Multichannel analysis of surface waves (MASW)—active and passive methods

Choon B. Park, Richard D. Miller, Jianghai Xia, and Julian Ivanov, Kansas Geological Survey, Lawrence, USA

The conventional seismic approaches for near-surface investigation have usually been either high-resolution reflection or refraction surveys that deal with a depth range of a few tens to hundreds meters. Seismic signals from these surveys consist of wavelets with frequencies higher than 50 Hz. The multichannel analysis of surface waves (MASW) method deals with surface waves in the lower frequencies (e.g., 1–30 Hz) and uses a much shallower depth range of investigation (e.g., a few to a few tens of meters).

Shear modulus is directly linked to a material's stiffness and is one of the most critical engineering parameters. Seismically, shear-wave velocity (V_S) is its best indicator. Although methods like shear-wave refraction, downhole, and crosshole surveys can be used, they are generally less economical than any other seismic methods in terms of 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, have the strongest energy, and their propagation velocities are mainly determined by the medium's shear-wave velocity. The 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.

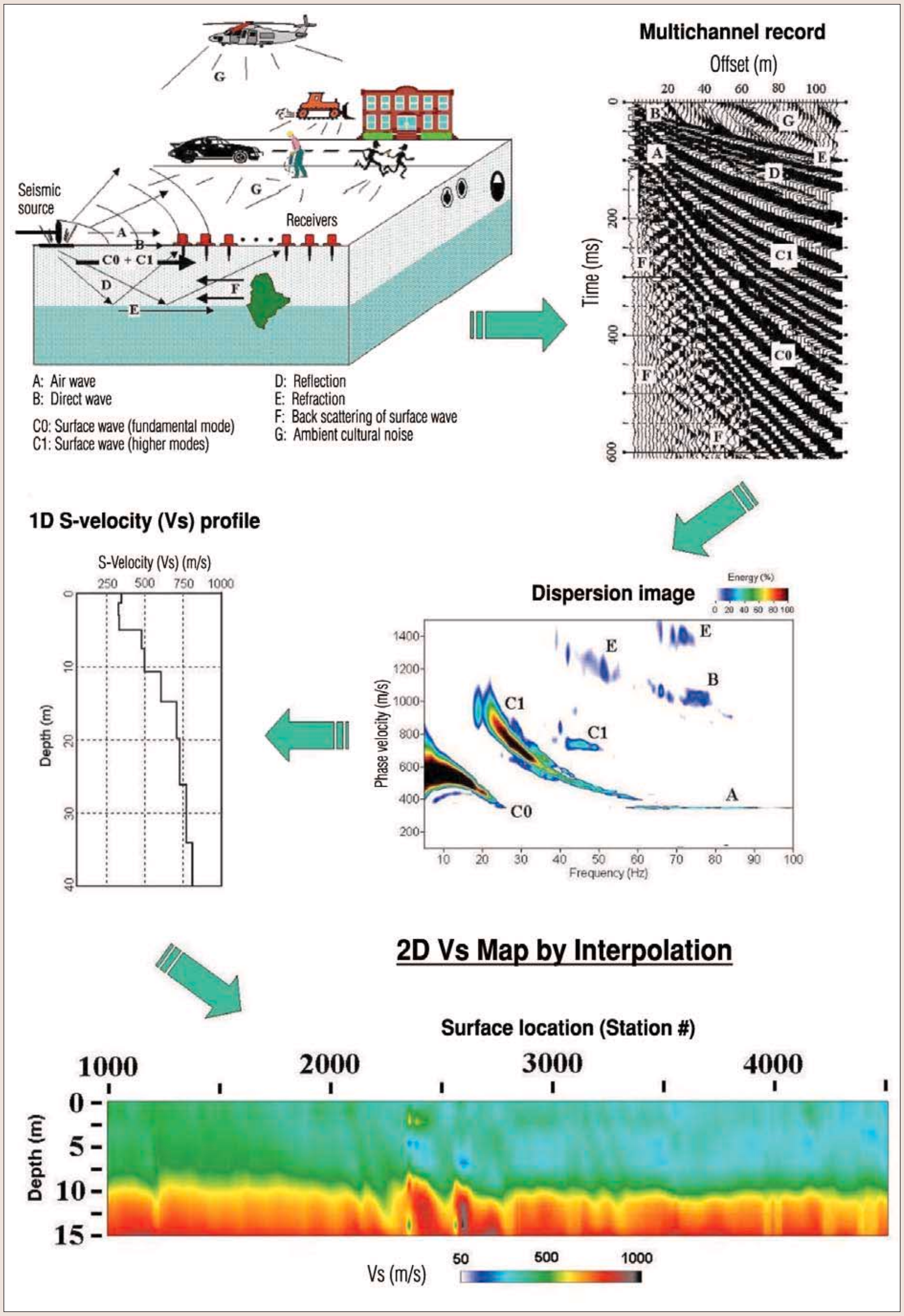

Figure 1. An illustration of the overall procedure and main advantage of the MASW method. Complicated nature of seismic waves is carried over into the measurement (multichannel record). Then, dispersion nature of different types of waves is accurately imaged through a 2D wavefield transformation. Certain noise wavefields such as back- and side-scattered surface waves and several types of body waves are automatically filtered during this transformation. Dispersion curves are then extracted to be inverted for a 1D V_S *profile, multiples of which can be prepared to make a 2D* V_S *map.*

