Computers and Geotechnics 64 (2015) 48–60

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Numerical simulation of damage and failure in brittle rocks using a modified rigid block spring method

C. Yao [a,b], Q.H. Jiang [a], J.F. Shao [b,*]

[a] School of Civil Engineering and Architecture, Nanchang University, Nanchang, China
[b] Laboratory of Mechanics of Lille, UMR8107 CNRS, University of Lille, Cité scientifique, 59655 Villeneuve d'Ascq, France

ARTICLE INFO

Article history:
Received 17 January 2014
Received in revised form 23 September 2014
Accepted 18 October 2014
Available online 22 November 2014

Keywords:
Damage
Failure
Discrete approach
Micromechanics
Rigid block spring method
Brittle rocks

ABSTRACT

This paper is devoted to the numerical simulation of damage and failure in brittle rocks using a modified rigid block spring method. The brittle rocks are represented by an assembly of rigid blocks based on a Voronoi diagram. The macroscopic mechanical behavior is related to that of interfaces between blocks. The mechanical behavior of each interface is described by a uniform distribution of normal and tangential springs, which together define the deformation and failure process of the interface. The elastic stiffness of springs can explicitly be related to the macroscopic elastic properties of material. The local failure process of interface is controlled by both normal stress and shear stress. Both tensile and shear failures are considered. Numerical simulations are presented and compared with experimental data to show the performance of the proposed model.

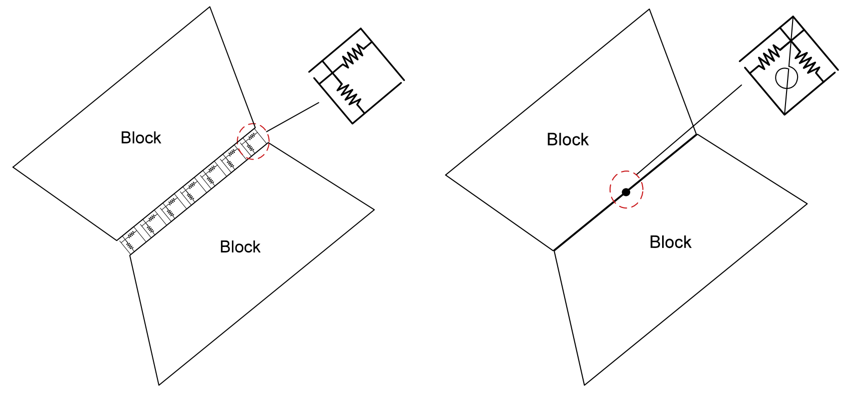
1. Introduction

Damage by the growth of microcracks is the main mechanism of inelastic deformation and failure in brittle rocks. The transition from diffused microcracks to localized fractures is the key challenge for the description of progressive failure process in such materials. Many phenomenological and micromechanical damage models have been developed during the last decades for brittle materials (we do not give here an exhaustive list of all these models). These models are generally able to describe the average macroscopic stress–strain behaviors until the post-peak regime, but fail to explicitly describe the onset of macroscopic fractures. On the other hand, extended finite element methods have also been proposed in order to consider the onset and propagation of fractures. These methods indeed opened ambitious perspectives for modeling of failure process but so far are generally limited to 2D conditions and fail to deal with problems with multiple fractures. As an alternative way, various discrete element methods have been intensively developed during the last decades either for granular media and cohesive materials [1–4 just to mention a few]. With this class of approaches, a cohesive continuum is replaced by an equivalent discrete assemblage of blocks or elements which are bonded together by cohesive forces, contact forces or cementation interfaces. Various discrete approaches have been successfully applied to modeling the damage and failure in heterogeneous geomaterials. For instance, Lan et al. [5] have studied the effect of heterogeneity of brittle rock on micromechanical extensile behavior during compression loading. Using discrete numerical simulations, Kazerani and Zhao [6] have investigated micromechanical parameters controlling compressive and tensile failure in crystallized rock.

Among the discrete approaches for cohesive geomaterials, the bonded particle model proposed by Potyondy and Cundall [4] is based on the distinct element method and can reproduce many features of the mechanical behavior of brittle rocks, including elastic deformation, damage due to microcrack propagation and induced material anisotropy, hysteresis loops during unloading and reloading cycles, volumetric dilation, microcracks coalescence and post-peak softening, etc. This method is so far considered as one of leading methods among discrete approaches. However, it is shown that the particle size has a strong influence on numerical results. Different packing assemblies of particles can also affect macroscopic behaviors of materials [7–9]. Therefore, each randomly generated packing specimen must be calibrated by using specific algorithms, such as that proposed by Lan et al. [5]. More generally, the mesh dependency is a common shortcoming for many discrete element methods. The main objective of this study is to propose a discrete numerical model for modeling the mechanical behavior of brittle rocks by minimizing the effects of mesh size and arrangement.

