

Combined Use of Active and Passive Surface Waves

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ABSTRACT

With a surface wave method to estimate shear-wave velocity (V_s) from dispersion curve(s) of known mode(s), accurate modal identification is obviously a crucial issue. In this regard, the dispersion imaging method is an essential processing tool as it can unfold the multi-modal nature of surface waves through direct wavefield transformations. When a combined dispersion curve of an extended frequency range is prepared from analyses of both passive and active surface waves attempting to increase the maximum depth of V_s estimation, the modal nature of the passive curve (as well as the active one) must be assessed although it has usually been considered the fundamental mode. We report two experimental survey cases performed at the same soil site, but at two different times, employing the passive and active versions of the multichannel analysis of surface waves (MASW) method for an increased investigation depth. In the earlier survey, the modal nature of the imaged dispersion trends from the passive (<20 Hz) and active (>20 Hz) data sets was identified as the fundamental mode, whereas it was confidently re-identified as the first higher mode from the later survey. Modal inspection with the dispersion image created by combining passive and active image data sets was the key to this confident analysis. The modal nature of the passive curve was identified from its context with active curves, whose confident analysis therefore had to come first. An active data set acquired with a small (<1.0 m) receiver spacing and an impact point located close to the receivers appears important for this purpose.

Introduction

As the surface wave method has been drawing attention in recent days as one of the viable tools to estimate shear-wave velocity (V_s) of near-surface materials, diverse applications are made in various types of geotechnical projects. While the active method using an artificial seismic source, like a sledgehammer, can often achieve the goal of V_s estimation down to a few tens of meters (for example, 30 m), there are instances of insufficient investigation depth due to either elastic properties of the near-surface materials or due to an unusually deep investigation depth sought in certain projects. Although a more-powerful active source like a heavy-weight drop is sometimes used to overcome this limitation, the gained depth range often may be trivial. It seems that the impact power necessary to achieve a significant gain in investigation depth may have to be several orders of magnitudes greater than the power delivered by most of active sources. Such a source, if invented, will not only be expensive but also inconvenient in field operations, which will discourage popular use in engineering projects. Instead, investigators are now turning their attention to those passive surface waves generated by cultural activities (for example, traffic) as their wavelengths are long enough to assure the necessary gain below the maximum depth achieved by an

active survey. While the active survey provides a dispersion curve in a relatively high-frequency range (for example, 20–50 Hz), the passive survey can fill the dispersion trend at lower frequencies (for example, 5–20 Hz). By combining these two sets of dispersion curves, a dispersion curve of known mode (such as the fundamental mode) is constructed to back calculate a V_s profile for a wide depth range.

It has usually been assumed that modal nature of passive surface waves is predominantly of the fundamental-mode of Rayleigh waves in the microtremor survey method (MSM) (Okada, 2003; Shaokong *et al.*, 2001; Asten and Henstridge, 1984; Toksöz, 1964). MSM usually utilizes passive surface waves of both natural (tidal, atmospheric, etc., motions) and cultural (traffic, factory, etc., activities) origins, and deals with frequencies (wavelengths) lower (longer) than a few hertz (a few hundred meters) (Okada, 2003). Most recent applications for engineering investigations utilize those surface waves of mostly traffic origin and deal with frequencies higher than about 5 Hz (wavelengths in several tens of meters) (Park *et al.*, 2004a; Asten, 2004; Yoon and Rix, 2004; Suzuki and Hayashi, 2003; Okada, 2003; Zywicki, 1999). For those passive surface waves with MSM being predominantly the fundamental mode, if possible the passive curve in the latter engineering case of applications is usually tied with an active curve identified as