The multichannel analysis of surface waves (MASW) method tries to utilize this dispersion property of surface waves for the purpose of V_S profiling in 1D (depth) or 2D (depth and surface location) format. Basically it is an engineering seismic method dealing with frequencies in a few to a few tens of Hz (e.g., 3–30 Hz) recorded by using a multichannel (24 or more channels) recording system and a receiver array deployed over a few to a few hundred meters of distance (e.g., 2–200 m). The active MASW method generates surface waves actively through an impact source like a sledgehammer, whereas the passive method utilizes surface waves generated passively by cultural (e.g., traffic) or natural (e.g., thunder and tidal motion) activities. The investigation depth is usually shallower than 30 m with the active method, whereas it can reach a few hundred meters with the passive method. The main advantage of MASW is its ability to take into full account the complicated nature of seismic waves that always contain noise waves such as unwanted 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 they are not properly accounted for. With the multichannel approach, 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 specific 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 the identified pattern. All other reflected/scattered waves are usually automatically removed during the transformation. The entire procedure for MASW usually consists of three steps: (1) acquiring multichannel field records (or shot gathers); (2) extracting dispersion curves (one from each record); and (3) inverting these dispersion curves to obtain 1D (depth) V_S profiles (one profile from one curve).

Then, by placing each 1D V_S profile at a surface location corresponding to the middle of the receiver line, a 2D (surface and depth) V_S map can be constructed through an appropriate interpolation scheme (Figure 1).

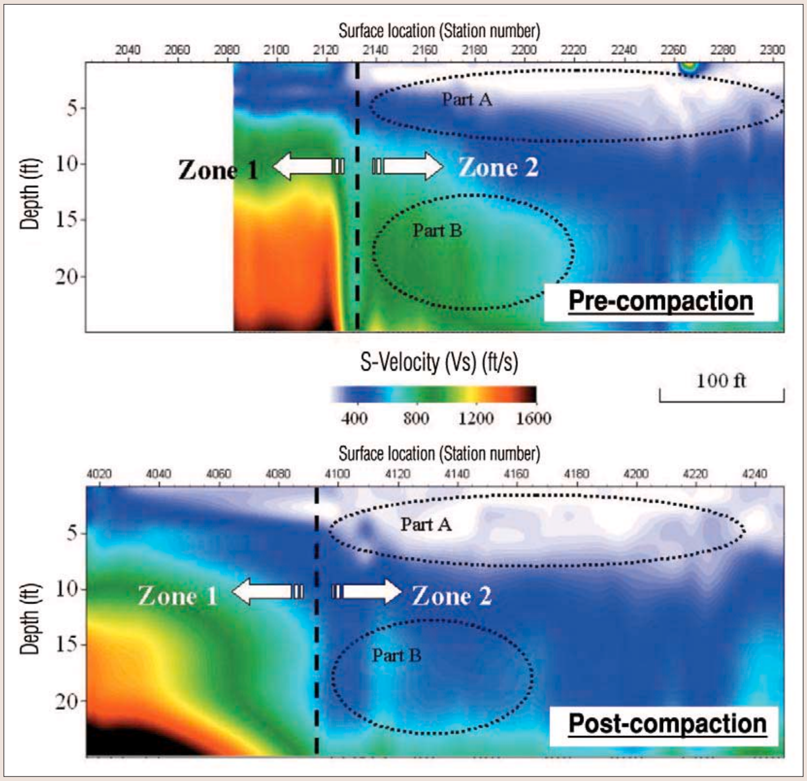

Figure 2. *A case study of active MASW applied to a soil site before and after compaction operations.*

