Comparison of downhole Vs profiles using conventional- and spectral- analysis methods

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ABSTRACT: Downhole seismic testing is commonly used to determine compression- and shear-wave velocity profiles. Conventional downhole analysis methods involve picking a common reference point on time-domain waveforms from which travel times of waveform groups or receiver pairs are calculated. Travel distances are calculated either from slant or vertical distances. Wave velocities are simply distances divided by travel times. However, it is implicitly assumed that these velocities have associated wavelengths that are equal to or smaller than the interval travel distance. This assumption is made in all conventional body wave measurements and ignores dispersion; that is, different wavelengths propagate with different velocities in varying-velocity profiles. To overcome this limitation, wavelength-to-travel-distance evaluation methods, based on the Spectral-Analysis-of-Body-Waves method, are presented. Two advantages of these spectral-analysis methods are more-accurate and higher-resolution profiles. Comparisons of Vs pro-files from conventional and spectral downhole methods and independent crosshole tests at a granular backfill are presented and discussed.

1 INTRODUCTION

As part of a subsurface characterization program of a potential site for two nuclear power plants, a compacted granular backfill test pad was constructed. The objective of the test-pad construction was to assess the potential of on-site granular soils fulfilling the requirements for a Category-1 compacted backfill as specified by the United States Nuclear Regulatory Commission. Several field seismic methods and dynamic laboratory tests were conducted to evaluate the stiffness of the compacted granular backfill material as described in Stokoe et al., 2018. The results presented in this paper focus on the shear-wave velocity (Vs) profiles determined in-situ using: (1) conventional downhole testing and data analysis methods, (2) spectral-analysis methods based on the Spectral-Analysis-of-Body-Waves (SABW) method as applied to downhole testing (Kim, 2012 and Hwang, 2018), and (3) crosshole seismic testing using both conventional- and spectral- data analysis methods. The downhole Vs profiles determined from conventional- and spectral- data analysis methods are presented, and the reasons for differences in the profiles are discussed. In addition, the downhole V_S profiles are also compared with V_S profiles determined by crosshole testing using both conventional- and spectral- data analysis methods.

2 V_S PROFILES DETERMINED IN THE GRANULAR BACKFILL BY CONVENTIONAL DOWNHOLE AND CROSSHOLE TESTING

2.1 *Construction of the granular backfill test pad*

The compacted granular backfill test pad was constructed in a wide, excavated trench to simulate compaction within an actual excavation (with some lateral confinement). The test pad was designed to have a length, width and thickness of nominally 18.3, 6.1 and 6.1 m, respectively. The field measurements that were used to characterize the backfill were generally performed in the central portion of the test pad as shown in Figures 1a and 1b. With the exception of the first lift, which was 178 mm thick (loose), all other loose-lift thicknesses ranged between 229 and 305 mm, with an average thickness of 267 mm. In total, 25 lifts of compacted backfill were placed, and the as-built thickness equaled 6.2 m. Lifts 1 through 13 comprised the lower approximately 3 m of the test pad which was mainly silty sand (SP-SM) with some clayey sand (SP-SC and SW-SC) layers. The clayey sand had an average fines content of 9 % and an average plasticity index of about 13 %. Somewhat coarser sand (SP) with less fines (2.4 %) was placed in Lifts 14 through 25 which comprised the upper approximate 3.2 m of the test pad. The average Proctor compaction levels of the lower and upper portions of the granular backfill were 103 and 101 %, respectively. More detailed information on the backfill test pad is presented in Stokoe et al. (2018).

2.2 *Conventional downhole and crosshole testing*

Conventional downhole and crosshole testing was performed using the four cased boreholes (CB-1 through CB-4) shown in Figures 1a and 1b, respectively. Downhole testing was conducted in accordance with ASTM D7400-14, and crosshole testing was performed in accordance with ASTM D4428/D4428M-14, with one exception. The exception was that the borehole spacing in the crosshole tests was about 2.1 m, rather than 3.0 m. The shorter travel path was used to minimize the impact of wave refractions in these rather shallow tests. The downhole and crosshole tests were performed in 0.61-m depth intervals, starting at a depth of 0.61 m and continuing to a depth of 7.9 m, which is slightly deeper than the test-pad thickness. Downhole testing involved four travel paths as follows: (1) the plank source located at S1 and 3-D receivers in boreholes CB-1 and CB-4, and (2) the plank source located at S2 and 3-D receivers in boreholes CB-1 and CB-2 as shown in Figure 1a. The downhole source was an aluminum plank (length, width and height = 81 × 21 × 8 cm) and a 7-kg sledge hammer. Crosshole testing involved six travel paths as follows: (1) the in-hole source in borehole CB-2 and 3-D receivers in boreholes CB-1, CB-3 and CB-4, and (2) the in-hole source in borehole CB-4 and 3-D receivers in boreholes CB-1, CB-2 and CB-3 as shown in Figure 1b. The crosshole source was a pneumatically-wedged, manually-operated, stainless-steel source with a 3-kg drop weight. Example downhole measurements that are presented in Sections 2 and 3 involved the plank source located at S1 and the 3-D receiver in borehole CB-4. Example crosshole measurements that are presented in Sections 2 and 3 involved the in-hole source in borehole CB-4 and the 3-D receiver in borehole CB-1. Hence, the Vs records and measurements are shown for testing in the same zone of granular soil.

