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Sensitivities of phase-velocity dispersion curves of surface waves due to high-velocity-layer and low-velocity-layer models

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ABSTRACT

High-velocity-layer (HVL) and low-velocity-layer (LVL) models are two kinds of the most common irregular layered models in near-surface geophysical applications. When calculating dispersion curves of some extreme irregular models, current algorithms (e.g., Knopoff transfer matrix algorithm) should be modified. We computed the correct dispersion curves and analyzed their sensitivities due to several synthetic HVL and LVL models. The results show that phase-velocity dispersion curves of both Rayleigh and Love waves are sensitive to variations in S-wave velocity of an LVL, but insensitive to that of an HVL. In addition, they are both insensitive to those of layers beneath the HVL or LVL. With an increase in velocity contrast between the irregular layer and its neighboring layers, the sensitivity effects (high sensitivity for the LVL and low sensitivity for the HVL) will amplify. These characteristics may significantly influence the inversion stability, leading to an inverted result with a low level of confidence. To invert surface-wave phase velocities for a more accurate S-wave model with an HVL or LVL, priori knowledge may be required and an inversion algorithm should be treated with extra caution.

1. Introduction

High-frequency (>2 Hz) surface-wave methods have been widely applied to estimation of elastic properties of near-surface materials in the field of environmental and engineering geophysics. Rayleigh and Love waves are two types of surface waves that commonly observed on the ground. Rayleigh wave is the result of interfering P- and Sv-waves. Particle motion of Rayleigh wave is elliptical and retrograde on a free interface. Love wave is the result of total internal reflection and refraction of multiple SH-waves and its particle motion is horizontal and perpendicular to the direction of wave propagation.

Surface waves are usually dispersive. A particular mode of surface waves possess a unique phase velocity for each wavelength. Longer-wavelength components of surface waves penetrate deeper than shorter-wavelength components do. For this reason, they are more sensitive to elastic properties of deeper layers (Babuska and Cara, 1991; Ali et al., 2014) and generally behaves as higher phase velocities for regular layered models (shear (S)-wave velocity growing with depth), while shorter-wavelength components are merely influenced by those of shallow layers. These characteristics lead to the dispersion of surface waves. Inversion of surface waves (dispersion curves) can provide accurate S-wave velocities of near-surface materials (Xia et al., 1999, 2002, 2003).

Rayleigh wave can easily be acquired and have attracted more attention in recent years (e.g., Xia et al., 1999, 2006; Miller et al., 1999). Love wave, however, could be observed only when there is a higher-velocity layer beneath the surface layer. Phase velocity of Love wave is independent of P-wave velocity (Aki and Richards, 2002) and this feature makes inversion of Love wave much more appealing than Rayleigh wave. Xia et al. (2012) discussed three advantages of using high-frequency Love-wave methods to estimate near-surface S-wave velocities and showed its excellent applications. Both multichannel analysis of surface wave (MASW) and multichannel analysis of Love wave (MALW) methods are non-invasive, non-destructive, environmental-friendly, low-cost, fast, and in situ seismic methods and possess stable and efficient inversion algorithms to invert phase velocities of surface waves (Xia, 2014).

Analyzing sensitivities of phase-velocity dispersion curves due to parameters of an earth models are critical in understanding the robustness of using high-frequency surface-wave methods to determine near-surface S-wave velocities (Xia et al., 2009). According to sensitivity results, modes and frequency ranges of dispersion data can be chosen appropriately during the inversion process to improve the stability of inversion and the accuracy of an inverted model. S-wave velocity and layer thickness greatly influence the Rayleigh wave dispersion curve (Song et al., 1989). Analysis on the Jacobian matrix by Xia et al. (1999)

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Table 1
Parameters of a regular (S-wave velocity increasing with depth) layered model. (ΔZ is thickness in m, Vs in m/s, Vp in m/s, ρ is density in g/cm^3.)

Layer	Model N			
	ΔZ	Vs	Vp	ρ
1	2.0	194	650	1.82
2	3.0	270	750	1.86
3	4.0	367	1400	1.91
4	5.0	485	1800	1.96
5	6.0	603	2150	2.02
6	∞	740	2800	2.09

demonstrated that phase velocities of surface waves are dominantly influenced by S-wave velocities among four groups of parameters (S-wave velocity, P-wave velocity, thickness, and density). In addition, higher modes are more sensitive to S-wave velocities and can stabilize the inversion and increase the resolution of the inverted S-wave velocities (Xia et al., 2003). Numerical studies by Feng et al. (2005) confirmed that sensitivities of different modes are concentrate in different frequency bands. Furthermore, studies by Safani et al. (2005) on analysis of the partial derivatives of phase velocity of surface waves (Lai and Rix, 1998) proved that sensitivity and inversion stability of Love waves are higher than those of Rayleigh waves for a given model.

