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Laboratory study on the dynamic response of rock under blast loading with active confining pressure

Chenglong He*, Jun Yang, Qi Yu

State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China

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1. Introduction

In recent years, the method of drilling and blasting has been widely used in deep mining and underground structure operations. Unlike surface rock, underground rock has high in-situ stress, high temperature and high pore pressure state. For instance, the vertical in-situ stress can be as high 27 MPa at a depth of 1000 m, and the horizontal in-situ stress can be approximately 13.5 MPa. Previous research has indicated that high in-situ stress has a strongly effects on the failure strength and dynamic crack propagation of rock under blast loading.[1,2] With the combined effect of confining pressures and blast loading, the dynamic response of rock becomes more complicated and is controlled by many factors, especially the confining pressure with different K (the ratio of the horizontal and vertical parts of the confining pressure). Consequently, studying the dynamic behavior of rock under in-situ stress and blasting is essential.

The attenuation process of blast loading from cylindrical charges has been investigated, and the properties of the explosive, rock materials and coupling media influence the dynamic response of rock subjected to blast loading. Generally, the explosion loading consists of shock waves and explosion gases, both of which contribute significantly to the dynamic response of rock.[3,4] High shock waves are generated initially and quickly spread to the borehole wall, and micro cracks appear due to shear band interconnection under extremely high pressures; as a result, the zone close to the blast hole is crushed and pulverized. Then, circumferential tensile stress followed by a compressive stress wave develops in the existing flaws or creates new radial cracks. The damage further extends by reflected waves in the boundary zone. Finally original cracks run through the specimen due to the subsequent explosion gas flow into cracks.[5–12]

In laboratory studies, the modified split Hopkinson pressure bar (SHPB) is widely used as a traditional method to study the dynamic properties of rock subjected to one-dimensional coupled static and dynamic loads. The experimental apparatus and test techniques for stress wave loading with confining pressure have been developed.[13] Wu set up accelerometers in both the vertical and radial direction to examine the propagation characteristics of blast-induced shock waves, and the results showed that the amplitude and principal frequency of shock waves are attenuated as the distance from borehole increases.[14] Li designed a new experimental facility and found that the strength of the specimens under coupling loads was higher than their corresponding individual static or dynamic strengths. Additionally, the strength of rock under coupling loads has been observed to decrease rapidly when the axial pre-compression stress exceeded 70% of the static strength of rock.[15] The dynamic tensile strength increases with the hydrostatic pressure, and the failure strength mainly depends on the loading rate when the confining pressure reaches a certain value.[16] The dynamic compressive strength was determined by a combination of static axial and lateral confining pressures, including the magnitude of the coupled stress and the ratio of their magnitudes.[2]

Given the above background, to study the dynamic response propagation of rock under confining pressures, laboratory-scale blast experiments have been conducted in quadrate samples of granitic rock. To remove the influence of explosion gases from the chemical reaction, a copper tube was tightly installed in the borehole to reduce explosion loading and prevent explosion gas from penetrating into cracks. Based on the advantages of the natural granite textures, High-speed Digital Image Correlation (DIC) and strain measurement techniques were used

* Correspondence to: Beijing Institute of Technology, Room 611, Building 9, No. 5 Yard, Zhong Guan-Cun South Street Haidian District, Beijing 100081, China.
E-mail address: hechenglong@bit.edu.cn (C. He).

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Table 1
Parameters of the nine experiments (σ_h is the horizontal confining pressure; σ_v is the vertical confining pressure; $K = \sigma_h/\sigma_v$).

Test	$\sigma_h = \sigma_v$ (MPa)	K	Test	σ_h (MPa)	σ_v (MPa)	K
1	0	1	6	0	8	0
2	2	1	7	2	8	0.25
3	4	1	8	4	8	0.5
4	6	1	9	6	8	0.75
5	8	1	–	–	–	–

to observe dynamic response process and test the dynamic strain under different confining pressures with $K = 1$ (0 MPa, 2 MPa, 4 MPa, 6 MPa, and 8 MPa) and different K (0, 0.25, 0.5, 0.75, and 1).

2. Experiment

2.1. Materials

The homogeneous natural grain of granite is suitable for DIC analyze, and the granite samples in the experiment were taken from the Fang Shan area of Beijing, China. To avoid the germination of micro cracks caused by drilling, all samples were obtained from the same parent rock, and water drilling technology was used to incise the rocks. The molecular constituents of the rock were characterized in the Beijing Center for Physical and Chemical Analysis (Beijing, China). SiO_2 was the dominant mineral and comprised 47.75% of the rock, followed by CaO (8.16%). Table 1

The quasi-static properties of granite are tested by the WDW-300 electronic universal testing machine in the Laboratory of Explosion at the Beijing Institute of Technology. SHPB was used to test the dynamic strength under a relatively high deformation rate of approximately 100/s at the China University of Mining and Technology. BHF strain gauges were manufactured by Huangyan Instruments Co. (Taizhou, China), and were used for strain measurement. The parameters of the Fang Shan granite were as follows: density = 2.43 g/cm^3, Poisson's ratio = 0.23, P-wave velocity = 4088 m/s, Young's modulus = 40.6 GPa, tensile strength = 6.14 MPa, compression strength = 87 MPa, and dynamic compressive strength = 120 MPa (strain rate = 115/s). Microscopic studies were performed to insight into the mineralogical composition via scanning electron microscopy (SEM), as shown in Fig. 1.

