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Research Paper

Numerical study of excavation induced fractures using an extended rigid block spring method

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ABSTRACT

This paper presents a numerical study of fracturing process induced by excavation around a gallery using an extended rigid block spring method (RBSM). The surrounding rock mass is characterized by an assembly of rigid blocks based on a degraded Voronoi diagram. The macroscopic mechanical behavior of rock is related to that of interfaces between blocks. The mechanical behavior of each interface is described by its elastic stiffness and failure criterion. The failure process of interface is controlled by both normal stress and shear stress. Both tensile and shear failures are considered. The macroscopic fracturing process is described by the coalescence of cracked interfaces. The rock structural anisotropy is taken into account through a spatial variation of elastic stiffness and failure strength of interfaces. A series of sensitivity studies are performed to investigate effects of gallery orientation, failure strength of interfaces and rock structural anisotropy on gallery deformation and fracturing. Numerical results are compared with in-situ observations in terms of fracture patterns.

1. Introduction

In the framework of management of high-level radioactive wastes and spent fuels, the geological disposal is considered as one of promising solutions and is under study in many countries. Hard clayey rocks exhibit a relative high mechanical strength, a very low permeability and a potential self-sealing capacity, which are favorable properties for the confinement of radioactive wastes. Therefore, such rocks are considered as a potential geological barrier and studied in France and other countries during the last decades. In this context, one of the topics is related to the characterization of the so-called excavation damaged zone (EDZ). Indeed, the excavation process can create cracks and fractures around underground openings. The existence of such damaged and fractured zones can significantly affect short and long term hydromechanical properties of surrounding rocks and the confinement capacity of geological barrier [1].

In France, under the coordination of the French national agency for radioactive waste management (Andra), an underground research laboratory (URL) is constructed in a Callovo-Oxfordian claystone (Cox) layer at Bure. A large number of laboratory tests have been conducted for the characterization of basic hydromechanical properties of the Cox claystone. Recently, a series of in situ experiments have also been realized at the Bure underground laboratory [2–4]. Similar investigations have also been performed on weak clayey formations, such as the Opalinus clay at the Mont Terri underground laboratory in Switzerland [5,6], and the Boom clay at the Mol laboratory in Belgium [7]. These experiments have clearly shown complex distributions of cracks and fractures around openings. Both tensile and shear cracks have been observed. The permeability in fractured zone is increased by several orders of magnitude. In order to describe the onset of propagation of such localized fractures, different numerical studies have been performed. In general and without giving an exhaustive review, one can find two complementary approaches, respectively using discrete elements methods [8,9] to capture displacement discontinuities in fractures and continuum mechanics methods by considering fractures as narrow strain localization bands [10,11]. However, these previous studies are not sufficient for a full understanding of physical mechanisms and evolution kinetics of fractured zones. Therefore, Andra organized a benchmark with several research teams on the numerical modeling of EDZ in the Cox claystone. The objective is to compare different constitutive models and different numerical methods in capturing different fracture patterns observed at the Bure URL around two galleries. The role of the present study in that benchmark is to investigate the performance of a discrete approach.

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The inelastic deformation and failure process in most quasi-brittle cohesive rocks are mainly driven by the creation, propagation and coalescence of microcracks. The description of the transition from diffuse microcracks to localized fractures is still an open issue for numerical modeling. The failure process is generally accompanied by the appearance of fractures with strong displacement discontinuities, which cannot be properly described by conventional continuum mechanics approaches. During the last decades, various discrete numerical models have been developed for the description of fracturing process in cohesive or bonded materials. Among them, the bonded particle model [12], which is based on the distinct element method [13], has the capability to reproduce many features of mechanical properties of brittle rocks, such as elastic deformation, inelastic deformation, volumetric dilation and induced anisotropy. This model showed a promising capability in modeling fracturing process in brittle materials. For example, Fakhimi [14] used a distinct element method to simulate failure around a circular opening in a biaxial compression test. However, only a little number of studies has been so far devoted to the application of discrete methods in modeling fracture processes around underground openings.

In the present work, an extended rigid block spring method (RBSM) is proposed and used in the benchmark. The rigid block spring method (RBSM) was initially proposed by Kawai [15] for modeling crack growth and fracturing in cohesive brittle materials. In this method, the cohesive material is replaced by an assemblage of polygonal discrete elements (rigid blocks) by using the Voronoi diagram. The blocks are bonded by contact interfaces. In the initial model, three springs were defined on each interface to describe relative normal and tangential displacements and rotations between two neighboring blocks. The RBSM method was so far successfully applied to modeling mechanical behaviors of cement-based materials [16–19]. This method has been successively improved by Qian and Zhang [20] and Zhang [21]. In the extended RBSM model, a continuous distribution of stress and relative displacements are defined on each interface through suitable interpolation functions. This allows to modeling the progressive failure of interfaces. The modified method was recently applied to modeling damage and failure of isotropic brittle rocks [22] and anisotropic brittle rocks [23].