* Corresponding author.
E-mail address: jian-fu.shao@polytech-lille.fr (J.F. Shao).

http://dx.doi.org/10.1016/j.compgeo.2014.10.012
0266-352X/



(a) Contact model for the modified RBSM (b) Contact model for the original RBSM

Fig. 1. Illustration of contact models for the modified and original RBSM.

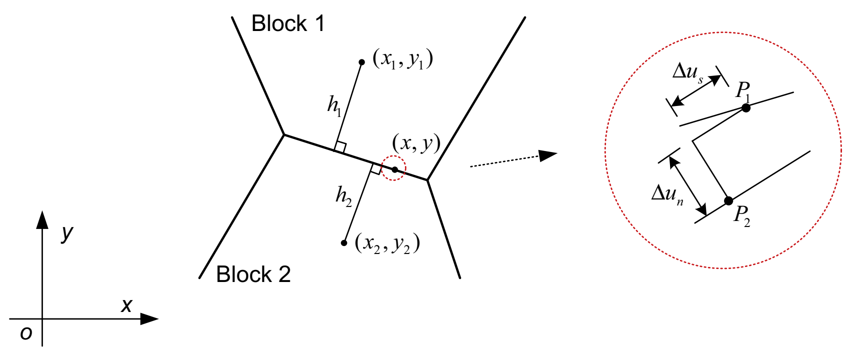


Fig. 2. Local displacement for a point on the contact interface.

The rigid block spring method (RBSM), initially proposed by Kawai [10], is a very suitable method for modeling damage and failure in brittle rocks and has also been applied to concrete and concrete structures [11–14]. This method has been successively improved by Qian and Zhang [15], Zhang [16] and Chen et al. [17] and used in the limit analysis of rock slopes and other engineering structures. In view of its computational scheme, this method is very similar to the DDA model (Discontinuous Deformation Analysis) initiated by Shi [18] and thus can be viewed as an implicit discrete element method. Their main difference lies in the fact that no deformation in blocks and no contact update are considered in the RBSM method. One of key points of this method is the mesh generation. Bolander and Saito [19] used the RBSM for fracture analysis of concrete with a uniform Voronoi diagram as the basic mesh. They found that this type of mesh has the advantage of ensuring elastic uniformity and maximizing the degree of isotropy with respect to potential crack direction. Voronoi diagram was also used for dense packing simulation based on distinct element method [20]. Moreover, the widely used software UDEC (Universal Distinct Element Code) has also incorporated Voronoi tessellation [21]. Damjanac and Fairhurst [22] used this tool to study the effect of decreasing fracture toughness due to stress corrosion on the strength of a crystalline rock and Gao and Stead [23] proposed a modified Voronoi logic for brittle fracture modeling at both laboratory and field scales. Based on the previous works, a modified RBSM is proposed in this study for modeling the mechanical behaviors of brittle rocks. Since this model is in an implicit form and no contact distribution needs to be updated, it is much easier to be implemented and can provide faster convergence. There is no need to introduce an artificial damping coefficient, compared to the explicit discrete element methods such as UDEC, PFC, and DEM. Furthermore, as it will be shown through examples in this paper, the proposed model is not less efficient in producing damage and failure process of brittle rocks under compression. The cohesive brittle rocks are represented by an assemblage of polygonal discrete elements which are based on uniformly and randomly generated Voronoi cells. A specific criterion is proposed to deal with both tensile and shear failure modes of interfaces. Macroscopic elastic and inelastic deformations, the transition from diffused damage to localized failure will be analyzed. In particular, effects of element size and mesh arrangement on the macroscopic responses will be investigated.

2. Basic principle of the modified rigid block spring method

In the modified rigid block spring method (RBSM), the cohesive brittle rock is represented by an assemblage of rigid blocks which are interconnected along their boundary surfaces. Each block has three degrees of freedom defined at its centroid, two translational and one rotational. Two neighboring blocks share a common boundary surface, the interface. The interface between two neighboring blocks is mechanically represented by a series of normal and tangential springs, uniformly distributed along the interface as shown in Fig. 1a. Inspired by the contact model proposed by Goodman [24], the elastic property of springs is characterized by the normal and tangential elastic stiffness coefficients, k_n and k_s. The basic difference of this modified RBSM with the original RBSM is that, in the original RBSM there are only three springs positioned at the mid-point of the interface, a normal spring, a tangential