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Role of filling materials in a P-wave interaction with a rock fracture

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ABSTRACT

The purpose of this study is to investigate the role of filling materials (e.g., quartz sand and kaolin clay) in the interaction between a P-wave and a rock fracture. The specific fracture stiffness reflects the seismic response of a filled fracture, while the wave transmission coefficient describes P-wave transmission across the filled fracture. A series of experimental tests using a split Hopkinson rock bar technique are conducted on artificial rock fractures that are filled with pure quartz sand, sand–clay mixtures with 30%, 50% and 70% clay weight fractions, and a pure clay matrix. The boundary conditions of the filled fracture, i.e., the displacement and stress discontinuities, are used in the method of characteristic lines to calculate the wave transmission coefficient in the time domain. The analytical results agree well with the experimental results. The specific fracture stiffness and the wave transmission coefficient decrease with increasing filling material thickness. When the clay matrix completely fills the void space of the quartz sand, the filled fracture exhibits the largest specific fracture stiffness and promotes P-wave transmission. In general, the wave transmission coefficient is strongly related to the specific fracture stiffness, regardless of the filling material composition or the filling material thickness.

1. Introduction

When seismic waves propagate through rock masses, rock fractures attenuate the wave amplitude and decrease the wave velocity. Natural fractures are often filled with weak materials, e.g., sand and clay. These filling materials and their mixtures influence the mechanical and physical behaviors of rock fractures, such as strength, porosity and permeability (Crawford et al., 2008). During seismic wave propagation across a filled fracture, wave attenuation is mainly determined by the dynamic compaction of filling materials and by wave reflection and transmission at fracture interfaces (Wu et al., 2013a,b). The seismic response of a filled fracture, such as opening and closure, may induce rock mass collapse. The interaction between a P-wave and a filled fracture is thus important to assess seismic energy radiation and rock mass instability.

A previous study (Wu et al., 2013c) investigated the effects of the fracture thickness, the particle size of the filling sand and the loading rate of an incident wave on the dynamic properties of a filled fracture. The fracture properties and the loading conditions affect the dynamic compaction of filling materials. The dynamic compaction also depends on filling material types. For instance, when a P-wave propagates across a filled fracture, the wave transmission coefficient for a clay-filled fracture is smaller than that for a sand-filled fracture (Ma et al., 2011). Moreover, a filled fracture often contains the mixture of weak materials. These component materials exhibit different dynamic responses and have different roles in wave transmission. Hence, understanding the dynamic compaction of filling materials and their mixtures is necessary to estimate the seismic response of a filled fracture and the wave transmission across the filled fracture.

This study follows the previous study (Wu et al., 2013c), utilizing the displacement and stress discontinuity model (DSDM) in the analytical prediction and employing the split Hopkinson rock bar (SHRB) in the experimental work. The purpose of this study is to investigate the role of filling materials in the interaction between a P-wave and a filled fracture. The P-wave transmission and the fracture response are described by the wave transmission coefficient and by the specific fracture stiffness, respectively. The wave transmission coefficient shows the portion of an incident energy that can pass through the filled fracture, and the specific fracture stiffness means dynamic stress change per unit fracture closure. The DSDM calculation is performed based on the method of characteristic lines. The wave transmission coefficient is thus calculated in the time domain to compare with the experimental results from a real-time measurement. A series of SHRB tests are conducted on fractures filled with pure quartz sand, sand–clay mixtures with 30%, 50% and 70% clay weight fractions, and a pure clay matrix. The clay weight percentage is controlled during the preparation of the filling materials. The filling materials are three phase media with mixed solids, water and air. The filled fracture is tested under an air-dry condition.