Waterfall plots of typical S-waveforms from both downhole and crosshole testing are presented in Figures 1c and 1d, respectively. In the downhole records, the first-peak arrival on the positive-polarity, S-waveforms was selected as the reference point. The opposite polarity signals from impacts in the opposite direction were used as a guide in selecting these reference points. This

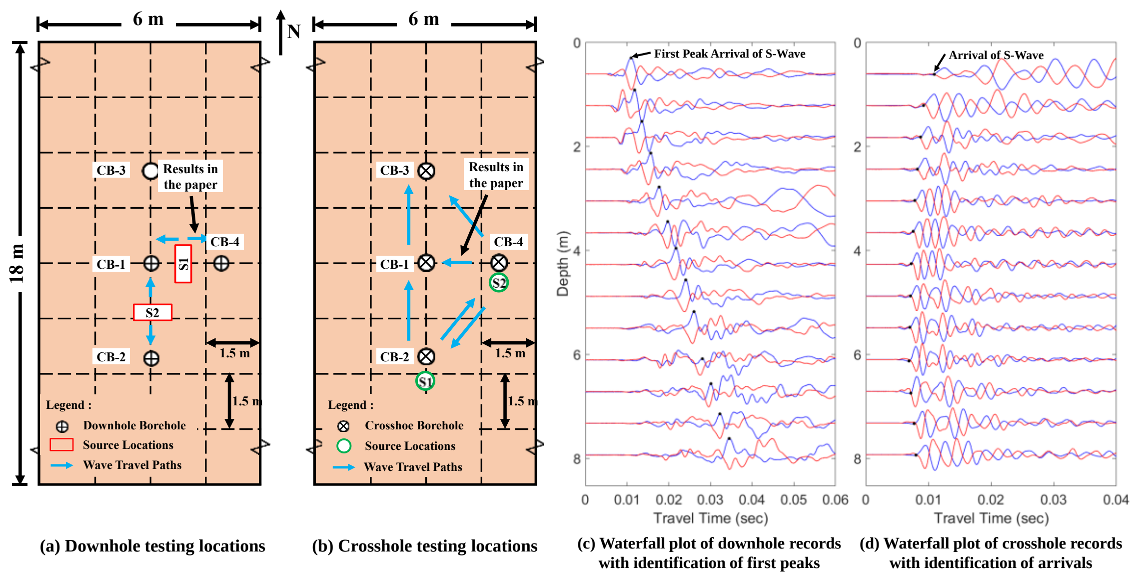


Figure 1. Location of the downhole and crosshole testing and the recorded S-waveforms

butterfly pattern in the waveforms was helpful in selecting the S-wave arrival by distinguishing the reasonably similar in-phase P-wave motions from the positive and negative polarities in motions of the S-waves that first diverged after the S-wave arrival. As seen in the downhole S-waveforms at a depth of 6.1 m in Figure 1c, there is wave interference, likely due to P- waves reflected from the bottom of the backfill. However, the S-wave arrival can still be identified around 0.28 sec where positive and negative S-waveforms diverge after reasonably in-phase P-wave motions.

