IMAGING DISPERSION OF PASSIVE SURFACE WAVES WITH ACTIVE SCHEME

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Abstract

In passive surface-wave surveys under urban environments there is usually one surface location from which a major portion of the surface wave energy—used for the dispersion analysis—originates. This is similar to an active survey, in which exact relative coordinates of both source and receivers are known prior to data processing. Using a method that scans through all possible incoming directions of those passive surface waves, the azimuth of the responsible source point can be estimated fairly accurately, especially when a method employing an integral approach for the calculation of surface wave energy at a particular azimuth and phase velocity is incorporated. Then, along with the distance information that only needs to be estimated very roughly, the passive data set can be processed by any active scheme. Key concepts are explained using both synthetic and field data sets, with comparisons made to some of the existing methods.

Introduction

Passive surface-wave methods for engineering purposes usually deal with surface waves of cultural origin, especially those caused by traffic (Park and Miller, 2008; Park et al., 2005; Okada, 2003; Louie, 2001). In case of traffic, surface waves are generated by moving vehicles as they exert relatively impulsive force onto irregular surface points on the road or trigger transient vibrations of parts of the road structure, such as bridges, ramps, etc. For a given survey site, a major part of the recorded surface wave energy usually comes from those waves generated from only one surface location near the survey site. There may be other locations contributing relatively weaker energy because they are further away or they generated weaker energy during a specific recording period. The location of this source point can be specified by its azimuth (θ) and distance (Ds) from the center of the receiver spread.

Existing methods to analyze dispersion of passive surface waves make the assumption of plane-wave propagation by ignoring the finiteness of the distance between the surveying area and the origin point of the surface waves. In the spatial autocorrelation (SPAC) method (Aki, 1957), the issue of azimuth is handled by using a mathematical transformation based on a symmetric receiver array (e.g., circular) that can cancel out the azimuth factor. The multi-azimuth case seems to act as a disturbance with this method as well, although some investigators (for example, Asten, 1983) reported the omni-directional nature can be an advantage with SPAC. The wavefield transformation method, on the other hand—for example, in f-k (Capon, 1969) or the imaging method by Park et al. (2004)—this issue is approached by continuous azimuth scanning with a specific angular increment (e.g., 5 degrees) during the transformation to account for all possibilities of incoming angles. In particular, Park et al. (2004) tries to sum all the scanned energy for a given single frequency along the azimuth axis so that energy from multiple azimuths can add up constructively. Although this summation approach gives an excellent solution to the issue of azimuth uncertainty, especially in the multi-azimuth case, its imaging effectiveness can be significantly improved in the uni-directional case by accounting for the location of the source point. Once this source-point location (azimuth and distance) is resolved, then the dispersion imaging process becomes identical to the active method in which relative coordinates of source and receivers are known. The accurate detection of the azimuth for the source point is far more important

than accurately determining distance, and this detection algorithm utilizes the azimuthal scanning method of Park et al. (2004) with a significant assistance from the incorporation of the broad-band summation (BBS) technique (Park, in preparation for publication in 2008).

Propagation of Passive Surface Waves of Cultural Origin

Source points of surface waves generated by cultural activities such as traffic always have a finite distance and azimuth (Figure 1). Wavefronts therefore should be regarded as spherical unless the distance is so great that it can be regarded as being infinite, in which case the wavefront is regarded as planar (Figure 1). Theoretically, if the source location is known, then the dispersion imaging process becomes identical to that of the active method where relative locations of both source and receivers are known (Park et al., 1998). In spherical propagation both azimuth (θ) and distance (Ds) have to be known, whereas only azimuth (θ) needs to be known in plane-wave propagation. Some formulations related to each can be found in Park et al. (2004).

