MULTICHANNEL SEISMIC SURFACE-WAVE METHODS FOR GEOTECHNICAL APPLICATIONS

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ABSTRACT

Unlike other seismic methods (e.g., reflection and refraction), the surface wave method has advantages in several respects. First, the field survey is easiest because of the strong nature of surface-wave energy that can be generated by using a simple impact source (e.g., a sledgehammer) and by following simple field logistics. Second, the data-processing step is usually so simple that it does not require highly-experienced personnel for reliable determination of optimum processing parameters. This also indicates the potential for full automation of the entire processing step. Third, surface waves respond most effectively to various types of near-surface anomalies that are common targets of geotechnical investigation. Because of all these merits, the chance of a successful survey is usually much higher with the surface wave method than with other seismic methods when dealing with detection of near-surface anomalies.

When surface waves are utilized to deduce a near-surface shear-wave velocity (v_s) profile (v_s versus depth), the analysis relies on the accurate calculation of phase velocities for the horizontally travelling fundamental-mode Rayleigh wave. In spite of the dominance of surface waves on acquired seismic data, interference by noise energy sometimes inhibits the reliability of calculated phase velocities when the whole wave field is inverted. The degree the noise contaminates the dispersion curve, and ultimately the inverted shear wave velocity profile, is dependent on frequency as well as distance from the source. Multichannel recording permits effective identification and isolation of these noise types according to their distinctive trace-to-trace coherency in arrival time and amplitude. Decomposition of a multichannel record into a time variable-frequency format, similar to an uncorrelated Vibroseis record, allows each frequency component to be separately and continuously displayed. This unique display format allows contamination by coherent noise to be examined in both frequency and offset space. Separation of these components permits real-time adjustments during acquisition and subsequent processing steps to maximize the signal-to-noise. Multichannel recording permits faster surveying of large areas throughout a broad depth range with only one or a few measurements without significant changes in field configuration.

The methodology of multichannel analysis of surface waves (MASW) is outlined. Effectiveness of the method being applied to near-surface targets that are commonly encountered in geotechnical projects is illustrated through some selected field examples. The examples are 1-D v_s profile and 2-D v_s imaging methods of MASW.

INTRODUCTION

In most surface seismic surveys when a compressional wave source is used, more than two-thirds of total seismic energy generated is imparted into Rayleigh waves (Richart *et al.*, 1970), the principal component of surface waves. As elastic properties (e.g., rigidity and Poisson's ratio) change with depth, each different frequency component of surface waves propagates with different velocities (called phase velocities) (i.e., dispersive) and experiences an attenuation that can be associated with different attenuation coefficient (Bullen, 1963). The frequency-dependent properties of Rayleigh-type surface waves are key to utilizing them as an imaging and characterization tool for various types of geotechnical projects.

Although surface waves are considered to be noise on body-wave surveys (i.e., reflection or refraction profiling), their frequency-dependent properties can be utilized to infer near-surface elastic properties (Park *et al.*, 1998a; 1998b; Miller *et al.*, 1999a; 1999b; Xia *et al.*, 2000; 1999). One of the most common uses of the dispersive properties of surface waves is to obtain a shear (S)-wave velocity (v_s) profile through the analysis of plane-wave, fundamental mode Rayleigh waves (Bullen, 1963). This analysis provides key parameters that can be used to evaluate near-surface stiffness variation with depth, a critical property to many geotechnical studies (Stokoe *et al.*, 1994). As well, the frequency-dependent attenuation property of surface waves can be utilized in combination with the dispersion property as a boosting parameter that can enhance the effectiveness in detection of certain types of near-surface anomalies such as voids.

In v_s profiling by surface wave method, the entire process involves three steps: acquisition of surface waves, construction of dispersion curve (a plot of phase velocity versus f), and backcalculation (inversion) of the v_s profile from the calculated dispersion curve. Broadband surface waves must be produced and recorded with minimal noise to allow accurate determination of the v_s profile. A variety of techniques can be used to calculate the dispersion curve (Stokoe *et al.*, 1994; McMechan and Yedlin, 1981). Back-calculation of the v_s profile (inversion of the dispersion curve) is accomplished iteratively, using the measured dispersion curve as a reference for either forward modeling (Stokoe *et al.*, 1994) or a least-squares approach (Nazarian, 1984). Values for Poisson's ratio and density are usually estimated during this step.