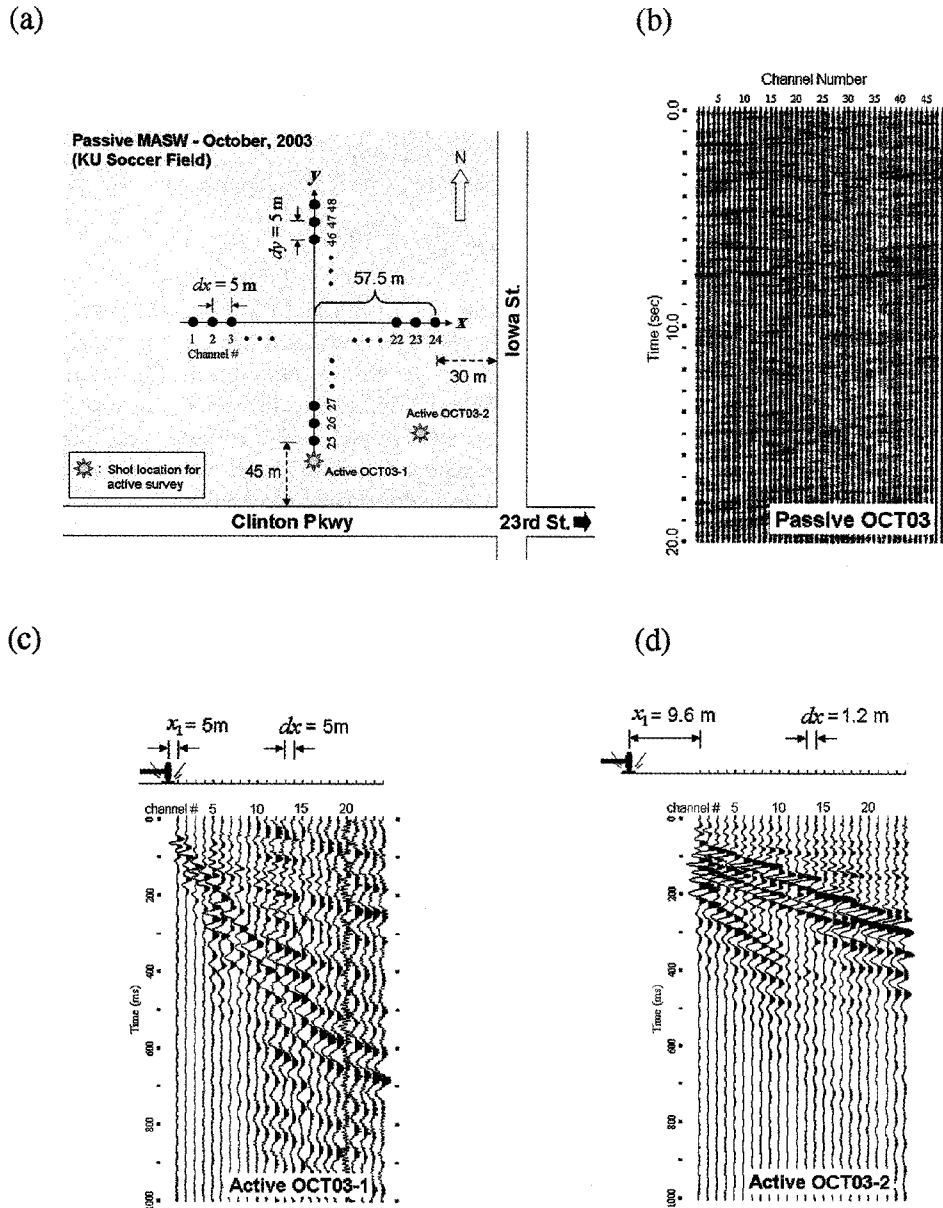


Figure 1. (a) Site map showing field geometry used for passive MASW survey performed during October 2003 with a cross receiver layout, (b) a passive record prepared by vertically stacking twenty (20) separate records of 20-s recording time, (c) and (d) active shot gathers acquired at two different places with shot locations marked in (a) and using different source offsets and receiver spacings.

the fundamental mode. Another reason for this bias may be a general notion that a strong dispersive trend occurring at low frequencies (for example, <20 Hz) should be the fundamental mode and the higher modes of considerable energy usually occur at high frequencies (>20 Hz). There has been insufficient investigations into the modal nature of passive surface waves of various different origins utilized for the shallower investigations.

In this paper, we confirm at least one instance where the modal nature of passive surface waves of mainly traffic

origin was a higher mode. This confirmation was made from the dispersion image created by combining two sets of wavefield transformation data; one processed from the passive and the other processed from the active data, both of which were acquired during a field test in October, 2004. There was a previous field test (Park *et al.*, 2004a) of both passive and active surveys at the same site during October 2003, whose analysis results were reevaluated as erroneous by the results from the more recent survey. Descriptions of both cases will dictate those aspects in acquisition and

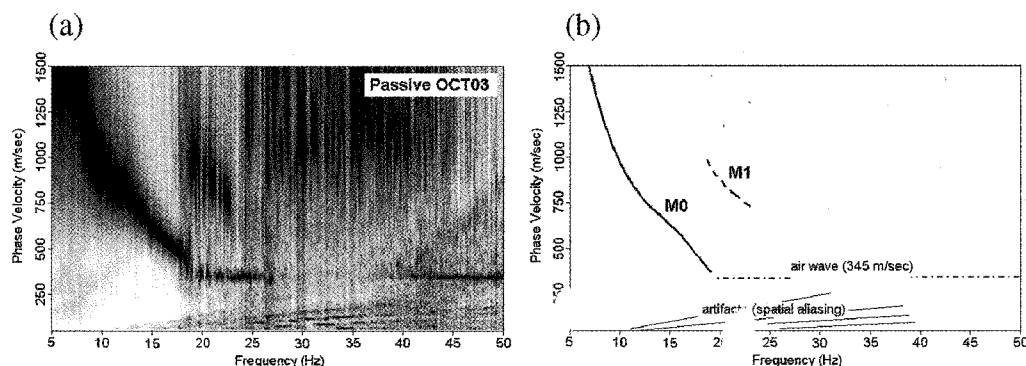


Figure 2. (a) Dispersion image of the passive record in Fig. 1b, and (b) its interpretation diagram.

processing that are critical to successful results. Active surveying appears to play a critical role in properly identifying the modal nature of the passive surface waves.

Surveys in 2003 and 2004 were conducted at a soccer field of Kansas University (KU), Lawrence, Kansas, located at a corner of a junction of two major city roads (Fig. 1a) by following both active (Park *et al.*, 1999a) and passive (Park *et al.*, 2004a) versions of the MASW method. The test site was chosen because it is located near two major city roads where steady traffic flow existed and it was also flat and spacious enough to alleviate such interfering influences as the irregular topography and near-field effects (Park *et al.*, 1999a; Stokoe *et al.*, 1994). Two 24-channel Geometrics Geode seismographs were used for the passive surveys to record 48-channel data sets, whereas only one Geode was used to collect 24-channel active data sets. We used 4.5-Hz geophones as receivers and a 16-lb sledgehammer as the source for the active surveys.

MASW Surveys in October 2003

Experimental field surveys were conducted during October 2003 to test a passive MASW method (Park *et al.*, 2004a) under development at the time. A cross-receiver layout was chosen on which the development was based.

Total dimension of the layout was chosen in such a way that V_s estimation as deep as 100 m might be possible. Geophones were deployed along a cross layout with 5-m receiver spacing consisting of both east-west (EW) and south-north (SN) transects of 24-receivers each (Fig. 1a). Twenty records of 20-s recording time were acquired at arbitrary times by manually triggering the acquisition system. Figure 1b shows a record (Passive OCT03) prepared by vertically stacking all twenty records together.

Two sets of active MASW data were acquired after acquisition of the aforementioned passive data at two different places within the passive site as marked in Fig. 1a. The first data set (Active OCT03-1) was collected by using the south-north (SN) receiver transect (24-channel) with 16-lb sledgehammer impacts (3 vertical stacks) at 5-m offset from the southern end (Fig. 1c). Then, all twenty-four receivers were reconfigured to make a shorter spread by using a receiver spacing of 1.2 m near the southern end of the SN transect. A shot gather (Active OCT03-2) acquired using this receiver spread with a source offset of 9.6-m (8-receiver spacing) is displayed in Fig. 1d.