Two types of conventional downhole analysis methods were used to determine the Vs profiles so that similarities and differences in the profiles can be illustrated. The two analysis methods are the: (1) direct method, and (2) pseudo-interval method (Kim et al, 2008). The direct method involves correcting slant travel times to vertical travel times using Equation 1:

$$t_c = D \times t_{SL}/L \tag{1}$$

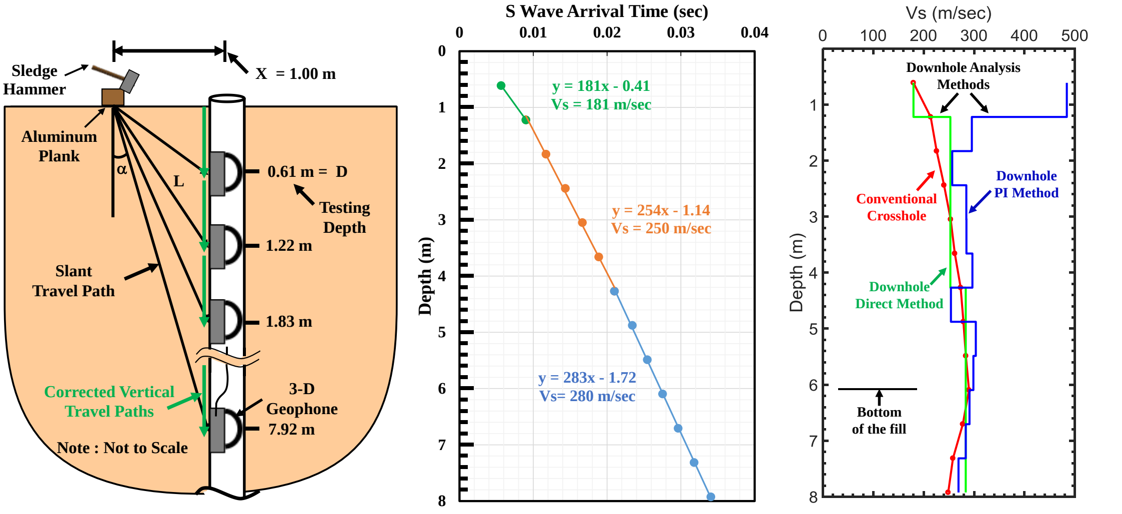
where t_c is the corrected vertical travel time, D is the testing depth, L is the straight ray-path distance, referred to as the slant distance between the source and receiver in ASTM D7400-14, and t_{SL} is the first-arrival time along the slant path (see Figure 2a). The velocity of each layer is determined from the slopes of lines fitting through groups of selected reference points as shown in Figure 2b. The Vs profile evaluated using the direct-analysis method is shown in Figure 2c by the green line. The second conventional analysis method, the pseudo-interval (PI) method, uses Equation 2 to determine the Vs values of each layer as:

$$V_{PI} = (L_2 - L_1)/(t_{SL2} - t_{SL1}) \tag{2}$$

where L_1 and L_2 are the slant distances between the source and the upper- and lower- receiver depths, respectively, and t_{SL1} and t_{SL2} are the associated measured slant-travel times (t_{SL}). The Vs profile evaluated using the PI method is shown in Figure 2c by the blue line. Differences in the Vs values determined by both methods are discussed below.

In crosshole testing that involves reversing the S-waveform by using sets of upward and downward impacts, the reference points are selected at the S-wave arrivals, where divergence in the positive and negative polarity waveforms first occurs as shown in Figure 1d. This “butterfly” pattern is again helpful in selecting the arrival time. The shear wave velocity is simply calculated from the horizontal distance at each measurement depth between the source and receiver, the near-edge to near-edge distance between boreholes CB-4 and CB-1 divided by the arrival time at that depth. The Vs profile determined from crosshole testing is shown in Figure 2c by the red line. Also it should be noted that the inclination of all boreholes were determined and any changes in travel distances were taken into account in the velocity calculations.

As seen in Figure 2c, V_S profiles evaluated using the conventional downhole direct method and the conventional crosshole method are in reasonable agreement over the complete profile depth. The crosshole measurements show, however, a more-detailed V_S profile which identifies the



(a) Generalized field setup for downhole testing at the backfill test pad (after Hwang, 2018)
(b) S wave velocity of each layer determined from the direct method using corrected vertical travel times
(c) Comparison of profiles from conventional downhole and crosshole testing methods

Figure 2. Generalized downhole field setup, wave-arrival times using the direct method, and Vs-profile comparisons evaluated in the backfill

gradual increase in Vs with depth in the backfill test pad followed by the lower shear wave velocities beneath the bottom of the backfill material. On the other hand, the direct downhole analysis method exhibits more averaging in the vertical direction due to the analysis procedure; hence, thicker constant-velocity layers (Kim et al, 2008). The profile evaluated using the PI downhole analysis method exhibits more scattering in the Vs values and results in an overestimation of the Vs values at shallow depths (depths less than 4.27 m), a misleading and erroneous result. The main reason that the Vs values are overestimated in the PI method is explained by the slant travel path and the velocity gradient near the surface where the largest change in Vs values occurred at depths less than 1.22 m. The S-waveform recorded at 0.61 m mainly propagated through the softest material near the surface; hence, measurement of a relatively longer travel time. The second measurement, with the receiver at 1.22 m, involved the wave traveling in a higher velocity material for a longer slant distance that is not accounted for. Therefore, an unrepresentative shorter time interval (Δt) is determined with the shallowest receiver pair in soil with a positive velocity gradient. This bias decreases with depth (see Figure 2c).

