EVALUATION OF SASW TEST CONFIGURATIONS AND ASSOCIATED DATA UNCERTAINTIES IN GENERATING SITE SPECIFIC DISPERSION CURVES

MOUSUMI MUKHERJEE i) and AMIT PRASHANT ii)

ABSTRACT

Spectral analysis of surface waves (SASW) technique is an in-situ nondestructive method used for near surface soil site profiling. In the present study experimental uncertainties related to this method are assessed in connection with test configuration specification and data quality. Field experimentations have been conducted for this purpose with various spatial configurations of source to near receiver distance and inter-receiver distance under various impact source magnitudes and heights of fall. Based on the experimental findings, a method has been proposed to identify the frequency range of interest based on a threshold minimum cross power spectrum value. Further, it is proposed to consider subset stacking combination with good data quality which can be estimated based on weighted evaluation of the coherence of each frequency and importance of different frequency ranges. A procedure of obtaining the site specific dispersion curve is illustrated with due consideration to the issues associated with data quality and power spectra.

Key words: coherence, dispersion, power spectra, rayleigh wave, SASW Test (IGC: C2/C8/D7)

INTRODUCTION

Near-surface soil site characterization is an important issue related to various types of geotechnical construction e.g., highway or railway track foundation and earthquake related problem. In-situ tests are widely used for determination of soil stiffness and material property for this purpose. Since its introduction in the mid-80s, the SASW (Spectral Analysis of Surface Waves) method has gained a large role into in-situ testing for determination of soil stiffness at small strains. This method can be used for testing a large area of soil deposits economically. SASW test is performed by generating waves of a wide range of frequency under a vertical impact loading. Waves in the form of signals are then captured by sensors and then soil profiling is done by generating experimental dispersion curve and applying subsequent inversion method. However, this method is affected by a large degree of uncertainties due to various factors such as far field and near field effects arising from attenuation of surface wave and body wave interference, mechanical and electrical noise at low frequencies, and specifications of data acquisition add to such uncertainties. As a result, the construction of the experimental dispersion curve is strongly affected by the operator’s experience and decision making for significant and corrected data actually required for interpretations. It leads to the analysis being a considerably time consuming process and involves significant human intervention and manipulation during the process.

Heisy et al. (1982a) first mentioned the concept of SASW. Nazarian and Stokoe (1986, 1987) developed the experimental and theoretical aspects of the SASW method as applied to geotechnical and pavement engineering. They developed a suitable method for conducting the in-situ tests. Sayyedsadr and Drnevich (1989) developed a software code SASWOPR to operate on SASW data for generating a combined dispersion curve. As coherence and phase values were directly used as input, data quality assessment depending on energy content and relevance of frequency range could not be considered, and coherence values were the sole signal quality deciding factor. Some literature is also available addressing the issues related to the source and receiver spacing and arrangement. Heisy et al. illustrated (1982b) the factors that affect the source and receiver geometry. Based on the experimental studies, it was suggested that the source to near receiver distance (S) might be equal to inter-receiver distance (d), provided that wavelengths $\lambda < 0.5d$ and $\lambda > 3d$ are eliminated from the data. Nazarian and Stokoe (1983) recommended that Common Receiver Midpoint (CRMP) geometry was the most suitable for SASW test in case of soil site due to less scatter in dispersion curve arising due to non-homogeneity. In CRMP geometry receivers are placed at equal distance apart from an imaginary centerline and they are shifted by equal distance

i) Formerly Research Fellow, Dept. of Civil Engineering, Indian Institute of Technology, Kanpur, India.

ii) Assistant Professor, ditto (aprashan@iitk.in).

The manuscript for this paper was received for review on August 11, 2008; approved on June 8, 2009.

