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Three-dimensional slope stability analysis using independent cover based numerical manifold and vector method

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ABSTRACT

A three-dimensional (3D) slope stability analysis method is presented in this paper based on three-dimensional independent cover based manifold method (ICMM3D) and vector sum method (VSM). ICMM3D is proposed in the framework of independent cover, which avoid the time-consuming and error-prone cover system generation of convention numerical manifold method (NMM). It is very suitable for the continuous/discontinuous deformation analysis in slope engineering. Then, with the stress field obtained by ICMM3D, VSM is employed to calculate the factor of safety, which is effective in computation and clear in physical meaning. In addition, a new strategy of discretization of the slip surface is proposed, which discretizes the slip surface into a set of calculating points in order to avoid errors caused by the special handling in the boundary columns in limit equilibrium method (LEM) and the tedious triangulation of the slip surface in VSM. Finally, genetic algorithm is employed to search for the critical slip surface. Numerical examples demonstrate the efficiency, accuracy and robustness of the proposed method.

1. Introduction

In the stability analysis of landslides, the rock masses are usually heterogeneous and contain large quantities of discontinuities, e.g., faults and joints. Besides recent advantages in remeshing procedure, see e.g. the seminal work of Areias et al. (2016a, 2013b, 2016b, 2015), Ghorashi et al. (2015), Jia et al. (2013), Nanthakumar et al. (2013), and Thai et al. (2014), the finite element method requires that the discontinuities are aligned to the discretization. A more elegant solution has been proposed in the context of so-called partition of unity enriched methods such as the extended finite element method (XFEM) (Belytschko and Black, 1999; Belytschko et al., 2001), generalized finite element method (GFEM) (Strouboulis et al., 2000) or specific improvements such as the smoothed extended finite element method (Nguyen-Xuan et al., 2008; Thai et al., 2012), isogeometric extended finite element methods (Ghasemi et al., 2015; Hughes et al., 2005; Nguyen-Thanh et al., 2014, 2015; Nguyen et al., 2016, 2015; Thai et al., 2015, 2016) or phantom node method (Chen et al., 2012; Song et al., 2006). In XFEM, the discontinuity can evolve arbitrarily in the discretization during crack propagation. However, modeling contact in the XFEM framework which is important for the analysis of landslides, remains a challenge. Meshfree methods (Belytschko et al., 1996; Li and Liu, 2002) offer an alternative to finite element methods. They are also based on continuum mechanics and can handle large deformations and contact (at least when Eulerian kernels are used) easier than finite element methods (Dilts, 1999; Libersky and Petschek, 1991; Rabczuk and Areias, 2006; Rabczuk et al., 2007a; Randles and Libersky, 1996; Ren et al., 2016; Vu-Bac et al., 2013; Zhuang et al., 2012b, 2014b) which is important in the simulation of landslides. Moreover, they are also well suited for modeling discrete fracture (Nguyen-Thanh et al., 2011; Nguyen et al., 2008; Rabczuk and Belytschko, 2007; Rabczuk et al., 2004, 2007b, 2010a, 2010b, 2010c; Zhuang et al., 2012a, 2014a, 2011). An alternative to methods which solve continuum mechanics equations are methods which account for the 'fine-scale' structure such as the discrete element method (DEM) (Cundall and Strack, 1979) or discontinuous deformation analysis (DDA) (Shi, 1988). They are capable of accounting for the faults and joints of the rock. However, capturing the macroscopic material behavior with those methods remains a major challenge. Therefore, coupling methods have been proposed that combine the strength of discrete methods and the finite element method (Munjiza et al., 1995); see also the contributions on multiscale methods for fracture (Amiri et al., 2014; Areias et al., 2013a; Budarapu et al., 2014; Quayum et al., 2015; Talebi et al., 2015; Vu-Bac et al., 2015).

A very powerful method for the solution of continuum-discontinuum problems is the numerical manifold method (NMM); see Ma et al. (2010) for a recent survey. The NMM was proposed by Shi (1991) and has been widely developed and extended to various two-dimensional problems, e.g. cover system generation (Cai and Wu,

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2016; Chen and Li, 2015), fracture (Ma et al., 2009; Zheng and Xu, 2014), slope engineering (Koyama et al., 2012; Ning et al., 2011; Zheng et al., 2014), to name a few. The NMM has also been implemented in 3D (Cheng and Zhang, 2007, 2008; He and Ma, 2010; Jiang et al., 2010, 2009; Terada and Kurumatani, 2005) and applied to joint rock slope stability analysis (He et al., 2013). However, the efficient 3D implementation remains a challenge since it requires advanced and efficient contact algorithms. One of the most important issues is the cover system generation. For two-dimensional problems, Chen and Li (2015) considered the mathematical mesh as the union of mathematical elements (MEs) rather than mathematical covers (MCs) which made the cover system generation more efficient. Cai and Wu (2016) employed a pre-defined symbol function by which large amounts of computational geometries were replaced by computational algebras facilitating the generation process of the cover system. There are comparatively few papers in three dimensions on the generation of the cover system. Li and Zhang (2014) proposed a 3D manifold cutting method based on the 3D block cutting approach (Jing, 2000) which is able to generate arbitrary 3D MEs based on tetrahedral and hexahedral mesh covers.

In order to solve the problems above, Cai and Liu (2015), Cai et al. (2013) proposed an independent cover based manifold method (ICMM). In the ICMM, various high-order cover functions are employed at the independent covers, and the corresponding elements are defined between the adjacent independent covers, which are different from the virtual springs in DDA and DEM. Complex algorithms for the cover system generation used in conventional NMM as well as the rank deficiency due to the linear dependence of the global degrees of freedom present in high-order NMM are completely avoided in ICMM. The continuous and discontinuous deformation analysis can be unified in one framework in the ICMM. Furthermore, the ICCM can be easily extended to three dimensions which is the key contribution of this manuscript. It will be extended to slope stability analysis for validation.

