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Propagation of high amplitude stress waves through a filled artificial joint: An experimental study

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ABSTRACT

This paper investigates the propagation of high amplitude stress waves through a filled joint using a modified steel split Hopkinson pressure bar (SHPB) system. Quartz sand fillings with various thickness are placed in a steel tube and then sandwiched between the incident and transmitted bars to simulate the filled rock joints. Using SHPB, the incident stress waves with similar frequency spectrum but varying amplitude are induced to load the artificial filled joints. The particle size distributions of the fillings after tests are analyzed. It is discovered that as the amplitude of the incident wave increases, the fillings experience three stages of deformation: *initial compaction*, *crushing* and *crushing and compaction*. In the *initial compaction* stage and the *crushing and compaction* stage, the fillings are mainly compacted, and thus the transmission coefficient increases with the amplitude of the incident wave. However in the *crushing* stage, the transmission coefficient decreases with the increase of the amplitude of the incident wave. This is a result of energy consumption due to particle crushing. The observed dependence of the transmission coefficient on the wave amplitude is consistent with the particle size distribution of recovered fillings.

1. Introduction

A rock mass consists of rock blocks separated by joints, which in turn control the mechanical behavior of the jointed rock mass (Goodman, 1976; Sun, 1988). The study of the stress wave propagation in the jointed rock mass is of great significance in rock dynamics, earthquake engineering and exploration geophysics. As the rock mass experiences discontinuity, it can slow down and attenuate the stress wave (King et al., 1986). The investigation of the seismic response of a joint is thus fundamental to the study of the stress wave propagation in the jointed rock mass.

In nature, there exist two types of joints: the filled joint and the unfilled joint. Many laboratory studies have been conducted to investigate the effect of the unfilled joint on the wave propagation using the ultrasonic wave method (Huang et al., 2014; Kahraman, 2002; Kurtuluş et al., 2012; Li and Zhu, 2012; Lucet and Zinszner, 1992; Nakagawa et al., 2000; Pyrak-Nolte et al., 1990a, 1990b; Sebastian and Sitharam, 2014; Zhao et al., 2006). Their experimental results showed that the joint stiffness, joint roughness, joint number, normal stress and the shear state of the joint influence the propagation characteristics of the ultrasonic wave, including the amplitude, wave velocity, phase and frequency change. However the amplitude of the ultrasonic wave is very low, which is different from the high amplitude stress waves encountered in practical engineering. Therefore the split Hopkinson pressure bar (SHPB) systems (Kolsky, 1953) were adopted to study the stress wave propagation through unfilled joints by various researchers (Chen et al., 2015; Ju et al., 2007; Li et al., 2011).

Out of the two types of joints, the filled joint is more common and it is often filled with granular materials such as clay, quartz sand and weathered rock as shown in Fig. 1. The thickness of the fillings is up to several centimeters, and fillings have a noticeable effect on the mechanical behavior of the filled joint (Barton, 1974; Sinha and Singh, 2000). When impinging on the fillings, only part of the stress wave can pass through while the remainder is reflected (Fig. 1). To understand the energy transmission though a jointed rock mass, it is very important to study the influence of the fillings on the seismic response of the filled joint.

Using modified rock SHPB, many tests have been carried out to investigate the seismic response of the filled joint (Li and Ma, 2009; Wu et al., 2012a, 2012b, 2013a, 2013b, 2014; Wu and Zhao, 2014). From these studies, the following conclusions have been reached: (1) the filled joint behaves nonlinearly under the dynamic loads; (2) there exists an obvious unloading effect for the deformation behavior of the filled joint; and (3) the filling thickness, the loading rate, water content and the grain size of the filling significantly affect the stress

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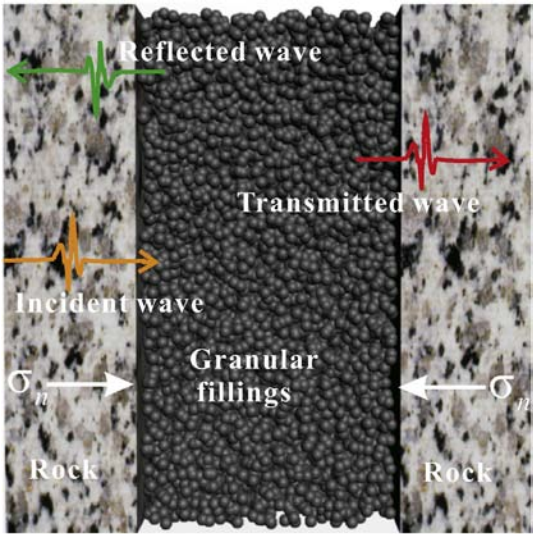

Fig. 1. An idealized fault filled with fault gouges (Modified from (Xia et al., 2013)). The granular fillings are sandwiched between the background rocks. The fillings bear a normal compressive stress σ_n under the combined role of the normally incident, reflected and transmitted stress waves.

wave propagation. However in these experimental studies, the amplitudes of stress waves in the rock SHPB was limited to 8 MPa (Wu et al., 2012a) for protecting the rock bars. On the other side, the practical blasting stress waves often have much higher amplitude according to the field test data (Khandelwal and Singh, 2007; Singh, 2002). It is therefore necessary to study the propagation of high amplitude stress wave through filled joints.

