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Seismic response of adjacent filled parallel rock fractures with dissimilar properties

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ABSTRACT

The purpose of this study is to analytically predict and to experimentally investigate the seismic response of adjacent filled parallel rock fractures with dissimilar properties (e.g., fracture thickness and stiffness). The time-domain recursive method is extended to predict that a P-wave propagates normally across the filled parallel fractures using the specific stiffness of each filled fracture and considering multiple wave reflections between the parallel fractures. The split Hopkinson rock bar technique is modified to simulate P-wave propagation normally across the sand-filled parallel fractures and to characterize the stress-closure relation of each sand-filled fracture. The P-wave transmission and the seismic response of the filled parallel fractures are an interactive process. The experimental results show the decreases of loading rate and dominant frequency when the P-wave propagates across each sand-filled fracture. The P-wave transmitted from the first sand-filled fracture strongly affects the seismic response of the second one. The P-wave attenuation in the filled parallel fractures is mainly due to the dynamic compaction of the filling sands. By comparison, the analytical method provides a satisfactory prediction to the experimental result. This study suggests considering the specific stiffness of each filled fracture to precisely predict the seismic response of filled parallel rock fractures.

1. Introduction

Seismic response of rock fractures is associated not only with a planar contact of country rock walls, but also with a gouge layer of viscoelastic materials filled between the walls. The filling gouges are found to be ubiquitous in rock fractures at all scales (Marone and Scholz, 1989). Gouge formation is mainly due to fragmentation of intact rocks exposed to sliding wear or implosive loading (Wilson et al., 2005). When an incident P-wave propagates, the seismic responses of the filled fractures largely affect how much seismic energy can travel through rock masses and how rock masses can resist the seismic disturbance. Understanding the mechanical and seismic roles of the filled fractures is thus essential to estimate seismic energy attenuation and rock mass instability (e.g., Ali and Jakobsen, 2011; Perino, 2011; Zhao et al., 1999).

A group of nearly parallel fractures in rock masses is generally known as a set. The seismic response of a set of parallel fractures has been studied using different analytical methods, such as the method of characteristics (Bedford and Drumheller, 1994; Cai and Zhao, 2000), the scattering matrix method (Aki and Richards, 2002; Perino et al., 2012) and the virtual wave source method (Li et al., 2010). Most of these methods are narrowed to non-filled parallel fractures and conclude that the seismic response of parallel fractures depends on the ratio between incident wavelength and fracture spacing (Zhao et al., 2006). The stiffness of each fracture can be considered identically, when the fracture spacing is much smaller than the wavelength. The fracture spacing may have no effect on wave transmission, when it becomes longer than the wavelength. Between these cases, wave superposition has great effects on wave transmission. Zhu et al. (2012) modified a recursive method in the frequency domain to estimate P-wave propagation across filled parallel rock fractures. The layered medium model assumes that each filled fracture has the similar physical and mechanical properties and spatial configurations. Many previous analytical studies on the seismic response of parallel fractures are based on this assumption (e.g., Li et al., 2011; Zhao et al., 2006). However, the discrete and strongly heterogeneous gouges may induce dissimilar physical and mechanical properties of the filled fractures in a fracture set, such as fracture thickness and stiffness. It has been found that this assumption may not precisely predict the seismic response of the filled parallel fractures (Wu et al., 2013a). Questions therefore remain open to the seismic response of filled parallel rock fractures with dissimilar properties.

This study analytically predicts and experimentally investigates the seismic response of adjacent filled parallel rock fractures with dissimilar properties. It studies the loading rate dependence and the dominant frequency dependence of the filled fractures in a fracture set, as well as multiple wave reflections between the parallel fractures. A P-wave is easy to be generated and measured experimentally and thus used to represent a seismic wave in this study. For

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simplification, two filled parallel fractures are considered and described as adjacent filled parallel fractures. The time-domain recursive method (TDRM) is extended to predict that a P-wave propagates normally across the filled parallel fractures with dissimilar properties. The split Hopkinson rock bar (SHRB) technique is modified to simulate P-wave propagation normally across the sand-filled parallel fractures and to characterize the stress-closure relation of each sand-filled fracture, in order to observe the changes of loading rate and dominant frequency and verify the analytical predictions.

2. Analytical method

The TDRM was originally proposed to effectively characterize the interaction between P-wave propagation and a set of parallel rock fractures with linearly elastic behaviors (Li et al., 2011). The TDRM can be extended for P-wave propagation across nonlinear fractures. With the known incident wave and the known mechanical properties of rock fractures, this method is practical to predict the seismic responses of non-filled and filled parallel rock fractures.

This study further develops the TDRM and overcomes the previous assumption that each fracture in a fracture set has the similar physical and mechanical properties. When an incident wave arrives at the front interface of a single fracture, the specific fracture stiffness obtained from the corresponding SHRB test is employed to calculate the related transmitted wave at the rear interface. Meanwhile, multiple wave reflections between the parallel fractures are also considered by the recursive method in the time domain.