3 V_S PROFILES DETERMINED FROM THE SPECTRAL-ANALYSIS METHOD APPLIED TO DOWNHOLE TESTING (HWANG, 2018)

3.1 *Calculation of phase velocities, V_{PH}*

The time difference between two receivers at different depths can be evaluated from the phase difference determined between receiver pairs. For each receiver pair, body-wave phase velocity is calculated at each frequency from:

$$V_{PH} = f \times 360°/\varphi \times d \quad (3)$$

where V_{PH} is the phase velocity, f is the frequency in Hz, φ is the phase difference in degrees between two receiver signals at the given frequency, and d is the distance between the two receivers. The equation relating phase velocity and wavelength is simply:

$$V_{PH} = f \times \lambda \quad (4)$$

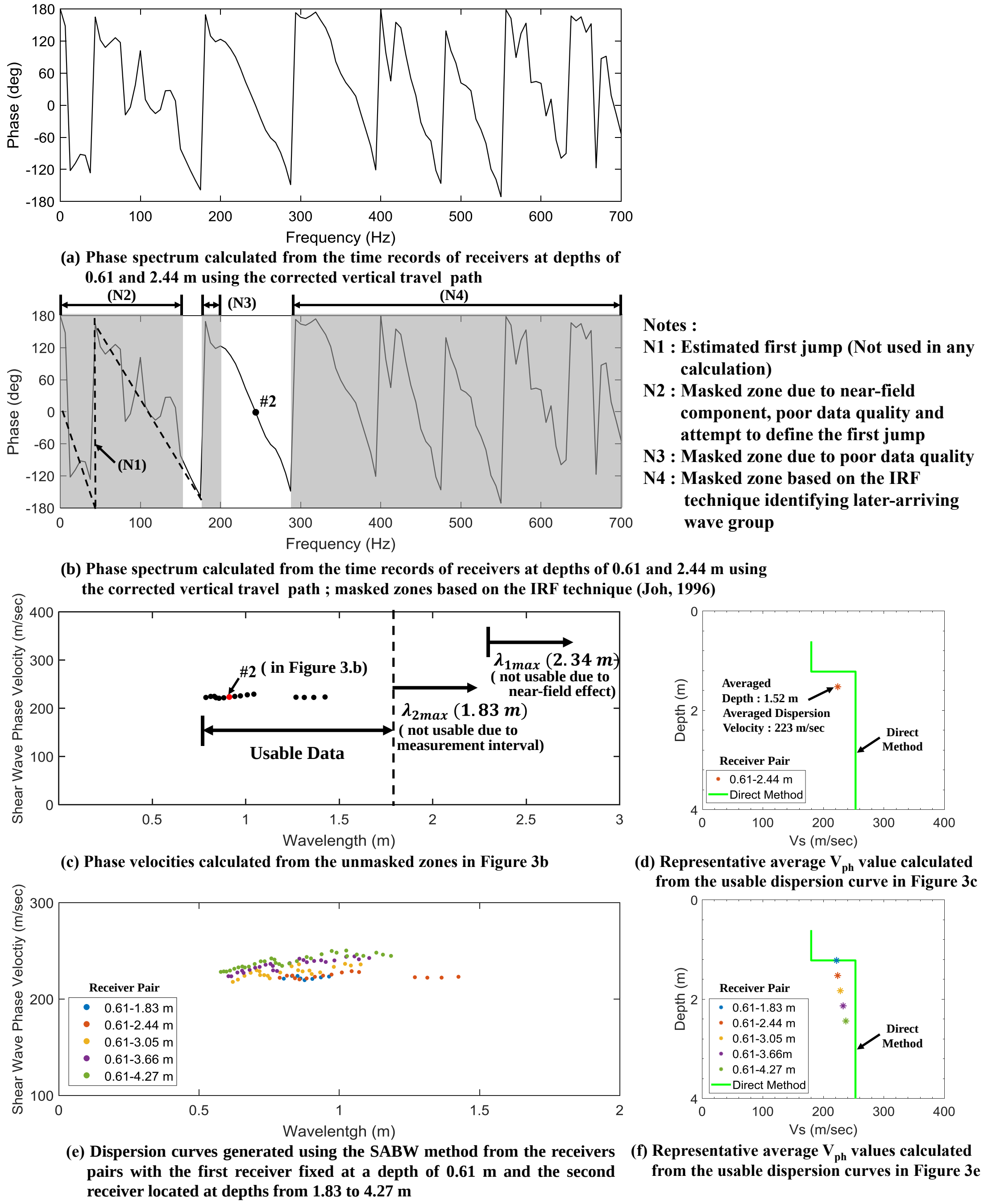
where λ is the wavelength associated with frequency, f. By combining Equations 3 and 4, the wavelength associated with each frequency is calculated from:

$$\lambda = 360°/\varphi \times d \quad (5)$$

Equations 3, 4 and 5 are used in the Spectral-Analysis-of-Body-Waves (SABW) method (Kim, 2012) to calculate the phase velocity associated with each wavelength. Following this procedure, a plot of V_{PH} versus f, called a dispersion curve, is generated as discussed below.

An example of the spectral-analysis method is presented in Figure 3. The wrapped phase spectrum calculated from receivers at depths of 0.61 and 2.44 m in the backfill test pad is shown in Figure 3a. To implicitly account for the higher velocity gradient in the poorly graded sand (SP) near the surface, the vertical travel time calculated using the direct-analysis method (Equation 1) rather than the slant travel time in the PI method is used in the phase-spectrum calculation because of the larger overestimation of Vs created by the PI method at shallow depths (less than 4.3 m). On the other hand, the profile determined from the direct method results in closer agreement with the V_S profile from crosshole testing as shown in Figure 2c. Generally, using the vertical travel time is effective when the angle, α, between the vertical and the slant path from the source to the receiver (see Figure 2a) is larger than 15°. However, this approach is not completely correct, so that further study is recommend to investigate travel paths at shallow depths. The approach using the vertical travel path is recommended only when the profile determined from the PI method is considerably above the Vs profile from the direct method at shallow depths.

Once the wrapped phase spectrum for a given receiver pair is calculated, the masking procedure is then performed to eliminate zones of data with poor signal quality, near-field data and to define the "-180° to +180 jumps" in the wrapped phase relationship. This procedure often requires some level of "engineering judgement". If the saw-tooth pattern of the wrapped phase spectrum is rather complex, the individual unwrapping of the phase spectrum becomes more complicated as discussed below. In addition, the near-field component of the phase spectrum, where wavelengths are more than twice the receiver spacing, the unwrapped phase is less than 180° and must be



(a) Phase spectrum calculated from the time records of receivers at depths of 0.61 and 2.44 m using the corrected vertical travel path

(b) Phase spectrum calculated from the time records of receivers at depths of 0.61 and 2.44 m using the corrected vertical travel path ; masked zones based on the IRF technique (Joh, 1996)

(c) Phase velocities calculated from the unmasked zones in Figure 3b

(d) Representative average V_{ph} value calculated from the usable dispersion curve in Figure 3c

(e) Dispersion curves generated using the SABW method from the receivers pairs with the first receiver fixed at a depth of 0.61 m and the second receiver located at depths from 1.83 to 4.27 m

(f) Representative average V_{ph} values calculated from the usable dispersion curves in Figure 3e

Figure 3. Example of the calculation procedure used to evaluate S-wave phase velocities (V_{ph}) from different receiver pairs in downhole testing

masked as shown in Figure 3b. Engineering judgement can be based on: (1) an aprior estimation of wave velocities of the surrounding layers, and/or (2) the overlapping in phase velocities between adjacent receiver pairs. It is recommended to use the Impulse Response Filtration (IRF) technique as a guideline tool to unwrap complicated phase spectra in the downhole method (Hwang, 2018). The masked zones in this study are determined with the IRF technique. Detailed information about the IRF technique is presented in Joh (1996) and Hwang (2018).