Written discussions on this paper should be submitted before May 1, 2010 to the Japanese Geotechnical Society, 4-38-2, Sengoku, Bunkyo-ku, Tokyo 112-0011, Japan. Upon request the closing date may be extended one month.
from that line after each test set up during field test, as illustrated in Fig. 1. Hence, the soil site under testing remains the same after the whole test assuring relatively homogeneous soil site condition. Sanchez-Salinero et al. (1987) analytically studied the most feasible source-receiver configuration. They indicated that a desirable distance between the source and the near receiver is equal to the distance between the adjacent receivers and for that set-up the wavelengths (\( \lambda \)) considered during analysis of the field data were suggested to be equal to or less than one half of the distance between the receivers (\( \lambda < 0.5d \)). Hiltunen and Woods (1990) presented an experimental study to predict the variables affecting the testing of pavements by the surface wave method. Different inter-receiver distance with varying source type and source distances were used to predict the effect of \( S \) and source type. It was found that phase velocities were independent of \( S/d \) for values of \( d/\lambda \geq 0.5 \) indicating no further effect of body wave energy. Earlier works mainly focused on the effects of previously mentioned issues on pavement systems with difficulties in high frequency range. Not much literature is available addressing such effects on soil site characterization by SASW method and further investigations are needed for automating the dispersion curve generation process.

As discussed above, the interpretation of SASW test is largely affected by several uncertainties related to data quality, source-receiver configuration and source type used. Marosi and Hiltunen (2004) presented a study on measurement uncertainty related to shear wave velocity in SASW testing. They proposed an analytical method to determine uncertainty in measured shear wave velocity in SASW test based on statistical distribution and measured uncertainty in phase angle and phase velocity data. For predicting the results with reasonable confidence, a proper methodology is required considering different data stacks for various source type and source-receiver arrangements. To progress with the above mentioned discussion further experimental investigation was carried out during this study to investigate the effect of both source impulse and \( S/d \). Based on the experimental findings, a method has been proposed to identify the frequency range of interest based on cross power spectrum and quality data was determined by different stacking combinations.

**EXPERIMENTAL PROGRAM**

The experiments were conducted at a site located in the campus of IIT Kanpur. The tests were performed following Common Receiver Midpoint (CRMP) geometry configuration (Nazarian and Stokoe, 1983) for different inter-geophone distances (2 m, 4 m, 6 m). The borehole data for the tested soil site is given in Table 1. Different \( S \) values with \( S/d = 0.5, 1, 2, 3 \) were used for each inter-geophone distance. Tests were performed with drop mass of 1 kg, 2.5 kg, 5 kg, 10 kg and 18 kg and height of fall of the mass were maintained as 0.25 m, 0.5 m and 0.9 m at each test configuration. Figure 2 illustrates the above mentioned test configurations in detail. The drop mass, channeled through a guide rod, was made to fall on a base plate; thus, producing an impulse as a consequence of the impact. Figure 3 depicts the schematic diagram of the loading arrangement. The test was repeated for both forward and reverse side of the receiver geometry. Six

![Fig. 1. Common receiver mid-point (CRMP) array](image1)

![Fig. 2. Various test configurations in Experimental Program](image2)
data stacks were recorded for each setup configuration. The SASW control unit was used for data recording during the test.

Two geophones with 4.5 Hz natural frequency were used as sensors. Figure 4 gives the response curve of the geophones used in the present study with shunt resistance of 34\ohm. The shunt resistance controls electrical damping of the geophone. A large value of shunt resistance decreases the sensitivity of sensor to mechanical vibration and at the same time reduces amplification in response due to natural frequency of geophone. Though the linear output is obtained from 20 Hz, the minimum frequency range considered for the present analysis is twice the natural frequency, i.e., 9 Hz to avoid loss of lower frequencies which are important for deep soil site profiling. The nonlinearity due to electrical resonance of the geophone for the frequency range 9–20 Hz may not significantly affect the obtained results. Below 9 Hz, output value does not truly represent the variation due to input signal and original signal along with the ambient noise get amplified creating swamp in the output signal. The maximum frequency required for analysis depends upon the depth of interest and in case of near surface soil site characterization the minimum depth of interest is approximately 0.5 m. It is observed that 150–200 Hz frequencies are able to yield waves of such depths (Nazarian, 1984; Foti, 2000; Ganji et al., 1998). For the present study maximum frequency considered is 200 Hz.