The surface-wave methods need the planar, fundamental mode of Rayleigh waves as the main component for the analysis. Although surface waves usually take most of seismic energy generated, a variety of wave types are produced along with the fundamental Rayleigh waves. Among these are body waves, nonplanar surface waves, higher-mode Rayleigh waves, back-scattered waves, and ambient noise. Relative dominance of each of these wave types depends on the elastic nature of the medium being investigated and certain acquisition parameters (e.g., source-to-receiver distance). The multichannel analysis of surface waves (MASW) (Park *et al.*, 1999) makes it possible to observe and therefore effectively control each of these otherwise harmful waves during data acquisition and processing periods. Ultimately MASW allows the recording and unique identification of broad bandwidth and highest signal-to-noise ratio (S/N) surface waves.

The multichannel recording method also allows an effective coverage of a fairly large area in a continuous mode. This provides not only the redundancy in measurement that can be utilized to improve accuracy of the result, but also the flexibility in analysis method and display mode. A two-dimensional (2-D) (or cross-section) image of v_s distribution below the survey line is therefore possible that can provide critical information for the characterization of geotechnical sites. Also, simultaneous recording and separate processing of refracted body waves can lead to an accurate construction of a 2-D image of Poisson's ratio distribution when the analysis is performed jointly with surface waves (Ivanov *et al.*, 1999).

In the early 1980s a wave-propagation method to generate the near-surface v_s profile, called Spectral Analysis of Surface Waves (SASW), was introduced (Nazarian *et al.*, 1983). SASW method consists of recording surface waves generated from a vertical, impulsive source by using a pair of receivers and calculating the phase velocities from the phase spectra of the recorded data. The method requires repeated measurements by changing field geometry to cover a certain depth range. This method has been widely and effectively used in many geotechnical engineering projects (Stokoe *et al.*, 1994). The single pair of receivers is configured and reconfigured as many times as necessary to sample the desired frequency range as dictated by the investigation depth range. Data are analyzed in the frequency domain to produce a dispersion curve by calculating the phase difference between each deployment of the receiver pair. The inclusion of noise during SASW measurements occasionally can be controlled using a set of empirical criteria tailored for each site investigated (Stokoe *et al.*, 1994; Gucunski and Woods, 1991). Optimizing these criteria is quite challenging due to the degree of changes possible in near-surface materials. Adding to the problems incurred due to the uniqueness of each site are the inherent difficulties evaluating and distinguishing signal from noise when only one pair of receivers is used to record these data. The necessity of recording repeated shots into multiple field deployments for a given depth range makes the whole procedure labor intensive and time consuming. MASW represents an improvement over SASW, overcoming the few but significant weaknesses of the SASW method.

MULTICHANNEL ANALYSIS OF SURFACE WAVES

A variety of wave types are produced during the generation of planar, fundamental mode Rayleigh waves. Among them are several types of body waves like direct, refracted, and reflected waves. In addition to these body waves, higher-mode surface waves are also generated that usually perturb the analysis of the fundamental mode (Stokoe *et al.*, 1994; Tokimatsu *et al.*, 1992). Surface waves propagating within a short distance of the source usually behave in a complicated nonlinear pattern and should not be treated as plane waves (Stokoe *et al.*, 1994). Back-scattered surface waves can dominate the shot gather if horizontal discontinuities such as building foundations, earth berms, or retaining walls exist nearby (Sheu *et al.*, 1988). The relative amplitude of each type of noise usually changes with frequency and distance from the source (offset). Each type of noise on a surface wave shot gather usually has distinct velocity and attenuation properties normally identified on a multichannel record by the unique coherency pattern, arrival time, and amplitude of each. Decomposition of recorded wavefields into a swept-frequency format permits the identification of noise based on frequency content and offset. It is, therefore, possible to make adjustments during acquisition to minimize noise and maximize signal. Selection of some data processing parameters such as the optimum frequency range for the phase-velocity calculation can be made more accurately from shot records. Once these records are decomposed, a simple multichannel coherency measure in the time domain (Yilmaz, 1987) or in the frequency domain (Park *et al.*, 1998b) can be used to calculate phase velocities. Accuracy of the calculated dispersion curve can be estimated through analysis of the linear slope of each frequency component recorded on a single shot gather. In this way, MASW allows the recording and unique identification of broad bandwidth and highest signal-to-noise ratio (S/N) Rayleigh waves. High S/N ensures accuracy in the calculated dispersion curve while the broad bandwidth improves resolution and depth range of investigation possible by the inverted v_s profile (Rix and Leipski, 1991).

