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Comparative analysis on penetrating depth of high-frequency Rayleigh and Love waves

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ABSTRACT

A particular mode of surface waves possesses a unique phase velocity for each wavelength. Different wavelengths primarily reflect geological information at different depths. In practice, knowledge on penetrating depth of surface wave data is extremely important to define an earth model for inverting their phase velocities. For a layered model, we use the Jacobian matrix to investigate the relationship between wavelength and penetrating depth. The results show that a different mode of surface waves is sensitive to a different depth range. No matter for Rayleigh or Love waves, higher mode waves can penetrate deeper than fundamental mode waves do. For a normal model (S-wave velocity increases with depth) and given the same wavelength, the fundamental mode Rayleigh-wave data can "see" 1.3–1.4 times deeper than that of Love waves. In addition, the higher-mode components of the two waves can penetrate the same depth. Our numerical studies based on sensitivity analysis of fundamental mode waves of two kinds of irregular models, HVL (high-velocity-layer model) and LVL (low-velocity-layer model), suggest that both Rayleigh and Love waves are insensitive to the layers beneath an HVL or LVL and the HVL itself. Therefore, wavelengths required for estimating S-wave velocity of these layers are much longer than the normal model.

1. Introduction

Rayleigh and Love waves are two types of surface waves that travel along a free surface, such as the earth–air interface, or along the earth–water interface. Surface waves are dispersive and guided except for the case of the elastic half space, which can be characterized by relative low velocity, low frequency, and high amplitude (Sheriff, 2002). Rayleigh waves (Rayleigh, 1885) are results of interfering P and SV waves. Particle motion of Rayleigh waves in a homogeneous medium moving from left to right is elliptical in a counter-clockwise direction along the free surface (e.g., Xia et al., 2009). High-frequency Love waves are formed by the constructive interference of multiple reflections of SH waves in a shallow subsurface and their displacements are perpendicular to the direction of wave propagation.

Shallow S-wave velocity is an important factor in ground-motion amplification and site response in sedimentary basins (Borcherdt, 1970; Stephenson et al., 2005). S-wave velocity as a function of depth can be derived from inverting the phase velocity of the surface (Rayleigh and/or Love) wave (Dorman and Ewing, 1962). In recent years, high-frequency Rayleigh and Love waves have obtained increasingly more and more attention in the near-surface geophysical community with application to a variety of near-surface geological and geophysical problems (Xia, 2014). Multichannel analysis of surface wave (MASW) analyzed high-frequency Rayleigh waves with a multichannel recording system to determine near-surface S-wave velocities (e.g., Song et al., 1989; Xia et al., 1999, 2003). The difference between the results and direct borehole measurements is approximately 15% or less and random (Xia et al., 2002). Compared to Rayleigh waves, fewer unknown parameters in multichannel analysis of Love waves (MALW) (Xia et al., 2012), in theory, make dispersion curves of Love waves much simpler. Real-world examples have demonstrated the success of reprocessing SH-wave data using Love-wave analysis (Xia et al., 2012). Main challenges associated with the MALW method are the same as multichannel Rayleigh-wave methods (Xia et al., 2009). At the several sites, within the same layouts, Rayleigh and Love waves are collected (Xia, 2014). The results have showed that Love-wave energy was strong and possesses more uniformed linearity than Rayleigh waves.

Sensitivity analysis is elementary in understanding detectability of estimating an S-wave model. More than one phase velocity, the fundamental mode and higher modes, can be associated with a given frequency of surface waves. A particular mode of surface waves will possess a unique phase velocity for each wavelength. Grant and West (1962) pointed that as mode increases, the energy penetrating the deeper

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Table 1
Parameters of six-layer earth models (modified from Xia et al., 1999). For Love waves, P-wave velocities are ignored.

Layer	Model 1	Model 2	Model 3			
	v_s (m/s)	v_s (m/s)	v_s (m/s)	v_p (m/s)	ρ (kg/m^3)	h (m)
1	194	194	194	650	1820	2.0
2	270	270	270	750	1860	2.3
3	367	367	367	1400	1910	2.5
4	485	140	800	1800	1960	2.8
5	603	603	603	2150	2020	3.2
6	740	740	740	2800	2090	Infinite

layer becomes easier. For a given mode, longer wavelength components of surface waves can penetrate deeper than shorter wavelength components do, and are more sensitive to the elastic properties of the deeper layers (Babuska and Cara, 1991). Xia et al. (2003) used Jacobian matrix to numerically analyze the penetrating depth of Rayleigh waves, and demonstrated that higher-mode Rayleigh wave data can "see" deeper when compared to the same wavelength components of the fundamental mode Rayleigh-wave data. Numerical studies by Feng et al. (2005) confirmed that the sensitivity of higher modes is greater than the fundamental mode for deeper parameters, and sensitivities are frequency-dependent. By calculating the normalized mean values of row vectors of Jacobian matrix of multimode surface waves for the six-layer model, Luo et al. (2007) demonstrated that a different mode of Rayleigh waves is sensitive to a different depth range. On the analysis of the partial derivatives of surface-wave velocities by the method of Lai and Rix (1998), Zeng et al. (2007) proved that the sensitivity and inversion stability of Love waves are higher than those of Rayleigh waves for a same model in Safani et al. (2005).

