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Self-adaptive method for high frequency seismic surface wave method

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ABSTRACT

When the high frequency multi-channel analysis of surface waves (MASW) method is conducted to explore soil properties in the vadose zone, existing rules for selecting the near offset and spread lengths cannot satisfy the requirements of planar dominant Rayleigh waves for all frequencies of interest and will inevitably introduce near and far field effects as well as spatial aliases at certain frequencies. To solve these problems, a self-adaptive method is developed to determine high frequency dispersion trends. In this method, an initial dispersion curve is obtained by a fixed-offset MASW method and used to estimate wavelengths at all frequencies of interest. At each frequency, the near offset and spread lengths are then set to be 0.2–0.6 and 2–4 wavelengths respectively. In other words, the near offset and spread lengths are self-adaptive to the corresponding wavelength. Furthermore, in order to avoid spatial aliases and minimize the number of sensors or sensor locations, a variable sensor spacing configuration is proposed, in which the spacing for the first 120 steps is set to be 0.5 cm and the next 40 steps start with 1 cm spacing followed by 1 cm incremental spacing for each subsequent step. In this study, an accelerometer was used as a sensor to detect surface vibrations generated by an electrodynamic shaker operating in chirp mode. Two field tests were conducted and the results from the fixed-offset, self-adaptive, and variable spacing MASW methods were compared. The study demonstrates the ability of the self-adaptive MASW method to preferentially identify the dispersion trends of either the fundamental mode or higher modes of Rayleigh waves. It is also found that the dispersion trends can be determined beyond the source frequency range due to nonlinear effects that generate high harmonics of surface waves. This nonlinear phenomenon deserves future investigation.

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1. Introduction

Many applications exist in today's world for near surface soil exploration, including areas such as farmland management, environmental studies, and battlefield condition evaluations. Of particular interest in these areas is the mechanical property of soils within a very shallow layer a couple of meters deep below the surface, the so-called vadose zone. This zone is characterized by unsaturated and weathered overburden soils. In practical applications, a non-invasive technique is always preferred. For this, a seismic technique known as the multi-channel analysis of surface waves (MASW) method appears to be very promising. The MASW method is based on spectral analysis of Rayleigh waves – a type of seismic surface waves – to determine shear wave velocity profile, i.e., shear wave velocity as a function of depth (Park et al., 1998a,1998b, 1999a, 2007; Xia et al., 1999; Miller et al., 1999; Foti, 1999). It has been increasingly applied to geotechnical and civil engineering projects such as mapping bedrock (Miller et al., 1999), detecting voids (Park et al., 1998a, 1999b) and buried objects (Grandjean and Leparoux, 2004), determining Poisson's ratio (Ivanov et al., 2000) and quality factor (Xia et al., 2002), evaluating the stiffness of water bottom sediments (Park et al., 2005), delineating fault zone and dipping bedrock strata (Ivanov et al., 2006), evaluating levees (Lane et al., 2008), and non-destructive testing of concrete pavements (Ryden et al., 2001, 2004, 2009; Ryden and Lowe, 2004; Alzate-Diaz and Popovics, 2009). For most of these projects, except for non-destructive testing of pavements, the MASW methods are aimed at exploring subsurface properties at depths from several meters to tens of meters and therefore employ a low frequency (less than 200 Hz) source for the targeted objectives. They usually treat the top layer of soil, typically with a thickness of a couple of meters of weathered parent material, as an effective layer with average properties. Therefore the detailed structural information of the top layer of soil cannot be determined (Park et al., 1999a).

Recently a high frequency MASW method has been developed, in which either an accelerometer or a laser-Doppler vibrometer is used as a sensor to detect surface vibrations generated by an electrodynamic shaker operating in chirp mode with frequency ranging from 40 Hz to 500 Hz and to explore subsurface soil with a depth of 2.5 m below the surface (Lu, 2014a; Lu et al., 2014). The method has found its applications in studies of seasonal and weather effects on shallow surface soils (Lu, 2014a) and in the detecting and imaging of a soil fragipan (Lu et al., 2014). Currently there is an on-going effort to extend frequency up to a few kHz and to study soil surface crusting and sealing (Lu et al., 2015).

Abbreviations: MASW, multichannel analysis of surface waves.
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When the high frequency MASW method was conducted and the collected time traces were processed in a traditional MASW manner, however, several problems emerged. First, existing rules for selecting the near offset and spread lengths cannot satisfy the requirements of planar dominant Rayleigh waves of the fundamental mode for all frequencies of interest. In the past, there were many discussions about optimizing sensor geometric configurations (Park et al., 1999a, 2001; Zhang et al., 2004; Xu et al., 2005; Ivanov et al., 2008) and they all focused on using fixed offsets. One of the most popular rules was that, for example, the near offset was set to be greater than half the maximum desired wavelength and spread length should be twice as large as the exploration depth (Park et al., 1999a). These rules were mostly concerned with the lowest frequency component of surface waves, rather than all frequency components. At high frequencies, seismic waves may propagate in far field distance, leading to predominant higher modes over the fundamental mode of Rayleigh waves.

Secondly, the attenuation coefficients of Rayleigh waves measured in the high frequency MASW test have much higher values and dynamic range than those of conventional MASW methods. As reported by a recent study (Xia et al., 2012), the attenuation coefficients were found in a range from 0.01 to 0.07 (1/m) within a frequency range from 10 to 70 Hz. In this study, the attenuation coefficients were obtained in a range from 0.05 to 1.3 (1/m) with frequencies ranging from 50 Hz to 500 Hz, as seen in Fig. 1(A).

