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Numerical investigation on the dynamic strength and failure behavior of rocks under hydrostatic confinement in SHPB testing

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ABSTRACT

Rocks in the deep underground engineering are commonly subjected to hydrostatic in-situ stresses and dynamic loadings simultaneously. Accurate characterizations of the strength and the failure behavior of rocks under coupled hydrostatic confinement and dynamic loading are crucial for the safety of engineering projects. Via discrete element method (DEM), this study systematically investigates the mechanical behavior of granitic specimens under different hydrostatic confinements in split Hopkinson pressure bar (SHPB) testing, regarding seven hydrostatic confinements varying from 0 to 225 MPa and six strain rates varying from 500 to 1500 s^{-1}. Our results show that the dynamic strength of hydrostatic pressurized rock specimen increases with increasing strain rate, while the rate sensitivity of rock strength decreases as the hydrostatic confinement increases. Simulated acoustic emission distribution demonstrates that the hydrostatic confinement significantly affects the dynamic failure patterns of rocks; as the confinement increases, the failure mode changes from a mixed failure of surface splitting and inner X-type shear to a failure in single shear band. Moreover, for a given strain rate, more integrated rock fragments are generated and the fragment size distribution becomes wider with increasing hydrostatic confinement. In addition, the mass cumulative fraction versus fragment size curves of specimen under different hydrostatic confinements can be characterized by a three parameters generalized extreme value distribution function.

1. Introduction

With increasing demand for resources and energy, a number of rock engineering practices are gradually turning to the deep underground, where pre-confined rocks are commonly subjected to dynamic loadings. The pre-confinement can be the in-situ stress (i.e., the gravity or the tectonic stress); the dynamic loading may be induced by blasting, rock bursts or earthquakes. Understanding the coupled effects of confinement and dynamic loading on the strength and failure behavior of rocks is crucial for disaster prevention and mitigation in the deep underground engineering applications.

Existing attempts to understand the effect of confinement on the mechanical properties of rocks were mainly concentrated on the quasi-static loading cases. Some researchers have conducted triaxial compressive tests on rocks, and they concluded that the strength and the peak strain of rock specimens increase with increasing confinement.[1–3] Using the standard dynamic testing facility, i.e., split Hopkinson pressure bar (SHPB), the effect of strain rate on the dynamic mechanical responses of rocks has been studied.[4] Dai and Xia[5] and Cai et al.[6] concluded that the dynamic strength and peak strain of rocks increase obviously with increasing strain rate. Li et al.[7] reported that the breakage degree of rocks turns weaker with decreasing strain rate. This dynamic testing method using the SHPB system has been suggested by the International Society for Rock Mechanics (ISRM) for determining the dynamic uniaxial compressive strength of rocks.[8]

In practical underground engineering, rocks are generally subject to the static pre-confinement and the dynamic loading simultaneously[9,10]; the mechanical behavior of rocks under coupled pre-confinement and high-rate loading significantly differs from that in the quasi-static triaxial test or the dynamic uniaxial compressive test.[11,12] Some researchers investigated the coupled effects of the high strain rate and confinement on the mechanical properties of rocks using two types of modified SHPB systems. For one, the sample was coated with a metal sleeve to apply the passive lateral confinement.[13,14] Yuan et al.[15] conducted dynamic tests on rock specimens at the passive confinement up to 132 MPa and the strain rate up to 1860 s^{-1}; they concluded that the dynamic compressive strength increases with increasing confinement and strain rate. However, this technique cannot provide a constant

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confinement on the specimen during the entire testing, and the friction between the sleeve and the specimen is uncertain. For another modified SHPB system, the confinement is provided by a servo-hydraulic load frame. For examples, Christensen et al.[16] and Sato et al.[17] performed experiments on pre-confined rock specimens at the strain rate of the order $10^2\ s^{-1}$. They obtained the dynamic stress-strain curves of rocks with different confinements, which revealed that the dynamic strength increases linearly with the increase of confining pressure.

It is known that rocks in the deep underground environment are subjected to triaxial pre-confinements. As reported by Hoek and Brown[18] and Zhu[19], the ratio of horizontal stress and vertical stress is around 1.0 as the depth exceeds 1000 m. Zang and Stephansson[20] further suggested that the three principal stresses of rocks in the deep underground are almost equal, i.e., hydrostatic stress state. Considering the difference of mechanical behavior between deep rocks and shallow rocks, it is essential to investigate the dynamic mechanical properties of hydrostatic pressurized rocks.[21] Li et al.[11] and Frew et al.[22] proposed an improved SHPB system for charactering the mechanical properties of rocks under coupled triaxial confinement and dynamic loading. Hokka et al.[23] conducted experiments on the granitic specimen at the hydrostatic confinement up to 225 MPa and the strain rate up to $600\ s^{-1}$. They found that the dynamic strength of the hydrostatic pressurized granite increases with increasing strain rate, and the strain rate sensitivity distinctly decreases under a higher confinement.