To comparatively examine sensitivities of these two parameters (θ and Ds), a synthetic 24-channel record of a circular array has been modeled by using a modeling scheme described in Park and Miller (2005). A 5-50 Hz frequency band and a constant phase velocity of 500 m/sec was used for propagating (phase) velocities with a constant Q-factor of 50 (Q=50) for the entire frequency band used. An arbitrary source point was assigned at a point 150 m away from the center of the receiver array in the direction of θ=45° (θ=45, Ds=150 m). Figure 2a shows the modeled 24-channel field record representing only one instance of surface wave generation from this source point at an arbitrary moment during the 5-sec recording window. The corresponding dispersion image obtained from this record using the scheme (Park et al., 1998) originally developed for the active multichannel analysis of surface waves (MASW) method by Park et al. (1999), with all known relative coordinates of source and receivers, is displayed in Figure 2b. It shows that amplitude peaks in the analyzed frequency band of 5-50 Hz correctly image the phase velocity of 500 m/sec. Figure 3 shows dispersion images when a certain amount of error was intentionally introduced to one of the parameters (θ and Ds) during the image construction by the same scheme. It is noticed that the image quality is highly sensitive to the accuracy in azimuth (θ) rather than the source distance (Ds). Therefore, it is more important to detect θ accurately than Ds if an active imaging scheme is to be used.

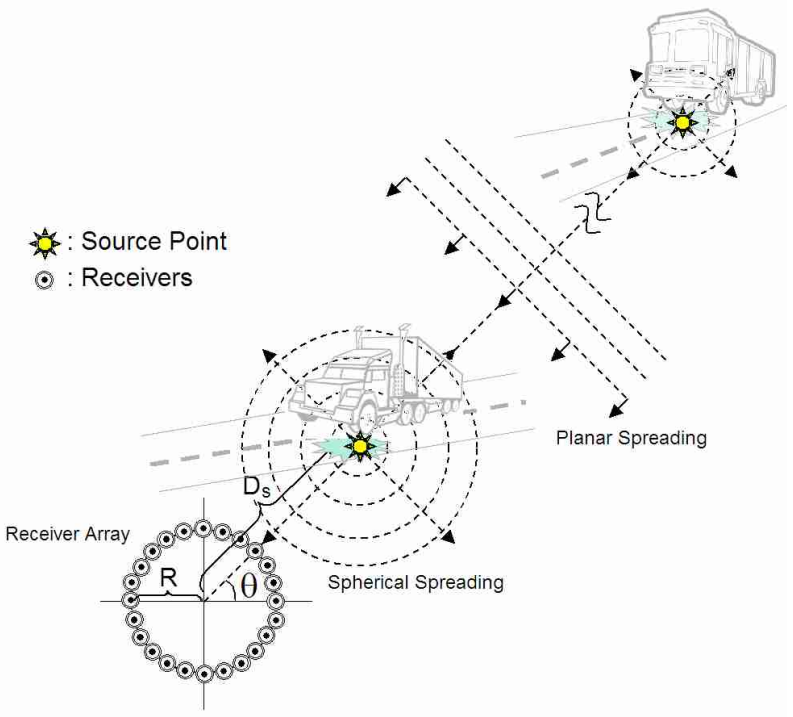

Figure 1. Schematic showing spherical and planar propagation of surface waves generated at relatively close and distant locations, respectively.

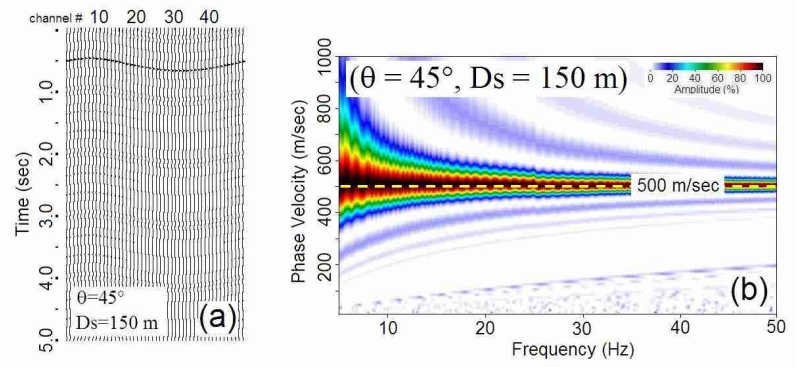

Figure 2. (a) Synthetic 24-channel record modeled with a circular array of radius=50 m with surface waves generated at (θ=45°, Ds=150 m), and (b) corresponding dispersion image obtained by using an active processing scheme by Park et al. (1998).