MASW—Field Procedure

A swept source (a vibrator, for example) or an impulsive source (a sledgehammer) will generate surface waves. For swept sources, raw uncorrelated data are optimum for multichannel analysis. Impulsive source data needs to be decomposed into the swept-frequency format (explained later in this section) to appropriately expose the phase velocity-frequency relationship of dispersive surface waves. The basic field configuration and acquisition routine for MASW is the same as that used in conventional CMP body-wave reflection surveys.

Even with the dominance of surface waves on seismic data, effectively recording surface waves requires field configurations and acquisition parameters be favorable to the recording of planar, fundamental mode Rayleigh waves and unfavorable to all other types of acoustic waves. Due to the undesirable near-field effects, Rayleigh waves can only be treated as horizontally traveling plane waves after they have propagated a certain distance from the source point (Richart *et al.*, 1970). The source to the first receiver (offset x_1) must be large enough to ensure the Rayleigh wave is behaving as a horizontally-traveling plane wave. Plane wave propagation of surface waves does not occur in most cases until surface waves have traveled a certain distance, called the near-offset (x_1), which is greater than half the maximum desired wavelength ($l_{\max}$) (Stokoe *et al.*, 1994).

$$x_1 \geq 0.5 l_{\max} \, . \tag{1}$$

On a multichannel record displayed in a swept-frequency format, these near field effects manifest themselves as a lack of linear coherency in phase at the lower frequencies which can be observed to return with increasing frequencies (Figure 1b). Different investigators have reported different optimum ratios between x_1 and $l_{\max}$ (Stokoe *et al.*, 1994; Gucunski and Woods, 1991). The normally accepted axiom is that penetration depth (z_l) of surface waves is approximately equal to its wavelength (l) (Richart *et al.*, 1970), while the maximum depth ($z_{\max}$) for which v_s can be reasonably calculated is about half the longest wavelength ($l_{\max}$) measured (Rix and Leipski, 1991). Rewriting equation (1) to represent maximum imageable depths,

$$x_1 \geq z_{\max} \tag{2}$$

provides a good rule of thumb for selecting near-offset distances.

As with all acoustic energy traveling in the earth, high-frequency (short wavelength) components of surface waves attenuate quite rapidly with distance away from the source (Bullen, 1963). If the maximum receiver offset is too large, the high-frequency components of surface wave energy will not dominate the higher frequency portion of the spectrum. Contamination by body waves due to attenuation of high-frequency surface waves at longer offsets will be referred to here as the far-offset effect. The far-offset effect manifests itself as a significant decrease in surface waves slope (increased apparent phase velocity) or the reduction in linear coherency and amplitude of specific frequency arrivals due to interference between low-velocity surface waves and high-velocity body waves (Figure 1c). Far-offset effects will initially be evident at farthest-offset traces, spreading inward on near-offset traces. This effect limits the highest frequency (f_{max}) at which the phase velocity can be measured. When the initial layer model is created according to the half wavelength criterion, f_{max} usually designates the uppermost thickness (H_1) imaged for a particular measured phase velocity (Stokoe *et al.*, 1994):

$$H_1 \geq 0.5\, l_{min} = 0.5 C_{min} / f_{max} \qquad (3)$$

where C_{min} and l_{min} are phase velocity and wavelength, respectively, which correspond to a particular f_{max}. Although the final inverted v_s profile may have shallow layers thinner than H_1, any calculated v_s value for these layers should be considered unreliable (Rix and Leipski, 1991). Equation (3) can be used as a rough estimation of the minimum definable thickness of the shallowest layer. If a smaller H_1 is sought, the length of receiver spread and/or offset from the source needs to be reduced by decreasing x_1, or decreasing receiver spacing (dx), or both.

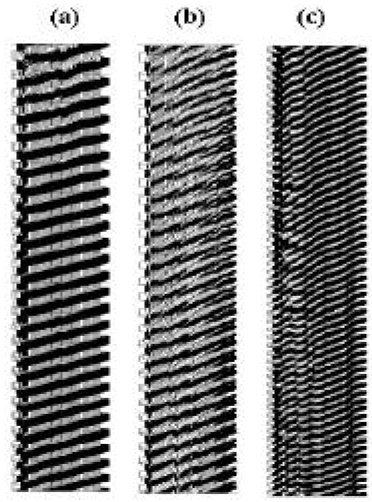


Figure 1. Field data examples of different quality in recorded surface waves displayed in swept-frequency format. Surface waves are shown with distinctive coherency over most traces in (a) indicating an optimum acquisition, whereas they appear as a packet of weak energy along with fragmented patterns due to near-field effect in (b) and as arrivals of decreasing slope (and coherency) with distance from source due to far-offset effect in (c). The distance (x_1) of the nearest receiver from the source is (a) 27 m, (b) 1.8 m, and (c) 89 m.

