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Failure characteristics of high stress rock induced by impact disturbance under confining pressure unloading

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Abstract: The failure characteristics under coupled static and dynamic loading were investigated by the improved split Hopkinson pressure bar (SHPB) with axial pre-pressure and confining pressure. The results show that the stress—strain curve of the rock under static−dynamic coupled loading is a typical class I curve when the dynamic load is comparatively high; With the decrease of the dynamic load, the stress—strain curve transforms to a typical class II curve. The dynamic failure process was recorded by high-speed photography. Analyses of fracture surface morphology show that the failure modes of specimens are tensile failure or combined shear failure when the impact load energy is low, but the failure modes of specimens become tensile failure when the impact load energy is high. The results of fractal dimension show that the elastic potential energy release leads to increase in the degree of crushing of samples when the energy of impact load is low under coupled static and dynamic loads with high stress.
Key words: high stress; coupled static and dynamic loading; impact disturbance; high-speed photography

1 Introduction

For the past few years, the rock mechanics, with the underground rock excavation increasingly deepened, have been observed different from traditional one, especially in high stress [1, 2]. Actually, in the circumstances of deep rock excavation with high stress the surrounding rock is not only under high static stress, but also under the influence of stress unloading owing to the formation of free surface which gives rise to stress state change from original three-dimensional to two-dimensional or unidimensional stress, as well as facing the blasting or drilling during excavation and other dynamic loads [3, 4]. The stress change process is shown in Fig. 1. In the combined action of high stress and dynamic loading and unloading, the rock mass in the excavation face is prone to rockburst. Therefore, study on the destruction mechanism of high stress rock under unloadng and dynamic disturbance is of great significance to practical engineering.

Currently, more attention is gradually paid to the failure phenomena of rock under stress unloading as a result of excavation activities and numerous conventional triaxial tests are conducted [5−8]. However, these studies are limited to the quasi-static situation. In reality, underground rock also experiences dynamic loading caused by mechanical shock or blasting operation, which involves the study of rock dynamic characteristics.

The study of rock dynamic characteristics and dynamic-static properties according to static-dynamic coupling loading was based on dynamic properties of SHPB, light gas gun, falling hammer [9]. LI and MA [10] conducted one-dimensionally dynamic-static combined loading test based on the static pressure of Instron system and micro perturbed dynamic stress; ZUO et al [11, 12] completed the study of rock failure mechanism under two-dimensionally dynamic-static load based on the former equipment. The loading rates in these laboratory tests were less than 1 s^{-1}. However, the high strain rate caused by the blasting execution in underground engineering cannot be simulated since it is between 10^1 s^{-1} and 10^2 s^{-1} or higher. LI et al [3, 4, 13] developed a dynamic-static impact loading system on the basis of the SHPB device and conducted related research experiments.

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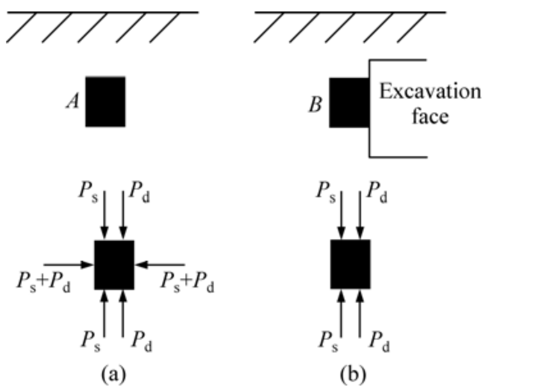

Fig. 1 Stress evolutionary models of rock in projects at deep level: (a) Initial state; (b) State after excavation (P_s—static load; P_d—dynamic load)

In this work, the mechanical properties of sandstone are studied when confining pressure is unloaded in high stress situation under different impact energy using the SHPB device. In addition, the effects of unloading confining pressure on the destruction of dynamic disturbance with high strain rate are analyzed.