The determination of the stability of slopes consists of two parts (Baker, 1980): calculate the factor of safety of a potential slip surface and search for the critical slip surface over all admissible slip surfaces. The definition of safety of factor is not unique. Zheng et al. (2006) suggested there are mainly two kinds of definitions in the abstract. One is the strength reserving definition, where the factor of safety is defined as "the factor by which the shear strength of the soil would have to be divided to bring the slope into a state of barely stability equilibrium" (Duncan, 1996), e.g. the limit equilibrium method (LEM) (Fellenius, 1939) and the strength reduction method (SRM) (Zeinkiewicz et al., 1975). By now, this definition is believed to be most familiar to engineers (Zheng et al., 2006). However, Ge (2010) pointed out that there are two problems for both the LEM and SRM. One is that the rationality of the strength reduction principle seems to be doubtful. For example, the cohesive force c and internal friction coefficient tanϕ of material divided by same F simultaneously is not very reasonable. If c and tanϕ are divided by different factors respectively, it will be complicated and infinite combining solutions could be obtained. The other is that because force is a vector, the algebraic sum of force is hold only for some special cases while the superposition principle of vectors should be hold in the analysis. The other definition of factor of safety is overloading definition. It defines the factor of safety as the scalar ratio of total resisting forces to total driving forces. The physical meaning is clear for a straight line or a circular slip line. However, it is questioned for a non-straight line or a non-circular slip line either, because it is neither the summation of force vectors in space nor the summation of projections of force vectors in a fixed direction. In order to overcome the problems above, Ge (2010) proposed the vector sum method (VSM), which estimates the stability of a slope by comparing the projection of the total resisting force with the total sliding force. The factor of safety is computed based on the real stress state and the vector sum algorithm, so the stress field needs to be calculated only once and the physical meaning is sound and clear. In this paper, the factor of safety is calculated using VSM based on the stress fields obtained by ICMM3D.

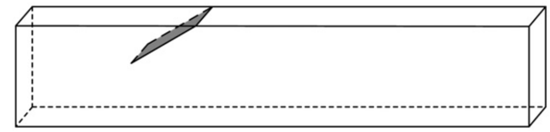

Fig. 1. An analysis domain with a joint.

The second step in slope stability analysis is finding the critical surface over all admissible slip surfaces. The aim is to find the best solution among available candidates by minimizing or maximizing an objective function. Optimization techniques are usually employed to determine the critical slip surface, e.g. pattern search methods (Bishop and Morgenstern, 1960; Greco and Gulla, 1985; Prater, 1979), calculus of variations (Baker and Garber, 1978; De Josselin De Jong, 1980; Friedli and Giger, 1978), dynamic programming methods (Baker, 1980; Yamagami et al., 1991), random search methods (Greco, 1996; Malkawi et al., 2001a, 2001b; Mowen, 2004; Yang et al., 2016), heuristic optimization methods (Bolton et al., 2003; Cheng, 2003; Cheng et al., 2008, 2005; Gao, 2015; Kahatadeniya et al., 2009; Kalatehjari et al., 2015), etc. In recent years, genetic algorithm has been widely used to locate the critical slip surface because of its elegance and efficiency. It has been found that genetic algorithm is a robust search technique which often gives global solution (Ahangar-Asr et al., 2012; Li et al., 2010; Manouchehrian et al., 2014; Sengupta and Upadhyay, 2009). In this paper, a search technique based on genetic algorithm and ellipsoidal shape is proposed to search for the critical slip surface. In addition, the potential slip surface during the process is discretized into a set of calculating points in order to avoid errors caused by the special handling in the boundary columns in limit equilibrium method (LEM) and the tedious triangulation of the slip surface in VSM.

In this paper, ICMM3D is firstly proposed to calculate the stress field, then VSM is employed to obtain the factor of safety. After that the critical slip surface is determined based on genetic algorithm among the potential ellipsoidal shape slip surfaces. Finally, five examples are investigated to demonstrate the accuracy of ICMM3D and the presented slope stability analysis method.

2. The basic theory of ICMM3D

2.1. Stiffness matrix of the independent cover

Fig. 1 illustrates an analysis domain with a joint. The associated finite element mesh based on hexahedra is shown in Fig. 2.

The NMM provides a unified framework for both continuous and discontinuous problems (Chen and Li, 2015). In the conventional NMM, a mathematical mesh, which is the union of mathematical covers (MCs), is first assigned to model the problem. MCs have three properties: (1) MCs are arbitrarily defined by users; (2) they are independent of physical features, but their union must completely cover all physical features; and (3) they may overlap. The finite element mesh is used to define the mathematical mesh for the numerical manifold method. Considering any node, all elements having this node form a MC. In Fig. 2, there are 20 nodes and each node has a MC, e.g. MC of node 9 is the region 5-6-8-7-13-14-16-15 as shown in Fig. 3.

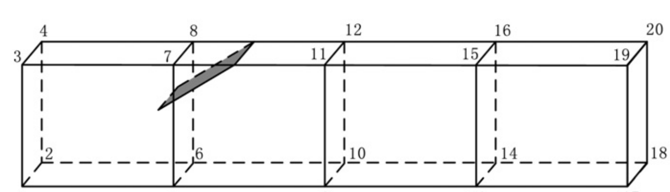

Fig. 2. Hexahedron element mesh.