Results From Surveys in October 2003

A processing scheme for passive surface waves was used to produce the dispersion image (Fig. 2) created from

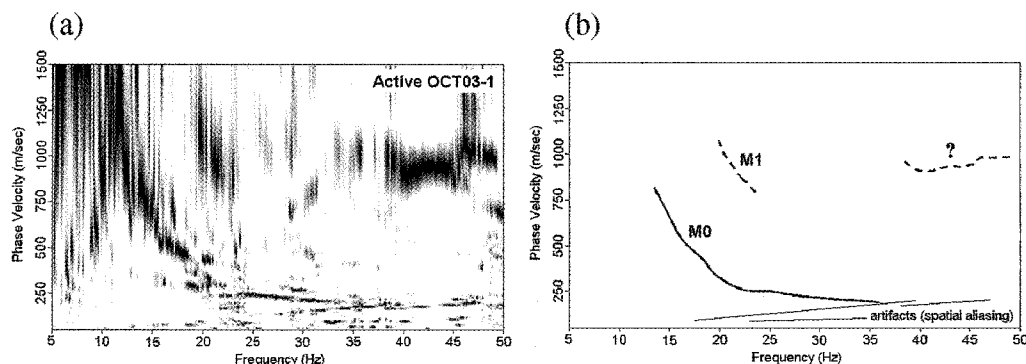


Figure 3. (a) Dispersion image of the active record in Fig. 1c, and (b) its interpretation diagram.

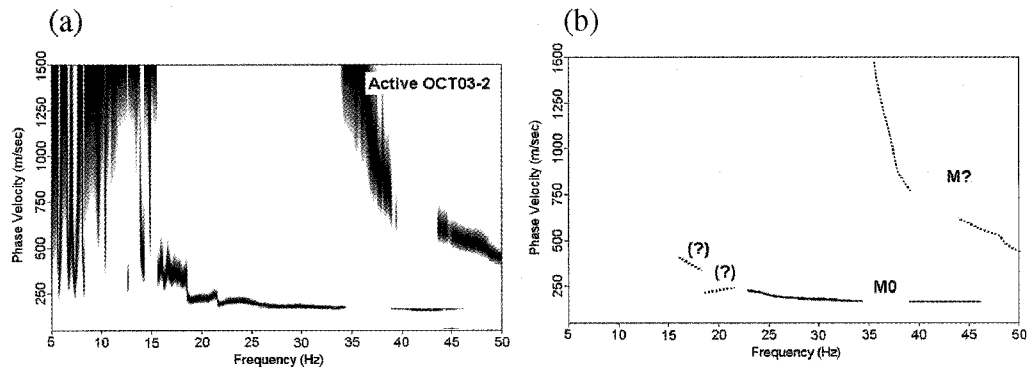


Figure 4. (a) Dispersion image of the active record in Fig. 1d, and (b) its interpretation diagram.

multiple wavefield transformations (Park *et al.*, 2004a). The aforementioned vertical stacking of passive records usually enhances the definition of dispersion in the image created from the multiple wavefield transformations (Park *et al.*, 2004b). Ranges of frequency and phase velocity used during the processing were 5–50 Hz with 0.1 Hz increment, and 50–1,500 m/s with 10 m/s increment, respectively. A 5-degree azimuthal increment was used during an intermediate transformation that scanned through all possible incoming angles (0–360 degrees) of passive surface waves propagating through the receiver layout. The same processing parameters in frequency and phase velocity (also, azimuth for passive processing) were used for all dispersion images presented in this paper. Interpretation of identified dispersion trends displayed in a diagram (Fig. 2b) indicates a prominent trend (7–18 Hz) identified as the fundamental mode (M0) followed by an abrupt modal shift with another trend (18–23 Hz) identified as the first higher mode (M1). The abrupt modal shift has been associated with rapid stiffness change in near-surface materials by some investigators (Ryden *et al.*, 2004; O'Neill, 2004). Non-dispersive air waves are also identified over a broad frequency range (20–50 Hz). Interpretation of M0 was based on the notion at the time that passive surface waves predominantly consist of the fundamental-mode surface waves.

Dispersion images of the two active-source shot gathers of different receiver spacings and source offsets are displayed in Figs. 3 and 4 with interpretation diagrams. The processing scheme by Park *et al.* (1998) was used for the imaging. A trend observed in low frequencies (<20 Hz) (Fig. 3) of the longer-receiver-spacing shot gather (Active OCT03-1) was identified as M0 as it closely follows the corresponding trend in the passive image, and then this trend of M0 was extended to another trend observed in higher frequencies (>25 Hz) as the overall trend after the extension appeared natural in spite of an ambiguity in the intermediate frequencies (20–25 Hz). The insufficient definition of the latter trend (>25 Hz) was attributed to the spatial aliasing effect that tends to degrade the imaging performance for those surface waves whose wavelengths are shorter than twice the receiver spacing (10 m) (Park *et al.*, 2001). Dispersion trends (Fig. 4) observed with the shorter-receiver-spacing shot gather (Active OCT03-2) consisted of a couple of broken trends (15–22 Hz) that could not be properly interpreted followed by two other trends at higher frequencies (>22 Hz) identified as M0 as it closely follows the M0 trend identified with the other active data (Active OCT03-1).

These two sets of the active image data were then combined (vertically stacked) with the passive image data

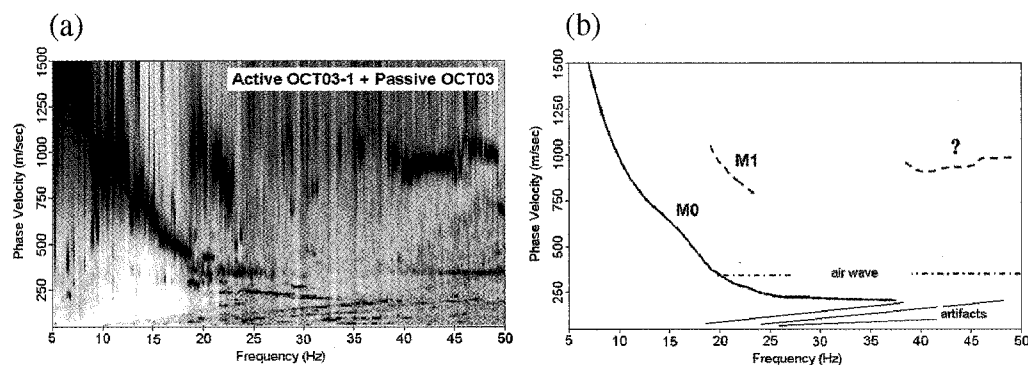


Figure 5. (a) Dispersion image prepared by combining image data sets of Fig. 2a–Figs. 3a, and (b) its interpretation diagram.