Azimuth (θ) Detection

The dispersion imaging scheme for passive surface waves by Park et al. (2004) presented a unique and simple approach to surface-wave energy mapping in a space of two-orthogonal axes of phase-velocity (c) and azimuth (θ) for a given frequency (ω) of analysis in which the most dominant surface-wave energy is identified from the prominent energy accumulation at a certain point (e.g., c_0 and θ_0) in c-θ space revealing the incoming angle and the phase velocity of surface waves at that particular frequency. Then, the dispersion imaging process continues to sum all the energy in this space along the θ-axis to come up with a 1-D (c-axis) curve showing the surface-wave energy variation with different phase velocities. The process repeats the same summation for all other analysis frequencies, leading to the construction of a dispersion image in which surface waves that could be multi-modal as well as multi-azimuth can be constructively stacked together to enhance imaging resolution. The method can also generate a by-product showing the variation of θ with different frequencies (Figure 4a) by summing the energy along the phase-velocity (c) axis (instead of θ) during the energy mapping. Although detecting the dominant azimuth (θ_c) in this energy mapping is usually visually obvious, for development of an automated algorithm to detect θ_c all the energy is summed together along the frequency axis to result in a 1-D (θ-axis) curve (Figure 4c) that depicts the energy distribution with different azimuths within the analyzed frequency band. A curve with a sharply defined peak is essential for the accurate detection of azimuth. Although this detection is shown to be perfectly

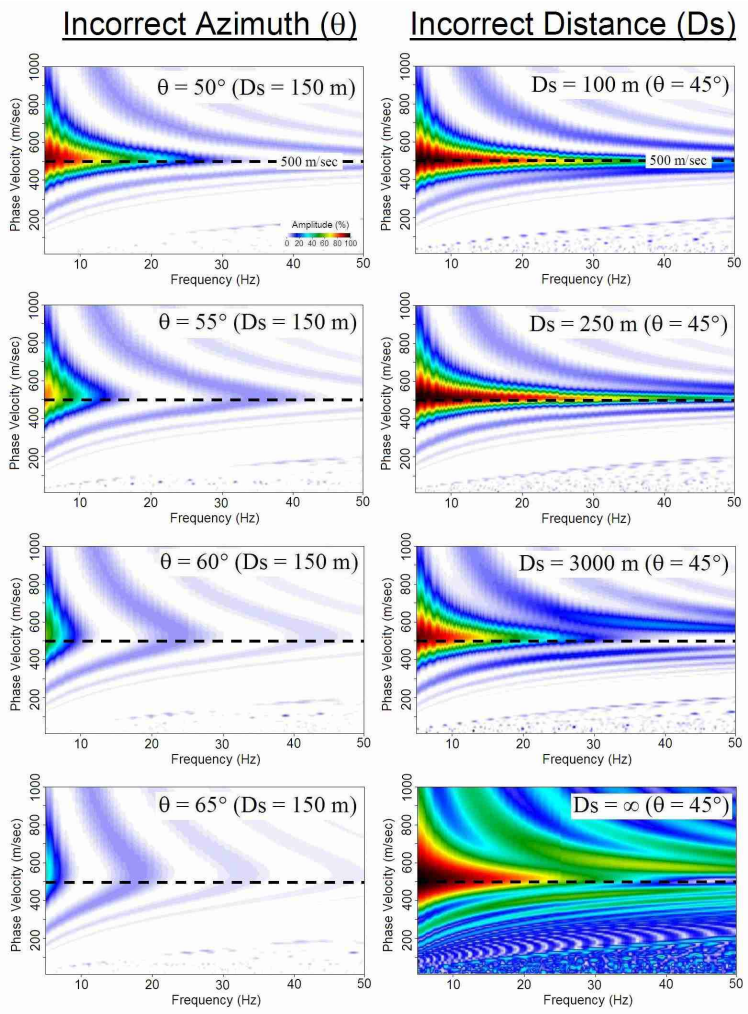

Figure 3. Dispersion images obtained from the synthetic record in Figure 2a by using an active processing scheme with incorrect azimuth (left column) and source distance (right column).