**EVALUATION OF DATA QUALITY WITH STACKING OF SIGNALS**

One of the main objectives of the present study was to find out quality data subset from the stacking done for each configuration. Considering various factors inducing the uncertainty of data, the procedure of evaluating the data quality for SASW test interpretation was divided in four major steps discussed subsequently.

**Interpretation of Coherence Function**

Generally coherence function is used to assess data quality at any frequency. It is a measure of the degree by which two signals are linearly correlated. Coherence function value close to unity is considered as a good quality data. Nazarian and Stokoe (1986) considered a minimum acceptable value of coherence function 0.9 in their analysis for pavement system. Sayyedsadr and Drnevich (1989) used a default value of 0.98 as a minimum coherence magnitude. Al-Hundai (1992) used a minimum filtering criterion of 0.9 for coherence function. For the present analysis threshold minimum coherence value was considered as 0.98 to ensure good data quality. The phase difference between two signals may be more than one cycle (2\pi); however, the phase angle is calculated to have its values between \[-\pi\] to \[+\pi\]. These values, which are referred to as wrapped phase angle, are corrected to include the number of missing cycles based on an expected response of phase distribution. Such process of the phase correction is called unwrapping in which the phase magnitude is shifted by 2\pi for each missing cycle. Figure 5 presents coherence and wrapped magnitudes of phase angle, each varying over the frequency range 9–200 Hz, for good and bad quality data. It can be observed that frequencies with low coherence (Fig. 5) lead to irregular jumps in the wrapped phase which can lead to misinterpretations in phase velocity calculations during further analysis. However, such irregular jumps were sometimes present in the wrapped phase in spite of high coherence values corresponding to those frequencies. These may be due to the low power content of both the signals resulting in a good coherence value, though the signal is affected by the background noise. Such irregular jumps can also be noted at soil layer interfaces due to sharp change of medium properties. These issues are further discussed later under the section on Signal Quality Based on Power Spectrum.

**Different Stacking Combinations for Enhancing Data Quality**

The coherence values were calculated by averaging the spectral quantities of signal over the number of data stacked. If it is assumed that the background noise is random in nature, by averaging the sum of the background noise in the signals, it can be reduced by a large extent (Nazarian, 1984). Theoretically, the higher the number of signals averaged the more enhanced the final results will be. Practically, the number of averages should be optimized. Law of statistics suggests that the reliability of
getting a value closer to the real value by averaging the signals is inversely proportional to the square root of the number of experiments. Based on their experimental study Nazarian (1984) proposed 5 stacking for averaging the signals.

In the present study experimental data were stacked six times and the spectral quantities were calculated for various stack combinations, considering three to six stacks out of six stacks obtained for each setup configuration. Such analysis helped in identifying the combination for which the noise effects were less in comparison to the other combinations. The good quality data was estimated through increase in magnitude of coherence function. Coherence values for different frequencies are presented in Fig. 6 for both 3 stack and 5 stack combinations. It is evident that 3 stack results yielded good result than 5 stacks. Though the interpreted data quality may increase by decrease in the number of selected stacks, it is imperative to maintain a minimum number of stacking to ensure confidence in representativeness of data. It was observed from the present study that four stacks combination may be taken to satisfy both coherence and representativity conditions.

