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Dynamic response of pre-stressed rock with a circular cavity subject to transient loading

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ABSTRACT

Scientists have attempted to investigate deep underground rock failure. A key challenge to study underground rock failure is the difficulty to survey its process. Therefore, a large number of important and insightful laboratory investigations of underground rock failure experiments are conducted. In this paper, an experimental method is proposed to explore dynamic failure process of pre-stressed rock specimen with a circular hole. The failure process of a rock specimen under different initial static stress coupled with dynamic loading is clearly illustrated by a high speed camera. The experimental results indicated that high static pre-stress coupled with dynamic loading induces rock debris to be ejected at the surrounding circular hole; however, lower static pre-stress coupled dynamic loading cannot induce rock failure. The dynamic stress concentration surrounding the circular hole by transient wave incidence was further demonstrated at the condition of half-sine wave loading. In this condition, the results demonstrated that combined action of static and dynamic stress concentrations induces the primary fractures of rock specimen.

1. Introduction

Human activities perturb the stability of deep underground rock mass surrounding excavations by changing the local stress state. When cavities or tunnels are excavated, the pre-existing stresses in the rock mass are disturbed and stress concentration surrounds underground cavities or tunnels. Meanwhile, during the mining excavation process, mechanical drilling and blasting operations occur frequently such that rock is inevitably subject to the dynamic disturbance. The energy of the dynamic disturbance is transmitted in the form of waves travelling through the rock material in the underground. When the waves transmit through the cavities, they are reflected and scattered, giving rise to elevated local stress states such that the phenomenon of dynamic stress concentration is induced.[1,2] Therefore, underground surrounding rock mass produces coupled static and dynamic situation, as conditions at the underground surrounding rock mass are very different from the normal ground state in terms of dealing separately with either static stress fields or dynamic loading fields and do not correspond sufficiently with underground excavation condition. Therefore, for stability assessment, as well as for support design, it is important to understand the factors leading to detrimental stress changes including static and dynamic stress concentration.

For a long time, because of the complexity of rock behaviour, static stress distribution and dynamic loading are two distinct research directions in the field of underground mining and civil tunnelling. For a static stress distribution around a cavity, people pay special attention to the quantitative representation of the stress distribution around the cavity. In 1898, Kirsch derived the analytical solution of the stress distribution around the circular cavity under the plane strain. Many investigations have since been conducted for cavities and other stresses occurring, such as elliptical, notches and reinforcements. The excellent monograph by Tan presented a compressive coverage on stress concentration in laminated composites.[3] However, for any irregularly shaped chamber section, it is not straightforward to gain the analytical solution after the stress redistribution. In terms of numerical simulations, Diederichs et al. simulated the evolution rules of the surrounding rock space stress field distribution during the excavation process by steps through the finite element programme.[4,5] Using an experimental method, Carter et al. analysed the size and stress gradient effects on rock fractures around cavities and indicated that the initiation of stress for fracturing types depends on the cavity size and the associated stress gradient.[6] These research studies indicated that the stress concentration around the hole is ubiquitous.

The dynamic properties of intact rock, including the stress-strain

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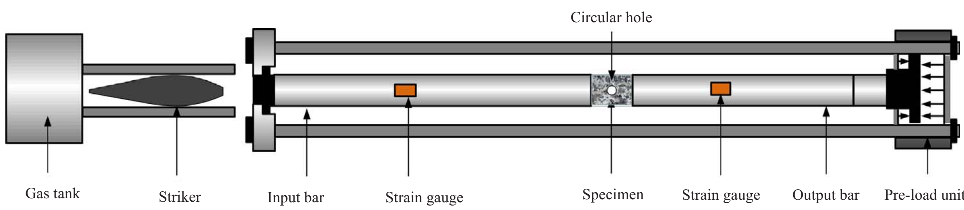

Fig. 1. Modified SHPB apparatus.

curve and failure mode, have been widely investigated using the Hopkinson bar[7–9] or the drop hammer.[10] The response of a cavity subjected to dynamic load distribution excitation is commonly simplified to be an incident stress wave. The diffraction or scattering of a wave normally impeding upon an infinitely long elastic cavity embedded in an elastic medium has been studied for many decades. Pao and Mow provides comprehensive coverage of wave diffraction and dynamic stress concentration by a classical monograph.[11] The solution for the plane P wave or SV wave has been presented by Liu[12] and other scholars.[13] The solutions of circular cavities and the half-space for response of tunnels to incident SH waves and diffraction of SH waves are discussed by using an analytical and numerical method based on Hayier's significant works.[14,15] Several recent scholars presented dynamic stress concentration results for spherical and spheroidal geometries embedded in an elastic medium.[16–18] However, the dynamic stress concentration is primarily focused on the cavities of circular and elliptical, not mention any other shape.