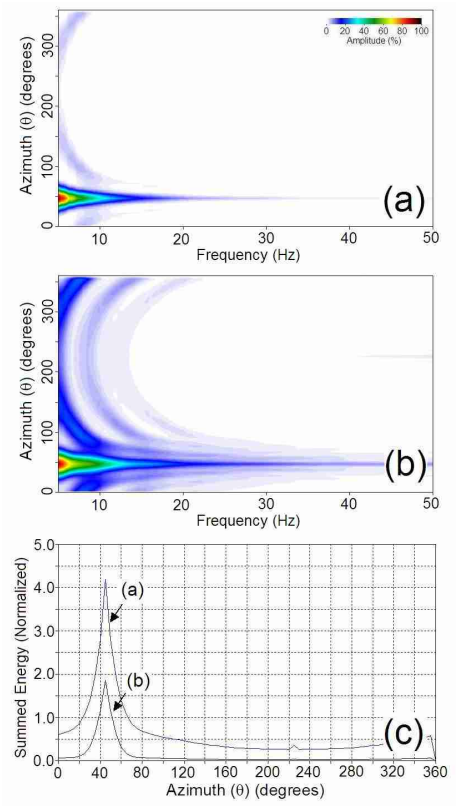

Figure 4. Images of azimuth energy distribution obtained from the record in Figure 1a (a) by using a scheme by Park et al. (2004) alone, (b) with an addition of another enhancement scheme of broad-band summation (BBS), (c) curves obtained by summing all the energy in (a) and (b).

effective in the modeling case illustrated in Figure 4a, ambient random noise can very often degrade the effectiveness of this approach, as will be illustrated with synthetic data with noise included. A noise-suppressing algorithm, called broad-band summation (BBS) by Park (in preparation for publication in 2008), can be utilized to enhance the effectiveness of azimuth detection. Figure 4b shows the azimuth image of the synthetic record in Figure 2a constructed by utilizing the BBS scheme and shows the more prominent energy accumulation at the correct azimuth of 45° for all the constituent frequencies, resulting in a more sharply defined azimuth curve (Figure 4c).

A significant amount of random noise is added to the previous synthetic record displayed in Figure 2a to further illustrate the advantage of the BBS scheme as well as other issues soon to be discussed (Figure 5a). The two azimuth images in Figures 5b and 5c obtained with and without, respectively, utilization of BBS clearly exemplifies the effectiveness. As can be seen in Figure 5d, the detection effectiveness can be further improved by focusing the process into the frequency band of prevailing energy, which is usually lower than 20 Hz in the case of surface waves from traffic.

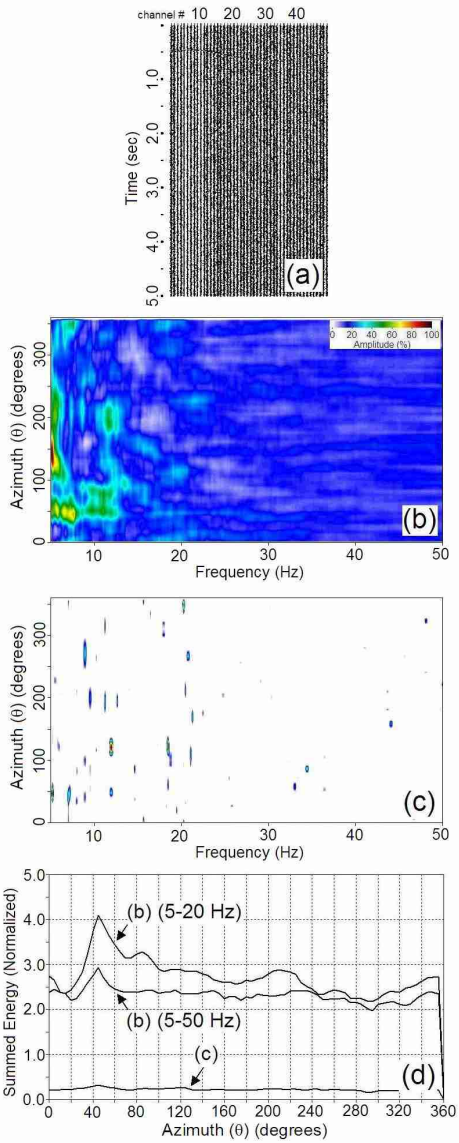

Figure 5. (a) Synthetic record in Figure 2a with random noise added, corresponding images of azimuth energy distribution obtained from the scheme by Park et al. (2004) (b) with and (c) without incorporation of BBS scheme, and (d) curves obtained by summing energy in (b) and (c).

