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Micro-mechanical modeling of the macro-mechanical response and fracture behavior of rock using the numerical manifold method

Zhijun Wu [a,c], Lifeng Fan [b,*], Quansheng Liu [a], Guowei Ma [b]

[a] School of Civil Engineering, Wuhan University, No 8 Donghu South Road, Wuhan 430072, China
[b] College of Architecture and Civil Engineering, Beijing University of Technology, Beijing, China
[c] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, China

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ABSTRACT

A micro-mechanical based numerical manifold method (NMM) is proposed in this study to investigate the micro-mechanisms underlying rock macroscopic response and fracture processes. The Voronoi tessellation technique is adopted to create randomly-sized polygonal rock micro-grains. A rock micro-grain based broken criterion is proposed and a corresponding grain breaking technique is developed. To better represent the contact behavior of rock grain bonds, a cohesive fracture model that considers tensile, shear and compressive behaviors together, is adopted to interpret the failure of rock grain bonds. The developed program is first validated by reproducing biaxial tests of Transjurane sandstone. Finally, the influences of micro-parameters on the rock macroscopic response and failure modes are investigated. The results show that the developed micro-based model can mimic the deformation and failure characteristics of the test closely. A parameter study shows that the grain contact cohesion has significant effects on the model uniaxial compressive strength. The fracture process and failure mode of rock are dependent on the ratio of grain contact shear stiffness to normal stiffness. With the increase of the contact stiffness ratio, the failure mode of rock under uniaxial compression changes from a diffuse pattern to a concentrated shear band.

1. Introduction

Rock, as a natural material, is closely related to the activities of human beings such as building, mining and tunneling. Therefore, the issue of rock deformation and fracture is of great importance to the safety of rock engineering, which has been studied intensively by many researchers over the past several decades (Frew et al., 2001; Shen et al., 1995; Zhang and Zhao, 2014; Zhou et al., 2004; Zhou and Yang, 2012).

Due to its complex characteristics, rock mechanical response and fracture propagation problem usually needs to be studied numerically. In the past decades, many modeling techniques have been developed and applied to investigate the rock dynamic failure problems (Camacho and Ortiz, 1996; Camborde et al., 2000; Cheng and Zhou, 2015; Li et al., 2005; Mahabadi et al., 2010; Zhao et al., 2011; Zhou et al., 2005; Zhou and Bi, 2012). The most commonly used techniques are continuum-based methods, which have been successfully applied to the assessment of global stability of rock masses and the analysis of stress and deformation, such as the finite difference methods (FDM) (Chen et al., 2004, 2007; Granet et al., 2001), finite element methods (FEM) (Camacho and Ortiz, 1996; Dai, 2011; Liang et al., 2004; Liu et al., 2004; Zhu and Tang, 2006), smoothed FEM (Chen et al., 2010; Nguyen-Xuan and Rabczuk, 2015), boundary element methods (BEM) (Pan et al., 1997; Saez and Dominguez, 2001) and meshless methods (Zhuang et al., 2012; Zhuang et al., 2014). However, these conventional continuum-based methods requires an explicit representations of fractures and fracture propagation processes, which makes the treatment of phenomena such as branching and multiple cracking more difficult (Rabczuk and Areias, 2006). To overcome the limitations of the explicit representations of fractures suffered by the conventional continuum-based methods, a meshfree method (EFG-P) motivated by cracking particle technique (Remmers et al., 2003), which does not require an explicit crack representation, has been successfully developed by Rabczuk and Belytschko (2004) for problems with multiple arbitrary cracks. The developed EFG-P was later further extended by Rabczuk and Belytschko (2007) and Rabczuk et al. (2010) to model 3D problems with arbitrary cracks. However, in this method, techniques such as smoothing the normals of the crack surfaces in order to avoid erratic crack paths are still needed. Peridynamics which treats the crack as part of the solution other than part of the problem on the other hand can handle complex fracture pattern without requirement of further techniques. However, the original bond-based peridynamics (BB-PD) (Silling, 2000) can only model the material with Poisson's ratio of one-third in 2D or one-fourth in 3D. In order to overcome the Poisson's

* Corresponding author.
E-mail address: fanlifeng@bjut.edu.cn (L. Fan).