**Finding the Best Stacking Combination Based on Cumulative Weight**

It was required to establish a qualitative index to get the best stacking combination out of all combinations under consideration for a setup configuration. Such index was calculated over the whole frequency range \( f_n \) of interest with emphasis on the data quality of each frequency and frequency range of importance for every combination of the stacks. In case of soil profile investigation, the lower range frequencies yielding longer wavelengths were of greater interest which could allow sampling of deeper soil stratum. Hence, the frequency range was first divided into two equal segments and a weight \( w_{1,i} \) was assigned for each of these frequency segments. The first segment containing lower range of frequencies was given higher weight than the second one. A cumulative weight \( CW \) was then calculated where further weights \( w_{2,i} \) were given based on the coherence value \( CH \) at the corresponding frequency.

\[
CW = \sum_{i=1}^{n} w_{1,i} \times w_{2,i}
\]

\( w_{1,i} = 2 \quad f_i \leq \text{mean value of the considered frequency range} \)

\( w_{1,i} = 1 \quad f_i > \text{mean value of the considered frequency range} \)

\( w_{2,i} = 0 \quad CH < 0.98 \)

\( w_{2,i} = 1 \quad 0.98 < CH < 0.99 \)

\( w_{2,i} = 2 \quad CH > 0.99 \)

Cumulative weights were used instead of normalized weighted average values to quantify the data quality of various combinations. Frequencies with coherence values less than 0.98 were masked out by assigning zero weight and cumulative weights were calculated for each combination. The best of various combinations was found based on the highest value of cumulative weight under the condition that the number of deleted points was less than 50% of total frequency points.

**Signal Quality Based on Power Spectrum**

The power spectrum of a signal gives an idea about the amount of energy associated with each frequency. Low magnitude of power spectrum means energy content is low under the test configuration. For the frequencies with low energy content, the interpretations may be highly misleading due to background noise and sensitivity of the geophones. Therefore, the spectrum values were also considered as one of the criteria of masking the frequen-
cies. The auto-power spectra give an estimate of the frequency distribution of energy for each signal. The cross-power spectrum helps in identifying the predominant frequencies that are present in both the signals. Figure 7 illustrates the cross power spectrum curve and coherence value distribution for test configuration $d=S=2$ m with impact mass of 10 kg and height of fall 0.9 m. It was observed that the power content was low up to 50 Hz and increases significantly for 60 to 100 Hz. Figure 8 shows the wrapped and unwrapped phase lag of second receiver with respect to the first one. Though coherence values (Fig. 7) were quite good for the region 0 to 50 Hz, the phase velocities were found to be negative due to negative phase lag (Fig. 8) obtained at frequencies lower than 20 Hz. On the contrary, unwrapping of such negative phases yields very low velocities at considered frequencies. Such negative phase lag values may be due to the presence of other background noise or signal with direction from second sensor to the first one. Hence, masking was required for obtaining feasible phase velocity for these frequencies.

On the other side of frequency range, from 100 Hz to 150 Hz the power value decreases again and after 160 Hz becomes nearly constant with a very low magnitude. From Fig. 7, it can be observed that the coherence value decreases to a large extent at these low power content regions and spurious jumps are also present in wrapped phase after 150 Hz (Fig. 8). In the present study, such low power regions were masked out to avoid these spurious jumps and for identifying the frequency range with good data quality. The regions of masking for low power have been indicated in unwrapped phase distribution shown in Fig. 8. The final dispersion curve after application of masking has been shown in Fig. 9. From the experimental results, it was observed that the threshold power magnitude value was 500 (mV)$^2$ for the instrument used for profiling of the soil site.

Each instrument carries specific sensitivity of measurement, which may depend on the specifications of both sensors and data acquisition system. The measurements with low power do not necessarily represent the true response, albeit the coherence value of such measurements may be high for few associated frequencies. The approximations in transformation of signal to frequency domain and interference of noise make it complex to accurately determine the threshold power value for each measurement. As a pragmatic approach, an instrument
can be calibrated for its response by performing a number of measurements in different configurations of testing, and then the threshold power value can be taken as an average magnitude of power below which the associated frequency range mostly shows: (i) considerably low coherence values for a number of frequencies, (ii) negative value of phase lag, (iii) irregular jumps in phase distribution, and (iv) unacceptable phase velocities. The same procedure was followed in this study (e.g., Figs. 5–8), which yielded the threshold power value of the instrument to be 500 (mV)².