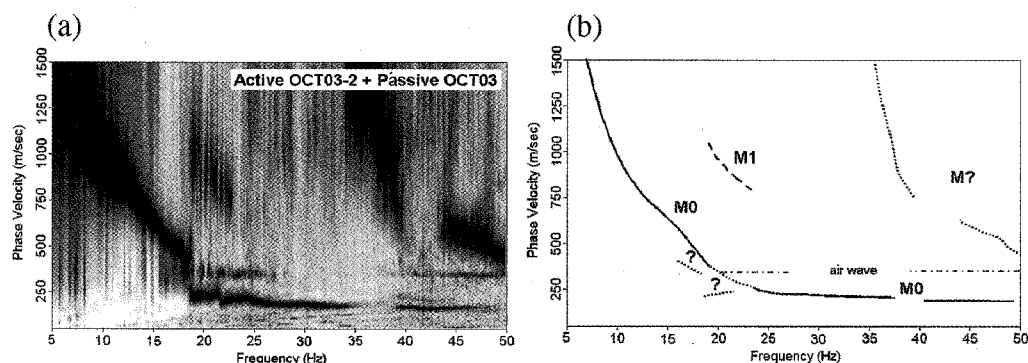


Figure 6. (a) Dispersion image prepared by combining image data sets of Fig. 2a–Figs. 4a, and (b) its interpretation diagram.

processed from Passive OCT03, producing two separate sets of the (passive-active) combined image data. These two sets of the combined image data are displayed in Figs. 5–6. Two modes (M0 and M1) interpreted in both images of combined data closely coincide in their frequency-phase velocity relations.

Surveys in October 2004

After extensive modeling tests with different types of receiver layouts for the passive MASW method, we concluded that a circular layout, instead of a cross, should yield dispersion images of higher definition. By this time, the processing scheme previously used was extended in such a way that it could accommodate any type of receiver layout (Park et al., 2004b). In addition, modeling tests indicated that a layout of multiple circles of different radii would be effective in ensuring the high-definition quality of dispersion images over a broad frequency range. A two-circle receiver layout of 58-m and 4.6-m radii totaling 48 channels was used to acquire the passive data (Fig. 7a) at the same site where the first field test was conducted the previous year. Figure 7b shows a 20-s passive record prepared by vertically stacking twenty records of the same record length collected at twenty arbitrary times during a 30 min acquisition period.

In an effort to better delineate the dispersion characteristics observed from the previous active surveys, a series of active tests were also conducted, but this time with a shorter receiver spacing of 0.6 m. The shorter spacing was chosen after consideration of the possible domination of higher modes at far offsets (Park et al., 1999a, 1999b). Several different source offsets were also tested. Figure 7c shows a shot gather (Active OCT04) collected with the closest source offset of 0.6 m, among all tested, that yielded the highest modal definition as will be described below.

Results from Surveys in October 2004

The dispersion image processed from the passive record is displayed in Fig. 8. A processing scheme modified from the previous year was used. Comparing this to the image (Fig. 2a) of the previous passive data collected by using the cross layout, it is certain that the overall definition of dispersion image is higher for this circular-layout data. In addition, a vague trend is identified in a high frequency range (>20 Hz) where no discernable trend was previously noticed. It appears that these components of surface waves may have originated from the occasional walking of field crews nearby (but outside) the inner circle of the receiver layout. Insufficient imaging for the air waves could be attributed to strong and gusty winds (20 mph) during the survey. Two prominent trends observed in the 7–18 Hz and 18–23 Hz ranges were identified as M0 and M1, respectively, as they coincided with corresponding trends identified with the previous passive data. We then tried to extend the M0 trend to follow the trend vaguely noticed in the higher frequencies (>18 Hz) as indicated in the interpretation diagram. This extension, however, showed a major deviation from the corresponding part of the M0 trend interpreted with data sets from the previous year as phase velocities were now in the 150–200 m/s range instead of the 200–250 m/s range in the previous case. This discrepancy stimulated a further analysis with active data sets collected by using other different field configurations.

The dispersion image of the active shot gather (Active OCT04) is displayed in Fig. 9 along with an interpretation diagram. In this image M0 and M1 were confidently identified in the 13–28 Hz and 28–50 Hz ranges, respectively. Phase velocities of M0 in frequencies higher than 25 Hz coincided with those vaguely noticed in the corresponding range with the passive image.

When these two sets of image data are combined, the new image shows the most complete modal characteristics over the broadest frequency range ever achieved (Fig. 10). It is now clear that the passive surface waves, in particular

