation and progress direction of new cracks by shear and tension failure criterions;
- (c) update of behaviors of the existing discontinuities and new cracks.

3 VERIFICATION BY MODEL EXPERIMENTS OF UNDERGROUND OPENING EXCAVATION

In order to verify the proposed method and judgment procedure presented above, the model experiments of underground excavation at depth are carried out by using the base friction model equipment. The model material is the mixture of sand, gypsum, lime and water. The mixture is poured into form at 30° C for one day and cured at 80° C for two days to keep off contraction of the mixture. 20mm wide 25mm thick long beam members are set on the base plate and formed an inclined and stratified rock mass model with a joint spacing of 20mm.

The frictional resistance on the bedding surfaces is measured in the plane shear test, and the mechanical properties of the intact model material are investigated by using laboratory tests. In

Table 1. Properties of intact rock.

Properties	Model	Object rock
Young's modulus(MPa)	415.5	7421
Poisson's ratios	0.136	0.136
Density(g/m ³)	1.505	2.5
Cohesion(MPa)	0.143	2.555
Friction(deg.)	34	34
Tension strength(MPa)	0.054	0.974

Table 2. Properties of the rock joint.

Properties	Model	Rock joint
Shear stiffness (MPa/m)	80.74	1442.1
Cohesion(MPa)	0	0
Friction angle(deg.)	31.2	31.2



Figure 2. Experimental result.

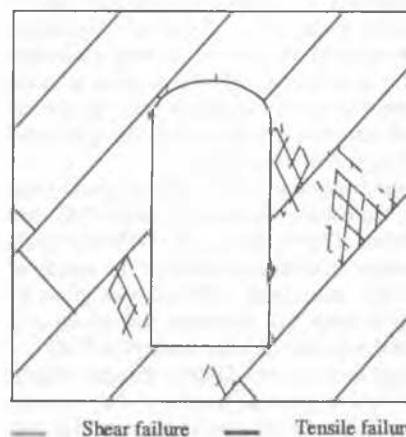


Figure 3. Simulation of generation of new cracks.

experiments, the geometry scale and stress scale of model are assumed as 400 and 17.86, respectively, so as the properties of intact rock and rock joints are calculated as in Tables 1 and 2.

Comparisons of model experiment and generation simulation of new cracks using EDEM are described in Figures 2 and 3. The 'x' mark on the model shows the generated new cracks due to shear failure or tension failure. In the geometrical distribution of joints as shown in Figures 2 and 3, the tension failure zones occurred on the middle wall of the right side and the left-bottom corner of the opening, and displacement of opening also shows a local behavior feature. Propagation simulations of new cracks had a good agreement with the model experiments about the position and direction of the new cracks.

4 APPLICATION TO DEEP UNDERGROUND OPENING EXCAVATION

4.1 General

Excavation simulation of a deep underground opening in the discontinuous rock masses is taken as the example problem by using the EDEM in which the proposed formulation of the existing joints and the judgment procedure for development of the new cracks have been built into the constitutive relation of a joint. The center of opening is 158m depths from the ground surface, height of opening is 50m and width is 25m. Figure 4 shows the bench excavation steps. After the initial *in-situ* stress state is reproduced based on the depth and the coefficient of lateral pressure, K_0 , bench excavation from arch part of opening without supports is carried out for investigating development of the key blocks in the surrounding rock masses of opening due to generation of new cracks. The intact rock is modeled as the elasto-plastic body.

4.2 Comparison and discussions

It can be considered from Figure 4 that there are no separated key blocks to move to the opening in the initial distribution condition of the joints. General continuum or discontinuum analyses will present the same results. Applying the EDEM proposed in this paper, however, will give the different answer for stability assessment and support design of opening.

Figure 5 shows the generation and development of the new cracks near the opening wall with the bench excavation process. The height of a bench excavation is 3m. When excavated the 9th bench, several key blocks that cavern into the space of the opening are caused newly due to shear and tension failures. The separated blocks needed to be supported by steel ribs, lining or bolts while the whole loading and the suitable setting locations of supports can be evaluated according to the size and movement direction of the new key blocks.