2. Analytical model

The method of characteristic lines is commonly used to express the relation between the particle velocity–time response $v(x, t)$ and the stress–time response $\sigma(x, t)$ during one-dimensional P-wave propagation in the time domain (Bedford and Drumheller, 1994). In an $x - t$

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plane (x is the distance and t is the time), Fig. 1 shows the conjunction points of the characteristic lines for the right- and left-running waves across a filled fracture at a distance x_i. Zhao et al. (2006) show that the responses at point a are determined by those at points b, c and d and the responses at time t_{j+1} can be derived from those at time t_j. In this study, we use the known responses at points b and d (or points c and d) to calculate the particle velocity–time responses at the front (or rear) interface of the filled fracture. The method defines that the quantity $zv(x,t)+\sigma(x,t)$ is constant along the right-running characteristic line ab with slope $1/c$

$$zv^{-}\left(x_i,t_{j+1}\right)+\sigma^{-}\left(x_i,t_{j+1}\right)=zv^{+}\left(x_{i-1},t_j\right)+\sigma^{+}\left(x_{i-1},t_j\right) \tag{1}$$

and the quantity $zv(x,t)-\sigma(x,t)$ is constant along the left-running characteristic line ac with slope $-1/c$

$$zv^{+}\left(x_i,t_{j+1}\right)-\sigma^{+}\left(x_i,t_{j+1}\right)=zv^{-}\left(x_{i+1},t_j\right)-\sigma^{-}\left(x_{i+1},t_j\right) \tag{2}$$

where z is the P-wave impedance in the rock material, $z=\rho c$, ρ and c are the rock density and the P-wave velocity in the rock material, respectively, and $v^{-}(x_i, t_{j+1})$ and $v^{+}(x_i, t_{j+1})$ are the particle velocity–time responses at the front and rear interfaces at time t_{j+1}, respectively. Similarly, $\sigma^{-}(x_i, t_{j+1})$ and $\sigma^{+}(x_i, t_{j+1})$ are the stress–time responses at the front and rear interfaces at time t_{j+1}, respectively.

It should be noted that the P-wave in the system consists of a positive wave (a right running-characteristic line), $\varepsilon^{p}(t)$, for the compressive strain–time response and a negative wave (a left-running characteristic line), $\varepsilon^{n}(t)$, for the tensile strain–time response. The displacement–time responses at the front and rear interfaces are $u^{-}(x,t)$ and $u^{+}(x,t)$, respectively.

In the DSDM (Zhu et al., 2011), the stress discontinuity across the filled fracture is

$$\sigma^{-}\left(x_i,t_j\right)-\sigma^{+}\left(x_i,t_j\right)=-\omega^2 m_n u^{+}\left(x_i,t_j\right) \tag{3}$$

where ω is the wave angular frequency and m_n is the initial mass of the filling materials.

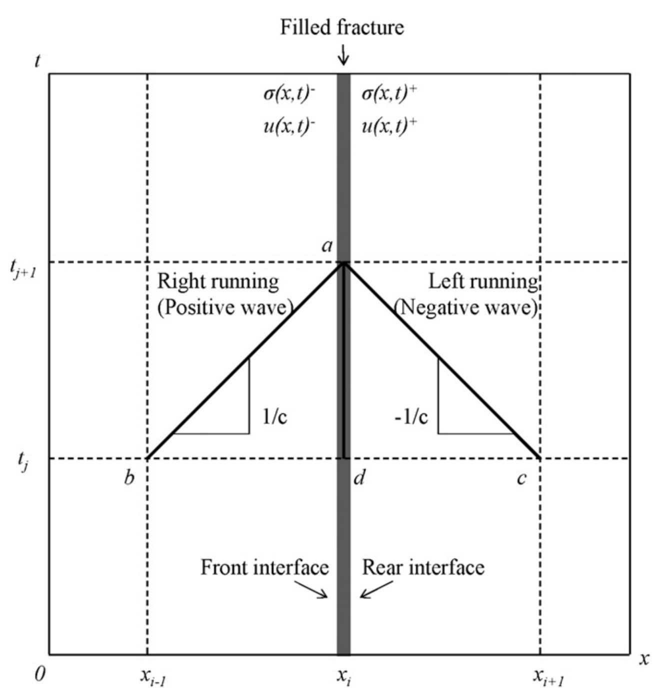

Fig. 1. Conjunction points of the characteristic lines for the right-running (positive) and left-running (negative) waves across a filled fracture at a distance x_i in an $x-t$ plane.

The displacement discontinuity is

$$u^{-}\left(x_i,t_j\right)-u^{+}\left(x_i,t_j\right)=\frac{\sigma^{+}\left(x_i,t_j\right)}{k_n} \tag{4}$$

where k_n is the specific fracture stiffness.

