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Modified contact model with rock joint constitutive in numerical manifold method

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ABSTRACT

In the classical numerical manifold method (NMM), contact conditions are enforced by applying or releasing contact springs repeatedly. Penalty spring stiffness is constant during the calculation process. In this study, a modified contact model describing joint mechanical behavior is proposed using the NMM. Two rock joint constitutive models, namely the BB model and hyperbolic model, are used to modify normal and shear stiffness, respectively. In the modified contact model, stiffness varies with normal and shear inter-penetration distance in each iteration step. Therefore, stiffness varies for different contact points. With increasing inter-penetration distance, the normal stiffness increases and shear stiffness decreases. As a result, the force needed for trigger sliding along the joint increased. Finally, three example simulations are conducted to validate the effectiveness of the modified contact model.

1. Introduction

The numerical manifold method (NMM) is a combination of the finite element method (FEM) and discontinuous deformation analysis (DDA) [1]. The NMM inherits the block movement and contact modeling from DDA and can solve both continuous and discontinuous problems in a unified framework. The most attractive feature of this method is its two independent cover systems, namely mathematical and physical cover, which allows the NMM to analyze discontinuous problems in a simple way.

In recent years, great advances have been made in the study and application of the NMM. For example, Chiou et al. [2,3] predicted mixed mode joint propagation using the manifold method. Zhang et al. [4] modeled fracture propagation problems containing multiple or branched joints using the NMM. Wu and Wong [5] investigated the effects of friction and cohesion on fracture growth from a closed flaw under compression using the NMM. Yang et al. [6] proposed a cover refinement method for the NMM to simulate fracture propagation in brittle materials, and Ning et al. [7] proposed a fracturing algorithm based on the Mohr–Coulomb criterion with a tensile cutoff that is included in the NMM code. Other types of joint problems have been solved successfully using the NMM [8–13]. The NMM has also been applied in rock dynamics [14,15], wave propagation through rock masses [16], rock stability and failure processes [17], rock creep [18], seepage problems [19–21], thermal-mechanics [22–24], combined with other methods [25,26], and others [27–31].

The calculation process of NMM includes three parts: generating and updating cover systems; searching contact pairs and calculating the element matrix; establishing and solving the global equilibrium equations. The contact model is essential for NMM calculation and simulation. The contact theory of NMM is inherited from the DDA method, and contact conditions are enforced by contact judgment during the open–close iteration (which indicates that equilibrium equation is solved repeatedly by applying or releasing contact springs). The original NMM repeatedly applies and removes the stiff springs between contact pairs to describe joint mechanical behavior. Present literature about contact theory can be divided into two groups. One group is the study of the present penalty method. Doolin et al. [32,33] indicate that calculation results can satisfy the accuracy requirement with a suitable stiffness. Wu et al. [34] studied the suitable range of step time and contact spring stiffness in DDA, determined the optimal spring stiffness for different time steps, and found that reasonable time step and spring stiffness can form a simply connected region. Jiang and Yeung [35] proposed a point-to-face contact model for three-dimensional DDA to identify contact types between two polyhedron-based blocks. Wang et al. [36] proposed a simple contact calculation approach for spherical discontinuous deformation analysis. The other group is new contact method. For example, instead of a penalty spring, Jiao et al. [37] presented a new two-dimensional contact constitutive model, which consists of a two-phase force-displacement and the Mohr–Coulomb criterion in the normal and shear direction, respectively, to simulate the fragmentation of jointed rock. To avoid artificial parameters and the open–close iteration, Zheng et al. [38,39] proposed a new method named mixed linear complementary theory into the DDA contact algorithm. Xu et al. [40] introduced the Munjiza method into NMM contact theory. Liu et al. [41] proposed

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a new NMM contact search algorithm with double-ended spatial sorting and improve contact detection efficiency.

From the above literatures, it can be found that the second group research proposed a series of new approaches for solving the contact problem in the origin NMM but it need be validated further. The first group researches focus on selection of contact parameters, including spring stiffness and time step. In this case, they just discussed which spring stiffness can acquire higher accuracy but the stiffness still keeps constant. In practice, using the same spring stiffness in different joints or rock mass is totally unreasonable and may cause an opposite results. This study is based on present NMM contact theory. Considering the importance of spring stiffness and the limitation of constant stiffness contact models in the original NMM, joint constitutive models are used to modify penalty spring stiffness of to obtaining more reasonable and accurate model predictions.

2. Basic theories

2.1. Fundamentals of NMM

The most innovative feature of the NMM is the adoption of two cover systems, namely mathematical cover (MC) and physical cover (PC), from which the manifold element (ME) is generated. The MCs are a set of overlapped small patches. The shape of the MC patches is arbitrary. MC patches should be large enough to cover the problem domain. The PC is the union of all the PC patches, which are the intersection of MC patches and the problem domain. The problem domain is dependent on the specific problem, thus, PCs are a subdivision of MCs in the problem domain. Then, the ME is generated from the common region of several overlapped PC patches. In the NMM, the interpolation grid and weight function are defined by the MC and integral area is defined by the MEs. The hexagon *MC(4)* is split by an internal discontinuity into two isolated pieces, and both are within the problem domain, thus it forms two PCs, which are *PC(4,1)* and *PC(4,2)* (Fig. 1(a)). A ME is the common area of several PCs, as shown in Fig. 1(b), *PC(4), PC(7),* and *PC(8),* form the *ME (4, 7, 8)*, which is marked by the shaded triangle.

