Engineering Rock Mechanics

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List of Abbreviations

AECL	Atomic Energy of Canada Limited
BDT	Brazilian Disk Test
CB	Chevron Bend
CCNBD	Chevron-Notched Brazilian Disk
CDG	Completely Decomposed Granite
CI	Crack Initiation
COD	Crack-Opening Displacement
CSTBD	Cracked Straight-Through Brazilian Disk
DEM	Distinct Element Method
DI	Depth Index
DPI	Drill Parameter Interpretation
FEM	Finite Element Method
FFRC	Free–Free Resonant Column
FPZ	Fracture Process Zone
GCD	Gouge Content Designation
HDG	Highly Decomposed Granite
ISRM	International Society for Rock Mechanics
LPD	Load-Point Displacement
LPI	Lithology Permeability Index
MTS	Maximum Tangential Stress
MWD	Measurement While Drilling
NGI	Norwegian Geotechnical Institute
REV	Representative Elementary Volume
RQD	Rock Quality Designation
RQD	Rock Quality Designation
SCB	Semi-Circular Bend
SNDB	Straight Notched Disk Bending
UCS	Uniaxial Compressive Strengths
XRD	X-Ray Diffractometry

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Preface

Engineering rock mechanics is the discipline used to design structures built in rock. These structures encompass building foundations, dams, slopes, shafts, tunnels, caverns, hydroelectric schemes, mines, radioactive waste repositories and geothermal energy projects: in short, any structure built on or in a rock mass. The text Engineering Rock Mechanics covers the basic rock mechanics principles. First chapter presents a comparison of the simulation of uniaxial compressive damage and true triaxial unloading failure by using a combination of experimental and numerical simulation. Second chapter focuses on stress/strain-dependent properties of hydraulic conductivity for fractured rocks. In third chapter, the relationships between the drill parameter interpretation (DPI) factors water and fracturing are examined in relation to grout volumes. The purpose of fourth chapter is to find out the condition to create slabbing failure under uniaxial compression and to determine the slabbing strength of hard rock in the laboratory. Fifth chapter reviews several landslide case histories and provides guidelines for characterizing sheeting joints and determining their shear strength. In sixth chapter, we investigate the mode I fracture toughness using a semi-circular bend (SCB) specimen. Seventh chapter presents the measured hydraulic conductivity results and the relationship among the hydraulic conductivity, RQD, DI, GCD, and LPI. Effect of partial water saturation on attenuation characteristics of low porosity rocks has been investigated in last chapter.

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Chapter 1

AN EXPERIMENTAL STUDY ON DEFORMATION FRACTURES OF FISSURED ROCK AROUND TUNNELS IN TRUE TRIAXIAL UNLOADS

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ABSTRACT

Joints and cracks are frequently encountered in underground rock mass. During the process of tunnel excavations or other underground construction, the rock will be exposed suddenly, and such sudden unloading process will cause crack expansion and destabilize the rock structure. In order to investigate the crack behaviour during this process, a true triaxial loading apparatus with a computer-controlled electrohydraulic servosystem was established, and a series of true triaxial loading and unloading experiments was conducted by using concrete specimens containing inclined cracks with inclinations of 15°, 30°, 45°, 60°, and 75°. The stress-strain behavior and the failure property of rock models during unloading process were obtained, and, additionally, the coefficient of brittle stress drop was investigated. The uniaxial compression tests were simulated by using finite element method.

INTRODUCTION

Tunnels constructed for road traffic and mineral mining in China can reach depths of 1000–2000 m. Deep roadway excavation usually results in unidirectional or two-direction unloading, which can weaken the stability of the surrounding rocks, leading to rock damage, typically unloading damage [1, 2]. Deep roadway excavation is a high-stress unloading process and may cause severe expansion of the rock in the unloading direction. The damage occurs mainly as tension fractures, as well as tensional shear fracture and shear fracture [3]. The failure characteristics of basalt, granite, and sandstone under unloading conditions have been studied extensively [4–7]; D. Huang and R. Q. Huang [8] examined the brittle stress drop of granite under equal triaxial confining pressure. Research on the related unloading failure mechanism based on damage-fracture mechanics is in progress to establish a complete stress-strain model under unloading conditions, including the nonlinear strengthening stage, stress drop stage, and strain softening stage [9].