MASW—Swept-Frequency Record

A swept-frequency record can be obtained either directly from an uncorrelated Vibroseis field record or from an impulsive record using a stretch function (explained later). There are three parameters to consider when preparing a swept-frequency record: the lowest frequency recorded (f_1), the highest frequency recorded (f_2), and the length (T) of the frequency-time plot or stretch function. Optimum selection of these parameters should be based on a series of “rules of thumb.”

It has been suggested that the lowest frequency (f_1) analyzed determines the maximum depth of investigation z_{max} such that

$$z_{max} = C_1 / (2 f_1)\,, \qquad (4)$$

where C_1 is phase velocity for frequency f_1 (Rix and Leipski, 1991). The lowest frequency recorded is usually limited by the natural frequency of the geophone and source type/configuration. If z_{max} is not sufficient to meet a desired depth, a different type of source that can generate more energy at lower frequencies along with lower-frequency geophones should be used.

The highest frequency that can be analyzed (f_2) should initially be chosen high (several times higher than the apparent frequency of surface waves), and lowered to the optimal value after examination of a few swept-frequency records during noise analysis.

Length (T) of the swept-frequency record should be chosen as long as feasible or possible to allow detailed examination of changes in the frequency of surface waves. A longer T is necessary when the near-surface properties change rapidly with depth. However, if f_1 and f_2 are properly selected, a T of no more than 10 s is usually sufficient.

An impulsive record $r(t)$ obtained by using a source like a sledgehammer or weight drop can be transformed into the swept-frequency record $r_s(t)$ by convolution of $r(t)$ with a stretch function $s(t)$ (Coruh, 1985):

$$r_s(t) = r(t) * s(t), \qquad (5)$$

where * denotes the convolution operation. The stretch function $s(t)$ is a sinusoidal function where frequency changes with time. A good choice for $s(t)$ is a linear sweep similar to those commonly used in Vibroseis survey (Waters, 1978):

$$s(t) = \sin\left(2pf_1 t + \frac{p(f_2 - f_1)}{T} t^2\right), \qquad (6)$$

where f_1, f_2, and T are lowest, highest, and length of $s(t)$, all of which can be determined using the previously outlined procedure.

MASW—Dispersion Curve

The generation of a dispersion curve is a critical step in all surface wave methods. A dispersion curve is generally displayed as a function of phase velocity versus frequency. Phase velocity can be calculated from the linear slope of each component on the swept-frequency record. With the excellent isolation potential of each frequency component, a multichannel coherency measure (Yilmaz, 1987) can be applied to a surface wave seismogram in the swept-frequency format. This is possible because each frequency component of the surface wave in a uniform media possesses a strong amplitude and a unique slope (phase velocity). A frequency-domain approach (Park *et al.*, 1998b; 1999) to calculate the dispersion curve can also be employed on impulsive data.

MASW—Inversion

A v_s profile is calculated using an iterative inversion process requiring the dispersion data as input. A least-squares approach allows automation of the process (Xia *et al.*, 1999). For the method employed here, only v_s is updated after each iteration with parameters such as Poisson's ratio, density, and thickness of the model remaining unchanged.

An initial earth model is specified to begin the iterative inversion process. The earth model consists of velocity (P-wave and S-wave velocity), density, and thickness parameters. Among these four parameters, v_s has the most significant effect on the convergence of the algorithm. Several methods are reported to ensure convergence after calculating the initial v_s profile (Heukelom and Foster, 1960; Vardonlakis and Vrettos, 1988). An initial v_s profile is defined here by making the simple assumption that v_s at a depth z_f is 1.09 times (Stokoe *et al.*, 1994) the measured phase velocity C_f at the frequency where wavelength l_f satisfies the following relationship:

$$z_f = a l_f . \qquad (7)$$

Here a is a coefficient that only slightly changes with frequency and has been empirically deduced (Park et al., 1999). The inversion method we use converges to a reliable result even when the initial model is significantly different from the converged model.

