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Exploration of damage evolution in marble due to lateral unloading using nuclear magnetic resonance

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ABSTRACT

Multi-scheme lateral unloading confining pressure tests on marble specimens were conducted by using an MTS 815 electrohydraulic servo testing machine, and nuclear magnetic resonance (NMR) tests were performed on the unloaded specimens for the first time to investigate the mesodamage evolution characteristics of the unloading rock. The change laws of stress-strain curves, rock porosity, and NMR parameters during the failure process were obtained. The results indicate that the rock sample exhibits evident plastic strain softening and shear dilation characteristics during the unloading process, and that the deformation modulus, Poisson's ratio, and axial compression strength decrease continuously with a decrease in the confining pressure. Given the different levels of unloading points, there are differences in the failure characteristics. When the unloading intensities were lower than 90%, the microfissures inside the sample extended uniformly, and the internal damage to the marble was mainly caused by the increases in the number of small pores. When the unloading intensities exceeded 90%, interpenetrating fissures developed and extended rapidly, and rock damage was mainly caused by the increase in the number and size of the large pores. The spectrum peaks area of large pores play a dominant role in the development of marble porosity. Furthermore, the development process of microcracks and fractures in rock specimens is dynamically indicated by NMR imaging.

1. Introduction

As a complex geological material, a rock mass is subjected to the combined influence of engineering activity and geological processes. Internal cracks accumulate and develop constantly and subsequently produce macrographic time-effect fractions that may lead to the failure of the rock mass. Several previous studies (Eberhardt et al., 1998; Basu and Mishra, 2014; Walton et al., 2015; Dob et al., 2016) indicated that stress-induced instability, squeezing, and large deformations of a rock mass mainly correspond to the results of the dilatancy and fracturing behavior including the pre-peak damage, microcrack initiation, crack extensions, and fracture coalescence. Extant studies (Gharouni-Nik and Fathali, 2013; Cao et al., 2015; Yang, 2016) increasingly considered rock deformation and failure as the result of damage and cracking that result in volume expansion. The mechanical behavior of rock under loading has been widely investigated, and a set of effective methods of tests and theories were established to include failure features under uniaxial or triaxial compression, the release of energy, and the relationship of deformation, confining pressure, and the failure process (Zhou et al., 2012; Mahanta et al., 2017).

Recently, disastrous accidents caused by engineering unloading were universally observed and included bottom bulging, roof fall, drop lumps, and collapses in the excavations of a tunnel; and landslides, collapses, rock bursts, and caked drill cores owing to engineering excavation. Extant studies examined the unloading failure of a rock mass given the demands of rock mechanics and engineering practices. Most previous experimental studies typically adopted a static loading approach in which the damage-dilatancy and post-peak failure behavior of the rock significantly differed from those during underground excavation in which the surrounding rock was continuously under an unloading confining pressure state. Several studies demonstrated that the rock mechanical behavior and failure characteristics under unloading were significantly different from those under loading (You and Hua, 2002; Xie et al., 2004). An examination of the unloading failure characteristics of a rock mass is extremely significant both in terms of theory and in practice, and the fatigue damage evolution of rocks is crucial for the stability of engineering structures.

Unloading failure was first reported by Poncelet, who investigated the failure process in glass specimens subjected to uniaxial compression and examined the formation of small cracks at the interface between the loading platen and the glass specimen (Alkana et al., 2007). Kimberley et al. (2010) observed the initiation and growth of cracks of

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single-crystal quartz during the removal of applied loads from specimens. The researchers inferred that residual stresses from inelastic strains accumulate during loading. These residual stresses are relieved through creep if the load is removed slowly, but if the load is removed quickly, then the stresses are released through crack initiation and growth. Furthermore, Wu (1997) also examined the unloading characteristics of rock material via triaxial tests and obtained a few good results. Kaiser et al. (2001) indicated that both the directions and values of the principle stresses changed during excavation and that the stress path evidently impacts the excavation stability. Based on the elastoplastic theory (Chen, 2005) and given the differences in the evolution process of the internal variables between the loading and unloading stress paths, there are several differences in strength and deformability, and the rocks exhibit significantly different deformation and failure characteristics under the two stress paths. Zhang et al. (2013), Qiu et al. (2014) and Li et al. (2017) performed unloading tests to examine the damage, failure properties, and constitutive models that are meaningful to understanding the rock response under unloading conditions, and indicated a few important results.

