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Dynamic strength of rock with single planar joint under various loading rates at various angles of loads applied

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A B S T R A C T

Intact rock-like specimens and specimens that include a single, smooth planar joint at various angles are prepared for split Hopkinson pressure bar (SHPB) testing. A buffer pad between the striker bar and the incident bar of an SHPB apparatus is used to absorb some of the shock energy. This can generate loading rates of 20.2–4627.3 GPa/s, enabling dynamic peak stresses/strengths and associated failure patterns of the specimens to be investigated. The effects of the loading rate and angle of load applied on the dynamic peak stresses/strengths of the specimens are examined. Relevant experimental results demonstrate that the failure pattern of each specimen can be classified as four types: Type A, integrated with or without tiny flake-off; Type B, slide failure; Type C, fracture failure; and Type D, crushing failure. The dynamic peak stresses/strengths of the specimens that have similar failure patterns increase linearly with the loading rate, yielding high correlations that are evident on semi-logarithmic plots. The slope of the failure envelope is the smallest for slide failure, followed by crushing failure, and that of fracture failure is the largest. The magnitude of the plot slope of the dynamic peak stress against the loading rate for the specimens that are still integrated after testing is between that of slide failure and crushing failure. The angle of application has a limited effect on the dynamic peak stresses/strengths of the specimens regardless of the failure pattern, but it affects the bounds of the loading rates that yield each failure pattern, and thus influences the dynamic responses of the single jointed specimen. Slide failure occurs at the lowest loading rate of any failure, but can only occur in single jointed specimen that allows sliding. Crushing failure is typically associated with the largest loading rate, and fracture failure may occur when the loading rate is between the boundaries for slide failure and crushing failure.

1. Introduction

Rock strength varies with loading rate, therefore, rock performs differently under drilling, blasting, earthquakes, landslides, and hydraulic fracturing for the construction of oil and geothermal wells, and defense-related rock engineering (Liang et al., 2011; Togo et al., 2014; Yang et al., 2014; Zhao et al., 2014; Kuo et al., 2015; Wisetsaen et al., 2015). Since the 1960s, relevant researches have been carried out using various experimental apparatus (Green and Perkins, 1968; Rinehart, 1965; Kumar, 1968). In the 1990s, dynamic tests on rock were commonly conducted using a split Hopkinson pressure bar (SHPB) for loading and measurement, and the precision of relevant calculations of strain and stress under high loading rates was substantially improved (Olsson, 1991; Li et al., 2000, 2016a; Zhang and Zhao, 2014; Xia and Yao, 2015; Li and Shi, 2016; Yin et al., 2016). Since then, various investigations of the influence of loading rate on rock strength have been published (Dai et al., 2010, 2016; Zhou et al., 2012, 2016; Liu and Xu, 2015; Wang et al., 2016a; Yao et al., 2017).

Zhang et al. (1999) applied wedge loading to a short-rod rock fracture specimen using MTS 810 and SHPB apparatus, and found that the static fracture toughness K_{IC} of Fangshan gabbro and Fangshan marble were almost independent of the loading rate, but the dynamic fracture toughness K_{Id} increased with the loading rate over a wide range of 10^{-2}–10^{6} MPa m$^{1/2}$ s^{-1}. Zhao (2000) examined

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the applicability of the Mohr-Coulomb and the Hoek-Brown criteria to the material strength of rocks subjected to dynamic uniaxial compression, uniaxial tension and unconfined shear. Testing results revealed that both the cohesion in the Mohr-Coulomb criterion and the uniaxial compressive strength (UCS) of the rock in the Hoek-Brown criterion varied with loading rate; moreover, the parameter m in the Hoek-Brown criterion appeared to be independent of the loading rate, thus the material strength of rock under dynamic loads was better described using the Hoek-Brown criterion. Li et al. (2005) carried out uniaxial compression tests on Bukit Timah granite at loading rates of 20–50 s^{-1}, and found that its dynamic fracture strength was directly proportional to the cubic root of the loading rate and that the granite exhibited large energy absorption at a high strain rate, yielding fragments consisting of very small particles. Dai and Xia (2010) and Dai et al. (2013) examined both the static and the dynamic flexural strengths of anisotropic Barre granite using dynamic indirect tensile testing and dynamic semi-circular bend (SCB) methods, which revealed that Barre granite exhibits strongly anisotropic flexural strength under static loading but less anisotropy under dynamic loading. Xia et al. (2017) carried out dynamic Brazilian disc (BD), dynamic SCB and dynamic direct tension test on Laurentian granite, and found that the dynamic direct tensile strength is consistently lower than the dynamic BD tensile strength, and the dynamic BD tensile strength is consistently lower than the dynamic flexural tensile strength obtained using the dynamic SCB test. Then they proposed two mechanisms for the strength over-estimation of the dynamic BD method: the overload effect and the internal friction effect.