NEAR FIELD AND FAR FIELD EFFECTS AND POWER SPECTRUM

Near field and far field effects were analyzed in the present study based on cross power spectrum values to avoid body wave effects and poor signal quality due to attenuation of surface waves respectively. The filtering criterion proposed by Heisey (1982) was considered in this study. According to that filtering criterion the minimum wavelength should be greater than half of the inter-receiver distance and maximum wavelength should be considered as thrice the inter-receiver distance. In the present analysis power spectrum curves were studied to predict the combined effect of source impact and spatial configuration of source and inter-receiver distance for satisfying the above mentioned filtering criterion. Far field effect could be eliminated by selecting proper upper frequency cut off from the threshold cross power spectrum value. Through masking of higher frequencies with lower power content, adulteration of signal quality due to attenuation of surface waves could be avoided.

From Fig. 9, it can be observed that the minimum wavelength yielded after masking satisfies Heisey's filtering criterion; i.e., minimum wavelength should be greater than half of the inter-geophone distance. Near field effects are related to the increase of phase velocity values due to presence of body wave in the wave generated by the impact load during SASW test. A detailed discussion on the spectral quantities has been presented in the following sections through a comparative study, which would guide to select the proper source type and its spatial arrangement to eliminate near field effect by satisfying Heisey's filtering criterion. The focus of discussion is the combined effect of source type, height of fall of impact load and S/d arrangement on the dispersion curve and power spectrum values.

EFFECT OF SOURCE TYPE

Figure 10 presents the variation in power spectrum magnitudes, Auto Power Spectrum at first station (APS1) and Cross Power Spectrum (CPS), under increasing source impact and different height of fall for a test setup with \( d = 2 \text{ m} \) and \( S = 1 \text{ m} \). For the same \( S \) and \( d \) configuration, increase in either the magnitude of load (wt) or the height of fall (ht) of impact load increased the power spectrum values due to increase in input energy. A continuous increase in coherence function (Fig. 11) indicated improvement in the data quality, with increase in impact loads due to increased energy values for the same spatial configuration of experimental set-up. Figure 10 indicates that the distribution of energy over the frequency range was independent of the height of fall and it only depended on the mass used for generating the impact. For
lower mass (5 kg) the energy was distributed over a wide range of frequency (40–170 Hz) with peak value at 110–120 Hz. Whereas, in case of higher mass (18 kg) the energy distribution was concentrated over a lower range of frequency (35–140 Hz) and peak values at 100–110 Hz. Figure 12 depicts the experimental dispersion curve for 5 kg and 18 kg load with the same height of fall of 0.9 m spatial configuration of $d = 2$ m and $S = 1$ m. For the lower mass (5 kg), the upper frequency cut off extended to a higher frequency and smaller wavelengths were present in the experimental dispersion curve. Similarly, in case of 18 kg higher wavelengths were present in the dispersion curve due to dominant lower frequencies.

**EFFECT OF SPATIAL CONFIGURATION OF SENSOR AND SOURCE**

Auto power spectrum and cross power spectrum curves were observed for different configurations of $S$ and $d$. Subsequently, the change of coherence function values and the quality of dispersion curve were also analyzed for such test configurations.

