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Understanding progressive rock failure and associated seismicity using ultrasonic tomography and numerical simulation

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ABSTRACT

Monitoring the stability of underground rock excavation zones, such as tunnels and underground mines, is critical to their operational safety. The stability of these structures is related to the stress redistribution introduced by the excavation process and disturbance during the operation. Therefore, the characteristics of progressive rock failure behaviour at different stress conditions must be investigated. In this study, we address this problem using a laboratory experiment, coupled with ultrasonic tomography (UT) and numerical simulation. A time-lapse two-dimensional (2D) UT observation was conducted on a granite slab under uniaxial compression. This test was then reproduced numerically by the combined finite-discrete element method (FDEM). This innovative combination of technologies depicted the entire deformation and failure processes at macroscopic and microscopic scales. Quantitative assessments of the results suggested six precursory behaviours indicating the catastrophic failure of the rock: (1) decrease of the average wave velocity perpendicular to the loading direction, (2) increase of the heterogeneity and anisotropy of wave velocity, (3) exponential increase of seismic rate, (4) spatial localization of damage onto the failure plane, (5) increase of the dominance of shear failure, and (6) slight recovery of b-value, followed by a significant drop. An integrated monitoring and analysis of these indicators, accompanied by carefully calibrated numerical simulations, may provide vital information regarding the stability of underground structures.

1. Introduction

Many tunnels and underground structures are constructed through highly stressed brittle rocks. Under high-stress conditions, stress redistribution occurs during and after the excavation which generates energy imbalance in the rock mass. The resultant formation, propagation, and coalescence of microcracks alter the properties of the surrounding rock mass and impact the stability of underground structures (Chang and Lee, 2004). Therefore, fundamental studies evaluating the failure and damage mechanisms of rock at different stress states are of great importance to geo-hazard assessment and operational safety of underground structures.

Under this motivation, we conducted a time-lapse ultrasonic tomography (UT) observation on a granite slab subjected to a uniaxial compression test. UT has been used in medical science since the seventies (Greenleaf et al., 1974), but was only in the eighties that Neumann-Denzau and Behrens (1984) applied this technology to rocks. UT utilizes ultrasonic wave signals (> 20 kHz) to penetrate the sample and image the velocity structure of the sample interior (i.e. tomography). Due to the high scattering and attenuation nature of the ultrasonic wave, UT is typically used for laboratory and small-scale field applications. For example, UT was used by Falls et al. (1992) to investigate micromechanical response of the rock due to hydraulic fracturing in laboratory experiments; Jansen et al. (1993) used UT to monitor and study thermally induced damage in granite in laboratory scale tests; and Meglis et al. (2005) used UT to assess in situ microcrack damage during excavation process of a tunnel.

Ultrasonic wave velocity is influenced by a number of factors including: pressure, crack density and orientation, and pore fluid properties (Johnston and Toksöz, 1980; Lockner et al., 1977; Sayers and Kachanov, 1995; Stanchits et al., 2006). Extracting information regarding such factors from elastic wave velocity using tomography provides a non-destructive approach to study the rock interior and is ideal to study the property changes of the rock during compression tests (Paterson and Wong, 2005). Thus, we conducted a uniaxial compression test on a granite slab and used UT to investigate the progressive failure process of the sample.

On the other hand, micromechanics based numerical simulations

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have been used to improve the understanding of laboratory experiments. For example, Zhu and Tang (2004) used the Rock Failure Process Analysis Code (RFPA) to investigate the deformation and failure process of heterogeneous rock at the mesoscopic level. Mahabadi et al. (2014, 2012b) used the Y-Geo code to study microscale heterogeneity and microcracks on the failure behaviour and mechanical response of crystalline rocks. Hengxing et al. (2010) used grain-based Universal Distinct Element Code (UDEC) to simulate the role of micro-heterogeneity in controlling the micromechanical behaviour and the macroscopic response of granite when subjected to uniaxial compression loading. Hazzard et al. (2000) used Particle Flow Code (PFC) to examine crack nucleation and propagation in brittle rocks and the associated energy release.

In order to improve our understanding of the laboratory observations, we used the two-dimensional (2D) combined finite-discrete element method (FDEM) to numerically reproduce the uniaxial compression test. The FDEM model synthesizes the macroscopic behaviour of materials from the interaction of micro-mechanical constituents and provides insights into the failure processes of rocks from elastic and inelastic deformation to fracturing (Mahabadi et al., 2012a; Munjiza, 2004). FDEM was also used to simulate acoustic emission and micro-seismic activity (Lisjak et al., 2013; Zhao, 2017; Zhao et al., 2015, 2014).

The innovative combination of UT observations and FDEM simulations allowed us to characterize the deformation and brittle failure processes of the rock at macroscopic and microscopic scales. We quantitatively analysed the velocity anisotropy and statistical characteristics of simulated acoustic emission (AE). These results provided detailed information on the damage evolution in the rock and the variation of velocity anisotropy. Six evident precursors of the rock failure were identified, and by comparing with laboratory tests, field observations, and numerical simulations reported in the literature, we can infer that these precursors, which can also be obtained from field seismic monitoring, may provide information for forecast and mitigate rock mass catastrophic failure.

