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The 3D numerical simulation of damage localization of rocks using General Particle Dynamics

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ABSTRACT

The damage localization of rocks is an open issue in rock engineering. Moreover, it is difficult to observe directly the micro-scale process of damage localization and damage evolution of rocks. Therefore, in this paper, the General Particle Dynamic method (GPD) is developed to simulate the damage localization and failure process of 3D rock samples. The effect of the intermediate principal stress on the strength, the stress-strain curve and the damage localization modes of a cubical rock specimen subjected to the true triaxial compressive loads is investigated. The different failure modes including the single shear damage localization mode, axial splitting damage mode, X-shaped conjugate shear damage localization mode and Cone-shaped damage localization are found. It is found that the numerical results obtained from GPD are in good agreement with experimental observations. It is implied that the formation of damage localization band induced by the initiation and propagation and coalescence of micro-cracks in rocks can be well simulated using GPD.

1. Introduction

It is well known that rock materials undergo damage localization and failure under the compressive loads. The better understanding of the damage localization of rocks is of a significant importance due to its widespread applications to many types of geotechnical and geological engineering.

To study the local damage and failure of rocks, many experimental investigations were performed. For instance, Bésuelle et al. (2000) conducted triaxial compression experiments on sandstone and analyzed the development of damage localization phenomenon. Klein et al. (2001) carried out an experimental study on sandstone under conventional triaxial compression, and studied the effect of confining pressure on the damage localization process. Yang and Jing (2013) conducted triaxial compression experiments on red sandstone to investigate its strength and deformation failure behaviors. In parallel with the experimental studies, various theoretical models were also proposed to describe the damage localization and failure in rock materials. A micromechanics-based model was proposed to analyze the relationship between the localization damage and deformation of brittle rocks subjected to unloading (Zhou, 2005). Hu et al. (2010) studied an anisotropic plastic damage model for semi-brittle materials, and revealed that the evolution of damage is related to growth of weakness planes. Zhu and Shao (2015) remarked that inelastic deformation and damage evolution at microdefects can govern macroscopic behaviors of brittle solids, and raised a refined micromechanical anisotropic unilateral damage model for quasi-brittle geomaterials under compression. Along this line, a micromechanical model considering the damage-friction coupling for brittle materials was firstly proposed by Zhu et al. (2016) and Qi et al. (2016). It is found that the coupled model can be more accurate description of the damage localization evolution law. These physical and empirical models provide quite a direct interpretation of damage localization and evolution. However, the formulation of such models is complex, and the experimental identification of parameters is not easy.

Therefore, in order to describe more conveniently and more properly the damage localization of materials, a number of numerical tools were proposed to study the process from the damage localization to failure of rock-like materials. The localized degradation model was adopted to study the failure of the rock using FLAC3D (Fang and Harrison, 2002). In order to investigate the failure mechanism and mode of rocks, Wong et al. (2006) carried out a model which contains pre-existing flaws under uniaxial compressive loads using Rock Failure Process Analysis code (RFPA2D). Pan et al. (2012) studied the effect of the intermediate principal stress on rock failure process using Elasto-Plastic Cellular Automaton (EPCA3D), and found that local failure is

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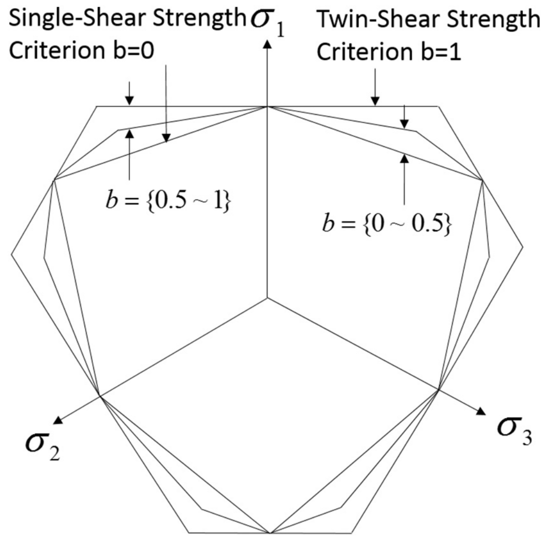


Fig. 1. Failure loci in the deviatoric plane for the nonlinear unified strength criterion. (a) Undamaged configuration. (b) Damaged configuration.