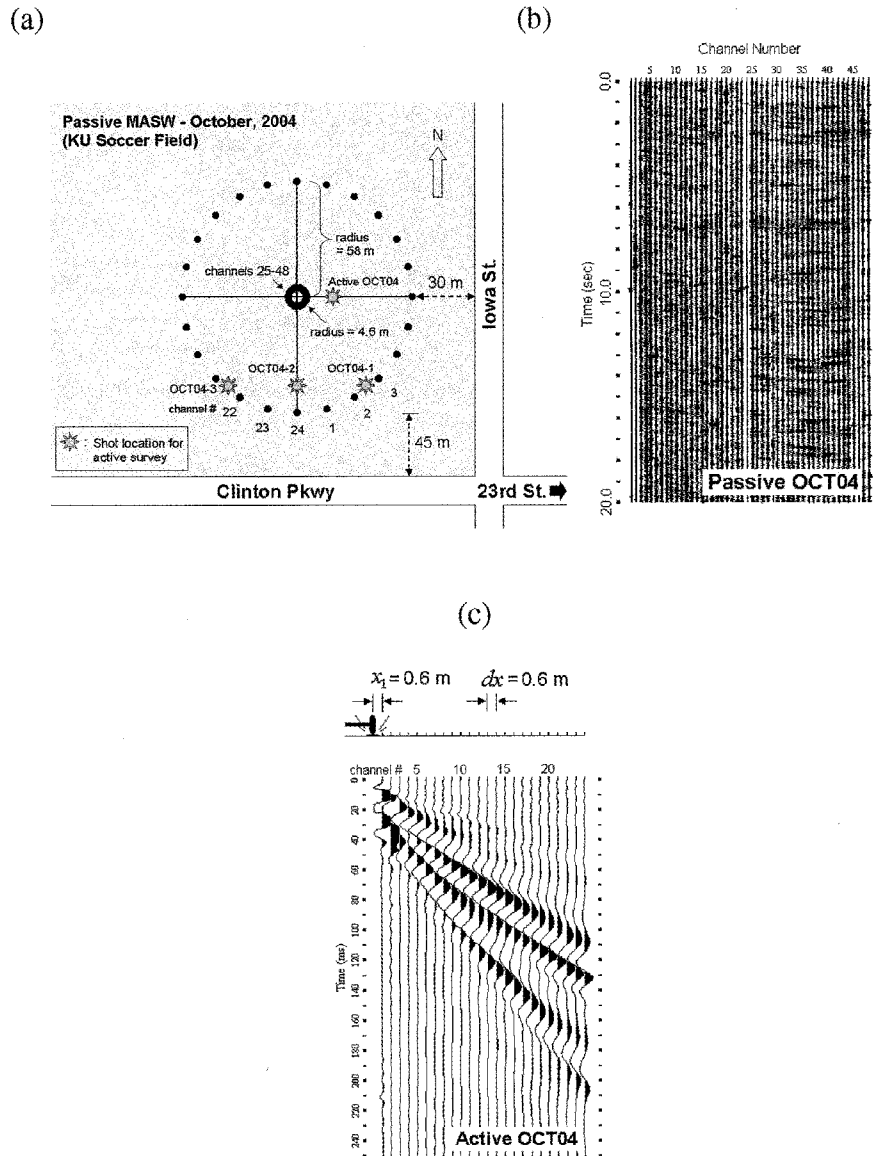


Figure 7. (a) Site map showing field geometry used for passive MASW survey performed during October 2004 with a two-circle receiver layout, (b) a passive record prepared by vertically stacking twenty (20) separate records of 20-s recording time, (c) an active shot gather acquired at a place within the passive survey area with its shot location marked in (a).

below 20 Hz, consisted predominantly of the first higher mode (M1) and, also, that all previous analyses with active data sets misidentified M1 as M0. Figure 11a shows a Vs profile analyzed from a forward modeling performed to match all three modes (M0, M1, and M2) identified in this combined image as closely as possible with the theoretical modes (Fig. 11b) by using the algorithm by Schwab and Knopoff (1972). Another Vs profile obtained based on the interpretation results (Figs. 5–6) from the previous year's surveys is also displayed to show the difference in Vs estimation between the two cases.

Considering that the lateral dimension covered by the active survey was much smaller than that covered by the passive survey, it can still be questioned if the two sets of images can be compared to each other because the active trends could be true only for a localized area, while all other areas may have such different trends that the passive trend (M1) can still be identified as the fundamental mode (M0). Figure 12 shows images obtained from active shot gathers (Active OCT04-1, 2, and 3) collected at three different places marked in Fig. 7a. They were acquired by using 1.2-m receiver spacing and source offset and one 24-channel

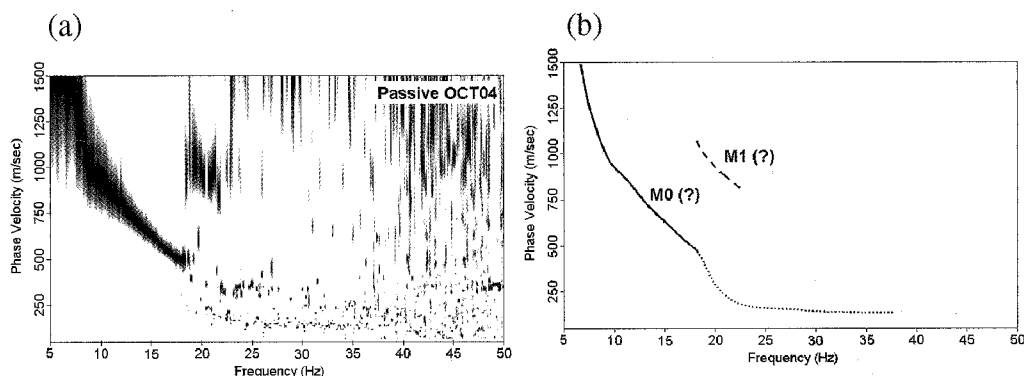


Figure 8. (a) Dispersion image of the passive record in Figs. 7b, and (b) its interpretation diagram.

seismograph with all receivers deployed in the east-west (EW) direction at the west side of each shot point. Images shown in Figs. 12a–c were obtained by processing only the near-offset (channels 1–12) traces because of the higher-mode domination at far offsets as explained in next section. All these images indicate that the passive trend (M1) should not be identified as the fundamental mode. Differences are noticed among these images that can be attributed to different near-surface conditions at each acquisition location.

Importance of the Active Survey

Successful results from the surveys in October 2004 indicate the relative importance of an active survey for accurate modal identification in the combined image. Once a confident modal identification is made from an active data set, the modal nature of the passive trend from either a cross or circular receiver layout will be properly identified, although the latter is preferred because of its higher-definition capability for a comparable dimension of the receiver layout (Park et al., 2004b). On the other hand, the advantage of the circular layout would be nullified if the active data could not achieve sufficient accuracy in modal definition.

Considering the higher-mode domination occurring usually at far offsets (Park et al., 1999a, 1999b), it is important to place the source point as close to the receiver line as possible. This is illustrated from a series of field data collected during the field test in October 2004. Several different source offsets were tested with the same 24-channel receiver spread used for the acquisition of Active OCT04, and corresponding dispersion images shown in Fig. 13 indicate the progressive domination by the higher mode as the distance between source and receivers increases. It is not clear what caused the change in M0 trend in the 15–20 Hz range, especially for those cases with the two longest source offsets (18 and 24 meters). Another example of the higher-mode domination is illustrated by using the active shot gather acquired at shot location OCT04-1 with 1.2-m receiver spacing and source offset. When all twenty-four (24) traces were used for imaging, the M0 trend becomes so ambiguous that it (M0) could almost be misidentified along the M1 trend (Fig. 12d).

