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Some modifications to the process of discontinuous deformation analysis

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ABSTRACT

This paper presents a modified method of discontinuous deformation analysis (DDA). In the presented method, open-close iteration may not be needed, small penetration is permitted among blocks, and springs are added between contacting block pairs only when a penetration takes place. The three contact patterns (i.e. sliding, locking and opening) in original DDA method are not involved, and the recognition of these contact patterns and treatment of transformation among patterns are not required either, significantly saving the computing time. In a convex to concave contact, there are two candidate entrance edges which may cause uncertainty. In this case, we propose the angle bisector criterion to determine the entrance edge. The spring stiffness is much larger than Young's modulus in the original DDA, however we find that the correct results can still be obtained when it is much smaller than Young's modulus. Finally, the penetrations by using penalty method and augmented Lagrangian method are compared. Penetration of the latter is 1/4 of the former. The range of spring stiffness for the latter is wider than the former, being 0.01–1 of the former. Both methods can lead to correct contact forces.

1. Introduction

Discontinuous deformation analysis (DDA) pioneered by Shi (1988) is a numerical method which is parallel to continuum-based analysis methods, such as finite element method (FEM), boundary element method (BEM). It has been the research focus in investigating the kinematics of blocky rock masses since its establishment in 1988. During the past two decades, great achievements have been made on DDA developments, and many efforts have been carried out to validate and improve its performance (MacLaughlin and Doolin, 2006). Among them, the drawback of block expanding due to rigid body rotation has been overcome (Ke, 1995; MacLaughlin and Sitar, 1996; Cheng and Zhang, 2000); higher order displacement function was proposed to consider the variable strain of blocks (Koo et al., 1995; Hsiung, 2001; Wang et al., 2007); contacts between blocks have been modeled by using an augmented Lagrangian method (ALM) instead of the penalty method originally proposed by Shi (Lin et al., 1996; Ning et al., 2009); an alternative scheme for the corner–corner contact was suggested (Bao and Zhao, 2010, 2012); and significant developments have been achieved in the research of three-dimensional (3D) DDA (Yeung et al., 2007; Beyabanaki et al., 2008, 2009; Keneti et al., 2008; Liu et al., 2009; Wu, 2010).

The open-close iteration is an important step and also a difficulty in DDA. The original DDA method conducts 5 iterations at each time step, which means that the global equations will be solved for 5 times within one time step. So the computation workload is much heavy. Moreover, there is few reports illustrating the detailed process of open-close iteration.

Bao and Zhao (2010) showed that the contact reference edges in the corner–corner contact are not unique, and it may lead to an indeterminate state in the numerical analysis. In this case, the original DDA method cannot correctly simulate the process of block movement. The approach proposed by Bao and Zhao (2010, 2012) to deal with this issue is to add a spring between the moving corner and target corner, then to remove the spring after the first open-close iteration.

In the original DDA method, the contact situations are classified into three patterns, i.e. opening, sliding and locking, and relevant operations are needed for the transformation among the patterns. Moreover, the penalty number is always much greater than the Young's modulus.

A modified method of DDA is proposed in this study. It can improve the classic DDA in the following aspects: (i) open-close iteration could be omitted and correct results can still be achieved, meaning that the computing speed can be improved; (ii)

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indetermination in corner–corner contact is solved with a simplified approach; (iii) there is no need to distinguish the three contact patterns and the transformations among them, therefore such modified method can be much simplified and computation can be speeded up; and (iv) stiffness in penalty method and ALM can be less than the Young's modulus while correct contact force can still be obtained.

2. Modification to DDA simulation process

In the original DDA method, the formulae of the complete first order approximation are adopted to calculate block displacements (u, v) at any point (x, y). When the rotation angle accumulates, block volume will expand. To solve this problem, precise formulae of the displacement for rotation should be adopted. Followed by Ke (1995), the rotation angle is replaced with the sine of rotation angle in the displacement variables of block i. Accordingly, the displacement matrix T_i is changed, and the stiffness and force terms in the global equations due to line load and inertia force should take the modified forms. Detailed information can be found in Ke (1995).

Blocks are not allowed to penetrate each other in the original DDA theory. Therefore, normal and shear springs are added in block system. This process is called penalty method. To ensure no penetration and no tensile force existing among blocks, open-close iteration must be carried out within every time step. However, the penetration among blocks could not be zero no matter how high the stiffness of spring is. In fact, the contact forces between two adjacent blocks are provided by springs in penalty method. If the contact forces are not zero, the penetration could not be zero either. So, if small penetrations are permitted to exist among blocks, no open-close iteration is needed in DDA simulation.

