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Analysis for oblique wave propagation across filled joints based on thin-layer interface model

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ABSTRACT

The thin-layer interface model (TLIM) for filled joints is extended to analyze wave propagation obliquely across jointed rock masses. In the paper, the filling material is equivalent as an elastic and continuum medium and the filled joint is modeled as a thin-layer interface with one thin thickness. By back analysis, the normal and tangential dynamic properties of the filled joint are theoretically estimated. Comparison is then carried out between the present approach and the existing analytical methods when an incident longitudinal (P) or transverse (S) wave normally or obliquely impacts filled joints. For the existing methods, joints are usually modeled as the displacement discontinuous boundaries with zero thickness. Finally, the effect of relevant parameters, such as the joint thickness, the frequency of the incidence, the incident angle and the ray path derivation, on wave propagation and the cause of the discrepancy between the thin-layer interface and the zero-thickness interface models are discussed.

1. Introduction

In the previous paper (Li et al., 2013), a thin-layer interface model (TLIM) was presented to study wave propagation normally across a filled joint, the dynamic behavior of which was not available in advance. Based on the TLIM, the normal stiffness of the filled joint can be estimated analytically. Different from the zero-thickness interface model (ZTIM) for joints in the traditional analytical method, such as the displacement discontinuity method (DDM) (Miller, 1977; Schoenberg, 1980), the effect of joint thickness on wave propagation was investigated. Compared to the normal incident cases, the analysis is much more complex and not readily available for wave propagation across filled joints with arbitrary incident angles, especially when the dynamic property of the joints is unknown. In nature, rock joints appear non-welded interfaces, large in extent and small in thickness with void spaces and asperities of contact or filled with some specific filling materials (Cook, 1992; Gentier et al., 1989; Hopkins, 2000; Pyrak-Nolte and Morris, 2000). During various geological processes, such as weathering, shearing, loading and thermal cycles, joint surfaces may be influenced and appear different matching and roughness (Zhao, 1997).

According to the direction of an incident wave, the interaction of the incident wave and a rock joint can be normal or oblique. When a plane wave of either longitudinal (P) or transverse (S) wave impinges on the interface of two media, both reflection and transmission take place (Kolsky, 1953). The relation between the propagation speeds and the emergence angles of the incident, transmitted and reflected waves was then established and called as the Snell's law. Based on the DDM and the Snell's law, many researchers addressed wave propagation normally or obliquely across rock joints. For example, Schoenberg (1980) derived the solutions for the reflection and transmission coefficients for harmonic plane waves impinging upon a plane linear slip interface with arbitrary incident angles. Pyrak-Nolte et al. (1990a,b) studied experimentally and analytically the effects of a linearly elastic joint on seismic wave propagation and obtained the complete solutions for all angles of incidence. Gu et al. (1996) studied the details of reflection, transmission and conversion of plan waves incident upon a linearly elastic joint at arbitrary angles. Cai and Zhao (2000), Zhao and Cai (2001), J. Zhao et al. (2006), and X.B. Zhao et al. (2006) adopted the method of characteristic (Bedford and Drumheller, 1994; Ewing et al., 1957) to analyze normal P wave propagation across a single and a set of parallel unfilled rock joints, respectively. The DDM and the method of characteristic were also adopted by Li et al. (2010) to analyze wave propagation across filled joints. Li and Ma (2009) investigated blast wave interaction with a joint with different incident angles based on the conservation of momentum at the wave fronts. Zhu et al. (2011) modeled filled joint as a thin viscoelastic interface with zero thickness to study wave propagation across filled joints. Perino et al. (2012) used the scattering matrix method to analyze wave propagation normally or obliquely across elastic and viscoelastic joints. Li et al. (2012) proposed a time domain recursive method which was applied to study wave propagation across linear and nonlinear joints with an arbitrary impinging angle (Li, 2013). In the foregoing analysis, the joints were modeled as zero-thickness interfaces so as to simplify the problem. To some extent, it is reasonable when the thickness of the joints is much smaller than the wavelength of incidences. This simplification is valid only when the joints are planar, large in extent and small in thickness compared with the wavelength of an incident wave.

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Meanwhile, the mechanical model for the joints should be available before wave propagation across the joints is analyzed.

Compared to the adjacent rocks, a filled joint in nature is usually considered as a soft layer with one thickness. The mechanical property of a joint is related to its relative deformation modes (Bandis et al., 1983; Sharma and Desai, 1992). In practical situation, when a stress wave propagates across a joint with different directions, there is a derivation in the ray path, as shown in Fig. 1. Meanwhile, a time delay appears during wave propagation. If the joint is assumed as a non-welded interface with zero thickness, the wave propagation keeps the original direction and there is a distinct jump in the displacement at the zero-thickness interface, which was modeled as the displacement discontinuity boundary condition in the DDM. Considering the effect of thickness, Desai et al. (1984) proposed a thin-layer interface concept to describe a joint or an interface between two solids. The joint can then be replaced by an equivalent solid or continuum medium with a finite and small thickness. Considering this concept, Li et al. (2013) addressed wave propagation normally across a filled joint, which was modeled as a thin-layer interface with one thin thickness.