Underground rock mass is subjected to three-direction loads, and they are not the same due to many factors involved, such as the geological structure, the nearby volcanic eruptions, or earthquakes. Joints and cracks are frequently encountered in the underground rock mass, and such cracks usually play a dominant role in the stability of brittle material structures. During the process of rock excavation, the cracks will be exposed and the state of stresses to which the cracks are subjected will alter, and subsequently, the cracks may propagate and may lead to disasters, such as rock burst. Therefore, it is necessary to study the behaviors of cracks during the unloading process.

Zhu et al. [10–15] conducted a number of studies on fracture criteria for a single crack and collinear cracks under compression loading conditions, but the crack behavior during the unloading process has not been focused. D. Huang and R. Q. Huang [8] conducted experiments to study the evolution of central fracture transformation and extension under equal confining pressure and unloading conditions. Xu and Jiang [16] discussed rock transformation and destruction in different loading stress paths based on a true triaxial experiment, and simulations of rock multistress path evolution under high ground stress were performed by Chen and Feng [17]. True triaxial experiments can simulate several stress paths and represent the complicated underground working environment of a mine. Underground excavation is dangerous because of the existence of cracks in the surrounding rock. Based on the photoelastic experimental method, Wang et al. [18] investigated the stress intensity factors of cracks surrounding tunnels with variable fracture inclination and discussed the mechanisms of unstable tunnel destruction caused by cracks. However, the unloading behavior of tunnels has not been addressed.

In this study we carried out triaxial unloading failure experiments by using a true triaxial loading device which is a computer-controlled electrohydraulic servo system. A group of physical models with different inclination angle cracks close to the unloading surface was conducted and was loaded by the true triaxial device. The stress-strain characteristics and failure property of the rock models with different inclination angle cracks during unloading process were obtained. Additionally, the coefficient of brittle stress drop based on these physical models was determined.

EXPERIMENT

Preparation of Physical Models

The materials of lime, cement, and silver sand at a ratio of 4 : 7 : 11 were used to construct the physical models. Hardened lime is brittle but has lower surface density and low strength; hardened cement has lower brittleness but high strength. Using cement and lime as gel materials creates a model that is brittle like rock and also of high strength and elasticity. The model size was 150 × 150 × 300 mm, the dry density ρ was about 2750 kg/m^3 , and the regular triaxial experiment elasticity E was 2.4 GPa, with a Poisson ratio n of 0.23.

Five different models were created with crack inclinations of 15°, 30°, 45°, 60°, and 75°; each model was made of six materials with a crack length of 50 mm. The spatial relationship is shown in Figure 1. To form the crack, the model material was poured over a 0.2 mm thick rigid plastic film that represented the crack. When the desired shape and strength were obtained, the material was heated and the plastic film was removed. When the material cooled, the crack closed naturally.