Active MASW. The active (Figure 1) MASW method was introduced in GEOPHYSICS in 1999. This is the most common type of MASW survey that can produce a 2D V_S profile. It adopts the conventional mode of survey using an active seismic source (e.g., a sledgehammer) and a linear receiver array, collecting data in a roll-along mode. It utilizes surface waves propagating horizontally along the surface of measurement directly from impact point to receivers. It gives this V_S information in either 1D (depth) or 2D (depth and surface location) format in a cost-effective and time-efficient manner. The maximum depth of investigation (z_{max}) is usually in the range of 10–30 m, but this can vary with the site and type of active source used. Field procedures and data processing steps are briefly explained at the Kansas Geological Survey (KGS) Web site (*www.kgs.ku.edu/software/surfseis/ masw.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 KGS.

Two surveys using the active MASW method were conducted over a soil site where a chemical treatment facility had been planned. The purpose of the surveys was to map soil stiffness characterized by shear-velocity (V_S) distribution before and after deep dynamic compaction (DDC) operations. Site soil consisted of very heterogeneous gravel and cobbles in a sand-and-silt matrix. Results from each survey are represented by two 2D V_S maps delineating V_S variation of soil below the surveyed lines (Figure 2). Results were analyzed in two different zones of previous reclamation (Zone 1) and natural soil (Zone 2). Portions with noticeable change in V_S were identified that indicated possible influence by the compaction operations.

Passive MASW. 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 needed to gain a few more Hz at the low-frequency end of a dispersion curve (e.g., 5–7 Hz)—and thereby to increase investigation depth by several tens of meters—often rises by several orders of magnitude, rendering efforts with an active source impractical

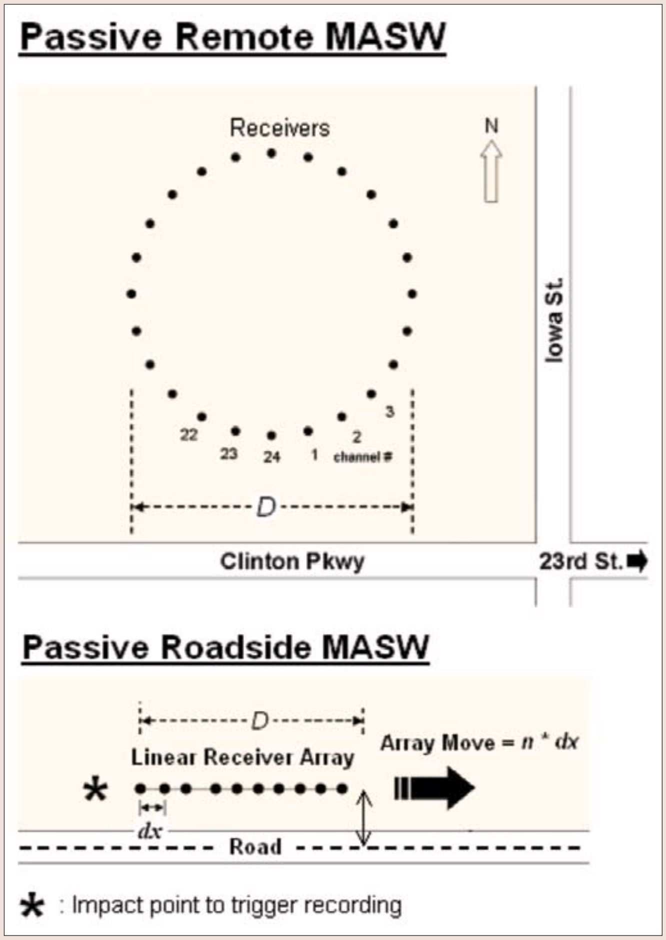

Figure 3. *Schematics of data acquisition with passive remote and passive roadside MASW.*