SELECTED FIELD EXAMPLES OF MASW

Example—1-D Shear-Wave Velocity (v_s) Profile

A sledgehammer is usually sufficient as a seismic source to effectively generate surface waves for this purpose. The multichannel data (shot gather) obtained during the walkaway tests may need to be decomposed into the swept-frequency format explained earlier to examine if the fundamental-mode surface waves comprise the major part of the seismic energy or if the target depth range is approximately met.

This capability of MASW is demonstrated by impulsive data acquired at a test site in San Jose, California (Figure 2a). Data from this site were recorded using a sledgehammer source and 4.5 Hz geophones. Figure 2b shows the swept-frequency record transformed from the impulsive record in Figure 2a. The first trace in this record represents the stretch function used to separate frequencies from 5 Hz to

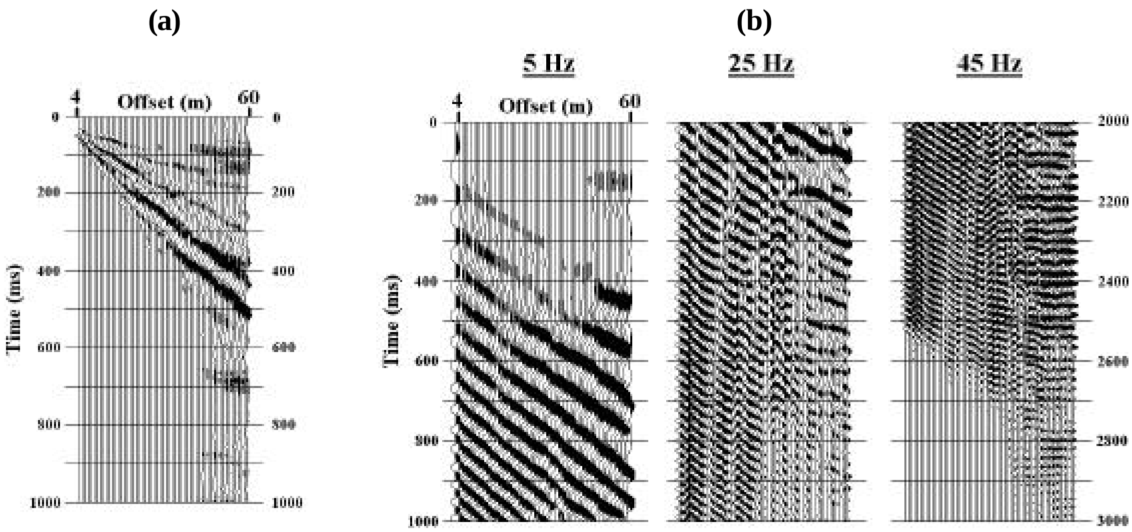


Figure 2. (a) A shot gather obtained using 12-lb sledge hammer as source at a soil site in San Jose, California, and (b) display of its 3-s long swept-frequency record obtained from a transformation using a stretch function (first trace). The swept-frequency record is being displayed here in three 1-s long segments for an enlarged display purpose. On top of each segment is shown an approximate frequency of the stretch function at the top portion of the display.

55 Hz linearly with time across the 2.5-s record. Near-field effects are obvious at low frequencies (< 10 Hz) on these data. Little energy appears to have propagated to far-offset (> 50 m) traces. Far-offset effects are obvious at high frequencies (> 25 Hz) as well on these data. This effect manifests itself as severe attenuation (25 Hz–45 Hz) and body wave contamination (> 45 Hz) on far-offset (> 30 m) traces. For these reasons, near-offset (4 m–30 m) and far-offset (30 m–60 m) traces were separated for phase-velocity calculations. This is equivalent to acquiring and processing two shot gathers with fewer traces and at different source-to-nearest-receiver distances. The calculated dispersion curve (Figure 3a) obtained by analyzing only the far-offset traces shows a reasonable trend at the lower frequencies (< 15 Hz), but, due to body-wave contamination, the trend for the higher frequencies is unrealistic. The lowest analyzable frequency in this dispersion curve is around 3 Hz. The dispersion curve obtained by analyzing only near-offset traces provides a realistic trend for most frequencies analyzed above 6 Hz (Figure 3a).

A composite dispersion curve (Figure 3b) constructed from the two dispersion curves in Figure 3a was used in the inversion process to generate a v_s profile in Figure 3c.