Low-velocity-layer (LVL) and high-velocity-layer (HVL) models are two kinds of irregular layered earth settings that most commonly confronted with in near-surface geophysical investigation. They are distinguished according to the type of the shallowest irregular interlayer. An LVL model refers to a model in which the shallowest irregular interlayer is an LVL. Similarly, an HVL model refers to a model in which the shallowest irregular interlayer is an HVL. Liang et al. (2008) found Rayleigh-wave phase velocities are insensitive to variations of S-wave velocities of layers beneath an LVL. Xia et al. (2005, 2007) analyzed HVL and LVL models and concluded that the most sensitive depth for an HVL is at around center of the depth to the half-space and for an LVL is near the surface. Systematical study of sensitivities due to regular models and models containing an LVL or HVL may provide a whole picture of detectability of MASW and MALW methods and expand our knowledge on inversion of high-frequency surface waves.

2. Computation of sensitivities

For linear inversion process, such as using the Levenberg-Marquardt (L-M) method (Levenberg, 1944; Marquardt, 1963), the analytic partial derivative, which is the kernel of sensitivity, is vital in determining modifications to model parameters and affects the convergence of inverse procedure dramatically (Xia, 1986; Xia et al., 1999). In solid geophysics, the methodology is established (Aki and Richards, 2002), where S-wave velocity is usually growing with depth. While in near-surface geophysics, there is strong possibility that earth models contain an HVL or LVL, and it may fail to work well. For layered earth models, sensitivities can be defined by the percentage changes instead of partial derivatives (Feng et al., 2001). As S-wave velocities are the dominant

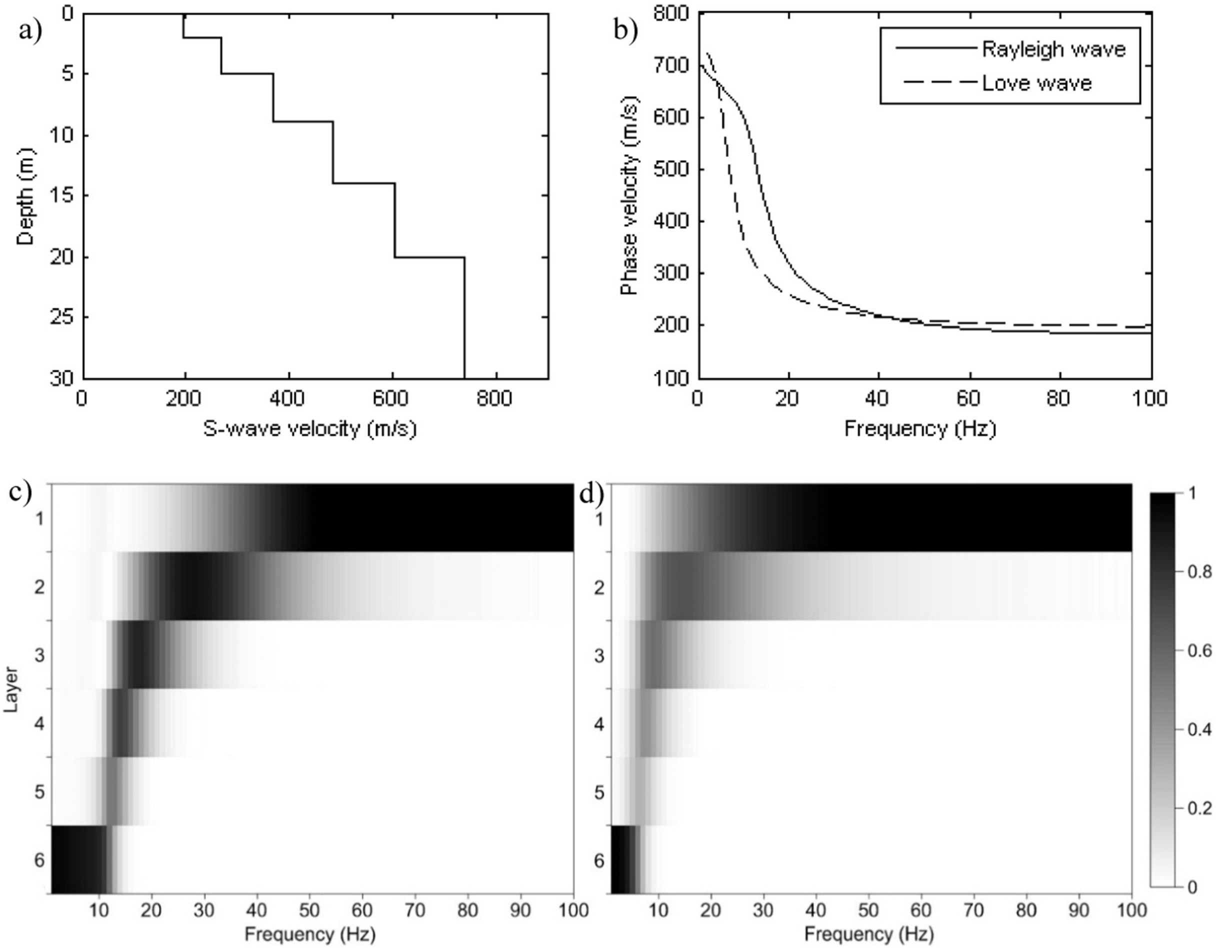

Fig. 1. (a) S-wave velocity profile of Model N. (b) Dispersion curves of the fundamental modes of Rayleigh waves and Love waves for Model N. Sensitivities of phase-velocity dispersion curves of the fundamental modes of Rayleigh waves (c) and Love waves (d) due to Model N.