Discontinuities in a rock mass substantially influence its engineering characteristics (Jin et al., 2015; Yang et al., 2016), reducing its strength and increasing its deformation and permeability (Amadei and Savage, 1991; Chen et al., 1998; Wang and Huang, 2014; Manh et al., 2015; Wang et al., 2015; Zhan et al., 2016; Zou et al., 2016). Most anisotropies in the engineering characteristics of a rock mass, and even factors that govern failure in rock engineering, are related to rock discontinuities (Ismael et al., 2014; Noorian Bidgoli and Jing, 2014; Gao et al., 2015). Most existing methods for characterizing rock masses and quantitatively estimating engineering parameters, both theoretical (Jaeger, 1960; Wang and Huang, 2009) and empirical (RMR, Q and GSI methods) methods, take into account rock discontinuities. Numerous studies have focused on the effects of loading rate on the engineering characteristics of the intact parts of a rock mass, but not those of the discontinuities in the rock mass. Ju et al. (2007) prepared marble and granite specimens with fractal and smooth joints for SHPB tests, and it was shown that the rougher a joint is, the more permanent deformation occurs, and the more the stress wave is attenuated. Li et al. (2011) prepared marble specimens with vertical joint to investigate the transmission and reflection of stress waves across joints. Results of SHPB tests revealed that as the roughness of joint surfaces increases, the transmission coefficients decrease, and the reflection coefficients increase subsequently. Li et al. (2016b) used artificial non-filled joints and joints filled with sand and clay for modified SHPB testing with short rock bars, and suggested that the water content, the thickness of filling layer, the intensity of loading pulse, the loading rate, the joint matching coefficient, and the spatial geometry of joint surface all affect the dynamic properties of rock joints. Wang et al. (2016b) prepared rock specimens with a single planar joint at different included angles between the joint plane and the loading direction for SHPB tests. Their experimental results indicated that the loading rate and associated angle of load applied influence the failure patterns and dynamic strength of the specimens. Li (2017) prepared artificial joints that contained regular asperities with dip angles of 15° and 30° and conducted double shear tests on them under constant normal load at shear rates in the range of 10^{-2}–10^{1} mm/s. Experimental results demonstrated that the shear rate, asperity dip angle, and normal stress all influence the failure mode of the asperity. In this case, both the basic friction angle of the rock joints and the shear strength of the asperity increase with the shear rate when the asperity cut-off occurs. Consequently, the effects of loading rate and the angle of a load applied on the engineering characteristics of a rock mass need further investigation. Li et al. (2017) carried out SHPB tests on rock masses with different contact area ratios of joint, indicating that the transmission coefficient for wave propagation across a jointed rock specimen generally increases with the increase of joint contact area ratio. In summary, the features regarding wave propagation across a joint have been extensively studied, but the influence of joint under various loading rates at various angles of load applied on the engineering characteristics of jointed rock is rarely reported.

In this study, a series of intact rock-like specimens and specimens containing a single, smooth planar joint at various angles is prepared for SHPB testing. The failure pattern of each specimen and the dynamic peak stresses under various loading rates are determined experimentally, and the effects of loading rate and angle of load applied on the engineering characteristics of a rock mass are investigated.

2. Experimental setup

This study concerns two factors that may affect the engineering characteristics of a rock mass: the loading rate and the angle between the loading direction and the joint plane. Various magnitudes of loading rates can be generated by regulating the pressure of a gas chamber of an SHPB apparatus that is used to release a striker bar, or by providing an additional buffer pad to absorb the shock that is generated by a gas gun; the latter is varied by controlling the joint angles of the prepared rock specimens. The experimental design is introduced below.

2.1. Preparation of specimens

Man-made specimens of rock-like materials with homogeneous properties are produced by mixing gypsum powder, quartz powder and pure water. The gypsum, a pottery plaster class of the YCG (the company produces gypsum) product, has a consistency of 74–78% and an expansion of 0.12% and is good for casting mold. The quartz powder has a grain size distribution curve with D_{50} and D_{10} (cumulative 50% and 10% points of diameter) of 12.92 μm and 2.45 μm, respectively. Both intact specimens and specimens containing a single, smooth planar joint (referred to as "single jointed specimens" hereinafter) with various dip angles are prepared. Fig. 1 shows the specimen that contains a single planar joint. The angle between the direction of load and the joint plane, β varies between 45° and 90° with intervals of 15°. All specimens are cylindrical with diameter of 40 mm. The specimen with $\beta = 45°$ has a height of 50 mm while the others are 40 mm high. The weight ratio of gypsum powder to quartz powder to pure water used in producing all specimens is 1:0.272:0.45. The gypsum powder, quartz powder and pure water in consistence with this weight ratio are put into a stirring machine for mixing. After 3 min, the homogeneous mixture is cast into an acrylic mold, which is placed on a vibrator to remove any air that was trapped in the mixture. After its top surface is slicked, the specimen is stewed for 60 min to develop strength, and then removed from the mold. The specimen is cured in an oven at temperature of 20–30 °C and relative humidity of 45–50%. The unit weight of each specimen remained constant after approximately 5 d of curing.