formed when the intermediate principal stress reaches a certain value. Wu et al. (2015) studied the damage localization for solid using the extended embedded finite elements (XFEM). Shao et al. (2006) and Jiang et al. (2011) investigated the deformation localization and crack formation in elastic-brittle materials using the discrete numerical method (DEM). Although the above numerical methods succeeded in one or another aspects, most of these methods were based on the finite element (FEM) or discrete element methods (DEM), which have many limitations. For instance, the numerical modeling of fracture with traditional mesh-based technique (e.g. FEM) requires a very fine mesh to model the singular stress field in the neighborhood of damaged material (e.g. crack tip) (Zhou et al., 2015a,b). As the damage evolves, the structure needs to be re-meshed to consider the localized change in geometry and certain inaccurate results (Fernández-Méndez et al., 2005). In addition, it is very difficult to investigate the 3D localization phenomenon of geomaterials using FEM. Moreover, it is found that the particle size has a strong influence on numerical results in the discrete element-based numerical methods (DEM) (Yao et al., 2016). Therefore, there is a need to develop other efficient numerical methods for minimizing effect of mesh size and particle size.

It is attractive to adopt the mesh-less approach to simulate damage localization. The advantage of this approach is that no remeshing is needed. A number of mesh-less methods including Smoothed Particle Hydrodynamics (SPH) (Leblanc et al., 2014), the continuous/discontinuous deformation analysis (CDDA) method (Cai et al., 2014), the mesh-less Shepard and least squares (MSLS) (Zhu et al., 2011), a numerical

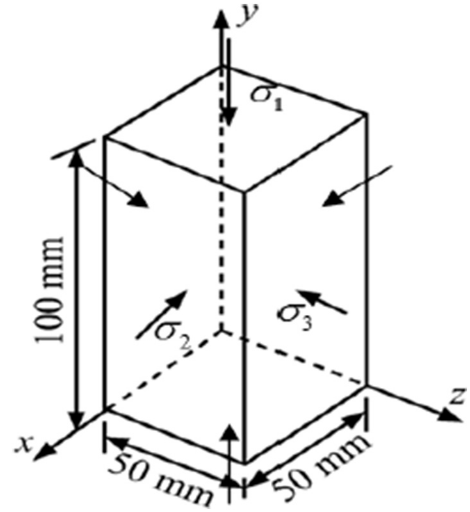


Fig. 3. Geometry model.

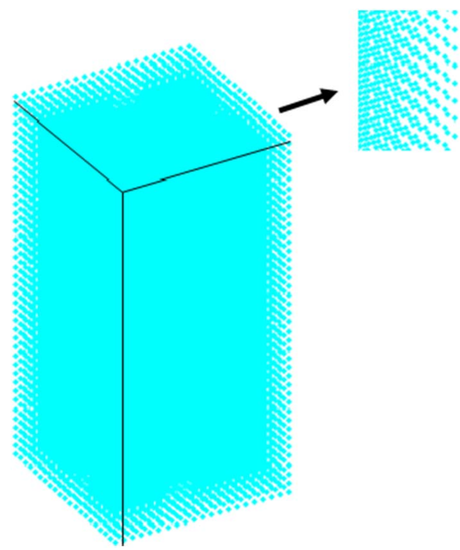
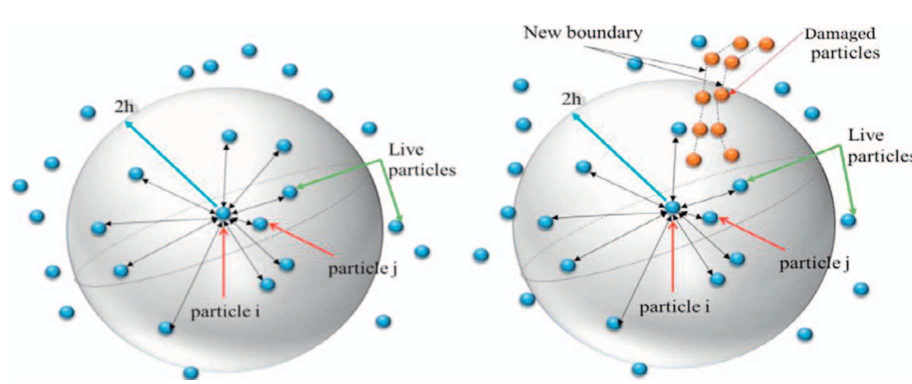


Fig. 4. The particle model.

procedure based on the edge-based smoothed finite element (Vu-Bac et al., 2013) and the three dimensional discontinuous deformation analysis (3D DDA) (Wu et al., 2014) were developed. In the above mesh-less methods, SPH has the advantage of robustly computing the material point history even at severely deformed configurations while avoiding the large computational costs of re-meshing in a Lagrangian



(a) Undamaged configuration. (b) Damaged configuration.

Fig. 2. The distribution of the 3D particles.