The masking procedure of the phase spectrum calculated from receivers at depths of 0.61 and 2.44 m is shown in Figure 3b. The phase spectrum between 300 to 550 Hz appears, based on engineering judgement, that it could be used for phase-velocity calculations. However, this phase spectrum results from a later-arriving wave group. This later-arriving wave group is identified and masked using the IRF technique. The phase velocities between receivers located at depths of

0.61 and 2.44 m are calculated with the unmasked zones in Figure 3b using Equation 4. As an example of the phase-velocity calculations, consider Point #2 in Figure 3b. Point #2 represents a shear wave with two wavelengths between the receiver pair (depths of 0.61 and 2.44 m) that has an unwrapped phase angle of 720°. The frequency associated with Point #2 is 244 Hz. The vertical distance between the two receiver depths, d, is simply 1.83 m. As a result, the phase velocity calculated at Point #2 is 223 m/sec. All phase velocities that were calculated from the two unmasked zones of the wrapped phase in Figure 3b are shown by the dispersion curve in Figure 3c, with Point #2 marked by the red dot.

Three filtering criteria are used to determine wavelengths that can be used in calculating the correct phase velocities in the test pad. The three filtering criteria are: (1) wavelengths should be shorter than the twice the slant travel path to the first (shallow depth) receiver to remove near-field effects, denoted as λ_{1max}, (2) wavelengths should be shorter than the measurement interval, the vertical distance between receiver pair, denoted as λ_{2max}, and (3) wavelengths should be shorter than the thickness of the transition layer, denoted as λ_{3max}. In the case of the receiver pair at depths of 0.61 and 2.44 m, λ_{1max} is equal to 2.34 m since the distance between the source and the borehole is 1.0 m. The value of λ_{2max} equals 1.83 m (the receiver spacing), and the value of λ_{3max} is irrelevant at this site since two rather similar cohesionless granular materials were used for the whole test pad. Therefore, at this interval testing depth, wavelengths shorter than λ_{2max} (1.83 m) can be used in developing the Vs profile which satisfies the filtering criteria.

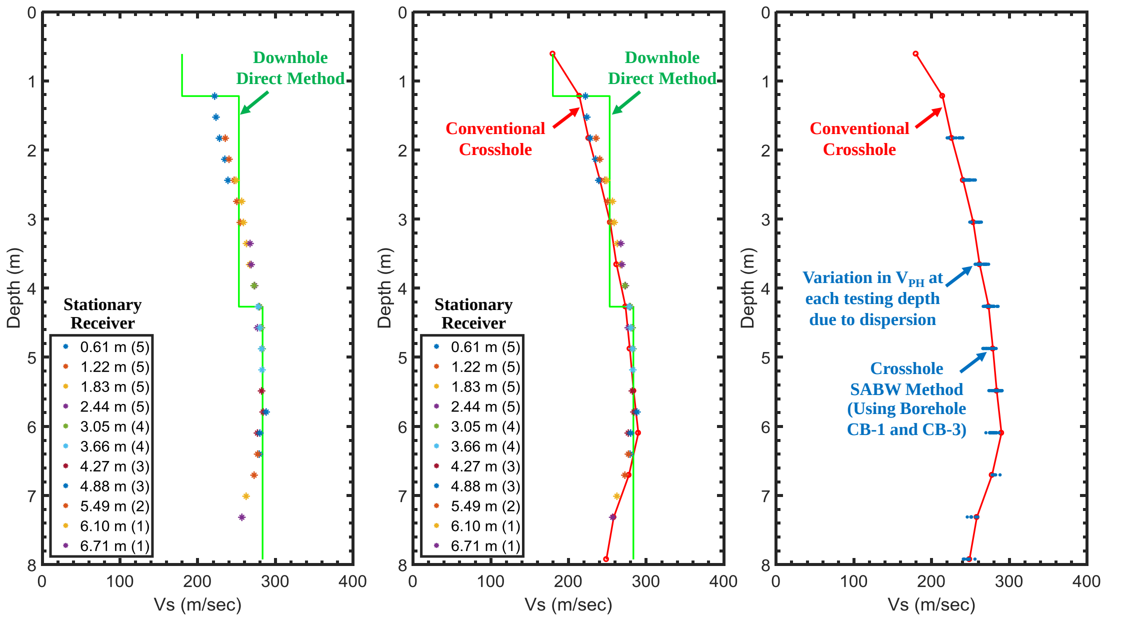
3.2 *Averaged Dispersion Velocity (ADV) Method*

The simplest way of calculating a representative value from the dispersion curve is by calculating the average value of the phase velocities that satisfies three filtering criteria described above. For example, the average value of the phase velocities from the usable portion of the dispersion curve shown in Figure 3c is 223 m/sec. This average value is plotted at the mid-depth between the two receivers which is 1.53 m as shown in Figure 3d. This method is called the Average Dispersion Velocity (ADV) method, and the average Vs value is shown in Figure 3d with the Vs profile determined from the conventional direct analysis method.