**Effect of Source to Near Receiver Distance**

The experiments were carried out at four different $S$ and keeping $d$ the same. Figure 13 depicts the variation of power spectrums (APS1 and CPS) with different $S/d$ ratio (for $d = 4$ m) for the same impact load (18 kg) and height of fall 0.9 m. It was observed that with increase in $S/d$ ratio power spectrum magnitude decreased significantly due to attenuation of energy for travelling greater source to receiver distance. The rate of decrease of power spectrums were higher when $S/d > 1$. In such cases, the power spectrum value went below 500 (mV)$^2$ which was below the threshold value. So, no dispersion curves could be obtained in such conditions. The coherence function and the dispersion curve (for $S/d \leq 1$) are presented in Figs. 14 and 15 respectively. The experimental dispersion curve was plotted after masking the zone with cross power spectrum values below the threshold value. The frequency range of analysis was chosen based on power spectrum (Signal Quality Based on Power Spectrum), and the considered frequency was 30–110 Hz in the case of $S/d = 1$ and 20–100 Hz in the case of $S/d = 0.5$. Coherence values (Fig. 14) of these regions were greater than the acceptable value (0.98) indicating a good data quality. Small variation was observed between the magnitudes of phase velocities (Fig. 15) at a particular wavelength, though the possible depth of exploration in case of $S/d = 0.5$ was more with maximum wavelength, $\lambda_{\text{max}} = 21$ m than that in case of $S/d = 1$ with $\lambda_{\text{max}} = 7$ m.
At low $S/d$ ratio, it is difficult to ascertain that the wave travelling to the receivers are surface waves and not body waves. It is quite likely that the interpretation of velocity at high $\lambda$ (low frequency) had some influence of body waves, which could mislead the interpretations. Heisey’s criterion for such near field effect suggests the maximum wavelength acceptable for a 4 m inter-receiver distance to be 12 m. Hence, the data obtained from $S/d=0.5$ condition can be considered in the analysis provided maximum wavelength considered as thrice the inter-receiver distance.

Effect of Inter-Receiver Distance

The depth up to which soil profile can be determined depends on the chosen inter-receiver distance and the applied impact load. Three inter-receiver distances were considered (2 m, 4 m, and 6 m) for $S/d=1$ condition and 18 kg impact source and 0.9 m height of fall. Figure 16 shows the cross power spectrum and dispersion curves are plotted in Fig. 17. In the case of $d=2$ m and 4 m, the CPS values (Fig. 16) were greater than the threshold power and their masking was performed based on the criteria described in Signal Quality Based on Power Spectrum. The dispersion curves were plotted after application of masking (Fig. 17) and it was observed that the maximum wavelength (19 m) obtained from $d=2$ m was greater than that (8 m) of $d=4$ m for 18 kg mass with height of fall 0.9 m. However, for satisfying the filtering criterion of near field effect, the maximum wavelength should be taken as 6 m for the inter-receiver distance of 2 m. Further, the minimum wavelength was nearly the same for both inter-receiver distances (2 m and 4 m). Hence, it is advisable to take lower masses (5–10 kg) for smaller inter-receiver distance to get a better representative frequency range (EFFECT OF SOURCE TYPE). In case of $d=6$ m, the CPS magnitude went below the threshold magnitude and a scattered dispersion curve is obtained (Fig. 17). For this condition, to get a better dispersion curve, it is suggested to use either a heavy source, or generate a greater impact under enhanced height of fall. In either case, greater input energy is required to be transferred to the soil. Input energy can also be increased by reducing the $S/d$ factor. However, in such case body wave interference may be present in the acquired signal and hence analysis results can be misleading.

COMBINED EFFECT OF SOURCE TYPE AND SPATIAL CONFIGURATION OF SOURCE AND RECEIVER ON POWER SPECTRUM

From EFFECT OF SOURCE TYPE and EFFECT OF SPATIAL CONFIGURATION OF SENSOR AND SOURCE it can be observed that the power spectrum values get largely affected by the source type and spatial configuration of source and receiver. For smaller receiver distance (2 m) higher frequencies are of more importance to generate low wavelengths for sampling shallow depths. Lower masses (5–10 kg) can be used for such cases for generating higher frequency range (Fig. 10). However, in such a case it is possible that such a mass may lead to a signal with low power and hence height of fall should be increased (height more than 1 m) to increase the energy content. On the other hand, for sampling greater depth with longer receiver distance (4–6 m or more), higher mass with lower frequency of excitation should be used. In the present study, it was observed that in case of $d=4$ m and 18 kg drop mass with 0.9 m height of fall under $S=d$ configuration was just able to fulfill the threshold power criterion. However, the same mass with $S/d=0.5$
configurations contributed more energy with little variation in wavelength and phase velocity (Effect of Source to Near Receiver Distance and Fig. 15). In the present study, it was observed that the effect of body wave not only depends on source configuration but also on its magnitude.