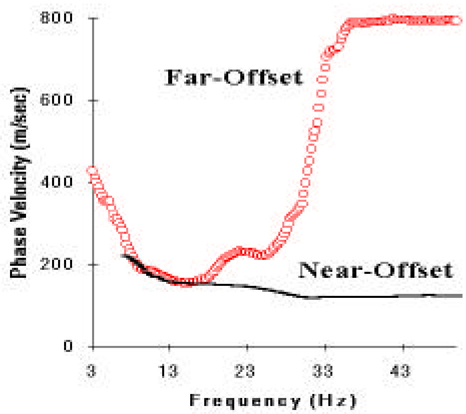
Figure 4 shows another example of a v_s profile analyzed from a sledgehammer shot gather. The shot gather was collected during the Kansas Geological Survey (KGS) crews' surface-wave experiment in the Fraser River Delta near Vancouver, Canada, at a well site for which no borehole data were available until the MASW v_s profile was obtained at the KGS (Xia *et al.*, 2000).

Example—2-D Shear-Wave Velocity (v_s) Imaging

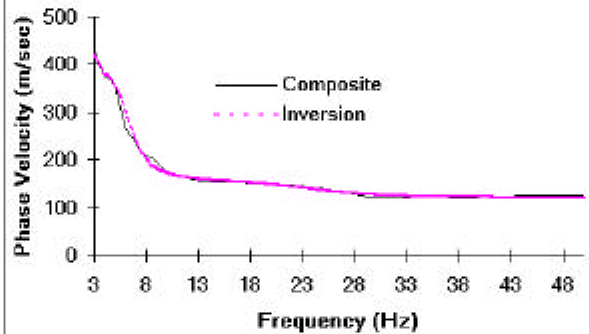
The basic field configuration and acquisition routine for this application of MASW is the same as that used in the conventional roll-along method of CMP body-wave reflection surveys. That is, a multiple number of shot gathers are acquired in a consecutive manner along the survey line by moving both source and reeiver spread simultaneously by a fixed amount of distance after each shot. Each shot gather is then analyzed for one 1-D v_s profile in a manner previously stated. In this way a multiple number of v_s profiles are generated. The v_s data are then assigned into 2-D (x-z) grid. Various types of data processing techniques can be applied to this 2-D v_s data. A countering, a simple interpolation, data smoothing, or combination of these may be applied at this stage.

When the v_s data are assigned to the grid, there is ambiguity in the horizontal coordinate (x) to be assigned because each v_s profile was obtained from a shot gather that spanned a distance too large to

(a)



(b)



(c)

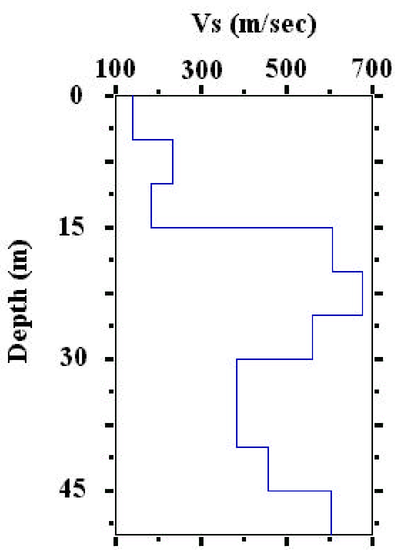


Fig. 3. (a) Dispersion curves obtained by processing near-offset (4 m–30 m) traces and far-offset (30 m–60 m) traces off the record in Figure 2a separately. (b) The composite dispersion curve created by integrating the two curves in (a) being compared with the dispersion curve corresponding to the inverted v_s profile in (c). The v_s profile in (c) was obtained from the inversion of the composite dispersion curve.

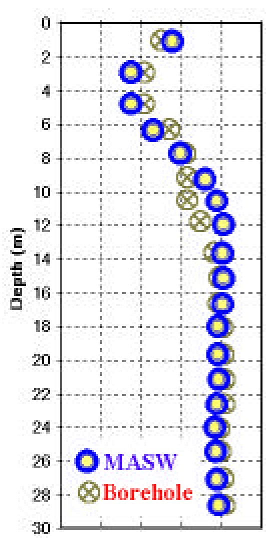


Fig. 4. A v_s profile ("MASW") analyzed from a multichannel surface wave record acquired at a borehole site near Fraser River Delta, Vancouver, Canada, during surface-wave experiments by Kansas Geological Survey (KGS) seismic crews. The down-hole v_s profile ("Borehole") was available only after the MASW profile was obtained.

be considered as a single point. It seems reasonable that the center of the receiver spread be the most appropriate point because the analyzed v_s profile represents an average property within the spread length. This was actually confirmed through field experiments.