In the available literature, however, the effect of confinement on the dynamic fracture process and the fragmentation of rocks have never been thoroughly investigated, resulting in a limited understanding of dynamic failure patterns and fragment size distributions of hydrostatic pressurized rocks. Fortunately, the numerical method, e.g., the discrete element method (DEM), provides an efficient access to characterize the dynamic fracture and fragmentation behavior of rocks. Compared with laboratory tests, DEM simulation owns the following advantages: (1) the exactly identical numerical specimen is available in the repeated simulations, eliminating the disturbance of geometrical errors or material heterogeneity of rock samples in the laboratory experiments; (2) all the numerical data are accessible at any arbitrarily instantaneous moment, even in the high-rate loading conditions; and (3) the progressive fracture processes of rocks involving the initiation, coalescence and propagation of micro-cracks can be explicitly exhibited by the breakage of inter-particle bonds. Moreover, the fragments of rocks can be reliably traced and characterized as well by virtue of a fragmentation detection algorithm in DEM.[24] Indeed, DEM has been proved to be an efficient method for reproducing the mechanical behavior and failure process of rocks under dynamic loading conditions.[25,26]

In this study, we systematically investigated the dynamic strength and failure behavior of rocks under hydrostatic confinement in SHPB testing via DEM. This paper is organized as follows. Section 2 briefly introduces the numerical model in DEM, followed by a detailed validation of the model to simulate the dynamic SHPB tests on hydrostatic pressurized specimens, involving the stress wave propagation, the dynamic stress equilibrium and the stress-strain curves. Section 4 comprehensively reports the numerical results, including the effects of hydrostatic confinement on the dynamic strength, the fracture processes and the fragment size distribution. Section 5 concludes the whole study.

2. Numerical model in DEM

2.1. Brief description of DEM

The DEM open source code ESyS-Particle[27–29] is employed herein to investigate the dynamic strength and failure behavior of cylindrical

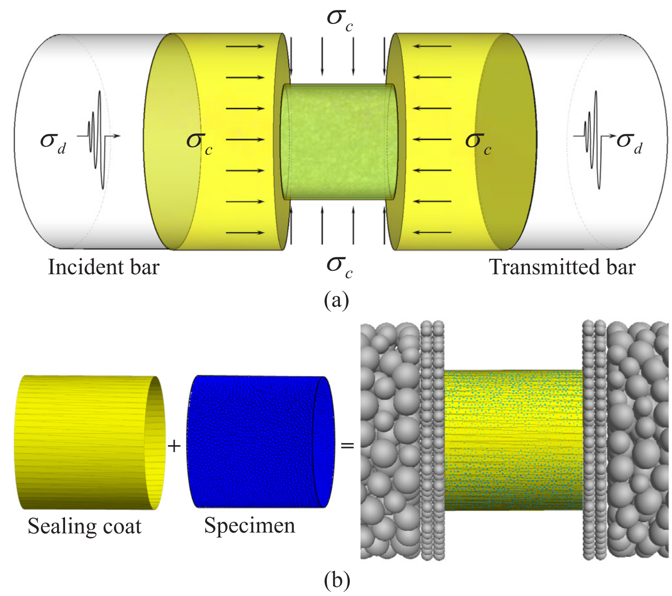

Fig. 1. (a) Schematic of split Hopkinson pressure bar device with hydrostatic confinement, (b) three-dimensional discrete element model.

rock specimens under various hydrostatic confinements in SHPB tests. In the DEM model, the rock specimen is simulated as an assembly of densely packed and bonded rigid spherical particles, in which two adjacent particles are cemented together by a bond particle model (BPM).[30–32] The following breakage criterion of BPM is employed in this study:

$$\frac{F_{nb}}{F_{nbMax}} + \frac{F_{sb}}{F_{sbMax}} + \frac{M_b}{M_{bMax}} \geq 1 \tag{1}$$

where F_{nb}, F_{sb} and M_b denote the normal bond force, the shear bond forces and the bending moment, respectively, and their maximum values are represented by F_{nbMax}, F_{sbMax} and M_{bMax}, respectively.

After the bond breaks, the particles will experience a cohesionless frictional interaction process once they contact with each other. The contact forces can be calculated as follows:

$$F_{nc} = K_n U_n,\ dF_{sc} = K_s dU_s \tag{2}$$

where F_{nc} and U_n denote the normal force and normal displacement between two particles, respectively, K_n and K_s are the normal and shear contact stiffness, respectively, dF_{sc} and dU_s is the incremental shear force and tangential displacement calculated at the current and previous time steps, respectively. These calculation equations have been receiving wide acceptance to simulate the progressive fracture mechanism of rocks,[33–35] including the dynamic fracture tests under high loading rates.[26,36,37]

2.2. Model setup

As shown in Fig. 1, the numerical model is established referring to the laboratory experiments conducted by Hokka et al.[23], in which the numerical cylindrical specimen has a diameter of 11.8 mm and a length of 11.6 mm. Considering the computing efficiency, the incident bar and the transmitted bar in the present work are reduced to 1200 mm and 1000 mm, respectively, which are long enough to ensure that the propagating wave in the bars are not superposed. The measuring spheres A-C and D-E (Fig. 2a) are assigned at certain locations to monitor the