This frequency-dependent attenuation nature prevents all frequency components of Rayleigh waves from propagating the same distance. The regressed curve in Fig. 1(A) was used to calculate the distance that the amplitude of the fundamental mode of Rayleigh waves attenuates 80% (−7 dB) from the source amplitude. In the calculation the effects of both geometric spreading and intrinsic attenuation were considered. The results are plotted in Fig. 1(B), where the distance of 80% decays in amplitude decreases rapidly with frequency. On the other hand, since higher modes of Rayleigh waves have longer wavelengths than those of fundamental mode Rayleigh waves, they penetrate deeper subsurface soils (Xia et al., 2003) and consequently are less attenuated than the fundamental mode. At certain high frequencies and distances, the energy of Rayleigh waves of the fundamental mode will not dominate over that of higher modes of Rayleigh waves, making it difficult and sometimes impossible to identify the fundamental mode of Rayleigh waves from an overtone image.

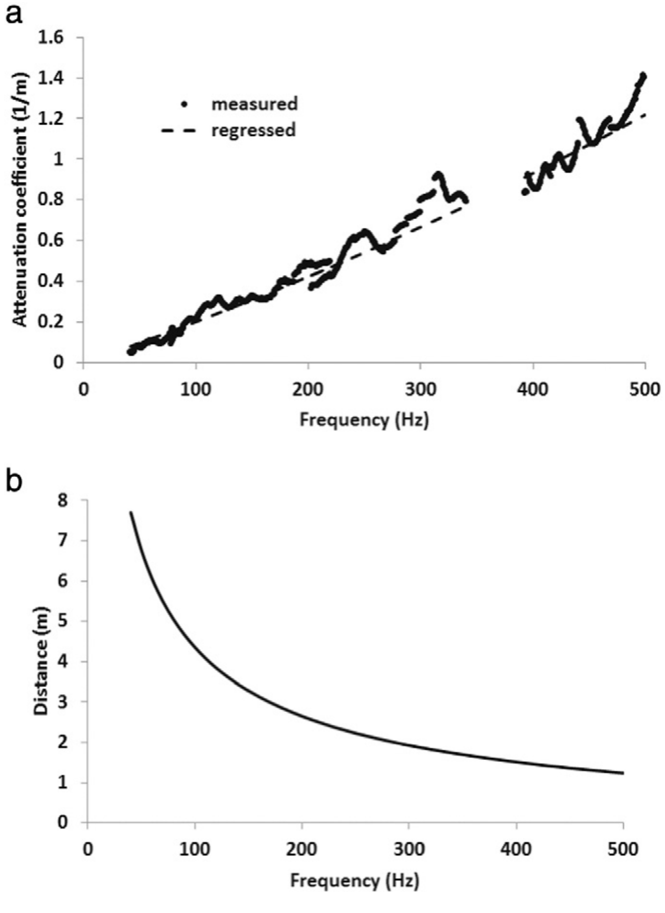

Fig. 1. (A) The attenuation coefficient of the fundamental mode of Rayleigh waves as a function of frequency, where the solid dots are measured data and the dashed line is a regressed curve, and (B) the distance that the amplitude of Rayleigh waves attenuates 80% (−7 dB).

Thirdly, sensor spacing may become larger than half the wavelength at certain frequencies, leading to spatial aliases at higher frequencies. To illustrate this, a typical dispersion curve obtained from this study is plotted in Fig. 2(A), along with one wavelength versus frequency.

It is clear that the phase velocity and wavelength decrease exponentially with frequency. In Fig. 2(B) two curves are plotted: 2.2 wavelengths (solid line) and 0.2 wavelengths (dashed line) versus frequency respectively. These two curves are defined as the far offset and near offset for this study and will be described later. Also plotted in Fig. 2(B) is an example of an equal sensor spacing configuration (horizontal lines) with 100 sensor step numbers and 0.12 cm spacing. The spread length of sensors increases linearly with the step number of sensors to cover a maximum length of 12 m. With such a sensor configuration, the low frequency part is well spatially sampled whereas certain high frequency parts may be under-sampled, failing to meet the Nyquist's sampling theorem and introducing spatial aliases at higher frequencies. To eliminate spatial aliases, one may intend to reduce sensor spacing by increasing the number of sensors. However, doing so will lead to prohibitively large numbers of sensors.

To overcome the above problems, a self-adaptive method is developed to determine high frequency dispersion trends (Lu, 2014b), which is a minor modification of the method proposed by Park and Ryden (2007) and Park (2011). The idea is to consider wavelength as a control parameter to define the near offset and far offset at each frequency. The time traces taken into account are selected using a rule related to the wavelength, in order to spatially filter out the influence of the near and far field effects. In detail, an initial dispersion curve is obtained by a fixed-offset MASW test and used to estimate wavelengths at all frequencies of interest. At each frequency, the near offset and spread lengths are then set to be multiples of the wavelength. In other words, the near offset and spread lengths are unique at each frequency and self-adaptive to the corresponding wavelength. Furthermore, in order to avoid spatial aliases and minimize the number of sensors or sensor locations, a variable sensor spacing configuration is proposed, in which the sensor spacing for the first 120 steps is set to be 0.5 cm and the next 40 steps start with 1 cm spacing followed by a 1 cm incremental spacing for each subsequent step.

The next section addresses the formulation of the fixed-offset and self-adaptive MASW methods and the variable sensor spacing configuration. The following section describes the experimental setup and its data acquisition parameters. The third section presents two field tests, comparing the results of the fixed-offset MASW method with the ones using self-adaptive and variable spacing MASW methods. The fourth section discusses some technical issues and further improvement of the current MASW method. The conclusion is drawn in the final section.

2. Fixed-offset MASW and self-adaptive MASW methods

For a fixed-offset MASW method, an overtone image, a graphic representation of intensity in phase velocity and frequency space, is obtained by a 2-D wavefield transformation method proposed by Park et al.

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