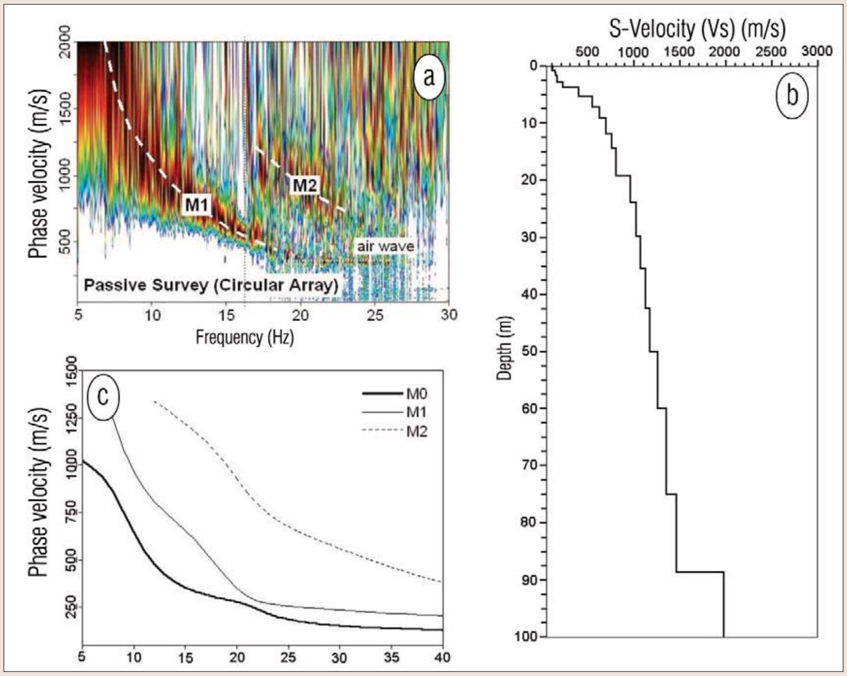

Figure 4. *(a) Dispersion image obtained from a passive remote MASW survey using a circular receiver of 115-m diameter. (b) 1D* V_S *profile inverted from the two dispersion trends interpreted in (a). (c) Theoretical dispersion curves calculated from the* V_S *model in (b).*

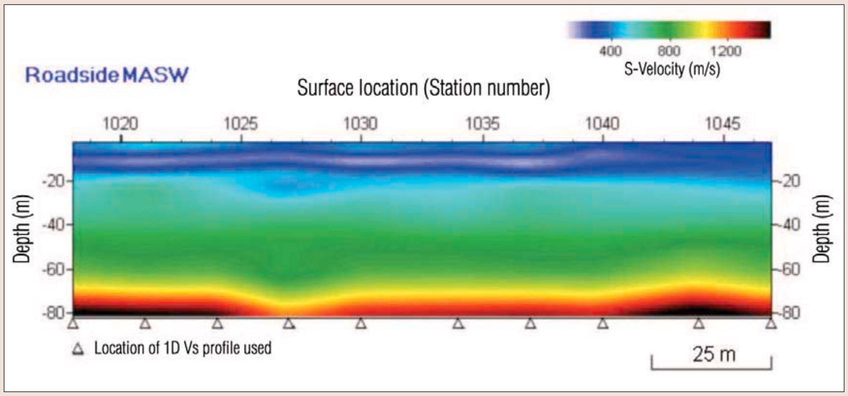

Figure 5. *2D* V_S *map obtained from a passive roadside MASW survey using a linear 24-channel receiver array of 5-m separation. A sledgehammer delivered impact at one end of the array to trigger 30-s recording. This 2D* V_S *map was obtained from a combined analysis of active (0–2 s) and passive (2–30 s) portions of each record.*

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 (1–30 Hz) nature with wavelengths ranging from a few km (natural sources) to a few tens (or hundreds) of meters (cultural sources), providing a wide range of penetration depths and therefore a strong motivation to utilize them. This type of application originated almost half a century ago in Japan and was called the microtremor survey method (MSM).

This method in its original form adopted a limited number (usually fewer than ten) of receivers (channels) for data acquisition. The passive MASW method, on the other hand, usually uses more (24 or more) channels than MSM and aims to fully exploit the advantages of multichannel recording and processing. It therefore has a greater flexibility in field logistics and an enhanced robustness in data processing with an increased resolution in the analysis of both the modal nature and azimuthal properties of surface waves. Passive MASW is divided into two different types based on field logistics and type of V_S profiles (1D or 2D) to be obtained, passive remote and passive roadside MASW surveys (Figure 3). The former seeks a 1D V_S profile of bulk materials ranging up to hundred meters along the surface and depth directions.