In order to achieve stress waves with high amplitudes, a feasible way is to substitute the rock bars with the high-strength metallic ones. Recently, the aluminum alloy SHPB system was applied to study the dynamic weakening and the acoustic fluidization of the granular fault gouge under the stress waves with high amplitudes (Xia et al., 2013). The purpose of the current paper is to report our experimental results on the propagation of high amplitude stress wave through a joint filled with granular materials, where high-strength steel bars are used to explore a wider deformation range of the fillings.

This paper is structured as follows. Section 1 reviews the previous experimental studies on the stress wave propagation in the jointed rock mass and analyzes the limitations in these studies. Section 2 describes the preparation of the artificial filled joint and the SHPB system. Section 3 shows the experimental results in detail and these results are discussed in Section 4. Conclusion is given in Section 5.

2. Experimental methods

The laboratory tests were conducted by a steel SHPB system located at the Impact and Fracture Laboratory of the University of Toronto as shown in Fig. 2. The setup is mainly composed of a gas gun, a striker bar, an incident bar and a transmitted bar. The incident and transmitted bars have a same diameter of 25.4 mm but different lengths of 2000 mm for the incident bar and of 1500 mm for the transmitted bar. The wave propagation in this SHPB system is essentially one-dimensional problem due to the large ratio of the bar length to diameter. In our configuration, a loading stress pulse can be induced by impact of a short striker bar with a length of 200 mm after launched by the gas gun. All bars are made of high-strength steel with density of 7980 kg/m^3 and bar-velocity of 5058 m/s.

To simulate the filled joint, we place a thin layer of coarse quartz sand between the incident and transmitted bars. The coarse sand has the bulk density of 1600 kg/m^3 and its initial grain size ranges from 0.25 to 2 mm. Because the influence of the fluid is not considered in this paper, the coarse quartz sand was fully dried before testing. The quartz sand fillings were constructed by loading particles into a steel holder, which is then sealed by bars. The holder has an inner and outer diameter of 25.5 mm and 37.5 mm, respectively (see Fig. 2). When loaded by the SHPB bars, the air can escape from the gap between the holder and the bars. Therefore, the influence of air can be neglected in the current research. Due to the existence of the holder, the 1D stress wave assumption is changed into 1D strain wave propagation within the sample. The sand was loaded dynamically by the one-dimensional incident, reflected and transmitted stress waves in the incident and the transmitted bars.

Stress waves with different amplitudes can be induced by setting different striking velocities, which can be realized through adjusting the gas pressure. We used pulse-shaper techniques (Frew et al., 2001; Xia et al., 2008) to achieve approximately half-sinusoidal stress waves. During the impact, the soft copper discs were adopted as the pulse shaper. The striker bar hits the shaper first and induces plastic deformation of the shaper, which results in increased rise time and extended duration of the incident wave. In our experiments, we used pulse shapers with the same thickness and diameter. Hence, the durations of the stress pulses are essentially identical. This results in similar frequency spectrum of the incident stress wave for the tests as will be discussed later.

We can record the complete dynamic stress histories by the strain gages (Fig. 2). One pair of strain gages were placed in the middle of the incident bar and the other pair were located in the point with 1100 mm length from the end of the transmitted bar respectively. Each pair of strain gages were attached symmetrically on the bar surface across a bar diameter. The signals from each pair of strain gages were

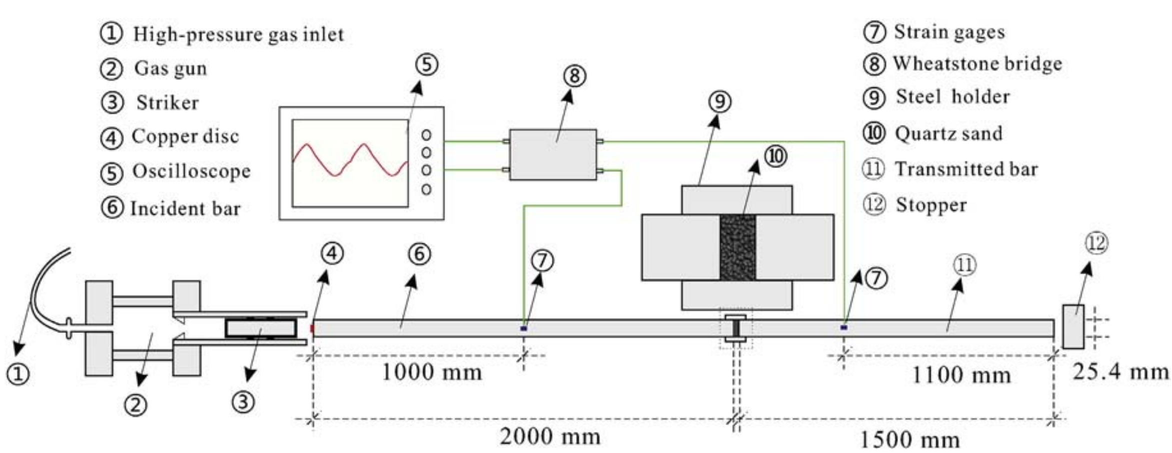

Fig. 2. Schematics of the experimental setup.