The ADV procedure is repeated for all receiver pairs over the depth range where the waveforms were measured. As an example, the five dispersion curves generated from receiver pairs with the shallowest receiver fixed at the depth of 0.61 m are present in Figure 3e. Each color represents a dispersion curve generated with the fixed shallow receiver at a 0.61 m and the other receiver (the second receiver) located at depths of 1.83 to 4.27 m. The single dispersion curve presented in Figure 3c is also shown in Figure 3e by the orange dots. Additionally, another four dispersion curves are presented in Figure 3e, that are associated with the other second-receiver locations. It can be seen that slightly higher phase velocities occur in the nearly same wavelength range as the second receiver depths increases. The phase velocity calculated from each receiver pair determine the “average” stiffness between the receiver locations. Hence, the phase velocities increase as the second receiver is located at deeper depths for this normally dispersive backfill condition.

The ADV method is applied to all dispersion curves generated from the first receiver fixed at a depth of 0.61 m. The five ADV values plotted in Figure 3f were calculated from the dispersion curves shown in Figure 3e. The averaged phase velocity from each dispersion curve is plotted in Figure 3f at averaged depths from 1.22 to 2.44 m using the same color code as in Figure 3e. The final Vs profile determined from the SABW method is shown in Figure 4a. Each color represents the depth of the first receiver (stationary receiver) location, and the number inside each parenthesis is the total number of receiver pairs used to generate the dispersion curve. As seen in Figure 4a, the ADV values from adjacent receiver pairs typically overlap, and the wave velocity gradient in the layer is well determined. In short, the phase velocity calculated using the IRF technique with wavelengths that satisfy the filtering criteria correctly represent the velocity profile.

Comparison of the Vs profiles determined from the conventional downhole and crosshole methods and the SABW method applied to the downhole measurements is shown in Figure 4b. As seen in the figure, the Vs profile determined from the SABW method is essentially the same as the conventional crosshole-testing profile, with a maximum difference of 4.5%. The ADV values calculated from adjacent receivers result in similar phase velocities and overlapped. At a depth of 2.44 m, the ADV values calculated from three different first-receiver locations of 0.61, 1.22 and 1.83 m are 239, 247 and 249 m/sec, respectively. The conventional crosshole Vs value is 240



(a) Profiles determined from conventional downhole analysis and the SABW method applied to the downhole records

(b) Profiles determined from conventional crosshole and downhole analyses and the SABW method applied to the downhole records

(c) Profiles determined from conventional crosshole analysis and the SABW method applied to the crosshole records

Figure 4. Vs Profiles determined from conventional downhole- and crosshole- analysis methods and the SABW method applied to the downhole and crosshole measurements

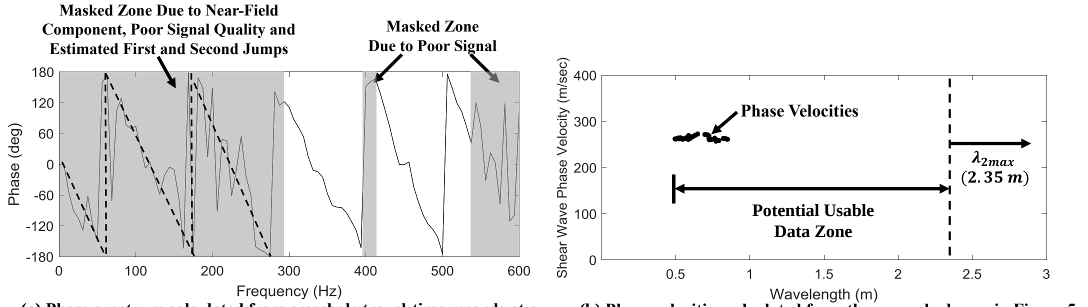
m/sec; an excellent comparison. Therefore, by using the overlapping characteristic of the ADV values from adjacent receiver pairs, a crosshole-like, detailed Vs profile can be developed.

To confirm the profile determined from the conventional crosshole analysis method, the SABW method was also applied to the crosshole measurements with the results shown in Figure 4c. The detailed procedures and small dispersion in the wave velocies are discussed in Section 4. The profile determined from the conventional crosshole analysis method is within the range of the profile determined from the SABW method. These close results are due to the advantages of crosshole testing which are: (1) consistent and relatively short (2.1 m) travel paths in the backfill, (2) consistent and strong signal-to-noises ratio at all depths, and (3) waves that are normally propagating through a single layer at essentially the same confining pressure.