Eq. (3) can be rewritten as

$$\sigma^{+}\left(x_i,t_j\right)=\sigma^{-}\left(x_i,t_j\right)+\omega^2 m_n\int_0^{t_j}v^{+}(x_i,t)dt. \tag{5}$$

If the time interval, Δt, is small enough, the derivation of Eq. (4) with respect to t becomes

$$v^{+}\left(x_i,t_j\right)-v^{-}\left(x_i,t_j\right)=\frac{1}{k_n}\frac{\partial\sigma^{+}\left(x_i,t_j\right)}{\partial t}=\frac{1}{k_n}\frac{\sigma^{+}\left(x_i,t_{j+1}\right)-\sigma^{+}\left(x_i,t_j\right)}{\Delta t}. \tag{6}$$

The stress–time response at the rear interface is

$$\sigma^{+}\left(x_i,t_{j+1}\right)=\sigma^{+}\left(x_i,t_j\right)+k_n\Delta t\left[v^{-}\left(x_i,t_j\right)-v^{+}\left(x_i,t_j\right)\right]. \tag{7}$$

Similarly, Eq. (6) can be expressed based on the stress–time response at the front interface

$$v^{+}\left(x_i,t_j\right)-v^{-}\left(x_i,t_j\right)=\frac{1}{k_n}\frac{\sigma^{-}\left(x_i,t_{j+1}\right)-\sigma^{-}\left(x_i,t_j\right)}{\Delta t}. \tag{8}$$

The stress–time response at the front interface is

$$\sigma^{-}\left(x_i,t_{j+1}\right)=\sigma^{-}\left(x_i,t_j\right)+k_n\Delta t\left[v^{-}\left(x_i,t_j\right)-v^{+}\left(x_i,t_j\right)\right]. \tag{9}$$

Substituting Eq. (7) into Eq. (1), the particle velocity–time response at the front interface is

$$v^{-}\left(x_i,t_{j+1}\right)=\frac{1}{z}\left[zv^{+}\left(x_{i-1},t_j\right)+\sigma^{+}\left(x_{i-1},t_j\right)-\sigma^{-}\left(x_i,t_{j+1}\right)\right]. \tag{10}$$

Substituting Eq. (9) into Eq. (2), the particle velocity–time response at the rear interface is

$$v^{+}\left(x_i,t_{j+1}\right)=\frac{1}{z}\left[zv^{+}\left(x_{i+1},t_j\right)-\sigma^{-}\left(x_{i+1},t_j\right)+\sigma^{+}\left(x_i,t_{j+1}\right)\right]. \tag{11}$$

The positive wave at the front interface of the filled fracture from each SHRB test is first converted into the particle velocity–time response, $v_I(t)$. When the boundary conditions $v^{+}(x_1,t)=v_I(t)$ and $\sigma^{+}(x_1,t)=\rho c\, v_I(t)$ and the initial conditions $v^{+}(x_i,t_1)=v^{-}(x_i,t_1)=0$ and $\sigma^{+}(x_i,t_1)=\sigma^{-}(x_i,t_1)=0\ (i\neq 1)$ are all known, the particle velocity–time responses $v^{-}(x_i,t)$ and $v^{+}(x_i,t)$ at the front and rear interfaces of the filled fracture can be calculated using Eqs. (10) and (11), respectively. The predicted wave transmission coefficient is

$$T=\frac{\max\left[\varepsilon^{p+}(x_i,t)\right]}{\max\left[\varepsilon^{p-}(x_i,t)\right]}=\frac{\max\left[v^{+}(x_i,t)\right]}{\max\left[v^{-}(x_i,t)\right]} \tag{12}$$

where $\varepsilon^{p-}(x_i,t)$ and $\varepsilon^{p+}(x_i,t)$ denote the positive waves at the front and rear interfaces, respectively. The particle velocity–time response is equal to the strain–time response multiplied by the P-wave velocity in the rock material, $v(x,t)=c\,\varepsilon(x,t)$.

3. Experimental study

The experimental study was conducted using an SHRB apparatus, described in detail by Wu et al. (2012). The schematic view of the