On the other hand, the latter type can generate a 2D V_S profile covering up to a hundred meters in depth and a surface distance determined by the survey length. These two passive MASW methods utilize those surface waves generated passively from ambient cultural activities such as traffic.

The passive remote (Figure 3) method employs a 2D receiver array such as a cross or circular layout to record passive surface waves. This results in the most accurate evaluation of 1D shear-wave velocity at the expense of more intensive field operation and the burden of securing a wide-open space for the array. This can be a good choice if relatively regional 1D V_S profiling is needed. Procedures in data acquisition and processing are briefly explained at the KGS Web site. Any type of 2D 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 indicate the circle may result in dispersion images with a slightly higher resolution and better definition. Figure 4a shows a dispersion image processed from a data set of the passive remote survey that used a circular receiver array with a diameter of 115 m. Two higher modes (M1 and M2) were identified on the image from a joint analysis with another image processed from an active-survey data set conducted at the center of the array. Figure 4b shows the corresponding 1D V_S profile analyzed from the multimodal inversion of these identified dispersions and Figure 4c the corresponding theoretical curves.

The passive roadside (Figure 3) MASW method adopts the conventional linear receiver array 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 V_S evaluation. With this method, the array can be set along a sidewalk or the shoulder of a road and the survey can continue in a roll-along mode for the purpose of 2D V_S 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 sledgehammer) can be applied at one end of the array