Detection of Source Distance (Ds)

As previously illustrated with synthetic data sets in Figure 3, a rough estimation of Ds is usually sufficient. The estimate can be a few (e.g., 2-3) to a few tens (e.g., 20-30) of times the dimension (or diameter) (D) of the 2-D receiver array used, or can be determined by estimating the closest area with the heaviest traffic (or most intense cultural activities). Once Ds becomes greater than a certain ratio (e.g., 20) with respect to D, then the plane-wave assumption is usually accurate enough. Therefore, several trial-and-error attempts may be necessary with

a probable range of Ds to determine the most probable Ds, which should result in a dispersion image of the greatest prominence. Or, alternatively an automated detection algorithm can be invented based on such aspects of the dispersion image as total sum of the peaks at each frequency component, total energy of the entire image space, standard-deviation (or variance) of the peaks in certain (or all) frequencies, etc. The attempt employing the first criterion detected Ds of the noisy record in Figure 5a as Ds=110 m after scanning through 50 m ≤ Ds ≤ 3000 m with a 10 m increment.

Test on Synthetic and Field Data Sets

The noisy synthetic record in Figure 5a is now tested on three different dispersion imaging schemes: (1) the azimuth-summation scheme by Park et al. (2004), (2) the plane-wave scheme that is in theory identical to the traditional wavenumber (k_x-k_y) method incorporated into the active MASW imaging scheme, and (3) the method presented in this paper that basically treats the passively-generated surface waves identical to those from active surveys by detecting the location of source point responsible for the generation of recorded "passive" surface wavefields. Figures 6a, 6b, and 6c show results from each of the three approaches (1), (2), and (3), respectively. The imaging improves progressively as more information about the location of the source point is accounted for during the imaging process, from the lowest signal-to-noise ratio (S/N) in the dispersion image with the azimuth-summation scheme (Figure 6a) to improved quality when accounting for the correct azimuth (Figure 6b), to the highest S/N when both azimuth (θ) and source distance (Ds) are determined (Figure 6c). The detected azimuth of 45° (Figure 5d) was obtained from an azimuth imaging with 5° increments (Figure 5b), and Ds was detected as 110 m, as previously mentioned. Figure 6d shows additional significant improvement in imaging when the BBS scheme is incorporated into the dispersion-imaging process as well as in the azimuth-imaging process previously described in Figure 5.

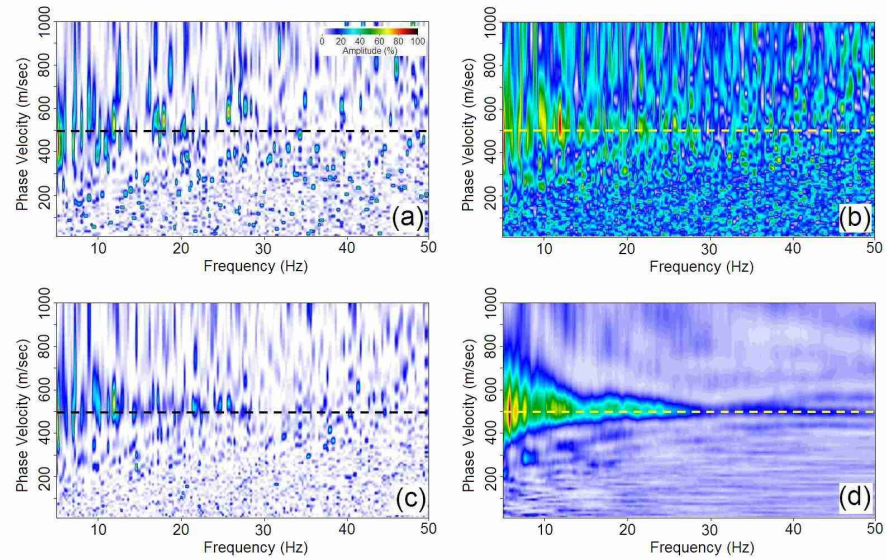

Figure 6. Dispersion images obtained from the record in Figure 5a by using (a) a scheme by Park et al. (2004), (b) the conventional wavenumber (Kx-Ky) approach incorporated into the active scheme by Park et al. (1998), (c) the method presented in this paper, and (d) the scheme used for (c) with incorporation of broad-band summation (BBS) scheme.