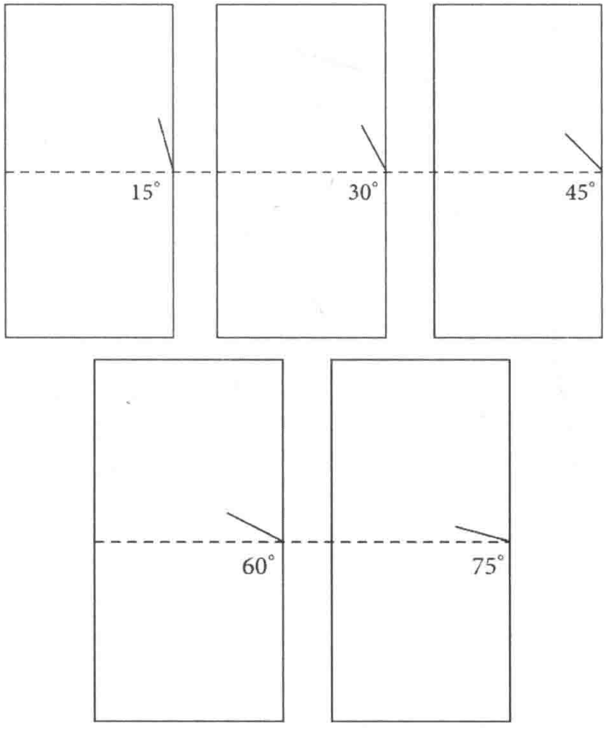


Figure 1: Diagram of the testing models.

The specimens used in the experiment were large; therefore, joints and cracks often occur in the interior of the specimen, affecting the experimental results. Hence, a special processing method was used that is suitable for analyzing naturally closing cracks. The method uses the thermal expansion and contraction properties of the material. A cutting method is used to create the cracks in the rock specimens, which results in a certain distance between the faces of crack; this affects the curve of the vertical axial stress versus strain. The mechanical properties of the specimens are similar to those of rock and the parameters of density and E are very close, as shown above.

Loading/Unloading Path

In the experiment, a true triaxial experimental apparatus was established by using computer-controlled electrohydraulic servo system, which was different from the MTS test machine [19]. The position of the model under load testing is shown in Figure 2. The lateral loads were hydraulic loads. The testing equipment measures and records the surface pressure and displacement of the specimens.

The feasibility of the testing method was first verified under loading and unloading conditions. Loading the specimens causes the cracks to extend and leads to destruction of the specimen. The experiment included two tests, a reference test and an unloading test, to confirm that material crack extension and connection are caused by unloading. The specific plan is as follows.

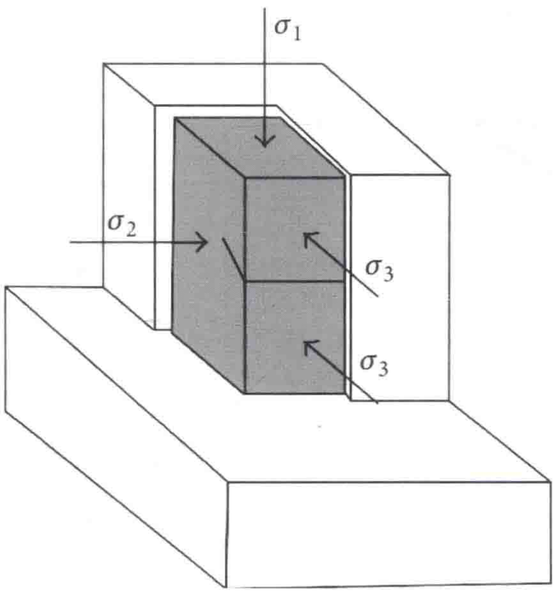


Figure 2: Diagram of load of testing model.

Reference Test

(a) Slowly add triaxial pressure to the designed load (15.6 MPa in the axial direction, 6.5 MPa in the lateral direction, and 5.7 MPa to the unloading surface). The vertical axial compression pressure controls the displacement (at a loading rate of 0.017 mm/s); the confining pressure controls the stress (at a loading rate of 0.03 MPa/s). (b) Maintain these conditions for 30 s. (c) Slowly unload in the axial direction at an unloading rate of 0.017 mm/s. Once reaching zero, unload the triaxial pressure at an unloading rate of 0.03 MPa/s.

Unloading Test

(a) Slowly add triaxial pressure to the designed load (15.6 MPa in the axial direction, 6.5 MPa in the lateral direction, and 5.7 MPa to the unloading surface). The vertical axial compression pressure controls the displacement (at a loading rate of 0.017 mm/s) and the confining pressure controls the stress (at a loading rate of 0.03 MPa/s). (b) Maintain these conditions for 30 s. (c) Quickly unload to the unloading surface at an unloading rate of 2 MPa/s while maintaining all the other conditions at their original state.