When the problem domain includes discontinuities, as shown in Fig. 2, there is a crack *AB* in the problem domain. The MCs are *MC(4), MC(7)*, and *MC(8)* as shown in Fig. 2(b). The PCs are defined from the formed MCs and physical boundaries. For example, *MC(4)* is intersected by the fracture boundary *AB* and forms two PCs, *PC(4,1)* and *PC(4,2)*. The MEs are created by overlapped PCs. For example *ME(1)* is formed by the overlap of *PC*(4,1), *PC*(7,1), and *PC*(8,1). In this way, the discontinuities in the physical domain that fully cut MCs are captured, and the discontinuities between fracture surfaces are described.

While the cover system is generated, a local approximation function (cover function) is defined on each PC, which reflects the local characteristic of the field. This local approximation function can be a constant basis function, a linear basis function or a higher-order polynomial function. Generally, a polynomial function is a convenient way to construct a basis of local approximation spaces, which can be expressed as

$$S_C = p(x, y) = \{1, x, y, \ldots x^n, x^{n-1}y \ldots xy^{n-1}, y^n\} \quad (n = 0, 1, 2 \ldots) \tag{1}$$

Therefore, the local displacement defined on each PC patch can be expressed as

$$u_i(x) = P^T(x) \cdot d \tag{2}$$

where d is the degrees of freedom vector of the unknowns to be calculated. The parameter P^T is polynomial basis, and for 2-dimensions problems

$$P^T(x) = \begin{bmatrix} 1 & 0 & x & 0 & y & 0 & \ldots \\ 0 & 1 & 0 & x & 0 & y & \ldots \end{bmatrix}$$

For the different n values, the displacement field can be constant, linear, or represented by higher-order polynomials. A constant cover function with $n = 0$ and higher order functions with $n >= 1$ can be used to improve approximation accuracy. Subsequently, the local approximation displacement function can be connected together using a weight function to form a global displacement function for a particular ME that is approximated to be the following

$$u(x) = \sum_i T_i(x) \cdot u_i(x) \tag{3}$$

where $T_i(x)$ is the weight function for each MC patch, which satisfies the following conditions

$$\begin{cases} T_i(x) \geq 0 & \forall(x) \in M_i \\ T_i(x) = 0 & \forall(x) \notin M_i \end{cases} \tag{4}$$

with

$$\sum_{(x)\in M_i} T_i(x) = 1 \tag{5}$$

Eq. (4) indicates that the weight function is non-zero only on its corresponding MC patches. The characteristics of the weight function depend on the shape of the mathematical mesh and the order of displacement cover functions. In this paper, regular triangular meshes are adopted. As a result, weight functions are equal to the triangular finite element shape functions.

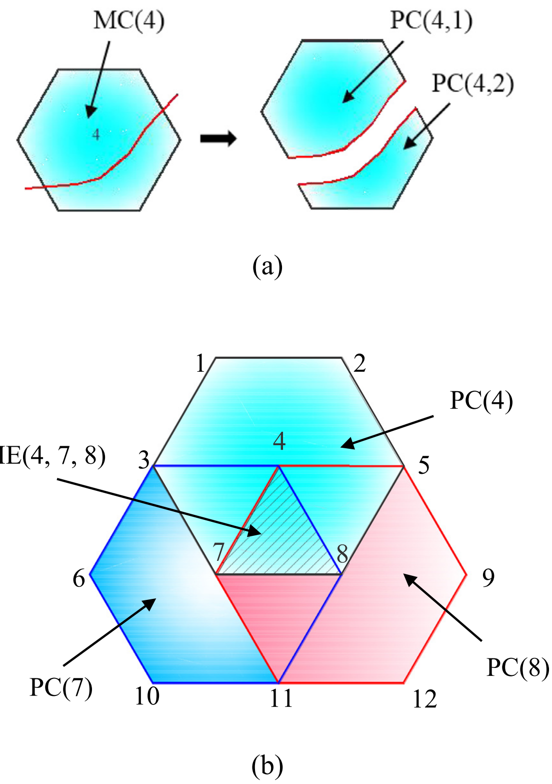

Fig. 1. Basic concept of the NMM. (a) Relationship between PC and MC, (b) Relationship between PC and ME without discontinuities.

2.2. NMM contact model

In the 2D-NMM, contact model is used to connect individual discontinuous boundaries into a system. Discontinuous displacements can be computed by finding the contacts and applying springs on contacts [42]. Potential contacts exist on MEs with different loops. As shown in Fig. 3, there are three different kinds of contacts within the NMM such as: angle to angle (AA), angle to edge (AE) and edge to edge (EE).Generally, EE