4 V_S PROFILES DETERMINED FROM CROSSHOLE TESTING USING THE SABW METHOD

The SABW method is also readily applied to crosshole testing using Equations 3, 4 and 5 to calculate phase velocities and associated wavelengths. Since the source is located at same depth as the two receivers, the horizontal travel path is represented by the distance between the receivers. To apply the SABW method to crosshole measurements, time records between receivers are required. Therefore, the example crosshole measurements presented in this section and in Figure 4c involved the source in borehole CB-2 and the receivers in boreholes CB-1 and CB-3.

In this example, the wrapped phase spectrum calculated using the receivers at depth of 3.66 m is shown in Figure 5a. The masking process is done using the IRF technique as a guideline tool. The phase velocities are calculated from the unmasked zones of the wrapped phase in Figure 5a. The resulting dispersion curve is shown in Figure 5b. In this crosshole application of the SABW method, only two filtering criteria regarding wavelengths are needed. These criteria are: (1) wavelengths should be shorter than twice the horizontal travel path from the in-hole source to the first receiver to remove near-field effects, denoted as λ_{1max}, and (2) wavelengths should be shorter than the measurement interval, the distance between the two receivers, denoted as λ_{2max}. In this case, λ_{1max} is equal to 4.58 m, twice distance of 2.29 m between the source and first receiver. The value of λ_{2max} is equal to 2.35 m, the distance between the two receivers. Therefore, at this interval



(a) Phase spectrum calculated from crosshole travel-time records at a depth of 3.66m ;masked zones based on the IRF technique (Joh, 1996)

(b) Phase velocities calculated from the unmasked zone in Figure 5a

Figure 5. Examples of the phase spectrum and phase velocities calculated from the crosshole testing at a depth of 3.66 m using the SABW method and receivers in Boreholes CB-1 and CB-3

testing depth, all wavelengths shorter than λ_{2max} (2.35 m) can be used in developing the Vs phase-velocity profile. All phase velocities in the usable data range shown in Figure 5b are plotted at a depth of 3.66 m in Figure 4c. This procedure is then repeated at all crosshole testing depths. The resulting phase velocities are simply plotted at each testing depth as shown in Figure 4c.

5 CONCLUSIONS

A field testing program was developed and implemented to evaluate the in-situ, shear wave velocities of a granular backfill test pad. The Vs profiles determined using conventional downhole (Direct and PI methods), crosshole, and the new SABW method as applied to the downhole and crosshole travel-time records are compared. The Vs profiles evaluated using the conventional downhole direct method and the conventional crosshole method are in reasonable agreement with the crosshole profile is more detailed and correctly identifying the Vs gradient in the top 4 m. On the other hand, the conventional downhole PI method gave erroneous Vs values, particularly in the top 2 m. The Vs profiles were also evaluated using the SABW method applied to the conventional downhole and conventional crosshole records. The conventional and SABW crosshole Vs profiles agrees. When the SABW method was applied to the direct downhole records, a crosshole-like, detailed Vs profile was evaluated, clearly showing the importance of the SABW method of analysis.

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7 REFERENCES

Hwang, S. 2018. Advanced data analysis techniques for downhole seismic testing. *Ph.D. Dissertation, The University of Texas at Austin, Austin, Texas*

Joh, S.H. 1996. Advances in the Data Interpretation Technique for Spectral-Analysis-of-Surface-Waves (SASW) Measurements. *Ph.D. Dissertation, The University of Texas at Austin, Austin, Texas*

Kim, C. Y. 2012, Development of the Spectral-Analysis-of-Body-Waves (SABW) Method for Downhole Seismic Testing with Boreholes or Penetrometers, *Ph.D. Dissertation, The University of Texas at Austin, Austin, Texas.*

Kim, D. S, Bang, E. S, and Kim, W. C. 2004, Evaluation of Various Downhole Data Reduction Methods for Obtaining Reliable Vs Profiles, *Journal of Geotechnical Testing, Vol. 27, No. 6, 585-597*

Stokoe, K. H, II, Hwang, S, Boone, M, Lewis, M. R, Wang, Y, Cooke, M. F, and Keene, A. K. 2018, Measured and Predicted Vs Values of a Granular Backfill Test Pad, *Proceedings of the Conference on Geotechnical Earthquake Engineering and Soil Dynamics V, ASCE, GSP 293, Austin, Texas, 473-488*