Multichannel Analysis of Surface Waves (MASW)— Active and Passive Methods

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Abstract

Shear modulus is directly linked to material's stiffness and is one of the most critical engineering parameters. Seismically, shear-wave velocity (Vs) is its best indicator. Although methods like refraction, down-hole, and cross-hole shear-wave surveys can be used, they are generally known to be tougher than any other seismic methods in field operation, data analysis, and overall cost. On the other hand, surface waves, commonly known as ground roll, are always generated in all seismic surveys with the strongest energy, and their propagation velocities are mainly determined by Vs of the medium. Furthermore, sampling depth of a particular frequency component of surface waves is in direct proportion to its wavelength and this property makes the surface wave velocity frequency dependent, i.e., dispersive. The multichannel analysis of surface waves (MASW) method tries to utilize this dispersion property of surface waves for the purpose of Vs profiling in 1-D (depth) or 2-D (depth and surface location) format. The active MASW method generates surface waves actively by using an impact source like sledgehammer, whereas the passive method utilizes those generated passively by cultural (e.g., traffic) or natural (e.g., thunder and tidal motion) activities. Investigation depth is usually shallower than 30 m with the active method, whereas it can reach a few hundred meters with the passive method. Overall procedures with both methods are briefly described.

Introduction

In most surface seismic surveys, more than two-thirds of the total seismic energy generated is imparted into Rayleigh waves (Richart et al., 1970), the principal component of ground roll. Assuming vertical velocity variation, each frequency component of a surface wave has a different propagation velocity (called phase velocity, C_f) at each unique frequency (f) component. This unique characteristic results in a different wavelength (λ_f) for each frequency propagated. This property is called dispersion. Although ground roll is considered noise on body-wave surveys (i.e., reflection or refraction profiling), its dispersive properties can be utilized to infer near-surface elastic properties (Nazarian et al., 1983; Stokoe et al., 1994; Park et al., 1998). Construction of a shear (*S*)-wave velocity (Vs) profile through the analysis of plane-wave, fundamental-mode Rayleigh waves is one of the most common ways to use the dispersive properties of surface waves (Bullen, 1963). This type of analysis provides key parameters commonly used to evaluate near-surface stiffness—a critical property for many geotechnical and engineering-geology projects (Stokoe et al., 1994).

The multichannel analysis of surface waves (MASW) method is such a surface wave method to evaluate shear-wave velocity (Vs) (or stiffness) of the ground. The active (Figure 1) MASW method was first introduced in *Geophysics* (Park et al., 1999). It is the conventional mode of survey using an active seismic source (e.g., a sledge hammer) and a linear receiver array, collecting data in a roll-along mode. It analyzes dispersion properties of surface waves propagating horizontally along the surface of measurement directly from impact point to receivers. It gives this Vs information in either 1-D (depth) or 2-D (depth and surface location) (Figure 2) format in a cost-effective and time-efficient manner. The main advantage of the MASW method is its ability to take a full account of the complicated nature of seismic waves that always contain harmful noise waves such as higher modes of surface waves, body waves, scattered waves, traffic waves, etc., as well as fundamental-mode surface waves (Figure 1). These waves may often adversely influence each other during the analysis of their dispersion properties if not properly accounted for. The fundamental framework of the MASW method is based on the multichannel recording and analysis approach long used in seismic exploration surveys (Telford et al., 1976) that can discriminate useful signal against all other types of noise by utilizing pattern-recognition techniques.