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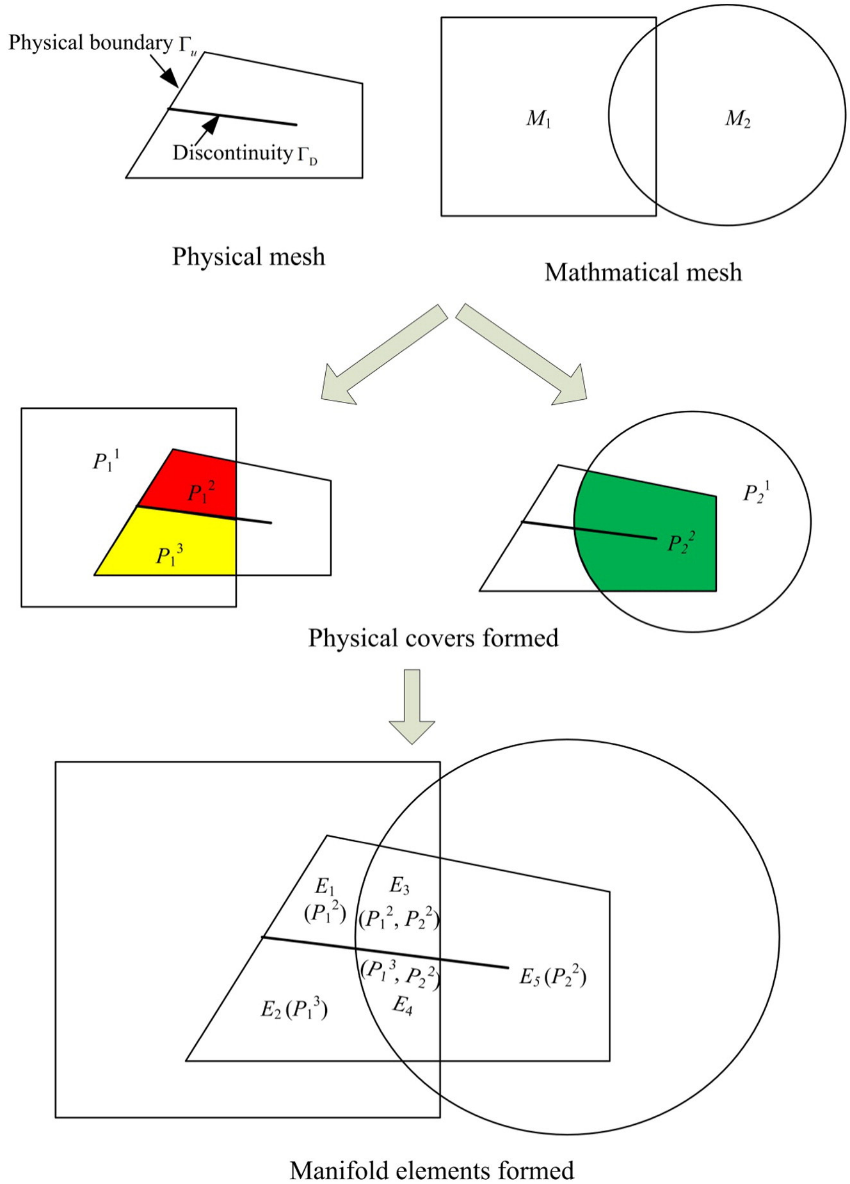

Fig. 1. Illustration of the finite cover system in NMM (Wu and Wong, 2014).

ratio restriction and reflect the horizons sizes variation effect, a new peridynamic formulation was proposed by Ren et al. (2015) by removing the issue of varying horizons and ghost force. However, to realistically represent the rock micro-structures and reflect the complex interactions between rock grains are still challenging.

In addition to classical continuum mechanics methods, discontinuous methods such as the distinct element method (DEM) (Cho et al., 2007; Cundall and Strack, 1979; Hentz et al., 2004; Kazerani et al., 2010b; Tang et al., 2013, 2014; Zeghal and Lowery, 2002), discontinuous deformation analysis (DDA) (Hatzor et al., 2004; Ning et al., 2011; Shi and Goodman, 1989; Zhang and Lu, 1998) and distinct lattice spring model (DLSM) (Kazerani et al., 2010a; Zhao et al., 2011), are powerful alternatives, which represent rock material as an assemblage of independent grains. By simply breaking the bond when the interaction force between two grains overcomes its tensile or shear strength, the discontinuous methods can easily model the fracturing process of rock explicitly. However, the fractures produced by these discontinuum-based methods are usually limited to the grain boundaries.

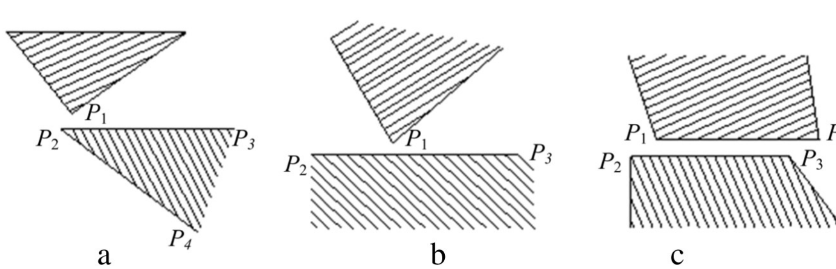

Fig. 2. Three types of contacts (Shi, 1995): angle to angle (b) angle to edge (c) edge to edge.

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