Figure 7b shows a field data set recorded using a 24-channel circular receiver array in a University of Kansas (KU) soccer field in Lawrence, Kansas (Figure 7a). Dispersion images obtained using each of the three aforementioned schemes, (1), (2), and (3), are displayed in Figures 8a, 8b, and 8c, respectively. The S/N of the image progressively improves, as it did with the synthetic data. The detected azimuth obtained during the implementation of scheme (3) was 290° and Ds was estimated at 200 m (with the Ds detection criterion previously used with synthetic data). The images of azimuth

energy distribution are displayed in Figure 9 in instances with and without incorporation of the BBS scheme. The detected location corresponds approximately to the junction of Iowa Street and Clinton Parkway, as shown on the field map in Figure 7a. There were a few relatively large-size surface reliefs identified on this part of the road and jolting sounds were constantly heard during the field operation as heavy vehicles passed this area. The dispersion image in Figure 8d was obtained using the BBS scheme incorporated into the imaging scheme and shows further improvement in imaging.

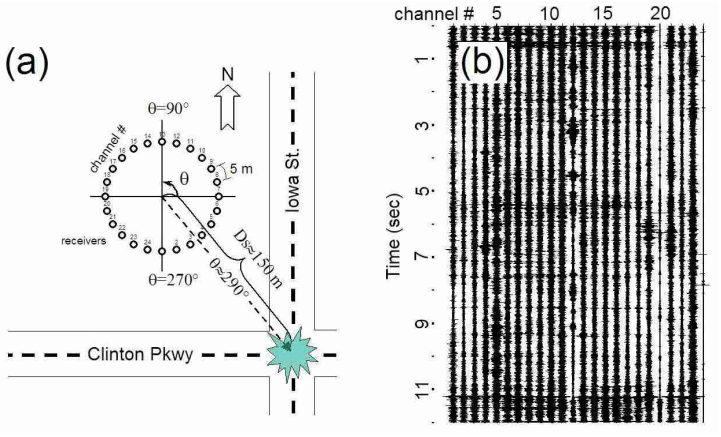

Figure 7. (a) Field map showing relative location of the receiver array and major point of surface wave generation during the survey at the University of Kansas soccer field, Lawrence, Kansas, and (b) a 12-sec long field record obtained from this survey.

