A mixture theory analysis for the surface-wave propagation in an unsaturated porous medium

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ABSTRACT

The mixture theory is employed to the analysis of surface-wave propagation in a porous medium saturated by two compressible and viscous fluids (liquid and gas). A linear isothermal dynamic model is implemented which takes into account the interaction between the pore fluids and the solid phase of the porous material through viscous dissipation. In such unsaturated cases, the dispersion equations of Rayleigh and Love waves are derived respectively. Two situations for the Love waves are discussed in detail: (a) an elastic layer lying over an unsaturated porous half-space and (b) an unsaturated porous layer lying over an elastic half-space. The wave analysis indicates that, to the three compressional waves discovered in the unsaturated porous medium, there also correspond three Rayleigh wave modes (R1, R2, and R3 waves) propagating along its free surface. The numerical results demonstrate a significant dependence of wave velocities and attenuation coefficients of the Rayleigh and Love waves on the saturation degree, excitation frequency and intrinsic permeability. The cut-off frequency of the high order mode degree of Love waves is also found to be dependent on the saturation degree.

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1. Introduction

From the viewpoint of acoustics, seismology, and geophysics, the research on the propagation characteristics of the surface waves in fluid-saturated porous media is of considerable interest. Many systematic theoretical studies of the surface waves in fluid-saturated porous media have been performed in the context of the fundamental theory initially introduced by Biot (1956). Deresiewicz (1961, 1962) firstly utilized the Biot theory to derive the dispersion equations for surface wave modes in the porous material. The high-frequency properties of the surface waves at a fluid half-space and a fully saturated half space were studied in detail by Feng and Johnson (1983a,b). Like the theory of mixtures in Bowen (1982) and Hassanizadeh and Gray (1990), Liu and de Boer (1997) investigated the dispersion and attenuation of the surface waves in the saturated porous media consisting of microscopically incompressible solid skeleton and pore liquid. Wang and Zhang (1998) developed an effective iterative method to solve the complex dispersion equation of Love waves in a transversely isotropic saturated porous layered half-space. Albers (2006) analyzed the surface waves in poroelastic media by means of the simple mixture model and compared their results to those of the authors using the Biot model or conducting experiments.

The papers mentioned above only considered the case of fully saturated media. Most of the earth's land surface, however, comprises notoriously geomaterials called 'unsaturated soils' which can be grouped into a certain family of unsaturated porous media. But so far, few studies can be found to systematically investigate the influence of saturation degree on the surface wave propagation. Degrande et al. (1998) incorporated Smeulders' modification of Biot's poroelastic theory (Smeulders, 1992) to study wave propagation in multilayered dry, saturated and unsaturated isotropic poroelastic media. Yang (2005) adopted the concept of homogeneous pore fluids to account for the effect of partial saturation. Similarly, the dependence of the velocities and attenuation of the surface waves on the saturation and frequency was implemented by Chao et al. (2006) by means of a modified Biot theory which introduces the frequency-dependent bulk modulus of the mixture. Over the last decades, the Biot theory was extended in order to consider the influence of the gas phase on the velocities and attenuation of the elastic waves in unsaturated porous media (Garg and Nayfeh, 1986; Berryman et al., 1988; Muraleetharan and Wei, 1999; Wei and Muraleetharan, 2002; Lo et al., 2005; Lo, 2008; Lu and Hanyga, 2005; Albers, 2009). The recent studies (Muraleetharan and Wei, 2002; Lo et al., 2005; Lo, 2008; Lu and Hanyga, 2005; Albers, 2009) have shown that in such a medium, there exist four body waves: three compressional waves (i.e. P1, P2, and P3 waves) and one shear wave (i.e. S wave), in which P1 and P2 waves are similar to the fast and slow compressional waves in the Biot theory, and P3 wave arises due to the presence of gas phase. The