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Estimation of near-surface shear-wave velocities and quality factors using multichannel analysis of surface-wave methods

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ABSTRACT

This overview article gives a picture of multichannel analysis of high-frequency surface (Rayleigh and Love) waves developed mainly by research scientists at the Kansas Geological Survey, the University of Kansas and China University of Geosciences (Wuhan) during the last eighteen years by discussing dispersion imaging techniques, inversion systems, and real-world examples. Shear (S)-wave velocities of near-surface materials can be derived from inverting the dispersive phase velocities of high-frequency surface waves. Multichannel analysis of surface waves—MASW used phase information of high-frequency Rayleigh waves recorded on vertical component geophones to determine near-surface S-wave velocities. The differences between MASW results and direct borehole measurements are approximately 15% or less and random. Studies show that inversion with higher modes and the fundamental mode simultaneously can increase model resolution and an investigation depth. Multichannel analysis of Love waves—MALW used phase information of high-frequency Love waves recorded on horizontal (perpendicular to the direction of wave propagation) component geophones to determine S-wave velocities of shallow materials. Because of independence of compressional (P)-wave velocity, the MALW method has some attractive advantages, such as 1) Love-wave dispersion curves are simpler than Rayleigh wave's; 2) dispersion images of Love-wave energy have a higher signal to noise ratio and more focused than those generated from Rayleigh waves; and 3) inversion of Love-wave dispersion curves is less dependent on initial models and more stable than Rayleigh waves.

To derive S-wave velocities of near-surface materials from high-frequency surface waves only utilizes their phase information. Feasibility of using their amplitude information to estimate near-surface quality factors (Q_s and/or Q_p) has been studied. Attenuation coefficients of high-frequency surface (Rayleigh and/or Love) waves can be calculated from their amplitude. And by inverting attenuation coefficients, it is feasible to obtain quality factors. Similar to inverting phase velocities of Love waves for S-wave velocities, attenuation coefficients of Love waves are independent of Q_p, which makes inversion of attenuation coefficients of Love waves to estimate Q_s simpler than that of Rayleigh waves.

Both MASW and MALW methods to estimate near-surface S-wave velocities are non-invasive, non-destructive, environment-friendly, low-cost, fast, and in situ seismic methods and possess stable and efficient inversion algorithms to invert phase velocities of surface waves. Real world examples demonstrated that near-surface S-wave velocities derived from phase information are reliable and that methods discussed in the paper to estimate near-surface quality factors from amplitude information are feasible.

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1. Introduction

Surface waves, Rayleigh and Love waves, travel along a "free" surface, such as the earth–air or the earth–water interface and are usually characterized by relatively low velocity, low frequency, and high amplitude (Sheriff, 2002, p. 168). Rayleigh waves are the result of interfering P and S_v waves. Particle motion of the fundamental mode of Rayleigh waves in a homogeneous medium moving from left to right is elliptical in a counter-clockwise (retrograde) direction along the free surface. As depth increases, the particle motion becomes prograded and is still elliptical when reaching sufficient depth. The motion is constrained to a vertical plane consistent with the direction of wave propagation. For the case of a solid homogenous half-space, the Rayleigh wave is not dispersive and travels at a velocity of approximately 0.9194Vs when Poisson's ratio is equal to 0.25, where Vs is the S-wave velocity of the half space (Sheriff and Geldart, 1983, p. 49). However, in the case of one layer over a solid homogenous half-space, Rayleigh waves become dispersive when their wavelengths are in the range of 1 to 30 times the layer thickness (Stokoe et al., 1994). Longer wavelengths penetrate greater depths for a given mode, generally exhibit greater phase velocities, and are more sensitive to the elastic properties of the deeper layers (Babuska and Cara, 1991, p. 30). Conversely, shorter wavelengths are sensitive to the physical properties of surface layers. Therefore, a particular mode of surface wave will possess a unique phase velocity for each unique wavelength, leading to the dispersion of surface waves.

Love waves result from total internal, multiple reflections of SH waves (Bullen and Bolt, 1985). The dispersion characteristic of Love waves is independent of P-wave velocity (Aki and Richards, 1980), thereby reducing the degree of nonuniqueness of an inverted S-wave velocity model. Moreover, Love waves of a layered earth model possess other unique properties such as the asymptote of the phase velocity at high frequencies approaches the shear (S)-wave velocity of the top layer and the asymptote at low frequencies approaches the S-wave velocity of the half space, which are useful in determining an initial model and constraints for inversion.

