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Underground rockfall stability analysis using the numerical manifold method

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ABSTRACT

The present study applies the numerical manifold method (NMM) as a tool to investigate the rockfall hazard in underground engineering. The crack evolution technique with crack initiation and propagation criterion, which has been successfully applied to handle cracking problems in rocks, is used in this study. A rockbolt element is introduced, which is first validated by a simple case. The mechanism of the rockbolt in reinforcing a layered rock mass is then investigated through a four-layered rock beam example. The developed NMM is then used to investigate the rockfall instability caused by either natural joints or mining induced fractures in an underground power station house or a tunnel. The results illustrate that the developed NMM can not only capture the entire dynamic process of the rockfall but also locate the key-block successfully. As such, corresponding reinforcement methods can be chosen reasonably.

1. Introduction

Rockfalls pose a great hazard to underground mine workers and infrastructure. Potentially unstable rock blocks, which are defined by natural joints or mining induced fractures, are commonly found in the roof and sidewall of excavations. The instability of those blocks, referred to as keyblocks, is driven by two successive mechanisms: the detachment of a block or rock compartment (i.e. failure) and its propagation [1]. The assessment of the crack propagation and failure within the rock mass is of main significance for a rigorous rockfall hazard assessment.

In the past decades, various methods have been proposed to help practitioners analyse and assess the susceptibility to rockfall hazard [2–5]. These studies have highlighted the intensity and frequency of events as the key parameters. However, detailed accounts of the entire failure processes, especially fracture related failure, which involves the crack initiation, propagation, and coalescence, were not always available. Due to the development of the computer technology, numerical methods have become promising tools for capturing the details of the progressive fracturing.

However, most of the numerical methods used in geotechnics have an implicit representation of the discontinuities, which only consider their influences on the physical behavior, such as deformability or strength, through equivalent constitutive laws. Since the first introduction of joint elements into FEM by Goodman [6], continuum-based methods have been progressing to deal with fracture propagation problems. Based on the Partition of Unity method (PU) [7], the Extended Finite Element Method (XFEM) [8,9] is one of the most advanced achievements in this field. However, the continuous description is still deficient in handling problems including a large sliding and a large amount of fractures.

An alternative to these continuum-based methods is to use discrete-based methods (DEM) which treat the material as an assemblage of independent elements. By incorporating artificial discontinuities and corresponding constitutive failure models, both the explicit DEM UDEC [10] and implicit DEM DDA [11] were successfully used to model failures in either intact rock or jointed rock mass [12–17]. However, the cracks in these methods can only develop along the block boundaries. Therefore, crack trajectories predicted by them are not arbitrary, but depending on the block discretization configuration (mesh configuration). The Particle Flow Code (PFC) by Itasca [18,19] can model the fracturing process occurring within the rock mass without assuming where and how cracks may appear. By simply breaking the bond between two distinct elements when the interaction force overcomes its tensile or shear strength, the PFC can model the arbitrary fracturing process [20–22]. However, as mentioned by Donze et al. [23], the element size and element shape used in the model both differ from those of

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real constituent grains in rocks, which give a cross effect on the simulation results.

Although both continuum-based and discontinnum-based methods provide useful means to analyse rockfall hazard problems, modeling complex failures related to both detachment along pre-existing discontinuities and the creation of new ones through fracturing of intact rock are still challenging. Actually, the rock mass is neither continuous nor discontinuous but the integration of two, which can be better represented by hybrid methods.

The Numerical Manifold Method (NMM) [24,25], which is also based on the PU concept, is such a hybrid method. It combines the widely used continuum-based method FEM and discontinuum-based method DDA in a uniform framework. By simply cutting the mathematical cover (MC) by the discontinuity, the physical cover (PC) will be separated and the discontinuity will, for most cases, be captured without further requirement of incorporating enrichment functions. Due to its capability in dealing with continuous–discontinuous problems, NMM has been successfully extended to simulate cracking problems [26–32] and cracking involved failure problems [33–35].

This study applies the cracking evolution technique developed in our previous work [30,31,35] to analyze the stability of rock blocks in the cavern/tunnel roof based on measured properties of fractures and joints. Using the developed NMM, the entire trajectories of the falling block intersected by natural joints and mining induced fractures under the action of gravity for both cases are reproduced. The excavation procedure is conducted to simulate the effect of in-situ geostress. The breakage of the shotcrete reinforcement is simulated. The influence of the lateral confining pressure on the failure mechanism of the rockfall around the tunnel is investigated. Most importantly, a simple truss rockbolt element is incorporated to investigate the mechanism of rockbolt in mitigating the underground rockfall hazard.

2. Background of NMM

2.1. Introduction

The core and most innovative feature of the NMM is the adoption of a two cover (mesh) system, on which the nodes and elements are generated. Similar to other PUMs, the finite covering of a problem domain is also the basic construction of the NMM.