The aim of the paper is to better understand the role of filled joints on transmission and reflection when an incident P or S wave obliquely impinges on filled joints. The surfaces of the joints in the study are simplified to be smooth and planar. The filling material is equivalent as an elastic and continuum medium and the filled joint is modeled as a thin-layer interface with one thin thickness. The two sides of the filling medium are welded to the adjacent rocks. According to the interaction between stress waves and one side of the filled joint and the time-shifting for the wave propagation between the two sides, the wave propagation equation across the filled joint is established for arbitrary incident angles. For normally incident P and S waves, the two relations are derived herein, one is between the normal stress and the closure of the joint and the other is between the shear stresses and the relative tangential displacement of the joint. Verification is then carried out by comparing the analytical results from the TLIM and the ZTIM used in the existing theoretical methods. Finally, the effect of relevant parameters on wave propagation and the cause of the discrepancy between the two interface models are discussed.

2. Theoretical formulations

2.1. Problem description

Fig. 1 schematically shows a rock mass with a joint filled with one geological material, such as soil or sand. The rocks beside the joint are identical, linear, isotropic and homogeneous. The filling material is equivalent as an elastic and homogeneous medium different from the adjacent rocks. The joint is modeled as a thin-layer interface. Its thickness is denoted as L and the two sides are welded to the adjacent rocks.

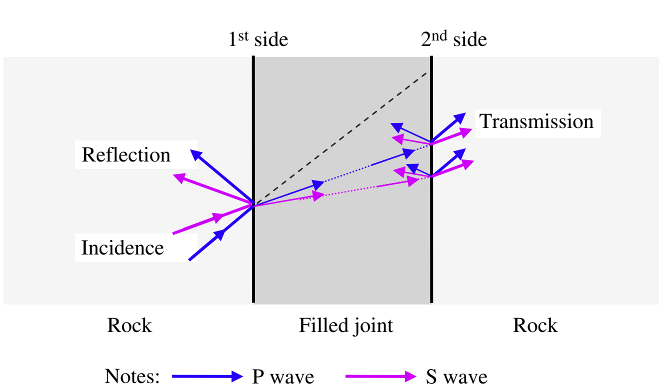

Fig. 1. Schematic view for wave propagation across a filled rock joint.

When a plane P or S wave impinges on the left side of the joint, reflection and transmission take place on the two sides of the joint. The propagation of the stress waves should satisfy the Snell's law, that is

$$\frac{c_{pr}}{\sin\alpha_r} = \frac{c_{sr}}{\sin\beta_r} = \frac{c_{pf}}{\sin\alpha_f} = \frac{c_{sf}}{\sin\beta_f} \tag{1}$$

where c_{pr} and c_{sr} (or c_{pf} and c_{sf}) are the P and S wave propagation speeds in the rock (or the filling medium), respectively; α_r and β_r (or α_f and β_f) are the emergence angles of the P and S wave propagation in the rock (or the filling medium). In this study, we only consider the case of $0 \le \alpha_r \le \alpha_c$ and $0 \le \beta_r \le \beta_c$, where α_c and β_c are the critical angles, and $\alpha_c = 90°$ and $\beta_c = \sin^{-1}(c_{sr}/c_{pr})$. The two sides of the joint are assumed to be parallel with each other. For the present problem, when an incident P or S wave propagates across the rocks and is reflected multiple times between the two sides of the joint, there exist four waves propagating in four directions in the rock and in the filling medium, respectively. We call the four waves in each medium as right-running (RR) and left-running (LR) P waves and right-running (RR) and left-running (LR) S waves, respectively.

2.2. Wave propagation equation

We first analyze plane wave propagation across an interface between two media, as schematically shown in Fig. 2. The interaction between the stress waves and the interface can be obtained from the derivation by Li (2013). That is, the normal and tangential stresses σ^m and τ^m on the interface are

$$\sigma^m = \left(z_p \cos2\beta v_{rp}\right)^m + \left(z_s \sin2\beta v_{rs}\right)^m + \left(z_p \cos2\beta v_{lp}\right)^m - \left(z_s \sin2\beta v_{ls}\right)^m \tag{2}$$

$$\tau^m = \left(z_p \sin2\beta \tan\beta/\tan\alpha v_{rp}\right)^m - \left(z_s \cos2\beta v_{rs}\right)^m - \left(z_p \sin2\beta \tan\beta/\tan\alpha v_{lp}\right)^m - \left(z_s \cos2\beta v_{ls}\right)^m \tag{3}$$

where the superscript m denote the symbols "−" and "+" referring to the wave fields before and after the interface shown in Fig. 2; v_{rp} and v_{lp} are the particle velocities of RR and LR P waves, respectively; and v_{rs} and v_{ls} are the particle velocities of RR and LR S waves, respectively; z_k (k is P or S) is the wave impendence of P or S wave, respectively, and $z_k = \rho c_k$; ρ is the density of one medium and c_k is the wave propagation velocity in the medium; α and β are defined as the emergence angles of the P and S waves, respectively.

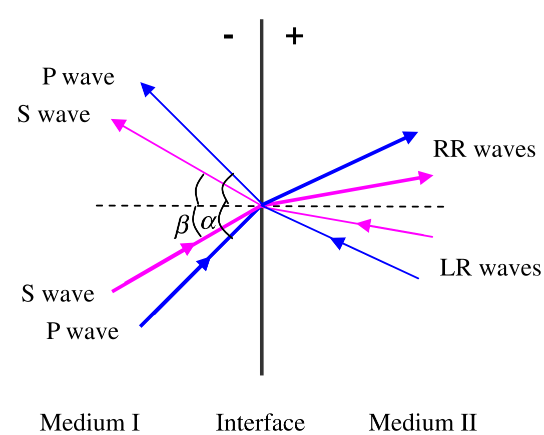

Fig. 2. Schematic view for left- and right-running P and S waves across the interface between two media.