Changing the depth of opening and geometrical distributions of the existing discontinuities, involved length and inclination angle, spacing, gap, clarified the deformational behaviour and stability of opening. It has been cleared that sizes and movements of new blocks are increased with increasing the depth of opening (Figure 6).

The supporting effects of rock bolt and cable bolt on controlling the occurrence and progress of new cracks are also investigated by using the same model and boundary conditions. The mechanical properties of bolts, such as bonding strength, normal stiffness and shear stiffness between bolt and grout material, are defined based on the previous references. Two bolting patterns with the different length and spacing on the opening wall are considered to investigate the effects so as to design the rational support system. Pattern ① has 5m length and 1.5m space on the wall and the length of cable bolts in pattern ② is 20m. Comparing with the case of no supports in opening (Figure 5), propagation of new cracks and movements of key blocks are effectively controlled by using rock bolts or cable bolts. The movements of the generated blocks, however, at the upper part of the right wall couldn't be restrained perfectly by rock bolts because the length of bolts is too short. Cable bolts presented the valuable effects on stabilizing the opening (Figures 8 and 9).

The key block theory and the DEM have been considering as the useful tools for lining design, selection of support type and stability assessment of underground opening excavated in the discontinuous rock masses. Based on the above discussions, it can be recognized that these methods give an inappropriate answer occasionally if the mechanical behavior of the existing rock joints and the new crack generation have not been defined faithfully based on the shear test and the site investigation. The numerical approach proposed in this paper given a new idea for improving the reliability and suitability of DEM.

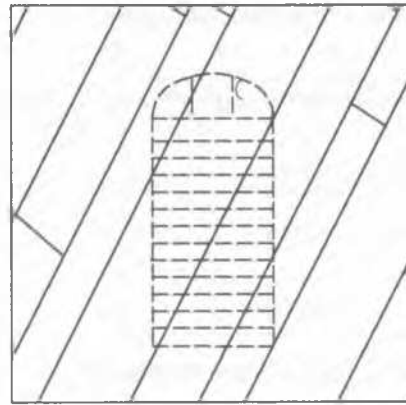
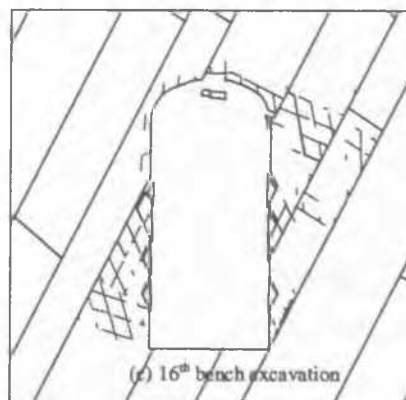
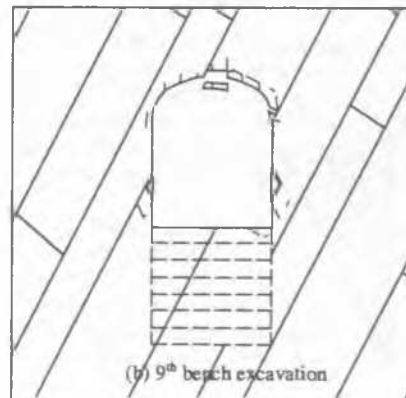
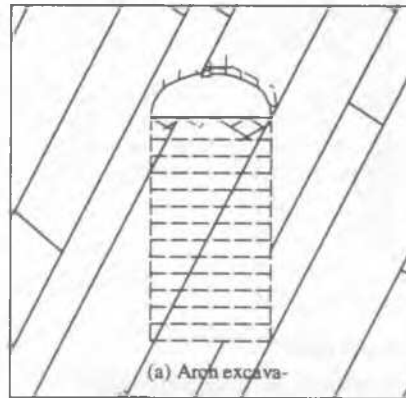


Figure 4. Simulation model of deep underground opening.



