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Technical Note

An improved equivalent viscoelastic medium method for wave propagation across layered rock masses

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ABSTRACT

The behavior of waves propagating through a rock mass is complicated by the discontinuous nature posed by the joints in the rock mass. However, at large scale, the jointed rock mass can be treated as an equivalent continuous medium. The purpose of this paper is to establish a method to determine the equivalent viscoelastic property of rock masses with different seismic quality factors, and to analyze seismic wave propagation across jointed rock masses. Each rock mass contains uniformly distributed joint sets with arbitrary orientation. The equivalent viscoelastic parameters are calculated for a rock mass with different seismic quality factors. The wave propagation equation is then derived for seismic wave across layered rock masses, where the parallel layer interfaces are assumed to be welded. Comparison between the improved equivalent viscoelastic medium method (EVMM) and the existing analytical methods is carried out for two specific cases: reflection at free surface, and transmission across a discontinuous interface between two media. The effects of some parameters, such as the incident angle, the thickness of the layer and the rock mass seismic quality factor, on wave propagation are discussed.

1. Introduction

Strata usually consist of periodic, layered rock masses. A variety of discontinuities, including joints, faults and bedding planes, often exist in each rock mass. Joints commonly appear in sets. The presence of the discontinuities leads to complicated process for wave propagation in a rock mass. Meanwhile, this process will be affected by layer interfaces during wave propagation within layered rock masses.

With increasing exploration and engineering activities in rock masses, for underground construction, mining, shale oil and gas production, understanding the behaviors of seismic wave propagation across layered rock masses is of great interest to geophysics, mining, petroleum, and constructions. Kennett [1] adopted the propagator matrix method to analytical study seismic wave propagation within the Earth's crust composed of isotropic-, nearly elastic-layered media.

Currently, there are two different theoretical approaches to investigate wave propagation across a jointed rock mass: the displacement discontinuity method (DDM) [2–4] and the equivalent medium method [5–10]. Generally, the DDM treats rock masses as discrete entities to solve the problems in the small-scale. By analyzing stress wave interaction with two surfaces of a joint, this method has been successfully applied for wave propagation across single joint [3,11–14] and a set of parallel joints [15–21]. For joints filled with a viscous fluid, the interaction between the seismic wave and the two fluid–solid boundaries were analyzed [22], when the incidence impinged on the layer with arbitrary incident angle.

On the other hand, the equivalent medium method is regarded to describe the macroscopic property of a jointed rock mass based on principles of continuum mechanics. This method can be applied for problems of large-scale. Recently, equivalent continuum models have been presented by various researchers. For example, from empirical formula and statistical analysis, Sitharam et al. [23] characterized the equivalent strength and stiffness of a jointed rock mass which was applied for FEM simulation. Min and Jing [24] determined the equivalent elastic properties to conduct distinct element numerical simulation for the mechanical deformation of fractured rock masses. Using AUTODYN software, Ma et al. [25] suggested an isotropic continuum damage model with damage scalar to simulate shock wave propagation in a rock mass. In the above studies, the constitutive models were derived from the relation between the average stress and strain over a representative elementary volume (REV), which consists of many fractures. Different from the REV adopted in the above numerical simulations, in many analytical studies a primary REV was defined as the basic block consisting of a rock with one joint. The effective

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length of the primary REV is equal to the spacing between two adjacent joints. Pyrak-Nolte et al. [7] derived the complete solution for wave propagation across this primary REV to estimate the effective moduli of a rock mass with a set of parallel joints. According to the analytical and test results for a purely elastic, isotropic medium composed of a set of parallel fractures, Pyrak-Nolte et al. [7] pointed out that the rock mass medium is no longer purely elastic but viscoelastic. Joints were the main contributor to the viscosity of the equivalent medium. By studying the viscoelastic characteristic of the primary REV, Li et al. [9] proposed an equivalent viscoelastic medium method (EVMM) to describe the viscoleastic property of a rock mass and to analyze wave propagation across equally-spaced parallel joints with linear elasticity. Later, Fan et al. [10] extended the EVMM for rock masses with nonlinear joints. In the EVMM, the primary REV was modeled as the auxiliary spring placed in series with the Voigt model. By comparison with the existing equivalent medium methods, the EVMM was proved to be effective to predict wave propagation across jointed rock masses [26].

In addition, some coupled approaches were presented for problems of double-scale. For example, Markov et al. [27] used differential effective medium model to determine the elastic properties of double-porosity rock. Fan et al. [28] coupled the EVMM and the DDM to analyze wave propagation across a rock mass with double-scale discontinuities. The EVMM was applied for the sedimentary rocks with microdefects.