The finite cover systems employed in the NMM are referred to the mathematical cover (MC) and physical cover (PC), respectively [24]. The MC, which is used for building PCs, can be either a mesh of regular pattern or a combination of some arbitrary figures. However, the whole mesh has to be large enough to cover the whole physical domain. The physical mesh, which includes the boundary of the material, joints, cracks, blocks and interfaces of material zones, is a unique portrait of the physical domain of a problem, and defines the integration fields. The intersection of the MC and the physical mesh, or the common area of the two systems, defines the region of the PCs. A common area of these overlapped PCs or an independent PC corresponds to an element in the NMM.

Fig. 1 illustrates the basic construction procedures of the finite covering system adopted in the NMM. As illustrated in the figure, the MCs first form from the mathematical meshes, such as the rectangular MC M_1 and the circle MC M_2. From the formed MCs and the physical meshes, the PCs are then defined. For example, MC M_1 intersecting with the physical boundary Γ_u and the discontinuity boundary Γ_D forms the PCs P_1^1, P_1^2 and P_1^3, while the MC M_2 intersecting with the physical boundary Γ_u forms PCs P_2^1 and P_2^2. Finally, the NMM elements are created by overlapping these PCs, e.g. elements E_3 and E_4 form from the overlapping of PCs P_1^2 and P_2^2, P_1^3 and P_2^2, respectively. The left independent areas of PCs then form the other manifold elements, such as element E_1 from PC P_1^2, E_2 from PC P_1^3 and E_5 from PC P_2^2.

On each PC P_i, a local approximation functions $d_i(x)$ is independently defined. A convenient way for constructing a basis of local approximation spaces is by using the polynomial functions. e.g.

$$l^c = \{1, x, y, \ldots, x^p, x^{p-1}y, \ldots, xy^{p-1}, y^p\} \tag{1}$$

for a two-dimensional problem, where the superscript "c" stands for conventional PCs.

Though the polynomials can approximate smooth functions well and capture the discontinuity directly for the conventional PCs, for PCs that are not fully intersected by the discontinuities (such as PC P_2^2 in Fig. 1), the smooth basis polynomial local approximations can capture neither the high gradient at the crack tips nor the jumps across the discontinuity surfaces. Therefore, special singular functions are needed to be used to enrich the approximation space for capturing the singularities without refining the meshes. In this study, the linear elastic asymptotic crack-tip fields as proposed by Belytschko et al. [36] are used as suitable enrichment functions for the singular PCs. Then the enriched local approximation functions for singular PCs become

$$l^s = \left[d^c, \sqrt{r}\sin\frac{\theta}{2}, \sqrt{r}\cos\frac{\theta}{2}, \sqrt{r}\sin\theta\sin\frac{\theta}{2}, \sqrt{r}\sin\theta\cos\frac{\theta}{2}\right] \tag{2}$$

where r and θ denote polar coordinates in the local system at the crack tip. The superscript "s" stands for singular PCs. Such enrichment not only leads to a better accuracy on relatively coarse meshes (with term $\sqrt{r}$, the high gradient stress/strain around the crack tip can be captured), but also enables the discontinuities across the cracks that only partially cut MCs be captured (with term $\sin(\theta/2)$, the discontinuity across the discontinuity surfaces for $\theta = \pm\pi$ can be captured).

After constructing the local approximation functions, the local approximation functions can then be connected together by the weighting function (the same as PU function) to form a global displacement function for each manifold element as follows:

$$u(x,y) = \sum_{i=1}^{n} w_i(x,y)u_i(x,y) = \sum_{i}^{n} w_i(x,y)\sum_{j}^{m} l_i^j d_i^j \tag{3}$$

where $w_i(x)$ is the weighting function, which satisfies

$$w_i(x,y) \geq 0, \quad \forall (x,y) \in P_i; \quad w_i(x,y) = 0, \quad \forall (x,y) \notin P_i$$

with

$$\sum_{x \in P_i} w_i(x,y) = 1 \tag{4}$$

$u_i(x,y)$ is the displacements of PC i, which is defined as:

$$u_i = \sum_{j=1}^{m} l_i^j d_i^j \tag{5}$$

where l_i^j is the basis of the approximation displacement function of PC i, d_i^j is the DOFs related to PC i.

Therefore, the displacement for each manifold element can be obtained as:

$$u(x,y) = \sum_{i=1}^{n} w_i(x,y)u_i(x,y) = \sum_{i}^{n} w_i(x,y)\sum_{j}^{m} l_i^j d_i^j \tag{6}$$

The characteristics of the weighting functions depend on the shape of the mathematical mesh and the order of the displacement approximation field. Detailed construction of the weighting function can be referred to the work done by Lin [37]. In this study, a regular triangular mesh and a linear displacement approximation field are adopted. The weighting functions are hence equal to the three node triangular finite element shape functions.