Upon loading, increase the pressure on the top surface, the excavated face, and the side of the model while constraining the other sides by normal displacement (Figure 2; σ_3 is the load of the excavated face).

Comparing the two tests for the same crack angle we see that, in the reference test, the materials remain intact after unloading and are in a state of densification, with no crack extension. However, in the unloading test, the materials are destroyed. This indicates that the extension and merging of the cracks are indeed caused by unloading.

NUMERICAL SIMULATION AND ANALYSIS

Since the studies by Griffith [20] showed the propagation of crack instability and the growth criterion introduced by Irwin [21] based on the stress intensity factor, fracture theory has undergone significant development. However, previous studies were limited to simple fracture behavior. Theoretical models that examined the mechanism for crack initiation, expansion, and coalescence were established in recent years with the development of experimental techniques and computer technology. This paper presents a comparison of the simulation of uniaxial compressive damage and true triaxial unloading failure by using a combination of experimental and numerical simulation.

The paper uses the finite element software ANSYS to analyze and simulate crack initiation, expansion, and coalescence under uniaxial compression by using the theory based on the overall failure criterion of rock energy dissipation [22]. For the two-dimensional model, $\sigma_2 = 0$. Thus, the formula found in the literature reduces to the following formula:

$$\sigma_c^3 = (\sigma_1 - \sigma_3)\left(\sigma_1^2 + \sigma_3^2 - 2\nu\sigma_1\sigma_3\right),$$

$$\sigma_t^3 = \sigma_3\left(\sigma_1^2 + \sigma_3^2 - 2\nu\sigma_1\sigma_3\right). \qquad (1)$$

The model uses a crack angle of 45° and uniaxial compression as the boundary condition (Figure 3).

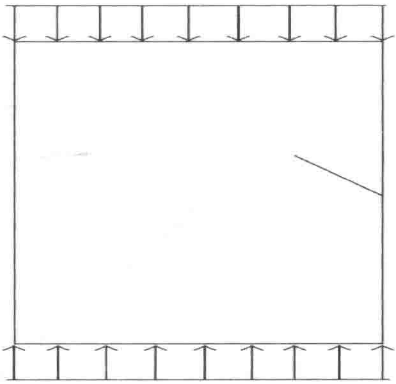
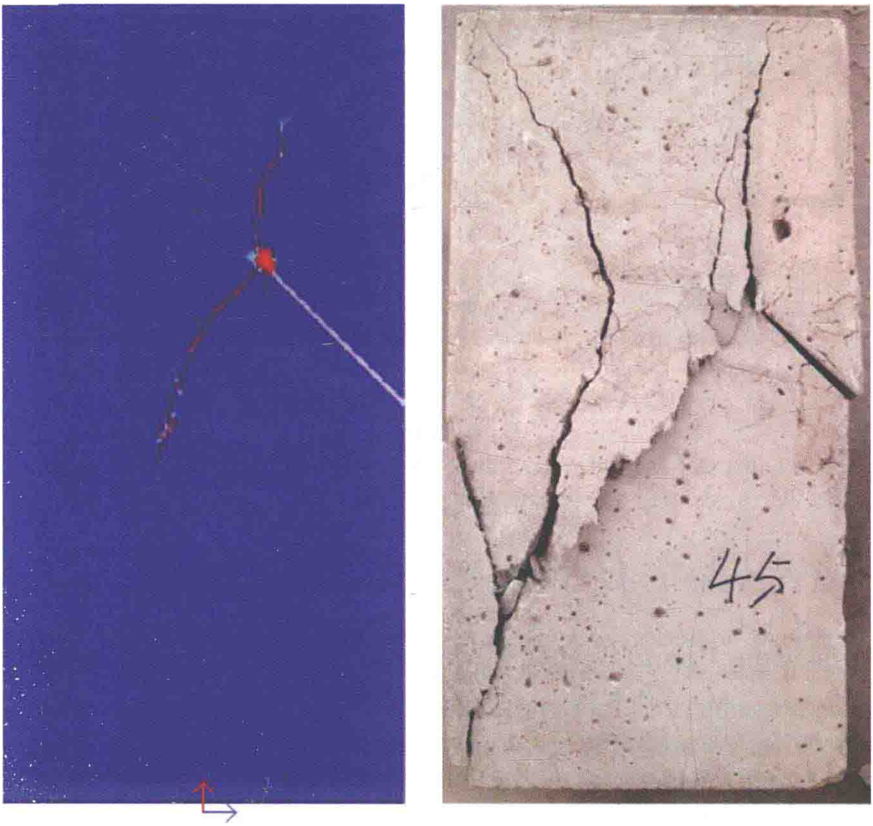