**GENERATION OF DISPERSION CURVE**

For each test set up, the waves were generated by impact load and captured at some distance with the help of two geophones. The process was repeated for six stacks. A procedure of obtaining the dispersion curve for the soil strata was developed with due consideration to the issues associated with data quality and power spectra. This procedure can as well be used for automated generation of dispersion curve from time domain data so as to be used further during inversion/forward analysis to eventually determine the shear wave velocity profile of the strata. The steps involved in this procedure are discussed below.

1. **Transformation of Time Domain Data to Frequency Domain:** The two time domain signals \( y_1(t) \) and \( y_2(t) \) acquired through the geophones during each stack were transformed into frequency domain using Fast Fourier Transform to obtain the corresponding linear spectra \( Y_1(o) \) and \( Y_2(o) \).

2. **Masking of Frequencies with Low Power Spectra Values:** Initially, the frequency range of analysis was considered as 9–200 Hz based on the sensor specifications (EXPERIMENTAL PROGRAM), and the spectral quantities (APS1, APS2 and CPS) were calculated for each of the data stack. Then these quantities were averaged in various combinations of five, four and three stacks out of the six stacks. Through observation over power spectra, the final frequency range of analysis was identified. The maximum frequency range among all the stack combinations where CPS values were obtained more than the threshold power value was taken as the frequency range of importance (Fig. 10). The minimum power magnitude was considered to be 500 (mV)\(^2\). One should note that the threshold power magnitude could be instrument dependent.

3. **Masking of Frequencies with Low Coherence and Finding the Best Quality Data Set:** In the next step, coherence values, cumulative weights based on frequency and coherence (Finding the Best Stacking Combination Based on Cumulative Weight) and count of deleted points were estimated for each of the combinations. The quality of each combination set was defined based on the cumulative weights as described in Finding the Best Stacking Combination Based on Cumulative Weight. The best data set was selected out of these combination sets based on the quality of data and degree of representativeness. The quality of data was assured by cumulative weight and at the same time degree of representativeness of data was retained by considering a minimum four stacks in combination set of analysis.

4. **Unwrapping of Wrapped Phase and Construction of Dispersion Curve:** The calculation of phase angle and its unwrapping was done for the best stacking combination. Using this phase information, Rayleigh wave phase velocity was calculated for each frequency from the known receiver distance. User interactive interfaces were used in the developed code during automated unwrapping of the phase data to avoid problem arising from fictitious jumps due to low coherence and real jumps with phase jump less than \( 2\pi \) due to change of stratification. To consider real jumps with phase jump less than \( 2\pi \) due to change of stratification, the jump tolerance was assumed to be \( 3\pi/2 \). For the phase jumps in between \( \pi \) to \( 3\pi/2 \), the unwrapping was first done both by considering and without considering the phase jump and dispersion curves were plotted. The decision was then made heuristically whether to consider the jump or not.

The accuracy of interpretations is governed by the representativeness of the data, and the output of proposed method promises more reliable data in comparison to the conventional procedures. Besides selecting good coherence data from multiple stacks, it is effective in minimizing ambiguities of unwrapping procedure and masking of the unrepresentative data based on simple rules. Hence, the strength of proposed method is its fast and effective automated procedure. Figure 18 illustrates an example of the advantages of the proposed method. Figure 18(a) shows three dispersion curves of different \( d \) values based on the conventional empirical approach considering the coherence \( \geq 0.98 \) for full stack combination and limits of included wavelengths as \( d/2 \leq \lambda \leq 3d \).