The best strategy for an optimum active survey, therefore, would be to use as small receiver spacing and source offset (for example, 0.5 m for both) as possible. At the same time, however, it is also important to prepare a shot gather of as long offset range (for example, 0.5–20 m) as possible to ensure a sufficient resolution in dispersion imaging

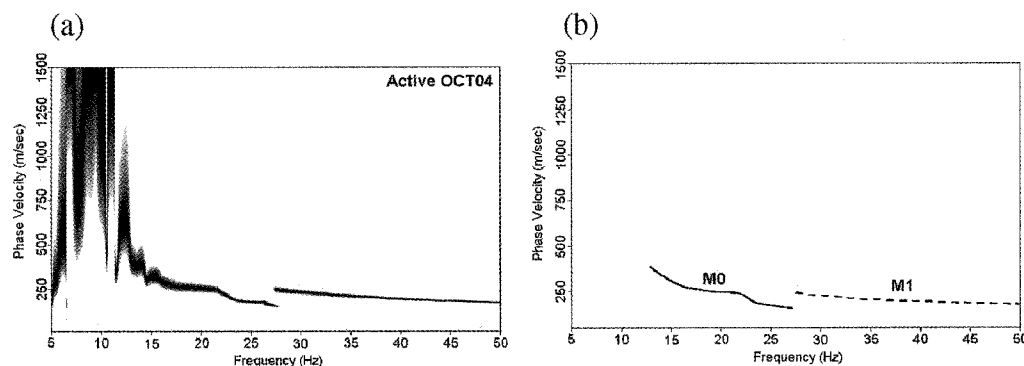


Figure 9. (a) Dispersion image of the active record in Figs. 7c, and (b) its interpretation diagram.

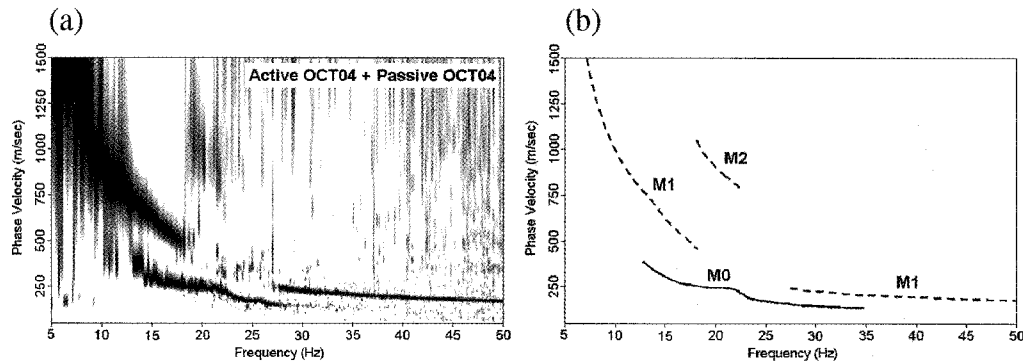


Figure 10. (a) Dispersion image prepared by combining image data sets of Fig. 8a–Figs. 9a, and (b) in interpretation diagram.

(Park *et al.*, 1998, 2001). This means a shot gather of many (for example, 24 or more) traces with a small trace spacing acquired with a close source offset would be most desirable. Then, the optimum offset range for the most accurate dispersion imaging can be selected through a series of test processing with different farthest offset chosen as previously illustrated.

Discussions

Domination of higher modes has been reported to occur usually at higher frequencies (for example, >20 Hz).

Observation of the strong higher-mode energy has been attributed to several causes; 1) such different damping ratios between modes that the fundamental mode dissipates rapidly with distance from source and energy of higher modes becomes relatively stronger at far offsets (Park *et al.*, 1999a, 1999b), 2) an intrinsic property related to stiffness structures such as those with rapid change and/or reversals with depth (Ryden, 2004; O'Neill, 2004; Foti, 2004), or 3) a combination of both. However, the domination by a higher mode in low frequencies, as in the field case reported in this paper, has not

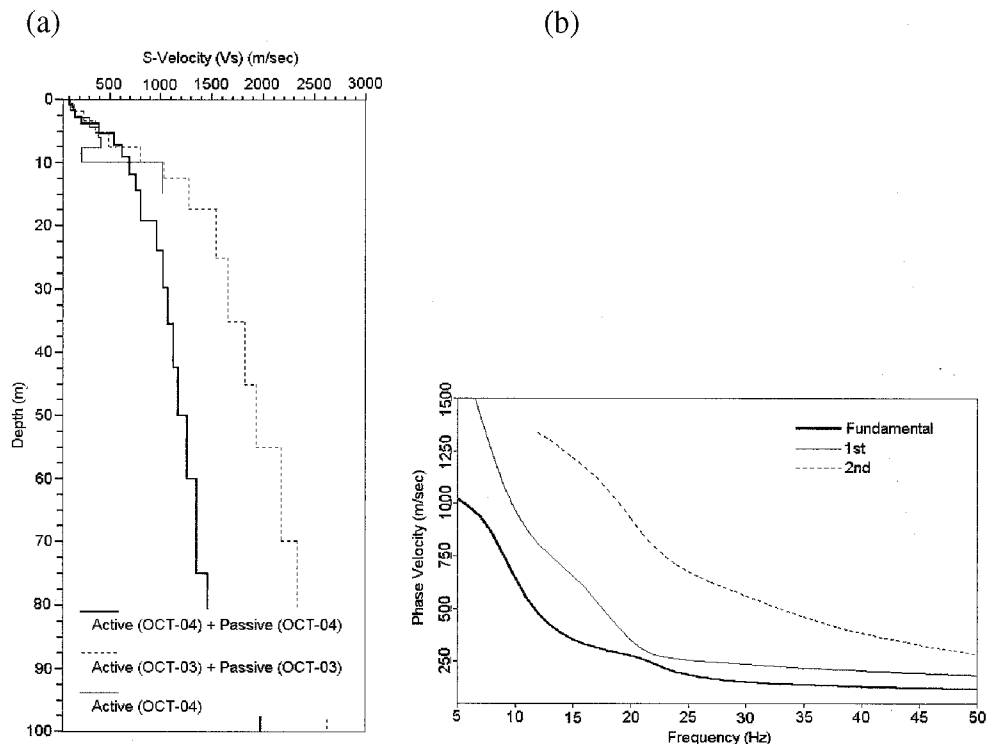


Figure 11. (a) Vs profiles obtained from forward modeling based on the interpretations of Fig. 10 (Active + Passive OCT04), Fig. 5 (Active + Passive OCT03), and Fig. 9 (Active OCT04), and (b) theoretical dispersion curves for the first Vs profile (Active + Passive OCT04) calculated for the fundamental (M0), and the first two higher modes (M1 and M2).