An experiment to detect a near-surface steam tunnel as an anomaly was conducted as a feasibility check of the method previously outlined. A soccer field on the campus of the University of Kansas, Lawrence, Kansas, was chosen as a test site where an underground steam tunnel (1.2 m x 2.0 m.) crosses under the field at a depth of 2.0 m (Figure 5a). Both shot and receiver intervals were 0.6 m, and 30 receiver groups of 10-Hz geophones were laid out. The source-to-first-receiver distance was 16 m. A total of 70 shot gathers were collected. Acquisition started in such a way that the first several shot gathers could be collected with both source and receivers being kept well out of the surface location of the steam tunnel. An IVI Minivib was used as source with a 10 Hz–150 Hz linear sweep and a 10-s sweep time. Figure 5b represents an image of v_s distribution after contouring was applied to this set of 2-D v_s data prepared by following the aforementioned procedure. Existence of the tunnel is obvious in this image as represented by the general trend of contour lines.

Figure 5c shows a 2-D image obtained from a different type of surface wave processing method (discussed in Park *et al.*, 1998a). This method utilizes both attenuation and dispersion properties of surface waves to accentuate the existence of anomalies. An averaged phase-velocity function for the fundamental-mode surface waves was prepared from these curves. This velocity function was then used for the dynamic linear move out (DLMO) correction of all shot gathers obtained in the swept-frequency format (Park *et al.*, 1998a). All traces in a DLMO-corrected shot gather are then stacked together to produce one stacked trace per shot. Figure 5c shows an early portion of the stacked section of these DLMO-corrected shot gathers. Depth scale is shown along with time scale. To display the depth scale in increasing order, the corresponding portion of the stacked data was flipped over and, therefore, the time scale is displayed in decreasing order. The depth scale represents half the penetration depth (one wavelength). For this reason, any feature interpreted from the stacked section should be linked to the average elastic property at the corresponding depth at the reference location.

Existence of the tunnel is obvious on the stacked section as indicated by an approximately rectangular zone with weak amplitudes. Accuracy of the image is remarkable, considering the generally accepted notion that the surface wave method is an average method. Along with the tunnel image, other anomalies at various other shallower parts are noticeable. These anomalies may be related to different moisture contents of the soil that affect the bulk density, or to different types of soil used during the construction of the tunnel and soccer field.

DISCUSSION

When MASW is used to generate a v_s profile, the nature of near-surface material can be treated implicitly as a layered earth model with no lateral variation in elastic properties. It is, therefore, important to keep the entire spread as short as possible to validate this assumption when lateral variations are suspected at a site. From an empirical perspective, the assumption is valid as long as good linear coherency is observed.

We do not see any appreciable difference in the overall effectiveness whether using a swept source or an impulsive source. Considering the relative importance of lower frequencies for deeper penetration, a heavy impulsive source seems to be an effective and economic choice. Due to this dependence on the lower frequencies, it is always recommended to use a high-output, low frequency geophone with no low-cut field filter. As far as the stretch function or Vibroseis sweep is concerned, we see no difference in the resulting v_s profile between up or down sweeps.

The frequency continuous approach makes the swept-frequency display much more useful when analyzing the interaction between several different types of seismic events, as compared with conventional filter panels. The optimum offset and lowest usable frequency outside the surface waves can be established more effectively using a swept-frequency display than from the impulsive record alone. This makes this decomposition of frequencies a potentially useful tool for compressional surveys as well.

The fact that it takes less than half an hour in the field to produce a twenty-layer v_s profile is an indication of the overall speed of the MASW process.