Elastic properties of near-surface materials and their effects on seismic-wave propagation are of fundamental interest in groundwater, geotechnical and earthquake engineering, environmental studies, and oil and gas exploration. S-wave velocity is a key parameter in construction and geotechnical engineering. As an example, Imai and Tonouchi (1982) studied P- and S-wave velocities in an embankment, and also in alluvial, diluvial and tertiary layers, showing that S-wave velocities in such deposits correspond to the N-value (blow count) (Clayton, 1993; Clayton et al., 1995), an index value of formation hardness in soil mechanics and foundation engineering. S-wave velocity is also an important parameter for evaluating the dynamic behavior of soil in the shallow subsurface (Kramer, 1996; Yilmaz et al., 2006). For example, both the Uniform Building Code (UBC) and Eurocode 8 (EC8) codes use V_s^{30}, the average S-wave velocity for the top 30 m of soil, to classify sites according to the soil type for earthquake-engineering design purposes (Dobry et al., 2000; Kanli et al., 2006; Sabetta and Bommer, 2002; Sêco e Pinto, 2002). In petroleum exploration, a near-surface layer acts as a filter that smears images of deep reflection events. To eliminate the smearing effect, accurate near-surface velocity information is critical. However, to determine near-surface velocities is a troublesome task, even for S-wave reflection/refraction survey. As discussed by Xia et al. (1999, 2002b), one successful alternative of determining S-wave velocities of near-surface layers is to use surface-wave methods.

Near-surface S-wave velocity can also be determined by inverting high-frequency Rayleigh/Love waves. Several seismic methods utilize dispersion of Rayleigh waves to determine S-wave velocities of near-surface materials. Stokoe and Nazarian (1983) and Nazarian et al. (1983) presented a surface-wave method, Spectral Analysis of Surface Waves (SASW), which analyzes the dispersion curve of Rayleigh waves to produce near-surface S-wave velocity profiles. Matthews et al. (1996) summarized the SASW method and the Continuous Surface Wave (CSW) method (Abbiss, 1981; Tokimatsu et al., 1991) with detailed diagrams.

For the last eighteen years, scientists at the Kansas Geological Survey (KGS), the University of Kansas and the China University of Geosciences (Wuhan) have utilized high-frequency surface-wave data (Fig. 1) to determine S-wave velocities and quality factors (Q) of near-surface materials and developed methods called multichannel analysis of surface waves (MASW) and multichannel analysis of Love waves (MALW), which can be traced back to the work by Song et al. (1989) to estimate S-wave velocities of near-surface materials (e.g., Ivanov et al., 2006; Miller et al., 1999; Park et al., 1999; Xia et al., 1999, 2002c, 2004). Both methods include acquisition of high-frequency broad-band Rayleigh/Love waves, extraction of Rayleigh/Love-wave dispersion curves from Rayleigh/Love waves, and inversion of dispersion curves to obtain near-surface S-wave velocity profiles. The MASW method has been given increasingly more attention by the near-surface geophysical community with application to a variety of near-surface geological and geophysical problems because it is non-destructive, non-invasive, low cost, and relatively highly accurate since the late of 1999. It has become one of the main seismic test methods in determining S-wave velocities for applications of geotechnical and environmental engineering. The MALW method, on the other hand, possess several attractive advantages, such as 1) Love-wave dispersion curves are less complicated than Rayleigh wave's; 2) dispersion images of Love-wave energy have a higher signal to noise ratio and more focused than those generated from Rayleigh waves; and 3) inversion of Love-wave dispersion curves is less dependent on initial models and more stable than Rayleigh waves.

The most common measure of seismic-wave attenuation is the dimensionless quality factor Q or its inverse Q^{-1} (dissipation factor). As an intrinsic rock property, Q represents the ratio of stored to dissipated energy (Johnston and Toksöz, 1981). The quality factor as a function of depth is routinely of fundamental interest in many groundwater, engineering, and environmental studies, as well as in oil and gas exploration and earthquake seismology. A desire to understand the attenuative properties of the earth is based on the observations that seismic-wave amplitudes are reduced as waves propagate through an elastic medium. This amplitude reduction is generally frequency dependent and, more importantly, attenuation characteristics can reveal unique information about lithology, physical state, and degree of rock saturation (Toksöz and Johnston, 1981). To fully understand seismic-wave propagation in the earth, the quality factors must be known.

Laboratory experiments (Johnston et al., 1979) show that Q may be independent of frequency over a broad bandwidth (10^{-2}–10^7 Hz), especially for some dry rocks. Q^{-1} in liquids, however, is proportional to frequency so that in some highly porous and permeable rocks Q^{-1} may contain a frequency-dependent component. This component may