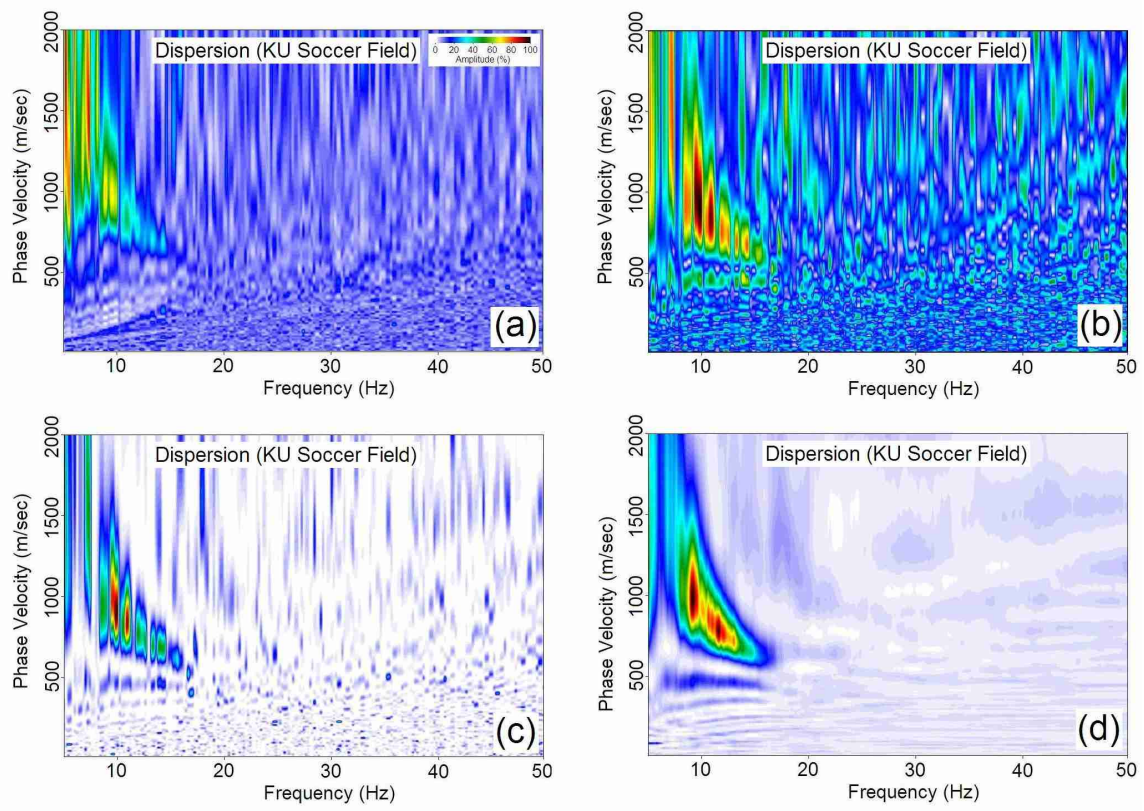

Figure 8. Dispersion images obtained from the field record of Figure 7b by using (a) a scheme by Park et al. (2004), (b) the conventional wavenumber (Kx-Ky) approach incorporated into the active scheme by Park et al. (1998), (c) the method presented in this paper, and (d) the scheme used for (c) with incorporation of broad-band summation (BBS) scheme.

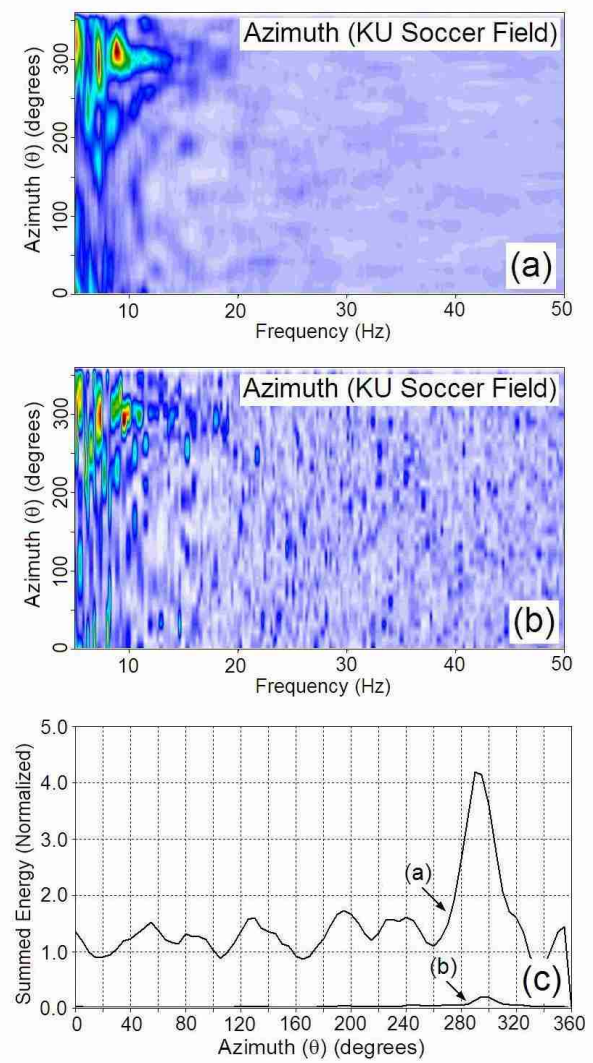

Figure 9. Images of azimuth energy distribution obtained from the field record of Figure 7b by using the scheme in Park et al. (2004) (a) with and (b) without incorporation of broad-band summation (BBS) scheme, and (c) curves obtained by summing energy in (a) and (b) along the frequency axis.

Discussions

More detailed description involving mathematical formulation of the three different imaging schemes mentioned in the previous section has been intentionally omitted due to space limitations. Future publications on this subject as well as the broad-band summation (BBS) are planned. The argument briefly mentioned in the introduction—that any situation violating the uni-directional surface waves will adversely influence the effectiveness of all existing dispersion analysis methods—will also be further clarified through systematic studies and presented in future publications.

Conclusions

Because most recorded energy of passive surface waves originates from a single location near the surveying area, the dispersion imaging process can be enhanced by using a scheme from active

surveys where the location of the responsible source point can be estimated with sufficient accuracy. The accurate estimation of the azimuth (e.g., within 10°) is far more important than the distance estimation. A significant improvement in the azimuth detection can be made by using an additional processing scheme called broad-band summation (BBS).

Acknowledgments

The field data set used for this study was collected while I was performing the research at the Kansas Geological Survey (KGS). I would like to thank KGS for its use in this publication.

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