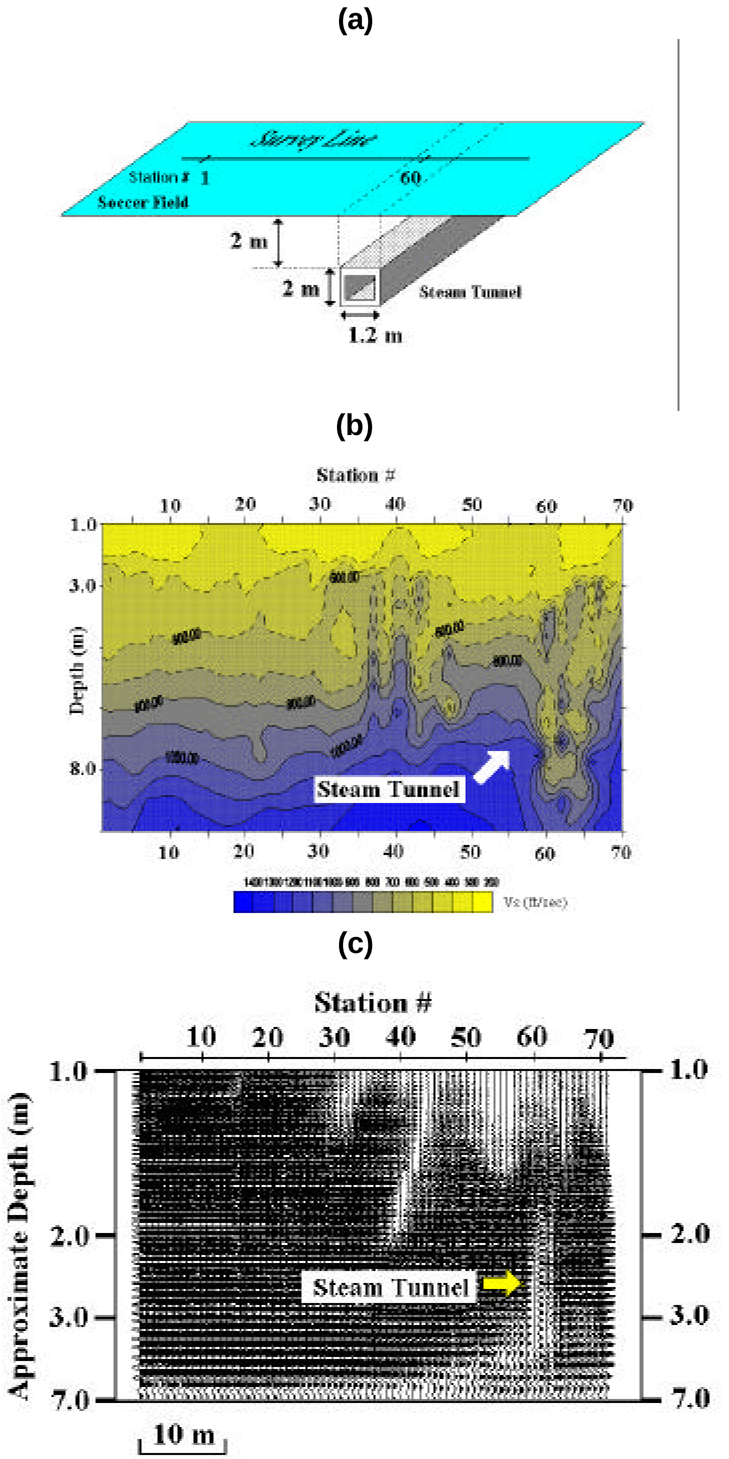


Fig. 5. (a) A diagram showing field geometry and location of steam tunnel. (b) 2-D contour image of v_s distribution obtained from the multiple number of v_s profiles assigned into a regular 2-D grid. (c) Stacked section of shot gathers after dynamic linear move out (DLMO) correction was applied by using the dispersion information at the beginning side (left end) of the survey line. Details of the data processing are explained in Park et al. (1998a).

CONCLUSIONS

When surface waves are acquired using a multichannel recording method and displayed in a swept-frequency format, different frequency components of Rayleigh waves can be identified by distinctive and simple coherency. This leads to a seismic surface-wave method that provides a useful non-invasive tool, where information about elastic properties of near-surface materials can be effectively obtained for the following reasons:

- The integrity of each single Rayleigh wave frequency can be readily examined for contamination by body waves or noise surface waves. This makes adjustments possible during data acquisition and processing steps to improve signal-to-noise (S/N) ratio.
- When using surface waves recorded on a single shot gather to generate a v_s profile, a highly accurate dispersion curve can be obtained and inverted to produce a v_s profile with high confidence and consistency.

ACKNOWLEDGMENTS

We would like to thank Joe Anderson, David Laflen, and Brett Bennett for their commitment during the field test. We also give special thanks to Lee Gerhard, former director of the Kansas Geological Survey (KGS), and Kathy Sheldon, chief of operations at KGS, for giving permission to acquire Vibroseis data at the KGS test site. We also thank Mary Brohammer for help in preparation of this manuscript.

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