This paper is organized as follows. The basic principle of the extended RBSM is first recalled with the presentation of both isotropic and anisotropic failure criteria of interfaces. This method is then applied to investigate fracturing process induced by excavation around two galleries. A series of sensitivity studies are presented in order to investigate effects of gallery orientation, mechanical strength of interfaces and rock structural anisotropy on the fracturing process. Numerical results are compared with in situ observations.

2. Summary of the extended rigid block spring method

In our previous work, an extended RBSM method has been developed to describe the progressive failure of initially isotropic rocks [22] and anisotropic brittle rocks [23] at the sample scale. In this work, this method will be applied to modeling the excavation induced damage zone around underground openings. The main features of the method are first recalled. The mathematical formulation of the RBSM is quite similar to that of the Discontinuous Deformation Analysis (DDA) method proposed by Shi [24]. The cohesive rock is divided into a number of polygonal discrete blocks which are cemented together through interfaces. The spatial distribution of blocks can be either a random one or an ordered one according to the microstructural nature of material [25,26]. Under the application of mechanical loads, some cemented interfaces are broken, inducing both normal opening and tangential sliding. Macroscopic fractures are created by the coalescence of broken interfaces. Compared with the initial RBSM, a more physically based interface model is proposed in the present work, allowing the description of progressive breakage of interfaces.

2.1. Principles of the extended rigid block spring method

The elastic property of interfaces is characterized by the normal stiffness (k_n) and tangential stiffness (k_s). Stresses on an interface are related to relative displacements between two surfaces of the interface by an elastic matrix. In the 2D configuration, one gets the following stress-strain relation:

$$\{\sigma\} = \{\sigma_n \quad \sigma_s\}^T = [D]\{\Delta u\}, \quad [D] = \begin{bmatrix} k_n & 0 \\ 0 & k_s \end{bmatrix}, \tag{1}$$

σ_n and σ_s are respectively the normal and shear stress and $\{\Delta u\}$ denotes the vector of relative displacements between two surfaces of the interface. Using the theorem of virtual work and making the integration over all interfaces in the domain, one obtains a system of linear equations to be solved, i.e.

$$[K]\{U\} = \{Q\} \tag{2}$$

$[K]$ is the global stiffness matrix, $\{U\}$ the global relative displacement vector and $\{Q\}$ the global force vector. The global stiffness matrix and the global force vector are obtained by an assemblage process on interfaces, similar to that used for the conventional finite element method. Their detailed expressions have been presented in [22].

It is important to notice that the elastic parameters of interfaces can be explicitly related to the macroscopic elastic parameters. For an isotropic material, one obtains:

$$k_n = \frac{E_0}{h_1 + h_2}, \quad k_s = r \cdot k_n \tag{3}$$

The variables h_1 and h_2 denote the distances between the centers of two neighboring blocks to the interface. E_0 and r are two intermediate parameters. According to the numerical studies performed in [22], the following empirical relations have been obtained to determine these parameters:

$$\begin{aligned} r &= k_s/k_n = 4.025\,v^4 - 6.087\,v^3 + 6.022\,v^2 - 3.966\,v + 1 \\ E/E_0 &= -0.629r^4 + 1.617r^3 - 1.678r^2 + 1.174r + 0.5162 \end{aligned} \tag{4}$$

E and v are respectively the macroscopic Young's modulus and the Poisson's ratio of the material. Therefore, from the macroscopic elastic parameters measured in laboratory tests, the elastic parameters of each interface can be easily determined with the relations (3) and (4). Notice that these parameters depend on the spatial arrangement and size of blocks.

2.2. Failure criterion of interface

In the RBSM, the macroscopic fracture process directly depends on the local failure condition of interfaces. In the present study, both tensile and shear failure are considered. The tensile breaking occurs when the normal stress exceeds the tensile strength of interface, here denoted by T. The shear sliding occurs when the absolute value of the shear stress reaches the shear strength of interface. For most rocks such as Cox argillite, the macroscopic compressive strength strongly depends on confining pressure in triaxial tests and on the mean stress in the general case. In the RBSM, this pressure dependency can be described by the fact that the shear strength of interface depends on the value of normal stress. Inspired by the Hoek-Brown criterion, a non-linear quadratic shear failure criterion is proposed in this work. For an isotropic