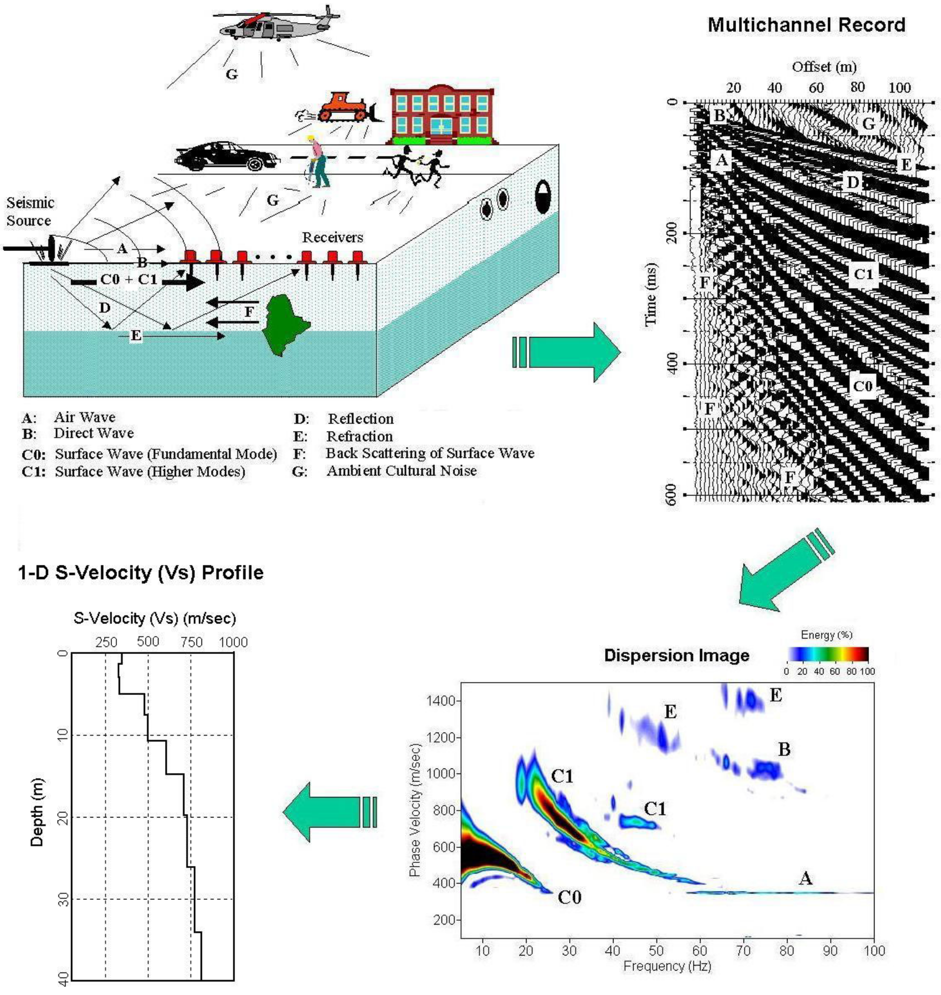

Figure 1. An illustration depicting the main advantage of the MASW method. Complicated nature of seismic waves is carried over without averaging into the measurement (multichannel record). Then, dispersion nature of different types of waves is accurately imaged through a 2-D wavefield transformation. Certain noise wavefields such as back- and side-scattered surface waves and several types of body waves are automatically filtered during this transformation.

As the surface-wave method is gaining in popularity among engineers and geophysicists, demand for increased investigation depth is also growing. However, the amount of active-source energy to gain a few more hertz at the low-frequency end of a dispersion curve, therefore to increase investigation depth by several tens of meters, often increases by several orders of magnitude, rendering efforts with an active source impractical and uneconomical. On the other hand, passive surface waves generated from natural (e.g., tidal motion) or cultural (e.g., traffic) sources are usually of a low-frequency nature with wavelengths ranging from a few kilometers (natural sources) to a few tens (or hundreds) of meters (cultural sources) (Okada, 2003), providing a wide range of penetration depths and therefore a strong motivation to utilize them.

The two passive MASW methods utilize surface waves generated passively from ambient cultural (and natural) activities such as traffic (and thunder, tidal motion, atmospheric pressure change, etc.). The passive remote (Figure 3) method (Park et al., 2004; 2005) employs a two-dimensional (2-D) receiver array such as a cross or circular layout to record passive surface waves. This results in the most accurate evaluation of shear-wave velocity (Vs) at the expense of more intensive field operation and the burden of securing an open-wide space for the array. This can be a good choice if a relatively regional one-dimensional (1-D) Vs profiling is needed. The passive roadside (Figure 3) MASW method (Park and Miller, 2006) adopts the conventional linear receiver array