2.2. Test system and equipment

Many factors must be considered when designing the experiment scheme, such as the specimen geometry size, types of explosive and uncoupling factors for the air medium decoupling charge structure. The fragments and spall cracks caused by reflected tension waves should be removed from the free surface prior to DIC testing. Because the diffusion of explosion gas will reduce the sharpness of photographs from High-speed stereo (HS), a nonpenetrative borehole was used to prevent the explosion gas from overflowing from the bottom of the borehole in the experiment.

Previous experimental studies on rock-like materials subjected to blasting have been performed. Simha experimented with Plexiglas sheets (305 × 305 × 50 mm), and the pentaerythritol tetranitrate (PETN) charge was 0.5 g (10 g/m);[7] McHugh used a Plexiglas cylinder sample with a length of 300 mm and a diameter of 300 mm, PETN charges had diameters of 3.2 mm (4 g/m);[18] Banadaki experimented with cubic samples (150 × 150 × 150 mm) or four cylindrical samples, and the diameters of the PETN cylindrical charges were 1.1–2.23 mm (1.2–5.3 g/m).[8] Finally, Rathore tested blasts in limestone blocks (550 × 300 × 250 mm) at the laboratory scale using the detonating cord with 8.5 g/m.[5]

Based on the above results, the experimental specimen used here consisted of two parts (A and B) measuring 300 mm square and 50 mm long. The strain sensor was pasted on one face of A and another face for the DIC test, whereas B was used to remove reflected waves from the strain sensor surface, as shown in Fig. 2(a). Two models were used to test, the dynamic response of the rock as the biaxial compressive stress increased (K = 1), and determine the radial crack propagation process under different K. Fig. 2(b) shows the first model, six target points were located with a spacing of 14 mm, and the nearest sensor was installed 35 mm from the center hole. In the second model, six hoop strain gauges were pasted along the track of quarter circles with radii of 60 mm, and the central angle between the two sensors was 18°, as seen in Fig. 2(c). The center borehole was drilled and had a diameter of 10 mm and a length of 50 mm. The distance between the DIC surface and the bottom surface was 10 mm to ensure that no gaseous product escaped from the DIC test surface. The PETN was pressed to a diameter of 4 mm and a length of 50 mm, and had a density of 1.0 g/cm^3. A copper tube (0.6 mm thick) was tightly installed in the borehole of each sample to prevent explosion gas from penetrating into the fissure.

A new experimental instrument coupling the biaxial confining pressures with the center explosion loading was constructed. The diagrammatic details of this new system are shown in Fig. 2(d), and mainly include the following: 1-ribbed plate, 2-steel frame, 3-oil cylinder base, 4-side steel plates, 5-hydraulic loading system, and 6-fixed screw. Two hydraulic oil cylinders were applied to square specimens under biaxial loading to simulate horizontal and vertical in-situ stress. Biaxial compressive stress was delivered by the hydraulic loading system, and hydraulic oil cylinders can provide different ratios of biaxial pressure from 0 MPa to 16 MPa simultaneously. Eight screws were employed to prevent confining pressure unloading during blast loading.

Strain gauges require a DC power supply and a Wheatstone bridge for signal amplification. The strains were extracted from the measured signals using bridge amplification and the calibrated gauge factor. The strain gauge signals were recorded by LTT24-Messsystem with a high sampling rate (2 MS/s). High-speed stereo vision with DIC has been

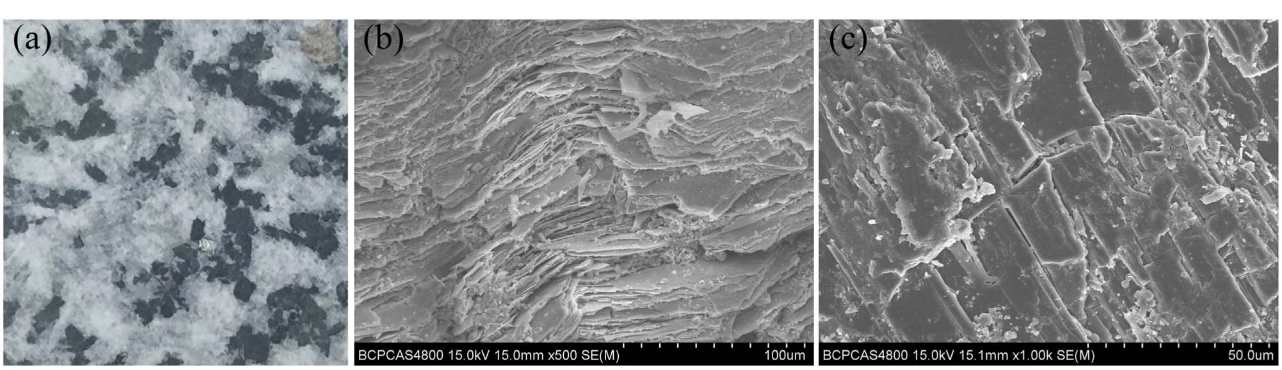

Fig. 1. Specimens and two different components were observed in SEM images. (a) Photograph of a rock sample. (b) SEM of 100 μm. (c) SEM of 50 μm.