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Damage analysis of rock mass coupling joints, water and microseismicity

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ABSTRACT

The behaviour of rock mass is governed by the properties of the intact rock, the joints and the water conditions. Moreover, this behaviour is also influenced by the temporal and spatial damage evolution patterns of the rock. Thus, in this study, an approach that couples joints, water and microseismicity is proposed to model rock engineering problems. Joints are used to reduce the global properties of the rock mass, water is used to reduce the local properties of the rock mass, and microseismicity are used to reduce the point properties of the rock mass. Using data from the Shirengou iron mine, the effects of water and joints on the properties of rock masses were investigated, and a representative elementary volume of rock mass was determined. Then, a coupled fluid–solid numerical model was established to simulate the evolution of rock mass damage while considering the effects of joints and water. Finally, an inversion model of rock damage based on microseismic moment tensor was proposed. A numerical simulation of rock mass damage that couples joints, water and microseismicity was performed. The rock mass damage mechanism was then analysed. Joints and water were found to significantly affect the damage zones. The rock mass damage estimate would not be accurate without considering the effects of joints and water. Thus, water was the critical factor in the studied damage pattern. Further integration of microseismic data aided in modifying the numerical results and in predicting the damage development. The proposed approach can efficiently assess rock mass damage evolution and provide a basis for rock support.

1. Introduction

Reliable estimates of rock mass properties are essential for almost any slope design and underground excavation (Hoek, 2007). Rock masses are natural geological bodies, and their behaviour depends on the properties of their constituent intact rocks and joints. The properties of rock mass are also influenced by the external conditions to which it is subjected, primarily water and in situ stress (Jing, 2003). In addition, rock mass properties also change through space and time as the rock mass is damaged. The complex combination of these factors makes mathematically representing a rock mass difficult.

Joints often have pronounced effects on the properties of rock masses. In rock engineering, joints are usually too numerous to be taken into account individually. Thus, it is necessary to define the properties of jointed rock masses using averaged and equivalent approaches (Min and Jing, 2003). Considerable effort has been devoted to methods for estimating equivalent properties of jointed rock mass, including both empirical and numerical methods. Empirical methods primarily include the rock mass rating (RMR) (Bieniawski, 1973), Q system (Barton, 2002) and geological strength index (GSI) (Hoek and Brown, 1997). These methods are widely popular for practical applications. However, in published examples, the ranges of rock mass properties are alarmingly large when inadequate laboratory procedures and poor site investigation techniques are applied (Hoek, 2007). In recent years, numerical methods have been developed to determine the elastic properties and strengths of jointed rock masses, or to establish a systematic methodology for homogenization and upscaling schemes (Esmaieli et al., 2010; Min and Jing, 2003; Pariseau et al., 2008; Pouya and Ghoreychi, 2001; Wang et al., 2016; Yang et al., 2014). In comparison with the empirical methods, numerical methods have the advantage that the role of irregular joint system geometries and complex constitutive models of intact rock and joints can be directly included in the derivation of the rock mass properties (Min and Jing, 2003). The most representative and contemporary method is to account for the size effect and define a Representative Elementary Volume (REV) via numerical simulation (Jing, 2003).

Water significantly influences rock mass mechanical properties, which may induce rock-engineering hazards. A series of events, including dam failures, landslides, water inrush incidents and injection-induced earthquakes, are believed to result from water and mechanical interactions (Bidgoli and Jing, 2015; Li et al., 2013; Rutqvist and Stephansson, 2003; Yang et al., 2011). Water affects the mechanical

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properties of rock mass in two ways. The most obvious is the strength reduction due to the effective stress. The concept of effective stress was first developed by Terzaghi (1923). The effective stress law can be expressed as $\sigma' = \sigma - p$, where σ' is the effective stress that controls the deformation and strength of rock, σ is the total stress, and p is the pore water pressure (Hoek and Brown, 1997). Pore water pressure reduces the normal effective stress of the rock, thereby reducing the potential shear resistance which can be mobilized by friction. A more important effect of water on rock mass properties is associated with the deleterious action of water on particular minerals (Brady and Brown, 2006). In some cases, such as in clay shales, water can lead to the complete destruction of the rock. More typically, a strength loss of 20–80% occurs in many rocks as a result of the chemical and physical deterioration of minerals (Hawkins and Mcconnell, 1992; Hoek and Brown, 1997; Vásárhelyi, 2005; Zhou et al., 2016). It appears that most studies focus on only the effects of one of these mechanisms while ignoring the combined effects of these mechanisms.