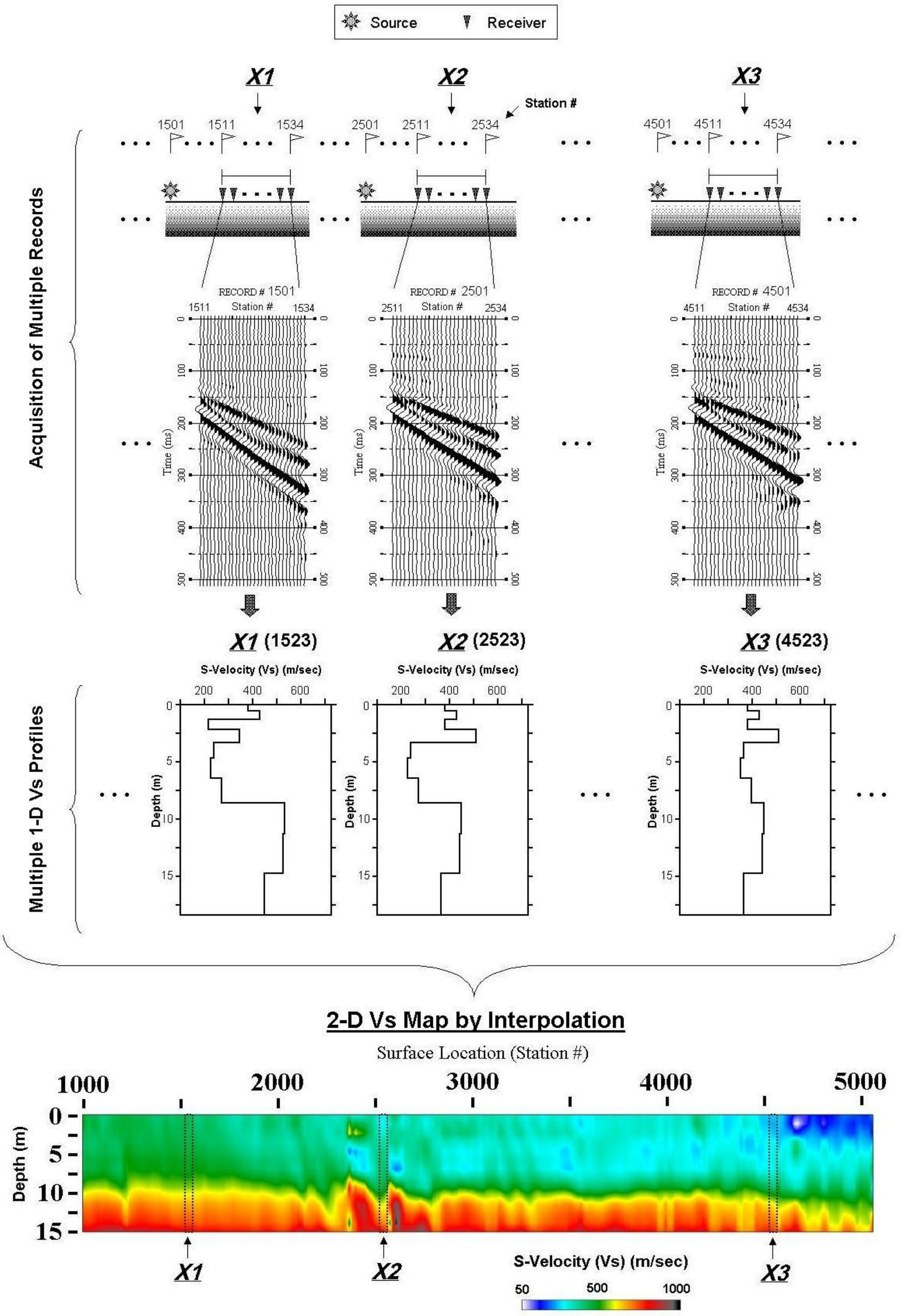

Figure 2. Overall procedure to construct a 2-D Vs map from the MASW survey.

and tries mainly to utilize those surface waves generated from local traffic. It tries to overcome limitations with the passive remote method such as difficulty in securing a spacious area and inconvenience in field operations by sacrificing the accuracy (usually less than 10%) of the Vs evaluation. With the passive roadside method, the array can be set along the sidewalk or the shoulder of a road and the survey can continue in a roll-along mode for the purpose of 2-D Vs profiling. Using a land streamer for the array can improve survey speed by as much as a few orders of magnitude. In addition, an active impact (e.g., by using a sledge hammer) can be applied at one end of the array to trigger a long (e.g., 30 sec) record of data. This can result in the active-passive combined analysis of surface waves for the purpose of obtaining both shallow (e.g., 1-20 m) and deep (e.g., 20-100 m) Vs information simultaneously (Figure 4).