2 Test system and scheme

2.1 Test system

The improved SHPB test system can provide both axial static pressure and confining pressure, as shown in Fig. 2 [3].

The test system can be used for impact tests under triaxial pre-pressure, and the axial static loading and the confining pressure are in the range of 0−200 MPa and 0−100 MPa, respectively. The material quality of the bullet and the maximum diameter of the projectile body are the same as those of the input bar and output bar. A conical bullet is used in the improved test system to eliminate the oscillation, and obtain a stable half-sine wave loading [13−15]. The confining pressure and static axial pressure are manually loaded. There is a hydraulic valve at the confining pressure and static axial stress loading equipment to control the stress unloading velocity by manually adjusting the valve opening level.

Conventional SHPB experiments are based on the hypothesis that the sample is under one-dimensional stress and is loaded evenly [10]; but for the improved test system, the sample is under axial static stress when installed correctly. The wave equation of the rock sample under coupled static and dynamic loading is the same as the classical one-dimensional wave equation [3]:

$$\rho \frac{\partial^2 u}{\partial t^2} = E \frac{\partial^2 u}{\partial x^2} \tag{1}$$

where ρ is the density of the bar; x is the location of the infinitesimal; u is the location of the infinitesimal at x under pressure; t is the loading time; E is the elastic modulus of the bar.

Therefore, the one-dimensional stress wave theory is applicable when the sample is under coupled static and dynamic loading. The impact stress $\sigma(t)$, impact strain $\varepsilon(t)$ and impact stress wave energy E_I are calculated by one-dimensional stress wave theory during the experiment using the following formulas [9]:

$$\sigma(t) = \frac{A_e}{A_s} E_e \varepsilon_t(t) \tag{2}$$

$$\varepsilon(t) = -\frac{2c_e}{L_S} \int_0^t \varepsilon_r(t')\mathrm{d}t' \tag{3}$$

$$\dot{\varepsilon}(t) = -\frac{2c_e}{L_S} \varepsilon_r(t) \tag{4}$$

$$W = \frac{A_e}{\rho_e c_e} \int_0^t \sigma^2(t)\mathrm{d}t \tag{5}$$

where c_e is the wave velocity of the elastic bar; L_S is the sample length; $\varepsilon_r(t)$ is the strain of the reflected stress wave at t; A_e is the cross-sectional area of the elastic bar; A_s is the cross-sectional area of the specimen; E_e is the elastic modulus of the elastic bar; $\varepsilon_t(t)$ is the strain of the transmitted stress wave at t; ρ_e is the density of the elastic bar.

2.2 Sample preparation

The samples were drilled from the same integral and uniform block of sandstone to ensure the homogeneity. The cylindrical specimens were made with the dimensions of 50 mm×50 mm, and carefully polished at both ends and lateral side. So, the no parallelism and the no perpendicularity are both less than 0.02 mm. The samples are gray and smooth on surface, with no distinct interspace. The average density of specimens is 2.50 t/m^3.

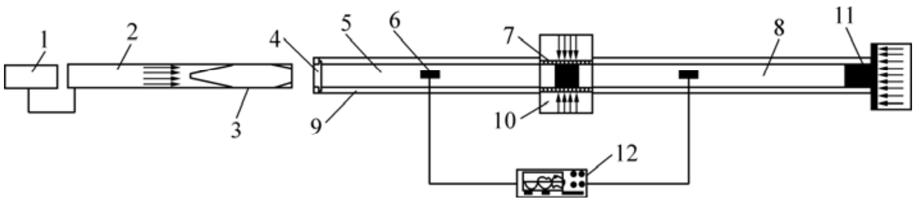

Fig. 2 Configuration of improved SHPB device: 1—Gas tank; 2—Pressure vessel; 3—Striker; 4—Thin baffle; 5—Incident bar; 6—Strain gauge; 7—Specimen; 8—Transmission bar; 9—Steel frame; 10—Confining pressure setup; 11—Pressure loading unit; 12—Oscillograph