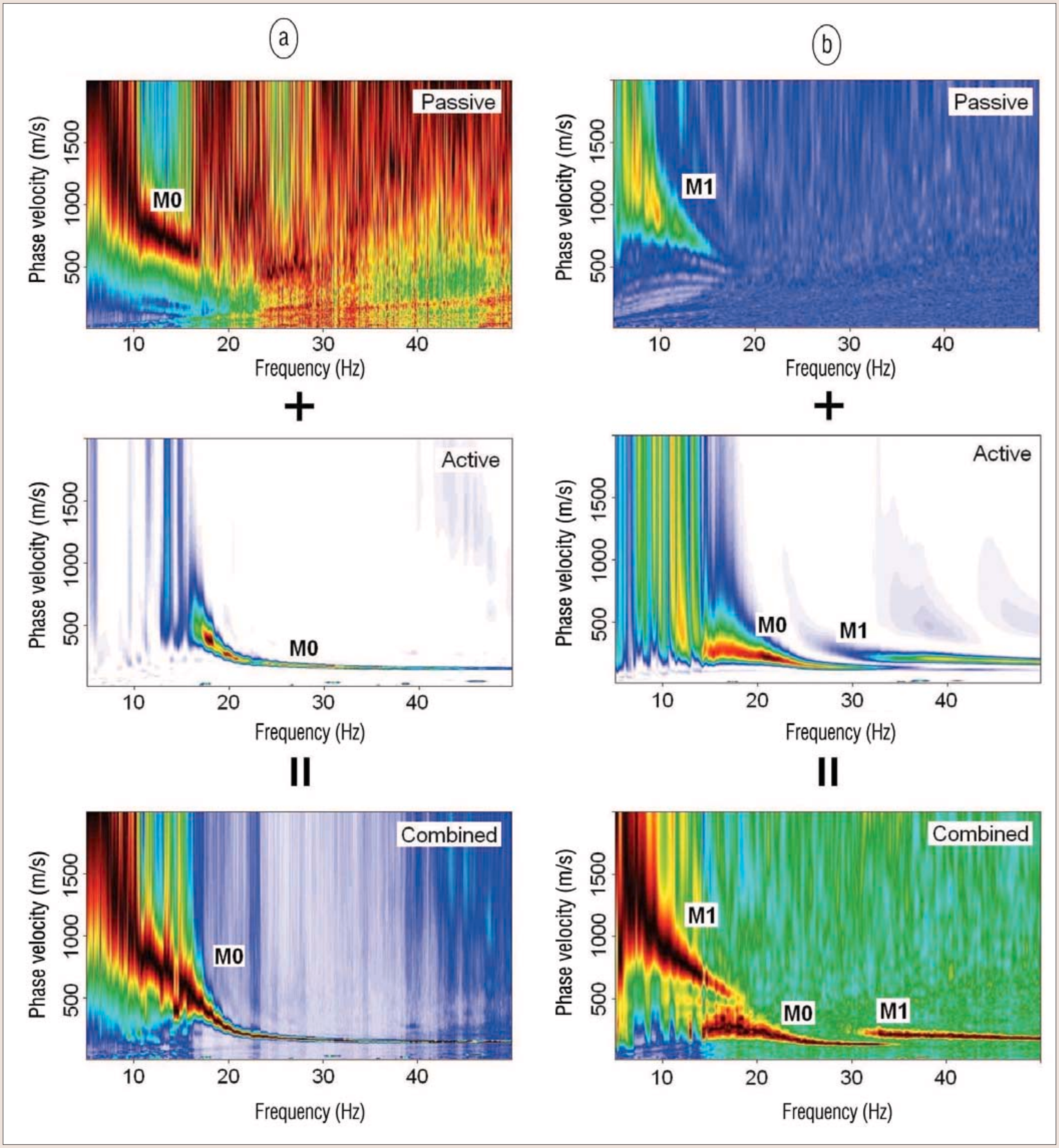

Figure 6. Dispersion images obtained from passive (top) and active (middle) MASW surveys. Two sets of image data are combined to enlarge the frequency range of dispersion (therefore to enlarge the investigation depth range) in (a), whereas in (b) they are combined to help modal identification of recognized dispersion trends and to enlarge the usable bandwidth of dispersion.

to trigger a long recording (e.g., 30 s). This can result in a combined active-passive analysis of surface waves to obtain both shallow (e.g., 1–20 m) and deep (e.g., 20–100 m) V_S information simultaneously (Figure 5). Although it can result in slightly overestimating (usually by less than 10%) V_S values in comparison to the remote method using a 2D receiver array, this survey mode can be useful and convenient because of the significant advantage in field operations. Procedures of data acquisition and processing are briefly explained at the KGS Web site.

The 2D V_S profile in Figure 5 was obtained from a roadside survey that used a linear receiver array of 5-m spacing and repeated recording at ten different surface locations by moving the array by four stations (20 m). A 10-lb sledgehammer delivered an active impact at the beginning of 30-s recording. Each record was then split into active (0–2 s) and passive (2–30 s) portions, respectively, to go through different data processing schemes, generating two different dispersion images that were combined together (vertical stacking) for the purpose of enlarging the bandwidth of dispersion patterns.