— Shear failure — Tensile failure

Figure 5. Generation of new cracks in bench excavation (H=158m).

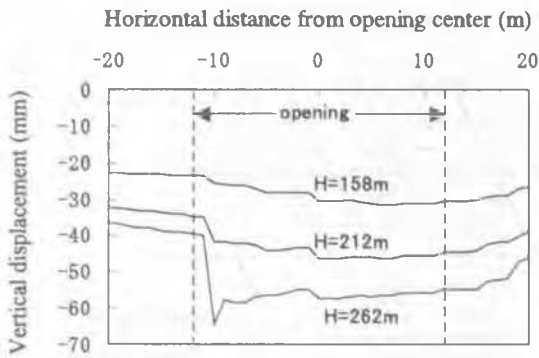
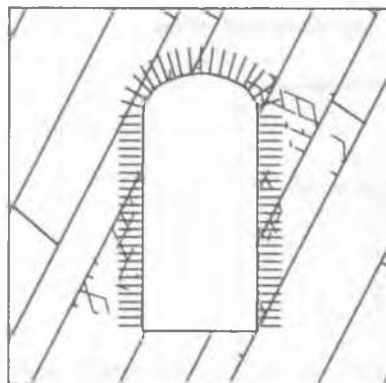
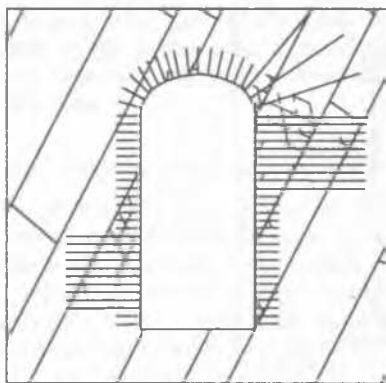


Figure 6. Vertical displacement at top of opening by changing depth.



— Shear failure — Tensile failure

Figure 7. Controlling effect of rock bolts on deformational behaviour and generation of key blocks(bolting pattern ①).



— Shear failure — Tensile failure

Figure 8. Controlling effect of rock bolts on deformational behaviour and generation of key blocks(bolting pattern ②).

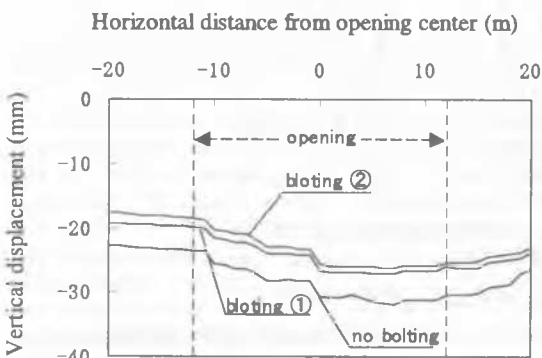


Figure 9. Vertical displacement at top of opening by changing bolting pattern.

5 CONCLUSIONS

A numerical approach for the simulation of generation and progress of new cracks due to shear and tension failure in the matrix blocks of jointed rock masses is proposed in this study by using the distinct element method (DEM). Generation location and progress direction, distribution frequency of the new cracks in the deformational blocks can be defined according to the distribution directions of the principle stresses in each element of the DEM model.

For the verification of the proposed methods, model experiments by using the base friction model equipment are also carried out on a deep and large opening in the stratified rock masses, and a good agreement has been obtained. As the applications of the proposed approach, changing the depth of opening and geometrical distribution of the existing discontinuities carried out bench excavation simulations of a deep underground opening in the jointed rock masses. Furthermore, the effects of cable bolts on controlling deformational behaviour and movements of key blocks are also discussed.

It was clarified based on the comparisons of the scale model experiments and the simulations using the EDEM that the proposed approach given a new idea for improving the reliability and suitability of DEM.

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