The dispersion curves in Fig. 18(b) are the results of proposed method, which eliminated the case of \( d = 6 \) m due to low power content. The large scatter of data in the case of conventional approach indicates uncertainty of data, and the interpretations based on any of the test configurations will have a large error bar associated with it. The proposed approach provides only the representative...
data based on the quality of collected multiple stacks. It encourages variation of test configurations for obtaining the data for wider wavelength range instead of using the unrepresentative data of a setup producing misleading results. As another example, in Fig. 8 the unwrapping at low frequencies to correct for the positive phase values could be avoided based on the assumption of low power being unrepresentative. Such unwrapping would have produced interpretation of velocity ranging from 150 m/s to 50 m/s for the wavelength between 1 m to 2.3 m, which was considerably lower than the velocities suggested by the other test configurations.

CONCLUSION

It is imperative to understand the amount and the cause of uncertainty induced through the instrument limitations and test configuration while interpreting the results from an SASW test. Several issues associated with loading arrangements, spatial configuration, sensor specifications, and analysis scheme were discussed in the paper. Based on the observations, a simple methodology was proposed eventually to obtain a representative dispersion curve for the measurement domain. Key findings of the present study are given below.

1. The power spectrum values could be used to determine the frequency range for which the response would be interpreted based on propagation of induced mechanical waves and not due to surrounding noise or sensitivity of sensors. It was proposed to consider a threshold minimum cross power spectrum value for selecting the frequency range. The magnitude of the value could be site and instrument dependent.

2. Different stacking combinations of the same test configuration were considered during analysis to obtain quality data. The best data stack was identified based on cumulative weight calculated over the frequency range of interest. The weights were assigned based on the magnitude of coherence of each frequency and importance of different frequency ranges for every combination of the stacks.

3. A comparative study was presented to show the importance of source impact magnitude to obtain a good quality data satisfying the coherence requirement and also its effect on frequency range of interest, power spectrum values and dispersion curve. The dominant frequency content produced by a source could be a key factor to be considered while performing a test for certain ground depth of interest. The falling mass source was used during this study and the results indicated that the interpretation could be influenced not only by the energy induced by the source but also by the mass of the falling object.

4. The effect of spatial configuration of source and inter-receiver distance was studied based on the cross power spectrum magnitude. Heisey’s filtering criterion was satisfied by choosing proper source ar-}

rangement and type depending on the power spectrum values for eliminating near field and far field issues. The depth of exploration can be increased by having larger inter-receiver spacing and sufficient impact energy with low frequency content propagating to both the receivers from the source.

5. The proposed method of analysis has the potential to automate the generation of experimental dispersion curve with reduced uncertainty. Such development will eliminate some decision making during data processing and will reduce the time of calculation of experimental dispersion curve by a great amount. This experimental dispersion curve then again can be used as input of the inversion procedure for profiling the soil site.

NOTATION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>APS1</td>
<td>Auto power spectrum at 1st geophone position</td>
</tr>
<tr>
<td>APS2</td>
<td>Auto power spectrum at 2nd geophone position</td>
</tr>
<tr>
<td>CPS</td>
<td>Cross-power spectrum of two geophones</td>
</tr>
<tr>
<td>d</td>
<td>Inter-receiver distance</td>
</tr>
<tr>
<td>f</td>
<td>Frequency</td>
</tr>
<tr>
<td>λ</td>
<td>Wavelength of Rayleigh wave</td>
</tr>
<tr>
<td>S</td>
<td>Source to near-receiver distance</td>
</tr>
<tr>
<td>w_{1,i}</td>
<td>Weight assigned for each of these frequency</td>
</tr>
<tr>
<td>w_{2,i}</td>
<td>segments</td>
</tr>
<tr>
<td>y_{1}(t), y_{2}(t)</td>
<td>Signals in time domain</td>
</tr>
<tr>
<td>Y_{1}(ω), Y_{2}(ω)</td>
<td>Linear Spectra obtained by transforming the time-domain signals into frequency domain signals using Fast Fourier Transformation (FFT)</td>
</tr>
</tbody>
</table>

REFERENCES


