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A thin-layer interface model for wave propagation through filled rock joints

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ABSTRACT

The present study essentially employs a thin-layer interface model for filled rock joints to analyze wave propagation across the jointed rock masses. The thin-layer interface model treats the rough-surfaced joint and the filling material as a continuum medium with a finite thickness. The filling medium is sandwiched between the adjacent rock materials. By back analysis, the relation between the normal stress and the closure of the filled joint are derived, where the effect of joint deformation process on the wave propagation through the joint is analyzed. Analytical solutions and laboratory tests are compared to evaluate the validity of the thin-layer interface model for filled rock joints with linear and nonlinear mechanical properties. The advantages and the disadvantages of the present approach are also discussed.

1. Introduction

Joints significantly affect the physical and mechanical behaviors of the rock masses. Besides unfilled joints, filled joints are also widely existed in rock masses in nature. Filled joints are typically joints with apertures filled with soft and loose materials, such as sand and clay. Under the effect of a stress wave, the deformation behavior of a filled joint is complicated. Meanwhile, the stress wave propagation across the filled joint is strongly influenced by the presence of the filling material.

For a rock joint filled with a specific filling material, it is generally to develop and utilize appropriate laboratory tests to evaluate the realistic physical and mechanical behavior of the joint. For example, by using a triaxial apparatus Sinha and Singh (2000) carried out the test for rock joints filled with gouge and found that the filling material significantly affect the stiffness and the strength of the filled joint. Based on the modified SHPB test, Li and Ma (2009) studied the dynamic property of the filled joints when the filling materials are sand and clay with different thickness and water contents. The test results show that under normal dynamic loads, the relation between the pressure and the closure of the joint is nonlinear. From the test results, Ma et al. (2011) proposed a three-phase medium model for the filled rock joints. Later, Wu et al. (2012) extended the SHPB test to study the loading rate dependency of filled rock joints.

The mechanical property of a joint is related to its relative deformation modes (Bandis et al., 1983; Sharma and Desai, 1992). Under dynamic or static loads, the deformation mode of a joint or an interface between two structures may be various, such as stick, slip, debonding and rebonding (Desai et al., 1984), for welded and non-welded interfaces. The stick mode belongs to the welded case. To investigate wave propagation, the interfaces in a layered media are often modeled to be welded (Bedford and Drumheller, 1994; Brekhovskikh, 1980; Ewing et al., 1957; Kennett, 1983; Miklowitz, 1978). The stress and displacement at the welded interface are both continuous.

Rock joints are usually considered as non-welded interfaces in a rock mass. Recently, wave propagation across a filled or unfilled rock joint has been addressed systematically using theoretical methods. The displacement discontinuity method (DDM) (Miller, 1977; Schoenberg, 1980) is one typical method, in which the joint is modeled as a non-welded interface with linear or nonlinear property. In the DDM, the stresses across a joint are continuous, whereas the displacements across it are discontinuous. Pyrak-Nolte et al. (1990a, b) adopted DDM to derive the close-form solution for a harmonic incidence across a rock joint. Coupled with the method of characteristic (Bedford and Drumheller, 1994; Ewing et al., 1957), the DDM was also used for analyzing normal longitudinal (P) wave propagation across a single unfilled rock joint with nonlinear property (Zhao and Cai, 2001). Based on the method of characteristic and the DDM, Li et al. (2010) analyzed wave propagation across a filled joint which was modeled as a non-welded interface with exponential behavior. Perino et al. (2012) used the scattering matrix method to analyze wave propagation across elastic and viscoelastic joints. To simplify the problem, the aperture of each joint was considered to be zero

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in the foregoing analytical studies. This assumption is valid only when the joints are planar, large in extent and small in thickness compared with the wavelength of an incident wave. In another word, the joint in the analytical methods was modeled as a zero-thickness interface.

Different from the assumption of the zero-thickness interfaces, a joint or an interface between two solids can be represented as a thin-layer interface, which was proposed by Desai et al. (1984). The thin-layer interface concept was that the joint should be replaced by an equivalent solid or continuum medium with a finite and small thickness. Sharma and Desai (1992) thought that a thin-layer interface or a zero-thickness interface for a joint should be essentially the same from the physical point of view. By modeling the interface between two solids as a thin viscoelastic layer with stiffness and inertia term, wave propagation was addressed by Rokhlin and Wang (1991). Later, the thin viscoelastic layer interface concept was extended by Zhu et al. (2011) to study wave propagation across filled joints. The results from Rokhlin and Wang (1991), Li et al. (2010) and Zhu et al. (2011) showed that the thickness of a filled joint influences wave propagation in a rock mass. In practical situation, when a stress wave propagates across a filled joint with one thin thickness, i.e. a thin-layer interface, the displacement $u(x,t)$ at each side of the joint is continuous, as shown in Fig. 1(a). If the joint is assumed as a non-welded interface with zero-thickness, there is a distinct jump in the displacement at the zero-thickness interface, which is modeled as the displacement discontinuity boundary condition and shown in Fig. 1(b). Meanwhile, there appears a time delay in Fig. 1(a), which may not happen in Fig. 1(b). Therefore, the calculation performance may be different from two treatments, i.e. the thin-layer and zero-thickness interfaces.