2. Material and methods

2.1. Material and experiment set-up

The rock sample investigated in this study is a Fangshan granite slab 110 mm wide, 220 mm long, and 30 mm thick. Fangshan granite is a coarse grain rock consisting of three main mineral phases: feldspar, quartz, and biotite, with an average grain size of 2.6 mm. A uniaxial compression test was conducted on this sample using an MTS–1000KN hydraulic test system (Fig. 1a), which is able to control the axial load with less than 0.5% error. During the compression test, the axial load was increased at a rate of 6 kN/min (~1.82 MPa/min). At the initial (i.e. 0 MPa), and every 20 MPa incremental stress level, a UT test was performed.

2.2. Ultrasonic tomography (UT)

The UT system used in this study consists of five main components (Fig. 1):

(1) Ultrasonic transducers. Two types of transducers were used in this study, Physical Acoustics Corporation (PAC) Nano-30 and Valpey-Fisher Pinducer model VP1093. The PAC Nano-30 transmitter has a bandwidth of 125–750 kHz, while the VP1093 transmitter has a bandwidth of 10–10,000 kHz. The mixed usage of transducers was due to the limited number of either type in our lab; however, as received signals showed no significant quality difference between the two types, we did not consider the error associated with the differences in used transducers. Ten transducers were placed on the left and right sides of the slab, with 20 mm vertical spacing, and three transducers were placed at the middle of the top and bottom sides of the slab, with 25 mm lateral spacing (Fig. 2a and b). These transducers were coupled to the sample using epoxy. Transducers on the top and bottom sides of the sample were embedded in specially designed slots on the loading platens.

(2) An ultrasonic waveform generator (National Instrument NI–5421). The NI–5421 device, which was configured with the PXI-100B chassis, has a frequency range from < 1 mHz to 43 MHz. We used a computer to control a digital to analogue channel of this device to generate a square wave signal at 1 MHz with a peak-to-peak voltage of 1 V, which was then amplified by an amplifier (Pintek HA–405) to 100 V.

(3) A custom multi-channel switch was used to replicate multiple identical ultrasonic signal traces from the amplified signal.

(4) A custom ultrasonic switchbox, operated by an NI–2567 device (not shown in the figure). The ultrasonic switchbox was used for switching sensors between transmitting signal and receiving signal during the experiment. Each UT test consisted of four stages, and during each stage, transducers on one side of the sample acted as transmitters while transducers on the other three sides acted as receivers. This operation started from the left side (i.e. transducers 1–10) and carried on counterclockwise (Fig. 2b).

(5) A 32-channel data acquisition system, which consists of 16 PAC PCI-2 boards. This system can acquire analogue signals from the transducers, convert them to digital signals and transmit them to the computer. The wave velocity between a source and receiver transducer pair can be directly estimated using the source-receiver distance divided by the travel time. This velocity is the result of the effects of the media along the wave path (i.e. raypath), and it only indicates the overall variation of velocity. In the following discussions, we refer to it as averaged velocity (v_a). We calculated the averaged P-wave velocities between transducer pairs perpendicular ($v_a^{\perp}$) and parallel ($v_a^{\parallel}$) to the loading direction and examine their variations against the stress condition. Note that at high stress levels, transducers 11 and 13 were loosely coupled due to sample deformation. In order to study $v_a^{\parallel}$ under high stress, we examined v_a between transducer 12 and transducers 24, 25, and 26.

In order to obtain the spatial variation of wave velocity in the rock, inversion of the velocity taking into consideration the rock heterogeneity (i.e. tomography) was required (Aki and Lee, 1976). Tomography was performed on grids with a grid cell size of 10 mm × 10 mm, resulting in a 2D velocity map of the sample. The raypath lengths were estimated using a wave front ray-tracing technique, and the damped least square (LSQR) iterative inversion method was applied, using a damping factor of 10, with 20 iterations (Paige and Saunders, 1982; Zhao et al., 1992). To obtain the initial velocity values of the iterative inversion, a linear fit of travel time and the travel distances between all source-receiver pairs at each stress level was carried out, and the slope of this fitted curve was used as the initial value in the inversion. Moreover, to constrain the inversion, the velocity of each grid was limited to the range of 3500–5500 m/s.

2.3. Combined finite-discrete element method (FDEM)

The FDEM model consisted of a 220 mm × 110 mm longitudinal section representing the rock sample and two rectangles at the top and bottom of the rock sample representing the loading platens. The model was discretized using a finite-element mesh with an average element size comparable to the rock sample grain size (i.e. 2.6 mm). The model recreated the Fangshan granite sample that the mineral phases were represented by approximately 10,000 elastic triangular elements connected to each other by four-node cohesive crack elements (CCEs) that represent grain boundaries. These CCEs can deform elastically, yield, and break according to the principles of non-linear elastic fracture mechanics, which allows FDEM models to capture the deformation and