Furthermore, rock mass properties are time-dependent and loading-dependent. The deformability and strength characteristics of rock mass are inevitably reduced due to rock damage induced by excavation disturbance. In recent years, the microseismic (MS) monitoring technique has developed rapidly as a type of 3D monitoring technology (Durrheim et al., 2007; Feng et al., 2012; Liu et al., 2017; Martini et al., 1997; Tang et al., 2010; Xiao et al., 2016; Xu et al., 2011). Many studies suggest that MS events are indicators of rock damage; therefore, MS monitoring is an efficient method for observing rock damage. This non-destructive technique can achieve fast, accurate and real-time source locating. The combination of numerical simulation and MS monitoring is a promising rock damage analysis method. The key issue is to establish a quantitative relationship between MS events and rock damage variables that modify the rock mass properties. Cai et al. (2001) proposed an anisotropic softening numerical model that used acoustic emission data as inputs to determine the damage state. Furthermore, Cai et al. (2007) presented a method to back-calculate the rock mass strength parameters using MS monitoring data. More recently, Xu et al. (2014) developed a rock damage evolution model based on MS monitoring data for feedback analysis of slope stability. However, no widely accepted theory is currently available on this aspect.

The aim of this study is to develop a method that couples joints, water and microseismicity to analyse rock mass damage (Fig. 1). Based on the data from the Shirengou iron mine, field geological surveys were conducted first. Then, the effects of water and joints on the rock mass were investigated. Next, an inversion model of rock damage based on the MS moment tensor was developed. Finally, a simulation of rock mass damage coupling joints, water and microseismicity was performed.

2. Engineering background and microseismic activity

2.1. Project overview

The Shirengou iron mine is located approximately 90 km from Tangshan City, China. The mine, with a length of approximately 2800 m from north to south and a width of 230 m from east to west, converted from open pit mining to underground mining in 2004. After this conversion, the stability at the pit bottom has been threatened by three primary processes, i.e., water seepage at the pit bottom, high and steep slopes on both sides and uncontrolled illegal extraction. Notably, several pillars are reported to have failed, and enormous sums of money have been invested to maintain the stability of the rock mass.

A MS monitoring system was installed in 2006 with the goal of monitoring stress, analysing failure progress and locating damage zones in the rock mass. As shown in Fig. 2, 22 MS sensors were installed in the system, forming a sensor array along the strike of the mine to cover the whole pit bottom. The study area, as shown in Fig. 3, is close to the lowest level of the pit. A backfill plant was built close to the eastern slope, from which backfill pipes extend downward to underground stopes. On the slope, areas were illegally mined, posing a threat to safe production. Water gathered at the bottom and formed a water pool, which then seeped farther underground. The blue blocks in Fig. 2 denote legal stopes at the −60 m level. In February 2010, an abnormal increase in water seepage was observed. This seepage resulted in drops of water in the drifts, as shown in Fig. 4. Water seeped into underground stopes through the pit bottom and affected production.

2.2. Spatial characteristics of MS activity

To verify the locating accuracy, an artificial blasting test was conducted. The average northing (N), easting (E) and depth (D) positioning errors are 4.12 m, 7.12 m and 5.05 m, respectively. The location error meets the accuracy requirements in engineering practice, and the obtained results are reliable. In total, 586 events were recorded from Oct. 28, 2009, to Mar. 21, 2010. During this period, stopes 1# and 2# were actively mined, and the others had been mined out. Fig. 5 shows the spatial distribution of MS events, which are coloured by moment magnitude and scaled by source energy. As shown, the events mainly clustered below the pit bottom and ranged in depth from −80 m to the surface.

3. Laboratory experiment

3.1. Sample preparation

Sample rock blocks were taken from the Shirengou iron mine. Rock specimens were cored from the rock blocks using a diamond core bit. They were processed following the protocols of the International Society for Rock Mechanics (ISRM). The rock cylinders were 100 mm in height and 50 mm in diameter with flat ends. They were thoroughly checked to avoid any visible flaws. The acoustic wave velocities of the specimens were investigated using TICO, an ultrasonic concrete tester manufactured by Proceq. The specimens with a large discreteness were excluded.

3.2. Petrography

The rock type of the Shirengou iron mine is primarily granitic gneiss. To conduct petrographic studies, representative samples were collected from the rock blocks. They were ground and polished into thin sections that were 30 μm thick. Then, these slides were studied under a microscope, and the minerals were identified based on their optical properties under cross-polarized light. The primary minerals included plagioclase, alkali feldspar, quartz, biotite, and hornblende, as shown in Fig. 6.

3.3. Physical properties

The physical properties of the samples, including density, porosity, ultrasonic velocity, Young's modulus, Poisson's ratio, uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS), were measured and are listed in Table 1. Density and porosity were measured using the buoyancy technique. The ultrasonic velocity was measured using TICO. The UCS and BTS were measured in a press testing machine. The average density of the granitic gneiss was 2.639 $\text{g}\cdot\text{cm}^{-3}$, and the average porosity was 2.05%. The average P-wave velocity was 4887 $\text{m}\cdot\text{s}^{-1}$. The average Young's modulus was 35.90 GPa, and the average Poisson's ratio was 0.27. The average UCS was 137.37 MPa, and the average BTS was 13.52 MPa.

3.4. Effect of water on rock

According to the petrographic analysis, the granitic gneiss from the Shirengou iron mine contains biotite and hornblende, which are quite