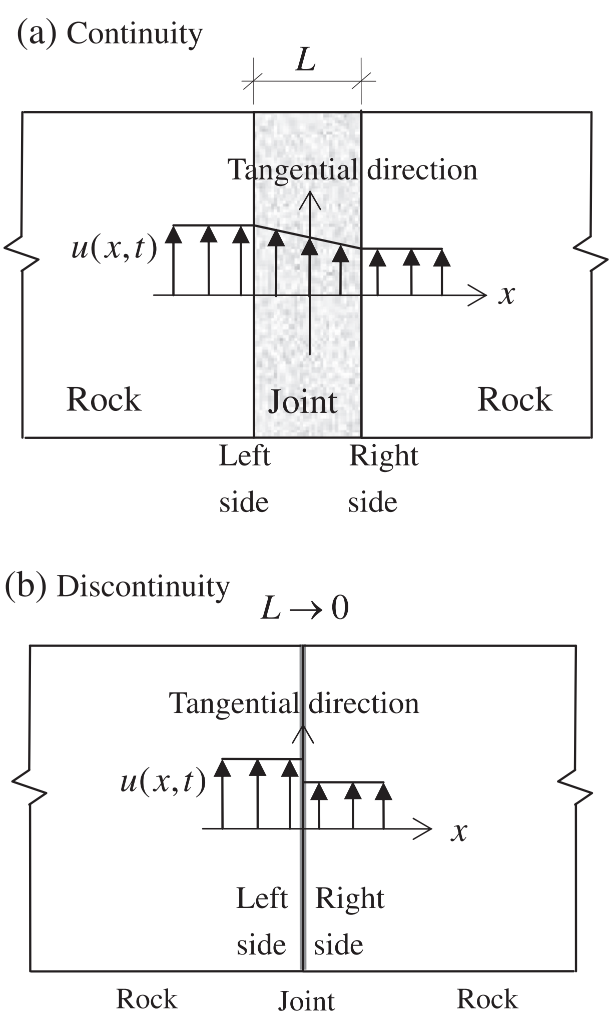

Fig. 1. Schematic view of the displacement at the two sides of a filled joint.

This study is motivated by the need to better understand the role of filled joints on the P-wave propagation. In the study, the filling material in a rock joint is supposed as a thin-layer elastic medium and the joint is equivalent to be a thin-layer interface with one thickness. The two sides of the filling medium are welded to the adjacent rocks. Based on the method of characteristic (MC), the interaction between a stress wave and the joint is analyzed. The wave propagation equation is established for the filled joint with the thin-layer interface model (TLIM). The normal stress and the closure for the joint are derived herein. Two verifications are then carried out, one is to compare the analytical results with those from the existing methods based on zero-thickness interface model (ZTIM), the other is to compare with the test results. Finally, the causes of the discrepancy between two interface models, the potential application and limitations of the present approach are discussed.

2. Theoretical formulations

2.1. Problem description

Assume there is a joint in a linear elastic, homogeneous and isotropic rock. The joint is filled with one geological material, such as soil or sand. Here the filling material is equivalent as an elastic and homogeneous medium different from the adjacent rock. The filled joint is considered as a thin-layer interface between two intact rocks. The thickness of the thin-layer interface is denoted as L, as shown in Fig. 1(a). When a plane P wave impinges on one side of the filling medium, reflection and transmission take place from the two sides of the medium, respectively. In the paper, the two sides of the filling medium are welded to adjacent rocks. During wave propagation, the stress and the displacements at the both sides of the filled joint are continuous. In this section, analytical study for wave propagation across the filled joint modeled in Fig. 1(a) will be conducted.

2.2. Basic equations for stresses and particle velocities

Based on one-dimensional wave propagation theory, two waves propagate in two opposite directions in one continuous medium. Bedford and Drumheller (1994) derived the relations between the particle velocity v and the stress σ. The relation shows that $zv(x,t)+\sigma(x,t)=const$ along any straight right-running (R–R) characteristic line with slope c and $zv(x,t)-\sigma(x,t)=const$ along any straight left-running (L–R) characteristic line with slope $-c$ in the $x-t$ plane, where z is the P wave impendence and $z=\rho c$, c is the P wave propagation velocity in the medium and $c=\sqrt{E/\rho}$, ρ is the density and E is the Young's modulus of the medium. For convenience, the compressive stress is defined to be positive and the tensile stress to be negative.

Fig. 2 schematically shows the characteristic lines at the interface of two media (Bedford and Drumheller, 1994). The position for the interface of two media is at x_i. The wave propagation velocities of the two media are denoted as c_1 and c_2, respectively, and the densities are ρ_1 and ρ_2, respectively. The two media can also be identical. Along the R-R characteristic line ab, there is

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

And along the L-R characteristic line ad, there is

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

where $v^-(x_i,t_{j+1})$ and $v^+(x_i,t_{j+1})$ are the particle velocities at time t_{j+1} before and after the interface at position x_i, respectively; $\sigma^-(x_i,t_{j+1})$ and