The entire procedure for MASW usually consists of three steps (Figure 1): 1) acquiring multichannel field records (or shot gathers), 2) extracting dispersion curves (one from each record), and 3) inverting these curves to obtain 1-D (depth) Vs profiles (one profile from one curve). Then, by placing each 1-D Vs profile at a surface location corresponding to the middle of the receiver line, a 2-D (surface and depth) Vs map is constructed through an appropriate interpolation scheme (Figure 2).

Power of Multichannel Approach

When seismic waves are generated, both surface and body waves are generated propagating in all directions. Some of these waves are reflected and scattered as they encounter shallow and surface objects (for example, building foundations, culverts, ditches, boulders, and so forth). Furthermore, there are always ambient vibrations from traffic and human activities. The main advantage of the multichannel approach is its ability to distinguish all of these waves from the signal wave (defined whatever type of waves the method aims to utilize) through diverse seismic attribute analysis. Dispersion properties of all types of waves (both body and surface waves) are imaged through a wavefield-transformation method that directly converts the multichannel record into an image where a dispersion pattern is recognized in the transformed energy distribution (Figure 1). Then, the necessary dispersion property (like that of the fundamental mode) is extracted from a specific pattern. All other reflected/scattered waves and ambient noise can be automatically removed during the transformation for an active method.

Active MASW

This is the most common type of MASW survey that can produce a 2-D Vs profile. The overall setup is illustrated in Figure 1. The maximum depth of investigation (z_{max}) that can be achieved is usually in 10-30 m range, but this can vary with sites and types of active sources used. Field procedures and data processing steps are briefly explained in Park et al. (1999) and also at www.kgs.ku.edu/software/surfseis/index.html where some of the field parameters, for example, source offset (x_1) and receiver spacing (dx), are described based on the most recent research results at the Kansas Geological Survey (KGS) and therefore may be different from those previously reported. Surface waves are best generated over a 'flat' ground at least within one receiver-spread length (D) (Figure 2). Then, overall topographic variation within an entire survey line should not matter. However, any surface relief whose dimension is greater than, say, 10% of D will cause a significant hindrance to surface wave generation.

Passive Remote

A passive surface wave survey with a 2-D receiver array (Figure 3) will give the most accurate evaluation of dispersion trend (Park and Miller, 2006). This mode of survey, however, requires a wide area for the 2-D array, which must be deployed some distance away (remote) from points of surface wave generation to meet the plane-wave-propagation assumption. In the case of roadside survey, this distance can be a fraction (e.g., 20%) of the dimension (D) of the receiver array. Procedures in data acquisition and processing are explained in Park et al. (2004) and also at www.kgs.ku.edu/software/surfseis/index.html.

Any type of 2-D receiver array of fairly symmetric shape can be used. An array of significant asymmetric shape, for example an elliptical or elongated rectangular shape, is not recommended due to bias toward a specific direction of incoming surface waves that do not necessarily coincide with the actual direction of major surface wave energy. Common array types may include the circle, cross, square, triangular, random, etc. A detailed study comparing each different type of array and its effect on dispersion analysis has not been reported yet, as far as systematic and scientific perspectives are concerned. Intensive modeling tests performed at KGS, however, indicated an insignificant difference between different types insofar as the symmetry of the array is maintained. It is, therefore, the convenience of field operation that determines the specific type to be used. Field experiments with circular and cross arrays indicated the circle may result in dispersion images with a slightly higher resolution and better definition.