With the in-depth cognition of actual stress features during the deep rock excavation, people gradually realized that the accumulation of static initial stress or static initial stored energies was only the internal cause of the occurrence of deep rock failure. The dynamic disturbance action was the external cause of the final induction of failure. The occurrence of rock failure was the result of the static and dynamic coupled action. Therefore, Li and his co-workers invented a testing technique of rock subjected to coupled initial static and dynamic loads,[19–21] and the experimental results indicated that rock behaves more differently than rock subjected separately to either static or dynamic loading. Meanwhile, a series of static and dynamic combination load experimental research studies and numerical simulation research studies fully verified that the underground rock failure was the result of the coupled action of initial stored energies of the rock mass and the external dynamic disturbance.[22–24] However, the former studies mainly concentrated on a specimen that is intact rock and the initial static stress is homogeneous conditions. In fact, cavity structure is a type of common phenomenon in geology and underground engineering. Because of the cavity, in the vicinity of the underground cavity, with the propulsion of the working face, the vertical stress is transferred towards two sides of the roadway, and the horizontal stress is centralized towards the top and bottom plates, i.e., a stress gradient exists around the cavity. The coupling of the intact rock with static and dynamic loading cannot perfectly describe the nature of the load around an underground working face because the initial static stress exhibits gradient in the vicinity of underground cavity. In addition, the previous study verified that most of the rock failures in the vicinity of the cavities occurred in the stress gradient zones.[6,25,26] Therefore, the rock failure of the deep underground must consider not only coupling the static initial stress and dynamic loads but also the stress gradient and concentration distributed characteristics by perturbing the cavities.

The present paper attempts to shed light on the above questions by conducting a series of experiments to study the effect of static stress and dynamic disturbance on the failure characteristics of rock sample with cylindrical cavity. Both the static and dynamic stress concentrations around the cavity are analysed. The location and time of dynamic stress concentration were employed. The rock failure process was further discussed based on the image taken by a high-speed camera. The results indicated that the combined action of static and dynamic stress concentration induces primary rock failure and even macro failure.

2. Test system of coupled static and dynamic loads and experimental procedures

2.1. Static mechanical properties of the rock specimen

The rock specimen is a 50-mm-diameter and 100-mm-long cylindrical specimen of granite with a central cylindrical hole. The diameter of the central cylindrical hole is 8 mm, which is adequate to prevent the blocks from bucking and to limit edge effects. The surface roughness and end surface perpendicularity of the specimens are less than 0.02 mm and 0.01 mm, respectively. All the specimens were cored from the same granite block and considered as homogeneous, density is 2640 kg/m^3, Poisson's ratio is 0.16, Young's modulus is 46.21 GPa, wave velocity is 4148 m/s, and uni-axial compression strength is 112 MPa.

2.2. Coupled static and dynamic test system

The modified Split Hopkinson Pressure Bar (SHPB) experiment apparatus is adopted in this study. This apparatus, as shown in Fig. 1, was developed at Central South University, and the details are described in our previous studies.[19] This apparatus is different than the conventional SHPB system, and the static stress can be loaded before impact loading conducted, i.e., static-dynamic loads can be coupled.

The rock sample is sandwiched between two cylindrical elastic bars during the tests. The elastic bars are made of steel with a density of 7800 kg/m^3 and elastic modulus of 250 GPa. Static pre-stresses are applied by the pressure-loading unit through elastic bars and limited to 200 MPa. Dynamic loading comes from the impact of a striker driven by high-pressure gas and a slowly rising half-sine wave generated by modifying the shape of the striker bar; the dynamic loading function can be described as follows:

$$\sigma(t) = \sigma_m \sin\left(\frac{\pi}{\tau}t\right),\ 0 \le t \le \tau \tag{1}$$

τ is the period, and σ_m is the peak stress, with the peak dynamic stress being limited to approximately 500 MPa in the laboratory.

To facilitate the description and analysis of the experimental phenomena and results, the problem geometry of dynamic loading conducted in the rock specimen is simply shown in Fig. 2.

The experimental requirement for conducting the SHPB test is maintaining good contact between the bars and the specimen. After careful calibration of the test system, specimens are placed between the input and output bars. When the striker is fired, the incident wave is generated and propagated along the input bar. Because of the difference

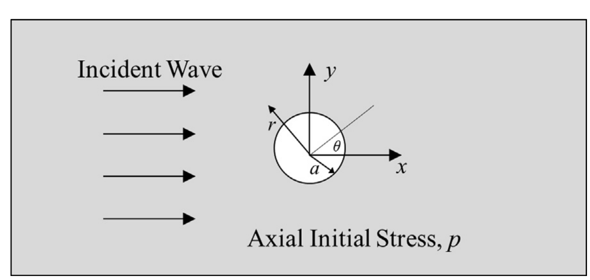

Fig. 2. Problem geometry.