In the original DDA process, contact patterns between adjacent blocks, such as opening, sliding and locking, should be recognized and recorded at each time step so that springs can be added to or removed from these blocks. In the modified method, contact detection among block system is performed at every time step, so the recognition of contact patterns will not be necessary. This will make the DDA process simpler and time-saving.

The modified DDA process can be summarized as the following steps:

(1) Input block geometry data, including each vertex's sequence number and coordinate, each block's sequence number, and then draw the graphics of blocks.
(2) Input physico-mechanical properties, such as Young's modulus, Poisson's ratio, density, friction angle, cohesion of joint material, and initial velocity.
(3) Input parameters for computing control, including length of time step, total simulation time, maximum displacement in one step, critical distance for separating vertex–vertex (V–V) contact and vertex-edge (V–E) contact, stiffness of normal and tangential springs.
(4) Set coefficient matrix $\boldsymbol{K}$ and matrix of free terms $\boldsymbol{F}$ in global equation to zero.
(5) Treat the fixed displacements in block system (generally zero, i.e. fixed points).
(6) Add body force-induced sub-matrices to global equations.
(7) Add elastic sub-matrices to global equations.
(8) Add inertia force-induced sub-matrices to global equations.
(9) Add other sub-matrices.
(10) Detect contacts among block system, and find the invading vertices and entrance edges. Only add normal and tangential springs or friction sub-matrices to global equations while invading takes place.
(11) Solve the global equations $\boldsymbol{K}D=\boldsymbol{F}$, where D is the block displacement.
(12) Calculate the displacement of vertices according to block displacement D.
(13) Update block coordinates, and draw blocks' geometry.
(14) Accumulate the time of simulation.
(15) Reduce the time interval for next time step if the maximum displacement in current time step is reached.
(16) Go to step 4 if the accumulated time is less than total simulation time.
(17) The end of program.

Block initial coordinates can be acquired by the following way: number all the vertices in the block system, and save all the coordinates of the vertices in a matrix; then input each block's sequence number in counter-clockwise; in the end, find out each block's vertex coordinates.

Fig. 1 shows an example without iteration, in which a block is sliding from rest along an incline. The block and incline are two right-angled isosceles triangles with edge lengths being 3 m and 10 m, respectively. Two vertices at the bottom of incline are fixed. The material properties for both blocks are as follows: Young's modulus $E = 50$ GPa, Poisson's ratio $\nu = 0.2$, mass density for unit thickness $M = 2.7 \times 10^3$ kg/m^2, acceleration of gravity $g = 9.8$ m/s^2. Simulation parameters are as follows: time interval $d_t = 0.001$ s, spring stiffness (penalty number) $p = 1$ GPa (note $p < E$), total time for simulation $totaltime = 1$ s, maximum displacement in a time step $step\_limit = 0.01$ m, the critical distance for separating V–V contact and V–E contact $critdis = 0.005$ m.

When the friction angle ϕ is less than 45°, the analytical solutions of displacements u and v in x and y directions are as follows:

$$u = v = -\frac{1}{2}g(\sin45^\circ - \cos45^\circ \tan\phi)t^2 \cos45^\circ \quad (1)$$

where t is the sliding time.

Displacements u and v of point A in sliding block for $\phi = 0°–45°$ and $t = 1$ s are calculated and compared with analytical solutions, as shown in Table 1. It can be seen that the relative error is 0.06%–0.66%.

3. Open-close iteration and contact stiffness determination

In some condition, open-close iterations may be needed. In that case, a loop from step 10 to step 12 described in Section 2 is

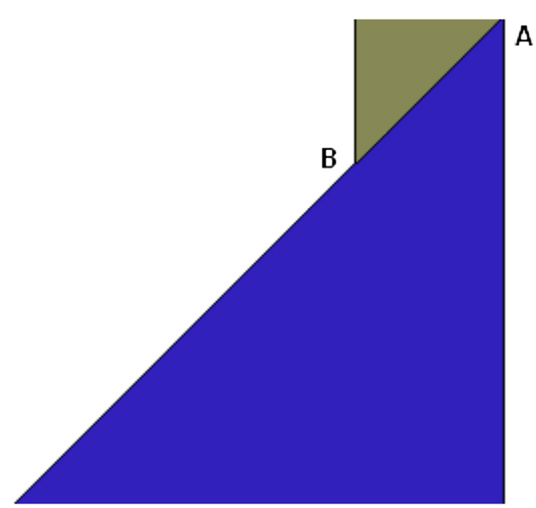

Fig. 1. Single block on an incline.