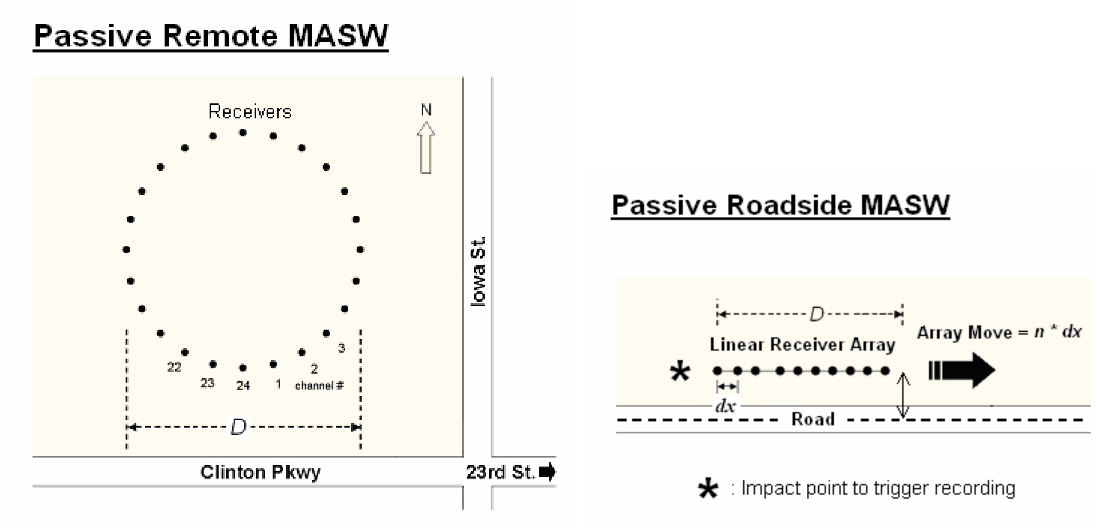

Figure 3. Schematics showing data acquisition with the remote and roadside MASW methods.

Passive Roadside

The survey with this passive MASW method can be implemented with a conventional linear receiver array (Figure 3). Although it can result in a certain degree (usually less than 10%) of overestimated Vs values in comparison to the 2-D receiver array (Park and Miller, 2006), this survey mode can be useful and convenient because in field operations it does not require a large open area for receiver deployment. In fact, the survey can be repeated by progressively moving the receiver array by a certain distance along the road (the roll-along survey mode) so that a 2-D Vs profile can be obtained. Procedures of data acquisition and processing are explained in Park and Miller (2006) and also at www.kgs.ku.edu/software/surfseis/index.html. A linear receiver array deployed along a roadside is used. Although it does not have to be close to the road, it is recommended to maintain the offline distance (between the array and the road center) fairly constant (for example, within ±30%) throughout the entire survey.

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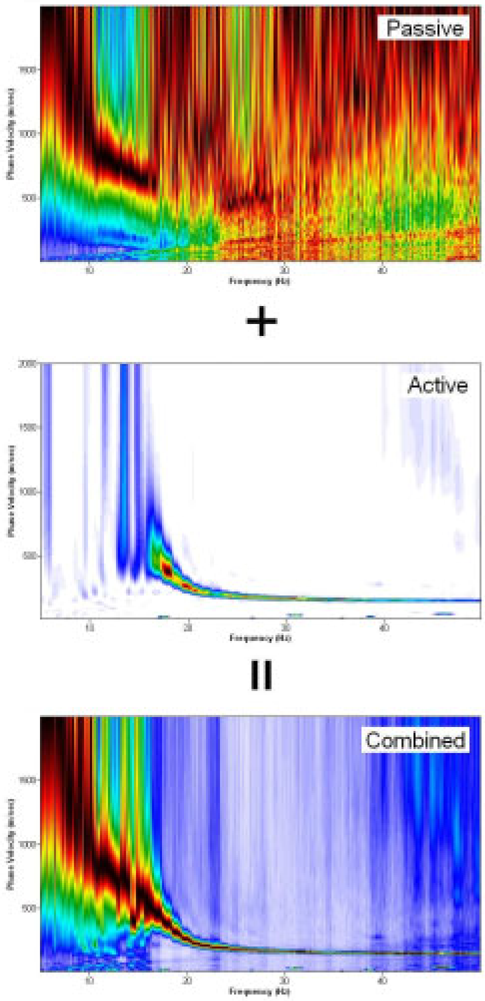

Figure 4. Dispersion images obtained from passive (top) and active (middle) MASW surveys. Two sets of image data are combined to enlarge the frequency range of dispersion (therefore to enlarge the investigation depth range) (bottom).