High-velocity layer (HVL) and low-velocity layer (LVL) models are two kinds of irregular models that contain an (or several) anomalous layer(s). As the low velocity layer traps the energy of Rayleigh-wave and attracts the wave travel within the layer (Liang et al., 2008), the low-velocity layer can strongly influence detectability of Rayleigh-wave phase velocity. According to a sensitivity study in an HVL model, Jin et al. (2009) pointed that the dispersion curve is more sensitive to the depth of the HVL than to its velocity and thickness. Xia et al. (2007) verified the point that sensitivity of Rayleigh-wave data due to depth of an HVL is mainly dependent on the S-wave velocity contrast. Shen et al. (in review) and Zeng et al. (2007) comprehensively compared the sensitivities of Rayleigh and Love waves due to irregular models. For both Rayleigh and Love waves, with an increase in velocity contrast between the irregular layers and its neighboring layers, the sensitivity effects will amplify.

In this paper, we first analyze the Jacobian matrix to define sensitivities of multimode surface-wave phase velocities to variations of S-wave velocities at different depths, and given a wavelength compare the penetrating depth between Rayleigh and Love waves. Second, we systematically study on a normal model (S-wave velocity increasing with depth) and two irregular models that include an LVL model or an HVL model, the propagation character of surface waves to an anomalous layer can be concluded. Finally, we conduct on the quantitative analysis to summarize the different penetrating depths of Rayleigh and Love waves.

2. Basic method

For a layered earth model, Rayleigh-wave phase velocity can be defined as a function of frequency and four groups of earth parameters: P-wave velocity, S-wave velocity, density, and thickness of each layer (Haskell, 1953; Schwab and Knopoff, 1972).

$$F\left(f_j, c_{Rj}, v_s, v_p, \rho, h\right) = 0 \ (j = 1, 2, \ldots, m) \tag{1}$$

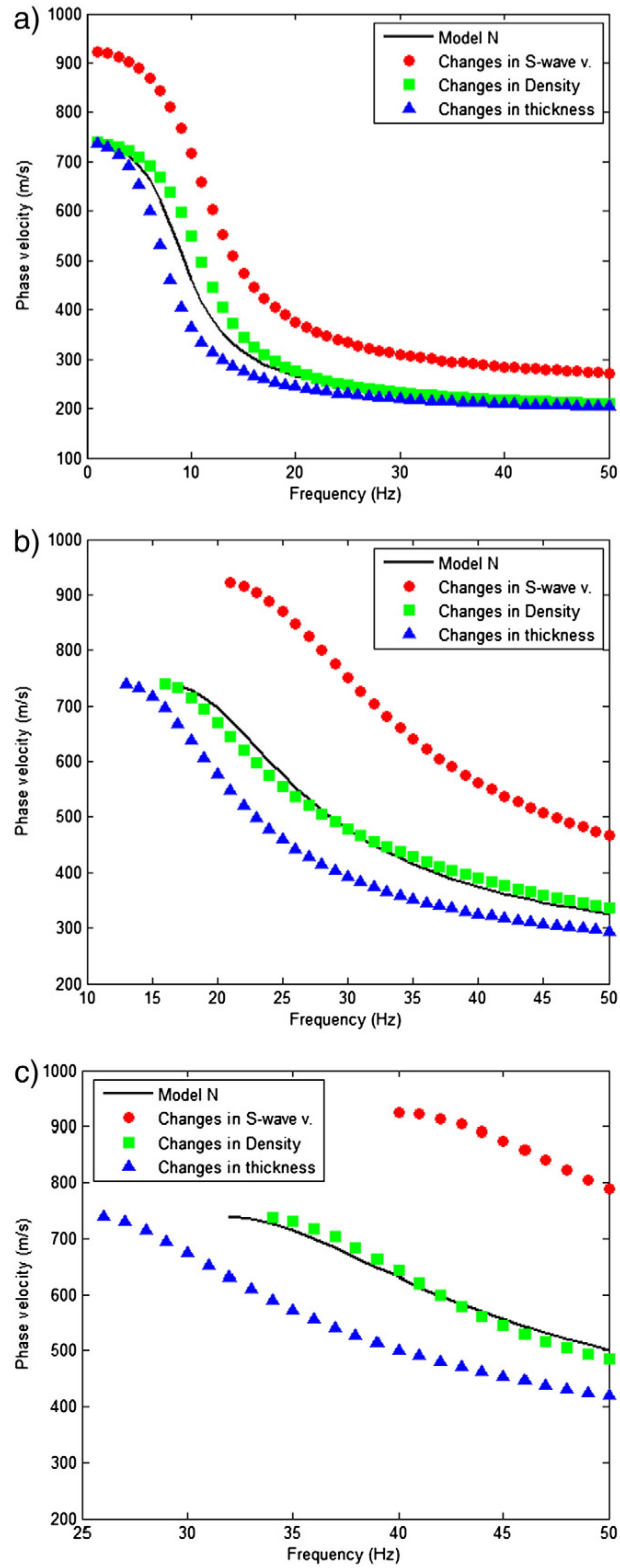

Fig. 1. Contributions to Love-wave phase velocity by 25% changes in each earth model parameters (Table 1). The solid line is Love-wave phase velocity attributed to the earth Model 1. Squares represent Love-wave phase velocities after 25% changes in density; triangles represent Love-wave phase velocities after 25% changes in thickness; and circles represent Love-wave phase velocities after 25% changes in S-wave velocity.