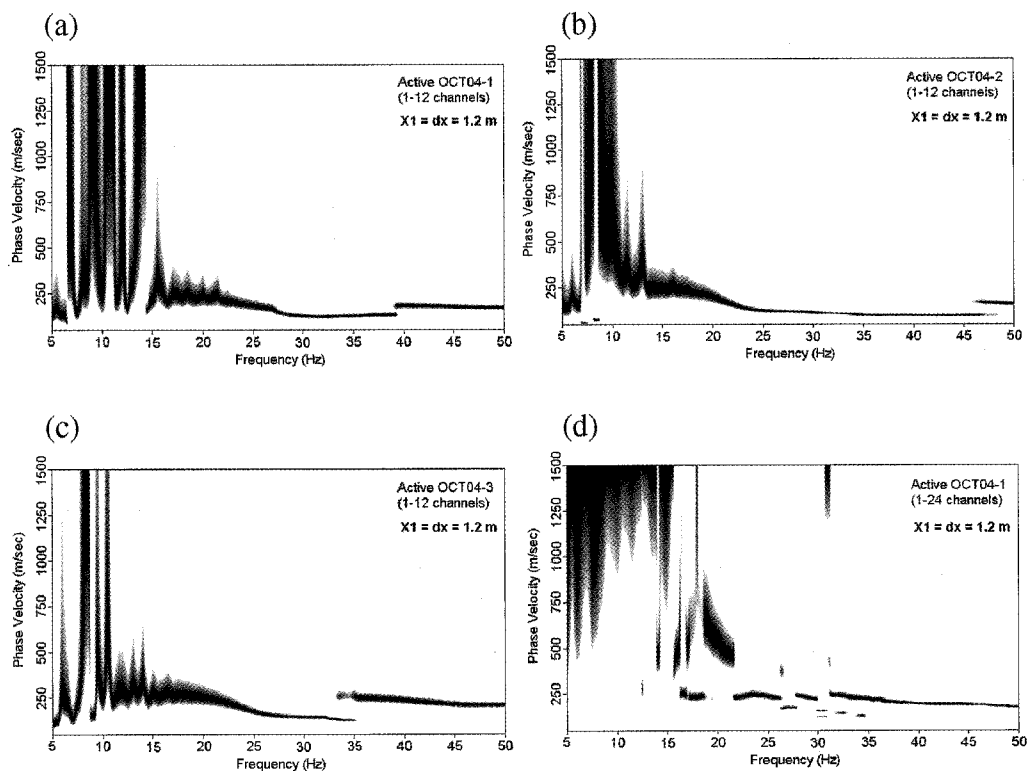


Figure 12. Dispersion images of active shot gathers acquired at three different places within the passive survey area of October 2004, with shot locations at (a) Active OCT04-1, (b) Active OCT04-2, and (c) Active OCT04-3 as marked in Fig. 7a. These images were processed by using the first twelve traces of each 24 channel shot gather. (d) Image processed by using all twenty-four traces of the shot gather acquired at Active OCT04-1.

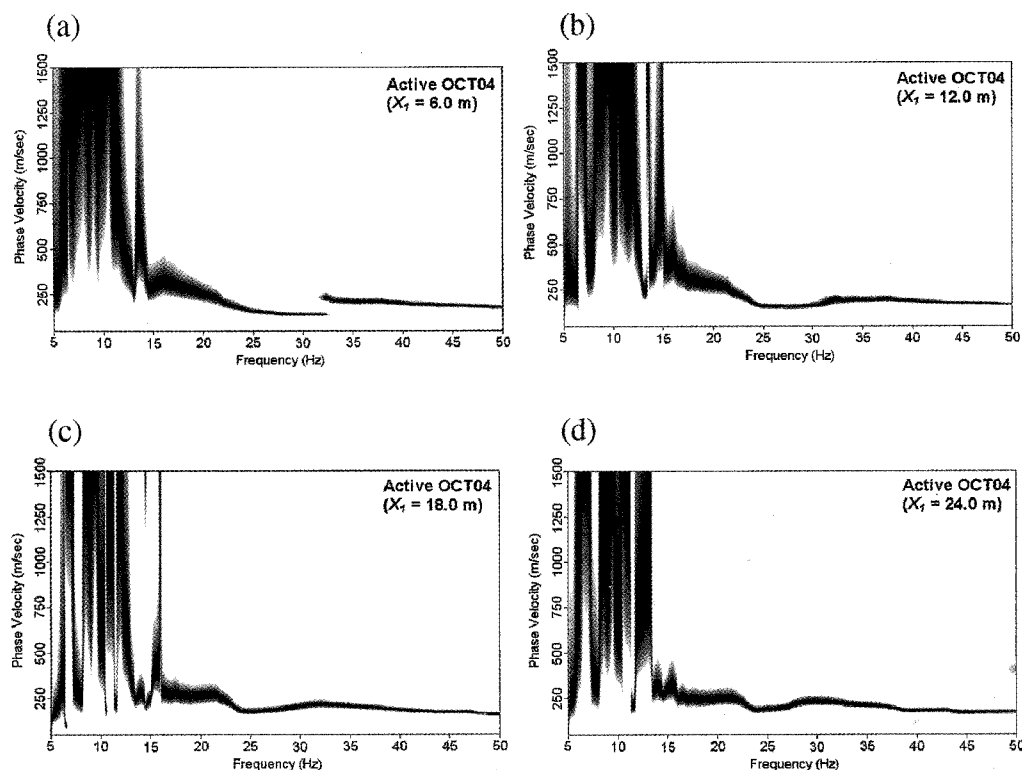


Figure 13. Dispersion images of shot gathers acquired by using the same receiver spread used to acquire the shot gather of Active OCT04 (Fig. 7c), but using different source offsets of (a) 6.0 m, (b) 12.0 m, (c) 18.0 m, and (d) 24.0 m.