However, there is a paucity of extant studies that conducted experimental tests corresponding to the surrounding rock under a confining pressure multistage unloading state. Different unloading paths were not sufficiently considered when investigating the damage evolution of unloading rock at the microscopic level. Conversely, the mechanical behavior of natural rock was investigated experimentally in extant studies, and various laboratory techniques including scanning electron microscopy (SEM) (Yang et al., 2009), infrared thermal imaging (Wu et al., 2002), computerized tomography (CT) (Nasseri et al., 2011), and acoustic emission (AE) (Aker et al., 2014) were used to observe the damage process of rock materials under load pressure. However, the application of these techniques to practical situations is difficult owing to rigorous test conditions, expensive infrastructure, and facilities.

Nuclear magnetic resonance (NMR) spectroscopy can be used to investigate porosity changes in a meticulous and intensive manner (Zargari et al., 2015). It exhibits significant application value as a practical test in areas including medical diagnosis, agriculture, food, and polymer materials and in the fields of geotechnical engineering, the mechanism of reservoir accumulation, oil and gas exploration and development, carbon sequestration, and investigating damage caused in rock mass (Li et al., 2016). Changes in porosity cause macro mechanical changes, and it is important to examine the changes in rock porosity by using NMR spectroscopy and to reveal the effect of porosity changes during the failure process on the macroscopic mechanical properties of rock and the relationship between these effects.

In the present study, multistage lateral unloading tests were conducted by using an MTS 815 electrohydraulic servo rock mechanics testing machine. The damage evolution of marble under different unloading intensities was measured by using NMR technology for the first time. Furthermore, the characteristics of NMR T_2 distribution, porosity, T_2 spectrum, and magnetic resonance imaging during the failure process were obtained and analyzed. This study demonstrates a new method to investigate the damage evolution characteristics of rocks.

2. Basic test

2.1. Testing instrument

The lateral unloading tests were conducted on an MTS 815 electrohydraulic servo rock mechanics testing machine, as shown in Fig. 1. The T_2 spectrum variation characteristics, rock porosity, and NMR images of the rock sample during the failure process were obtained by the AniMR-150 nuclear magnetic resonance (NMR) test system, as shown in Fig. 2.

Fig. 1. MTS 815 electrohydraulic servo rock mechanics testing machine.

Fig. 2. AniMR-150 nuclear magnetic resonance (NMR) test system.

2.2. NMR technology

Many nuclei such as hydrogen nuclei are characterized by a macroscopic magnetic moment resulting from an angular momentum of spin inherent to each proton and neutron of the nucleus. Generally, in a natural state, the spin axes of the hydrogen proton are random. However, they will be aligned in the direction of an external static magnetic field. Owing to the external magnetic field, nuclei are in an equilibrium states and are able to absorb electromagnetic energy. When a subsequent radio frequency pulse is applied, the magnetic moments will transform from their equilibrium state onto the perpendicular transverse plane. As the magnetic pulse is removed, they return to their initial positions, giving off energy to the surroundings and inducing magnetic signals, which can be measured and then be analyzed. The magnetization decay signal is featured by the relaxation time, which is associated with the type and properties of pore-filling fluids as well as their interactions with pares, pore size distribution, and surface relaxivity. Three types of relaxation, i.e., bulk relaxation, surface relaxation, and diffusion relaxation, are involved in the transverse relaxation time T_2 for fluids in rock pores. Generally, the bulk and the diffusion relaxation can be neglected for water-saturated rocks. Therefore, T_2 can be simply expressed as (Anovitz and Cole, 2015)

$$\frac{1}{T_2} \approx \frac{1}{T_{2F}} = \rho\left(\frac{S}{V}\right) \tag{1}$$

where T_{2f} is the transverse surface relaxation time (ms); ρ is the surface relaxivity, which is a factor for the intensity of the transverse surface relaxation ($\mu m/ms$); and S/V is the surface-to-volume ratio of the pore.

Based on the theory of magnetic nuclear resonance, the T_2 decay characteristics of the hydrogen protons are different owing to their different locations in the pores. By adding a gradient magnetic field to