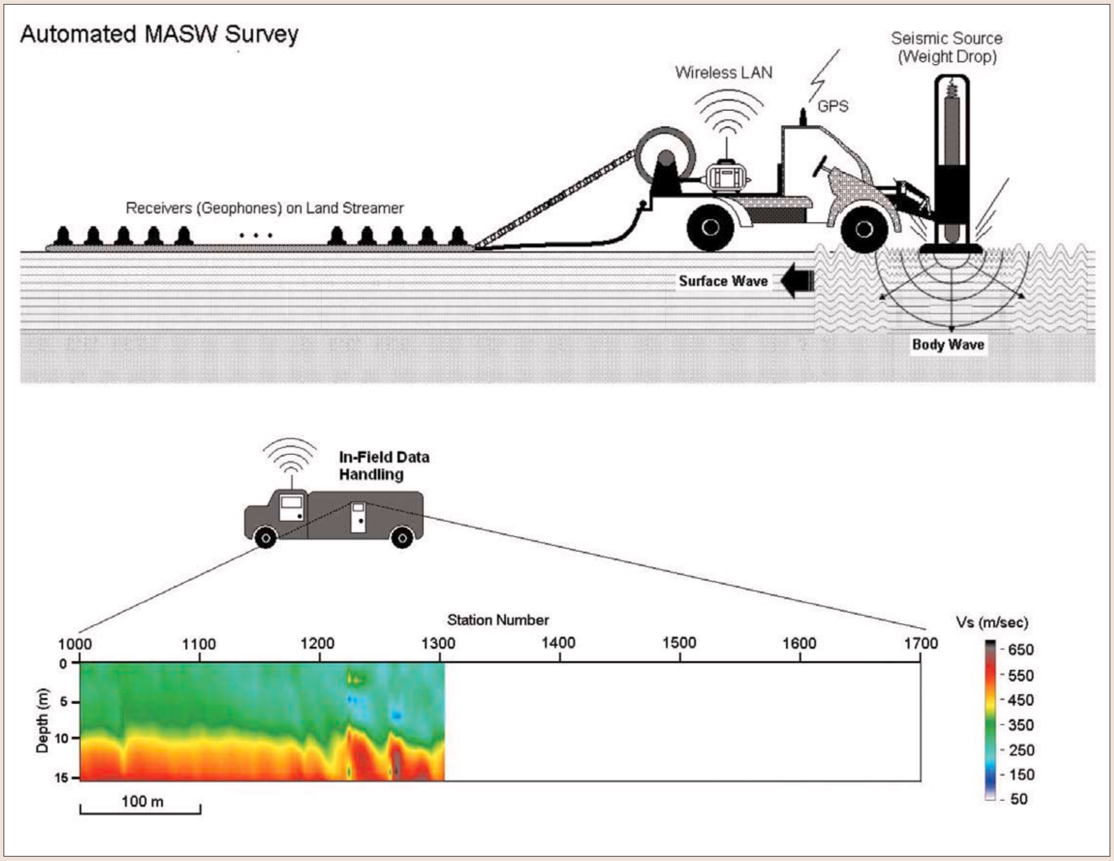

Figure 7. Schematic of a prototype field system recently developed and tested at KGS illustrating the mobility and effectiveness of the routine MASW survey in the near future.

Combining active and passive surveys. It is often useful or necessary to combine dispersion images processed from active and passive data sets for two reasons: (1) to enlarge the analyzable frequency (therefore depth) range of dispersion (Figure 6a), and (2) to better identify the modal nature of dispersion trends (Figure 6b). The passive image in Figure 6a obtained from a remote survey using a 48-channel cross receiver array deployed over a surface dimension of about 120 m shows a prominent dispersion trend in a 6–17 Hz range. In addition, the active image from a 24-channel active survey conducted with 1-m receiver spacing at the center of the passive cross array shows another dispersion trend in the higher frequencies (16–50 Hz). When these two images are combined by vertically stacking both sets of image data, two trends are merged naturally to make one continuous trend over a broader bandwidth (6–50 Hz). On the other hand, the passive dispersion image in Figure 6b obtained from another remote survey conducted over a different soil site shows a trend prominent in 5–20 Hz range that was originally interpreted as the fundamental mode (M0). When this image was combined with the active image obtained from an active survey at the center of the passive array, its modal nature is reinterpreted as more likely being a higher mode (M1).

The near future of MASW. As the land streamer can be effectively used for both active and passive MASW surveys, an acquisition system similar to the one illustrated in Figure 7 will be routinely used in the near future. This is a prototype recently tested at KGS to determine its efficiency in data acquisition and in-field data handling. Comparison of the data quality versus that of the conventional spike-coupled receivers showed insignificant difference because of the strong nature of surface waves. Relatively simple data processing procedures made the in-field data handling so effective that the vertical 1D V_S profile of the surveyed point on the ground could be continuously added to update the 2D V_S map almost in a real-time mode.

Due to the significantly increased mobility of the entire system, the survey can be conducted by only a few field personnel with one or two operating both source (for active survey) and receivers and another dedicated to in-field data handling.

Summary. MASW is a recently developed seismic method that deals with relatively lower frequencies and shallower investigation depth ranges than do conventional high-resolution seismic methods. It provides shear-wave velocity (V_S) information of near-surface materials in a highly cost-effectively manner. Because of the relatively significant value of this (V_S) information in most geotechnical engineering projects and also because of the relatively simple in-field operation and data processing, it is gaining popularity among engineering communities.

Suggested reading. "Roadside passive MASW" by Park and Miller (SAGEEP 2006 *Proceedings*). "Combined use of active and passive surface waves" by Park et al. (*Journal of Engineering and Environmental Geophysics*, 2005). "Imaging dispersion curves of passive surface waves" by Park et al. (SEG 2004 *Expanded Abstracts*). "Multichannel analysis of surface waves (MASW)" by Park et al. (GEOPHYSICS, 1999). "Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves" by Xia et al. (GEOPHYSICS, 1999). TLE

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Corresponding author: park@neptune.kgs.ku.edu