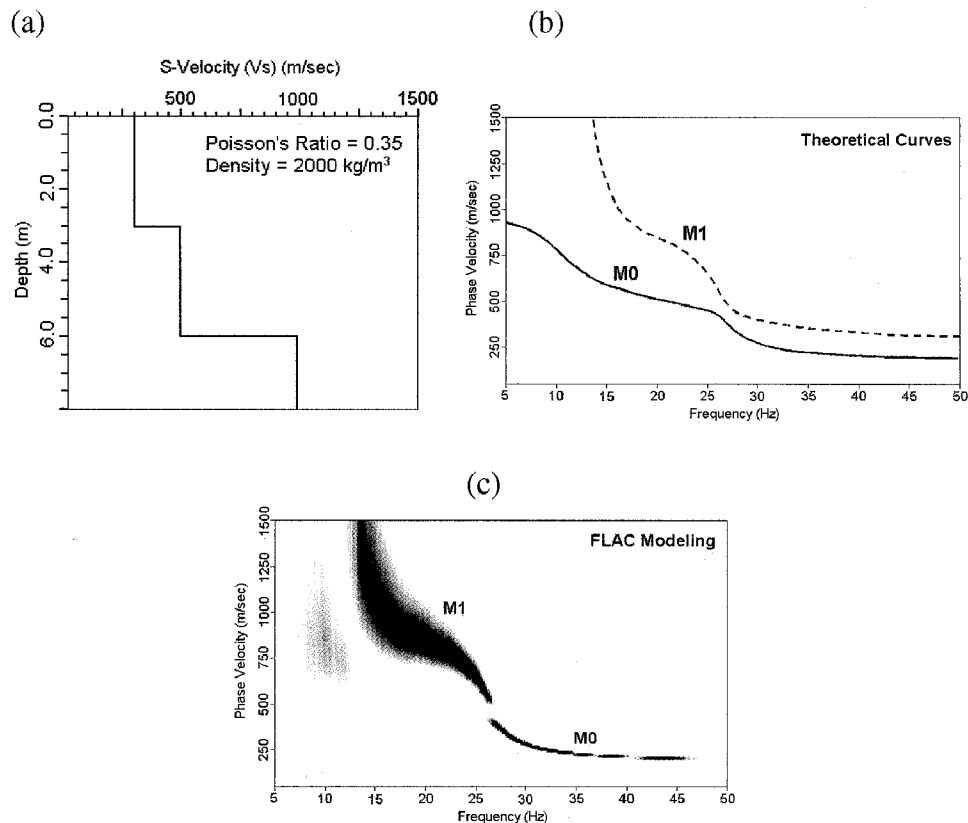


Figure 14. (a) A simple 3-layer earth model used for a complete elastic modeling of the shot gather, (b) corresponding theoretical dispersion curves of fundamental (M0) and the first higher mode (M1), and (c) dispersion image processed from the modeled shot gather.

been considered common or even possible at soil sites until recently. Socco *et al.* (2002) reported such a case; Ryden and Park (2004) and Ryden *et al.* (2004) predicted such a possibility being more common than speculated. More recently, Foti (2004) claimed such a case not only possible, but also common at those sites where a significant stiffness contrast exists, such as a soil-bedrock interface. Because of this difficulty resolving true modes, some investigators proposed different approaches to the surface wave inversion rather than traditional approach of matching measured and modeled modal curves (Xia *et al.*, 1999). Such recent methods use an impulse-response simulation of the field test and employ either the full-wavefield in the frequency domain, or, an automatically-picked dispersion curve for the optimization, removing the need for specific mode-identification (Forbriger, 2003; Ryden *et al.*, 2004; O'Neill, 2004). Figure 14c shows the dispersion image processed from a complete elastic modeling (shot gather) of a simple layer model (Fig. 14a) implemented by using the computer code FLAC (Fast Lagrangian Analysis of Continua) (Itasca, 2000), a commercially-available 2D explicit finite difference code. Although the layer model can be regarded as one of the

common models with soil sites, the image shows the higher-mode domination at low (<26 Hz) frequencies (Fig. 14b), a phenomenon considered uncommon or even impossible previously. The relative modal domination is determined not only by the layer model but also by the distance between source and receivers (Tokimatsu *et al.*, 1992; Foti, 2004; Ganji *et al.*, 1998). Therefore, it seems important to examine the modal nature through a series of dispersion imaging applied to different offset ranges from a shot gather.

Conclusions

As the modal nature of passive surface waves used for engineering purposes may not always be the fundamental mode, the mode must be examined before it is used in the subsequent inversion process. For this examination, an accurate modal delineation of active data sets has to be preceded by using a dispersion imaging method. An active shot gather acquired with a small (<1.0 m) receiver spacing and a close (<1.0 m) source offset is recommended for this purpose. For the purposes of modal examination with different offset ranges and also of increasing the imaging

resolution, it is recommended to prepare a shot gather of a large offset range, either by using a seismograph with many (>24) channels available, or by using the walkaway tests. Considering possible variation of near-surface materials in a lateral direction, the latter would be preferable. For the same reason, active surveys at several different places within a lateral dimension covered by a passive survey should also be considered to ensure the active modal nature representative of a comparable lateral dimension.

Combining two sets of the image data processed from passive and active field data, respectively, can be a highly effective approach to comprehend the overall modal nature in broad frequency and phase velocity ranges.

Acknowledgments

We thank David Thiel, Andrew Newell, and Brett Bennett for their help during the field operations. Appreciation also goes to Mary Brohammer for her preparation of this manuscript.

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