In practice, the seismic quality factor, which is also called as quality factor, is commonly used to describe the energy loss of a wave traveling across rock masses. The seismic quality factor [29] was defined as the maximum energy stored in a period of stress waves divided by the energy lost during the period. Pyrak-Nolte et al. [12] calculated the seismic quality factor by performing dynamic tests for wave propagation across the intact rock samples and jointed rock samples. The seismic quality factor was expressed as a function of the ratio of the spectral amplitudes of the intact to jointed samples. By analyzing wave propagation across a linear viscoelastic medium, Carcione et al. [30] derived the expression of the seismic quality factor, which was related to the wave attenuation and the variation of the phase velocity.

The purpose of the paper is to establish a methodology to determine the equivalent viscoelastic properties of jointed rock masses and to further investigate seismic wave propagation across layered rock masses. The equivalent viscoelastic model presented by Li et al. [9] is firstly improved to model the REV (i.e. a rock with one joint), where the seismic quality factor of a rock mass is considered to indicate the energy loss during wave propagation. The parameters in the improved equivalent viscoelastic model are calculated by analyzing P- and S-waves, respectively, propagating across the REV. Then wave propagation equation across a layered rock mass shown in Fig. 1 is established. Comparison between the improved equivalent viscoelastic medium method (EVMM) and the existing method is carried out for two specific cases. The effects of several parameters, such as the incident angle, the thickness of the rock mass layer and the seismic quality factor of the rock masses on wave propagation are discussed.

The present study to model layered rock masses as equivalent visocoelastic media and to analyze seismic wave propagation across layered rock masses may be of interest to seismic investigators and mining engineers.

2. Problem formulation

Plane wave propagation across rock masses containing three layers and two interfaces is considered for the analysis. The layer interfaces of the rock masses are assumed to be parallel and lie in Y–Z plane, as shown in Fig. 1. The rock mass in each layer contains uniformly distributed joint sets. Each set presents arbitrary orientation in the range of the dihedral angle. The rock material between the joints is assumed to be linear isotropic elastic. The joint follows an elastic linear model with constant normal and shear stiffness, k_n and k_s. For each set of joints, the spacing between two adjacent joints is S.

This section includes two steps to derive wave propagation across a layered rock mass. First, the equivalent medium model [9] is improved to simulate the viscoelastic property of a rock mass with different seismic quality factors. Then, derivation is done for wave propagation across a sandwiched layer rock mass whose seismic quality factor is different from those of the adjacent rock masses.

2.1. Equivalent viscoelastic medium model

The primary representative elementary volume (REV) and the corresponding equivalent viscoelastic medium model are shown in Fig. 2, where the equivalent length of the REV is defined to be the joint spacing S, and v_I and v_T are the incident and transmitted waves, respectively. When an incident wave v_I propagates across the REV, both of the wave attenuation and dispersion phenomenon are displayed. For a rock mass with different seismic quality factors Q_s, derivation for the parameters of the equivalent viscoelastic medium of the REV is addressed in the follows.

The normal direction of the joint shown in Fig. 2 is denoted as $\vec{x}$. For simplicity, if we consider a longitudinal (P-) or shear (S-)

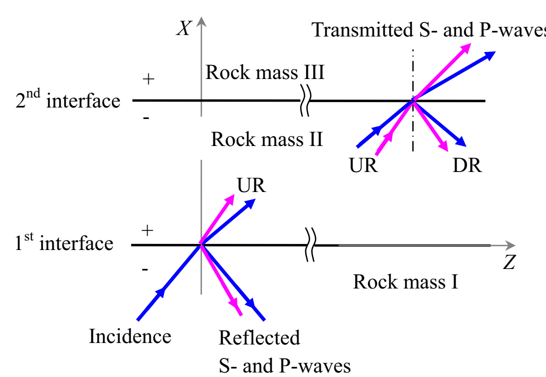

Fig. 1. Schematic view for wave propagation across a layered rock masse.

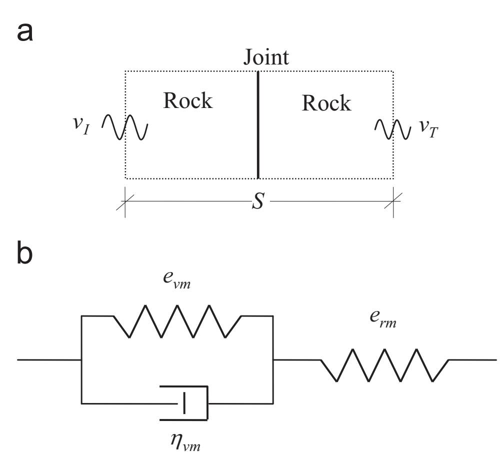

Fig. 2. The REV and the corresponding equivalent viscoelastic medium model. (a) Schematic view for the representative elementary volume (REV), (b) Equivalent viscoelastic medium model.