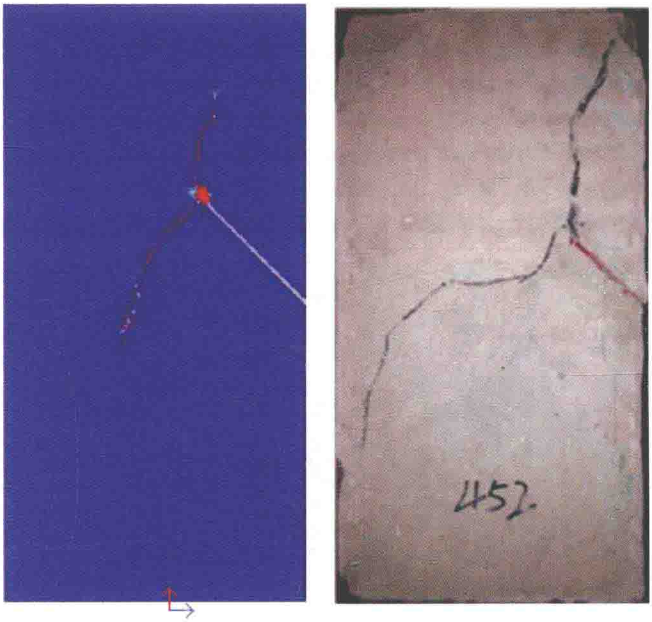
Figure 3: The numerical simulation models.

The numerical results show that the expansion mode of the crack, combined with predictive modeling based on fracture mechanics theory, is similar to that observed in the uniaxial compression test. In particular, the trajectories of the preexpansion mode are close to each other (Figure 4). These results, however, are quite different from the experimental results under triaxial unloading conditions (Figure 5). Under unloading conditions, it is difficult to use the existing and established theories to discuss and analyze the damage.



(a) (b)

Figure 4: Failure of fissured rocks: photos and numerical simulation. Numerical simulation (a) and uniaxial compression test (b).



(a) (b)

Figure 5: Failure of fissured rocks: photos and numerical simulation. Uniaxial compression test (a) and true triaxial unloading test (b).

ANALYSIS OF EXPERIMENT RESULT

Stress-Strain Characteristic Curve under Unloading Condition

The experimental results were processed by the Origin software package to construct the stress-strain curves which were then smoothed. Figure 6 shows typical complete axial-directional stress-strain curves under unloading conditions with crack inclination of 15°, 45°, and 75°. During the initial loading stage, the downward curve (OA) is obvious and presents a typical densification. As the crack angle becomes wider, the axial nominal strain generated when the crack completely closes increases. Therefore, as the crack becomes bigger, the densification becomes more obvious. This process is a reflection of the crack close-up in the loading phase. Before reaching the peak value of the axial-directional stress, the curve shows nonlinear deformation, but no yield platform. Judging from the after-peak curve, in the unloading phase, the axial-directional stress falls quickly to the residual strength level, with a sharp curve slope and small axial-directional deformation. It shows clear characteristics of brittle stress drop. In addition, for the models with a large inclination, the curve