According to the one-dimensional wave propagation theory, two waves propagate along and opposite to the loading direction, which are denoted as a positive wave and a negative wave, respectively. When an incident P-wave normally impinges adjacent parallel fractures along the loading direction, the P-wave propagation equations across the 1st or 2nd fracture (see Fig. 1 inset) can be simplified from the deviation by Li et al. (2011) and expressed as the differential form,

$$v^{n-}(t_i,J) = -v^{p-}(t_i,J) + v^{n+}(t_i,J) + v^{p+}(t_i,J) \tag{1}$$

$$v^{p+}(t_{i+1},J) = -v^{n+}(t_{i+1},J) + (1-k_n\Delta t/z)v^{p+}(t_i,J) + (1+k_n\Delta t/z)v^{n+}(t_i,J) + k_n\Delta t/zv^{p-}(t_i,J) - k_n\Delta t/zv^{n-}(t_i,J) \tag{2}$$

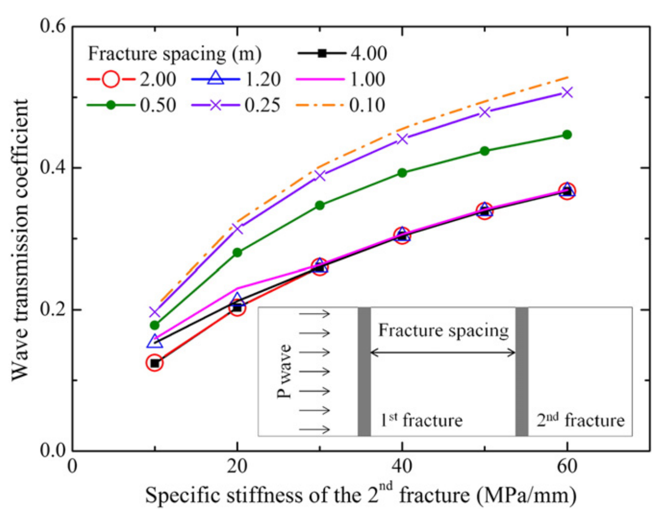

Fig. 1. Analytical prediction on the seismic response of adjacent parallel filled rock fractures. The specific stiffness of the 1st fracture keeps constant (60 MPa/mm).

where $J = 1, 2$ for the 1st, 2nd fracture, respectively, $v^{p-}(t)$ and $v^{p+}(t)$ are the particle velocities at the front and rear interfaces along the loading direction, respectively, $v^{n-}(t)$ and $v^{n+}(t)$ are the particle velocities at the front and rear interfaces opposite to the loading direction, respectively, Δt is a small time interval, k_n is the specific fracture stiffness, and z is the P-wave impedance and equal to the rock density, ρ, multiplied by the P-wave velocity in the rock medium, c. The rock medium between the parallel fractures is known as fracture spacing, S. The particle velocities across the fracture spacing can be written as the time-shifting functions,

$$v^{p-}(t_i,J) = v^{p+}(t_i - S/c, J-1) \tag{3}$$

$$v^{n+}(t_i,J) = v^{n-}(t_i - S/c, J+1). \tag{4}$$

Eqs. (1) and (2) show the P-wave propagation across a single fracture and Eqs. (3) and (4) are applied for the P-wave propagation between the parallel fractures. From Eqs. (1) to (4), multiple wave reflections between the parallel fractures are considered. With the initial conditions, $v^{p-}(t_1, J)$, $v^{p+}(t_1, J)$, $v^{n-}(t_1, J)$ and $v^{n+}(t_1, J)$ for each fracture, and the boundary conditions, $v^{p-}(t_i, 1)$ for the 1st fracture, Eqs. (1) to (4) are applied to determine the reflected wave $v^{n-}(t_i, 1)$ for the 1st fracture and the transmitted wave $v^{p+}(t_i, 2)$ for the 2nd fracture, where $v^{p-}(t_i, 1)$ is assumed as an incident P-wave. The incident wave from the experimental data is expressed as the strain-time response, $\varepsilon(t)$, and needs to be converted to the particle velocity-time response, $v(t)$, in the analytical calculation, where $\varepsilon(t) = v(t)/c$. The method is established in the time domain. There is no need to involve other mathematical methods, such as the Fourier and the inverse Fourier transforms. The calculating efficiency is thus improved.

In the calculation process, the positive wave at the front interface of the 1st fracture from the corresponding test is used as the incident P-wave for calculation. When a positive wave arrives at the front interface of a filled fracture, the specific fracture stiffness from the corresponding test is applied to calculate the positive wave at the rear interface. The positive wave at the rear interface of the 2nd fracture is then obtained as the transmitted wave after the filled parallel fractures. The wave transmission coefficient is defined as the ratio of the maximum strain of the positive wave at the rear interface of the 2nd fracture to that of the corresponding positive wave at the front interface of the 1st fracture in the time domain.

Fig. 1 shows the analytical prediction on the seismic response of adjacent filled parallel fractures. The specific stiffness of the 1st fracture keeps constant, 60 MPa/mm. The incident wave measured from the test N06, which is the positive wave at the front interface of the 1st fracture (shown as the incident wave in Fig. 4a), is used for this calculation. The test N06 is an SHRB test performed on the filled parallel fractures with the 1st fracture of 2 mm thickness and the 2nd fracture of 4 mm thickness, as shown in Table 1. The wave transmission coefficient generally increases with increasing specific stiffness of the 2nd fracture and with smaller fracture spacing between the filled parallel fractures. In this case, when the fracture spacing becomes longer than 1 m and the specific stiffness of the 2nd fracture is larger than 30 MPa/mm, the fracture spacing has no obvious effect on the wave transmission coefficient. Hence, the wave transmission coefficient of each filled fracture in the fracture set can be considered individually. When the fracture spacing is smaller than 0.1 m, the fracture set may be treated as a single fracture compared with the incident wavelength of 6 m. From this figure, it is observed that if the specific stiffness of the 2nd fracture becomes smaller than that of the 1st fracture, the assumption that each filled fracture has the similar physical and mechanical properties may cause an overestimation of the wave transmission coefficient.