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Role of Forward Model in Surface-Wave Studies to Delineate a Buried High-Velocity Layer

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ABSTRACT

Procedures are tested and compared for processing Rayleigh surface wave data to obtain one-dimensional shear wave velocity profiles for a hypothetical site that contains a buried high-velocity layer (HVL). The main purpose of such an investigation would be to discriminate and characterize the HVL. When target dispersion curves are derived from synthetic time histories, for the most part, the HVL is better identified when profiles are inverted using only the fundamental mode of Rayleigh wave propagation, rather than a more compatible but more complex forward model. The outcomes imply that in practice, a simple forward model might be more successful in recovering a complex profile than a more sophisticated model because for the latter, adequate interpretation of the field data requires more accuracy than might be achievable with conventional approaches.

Introduction

Carbonate-cemented layers are commonly encountered in sediment profiles of Las Vegas, Nevada and other arid settings. Carbonate-cemented soils can be found throughout the Las Vegas Valley, with the most extensively cemented soils occurring in broad alluvial fans in the western and central portions of the Valley (Wyman *et al.*, 1993). Thickness of the deposits might range up to about 3 m (Wyman *et al.*, 1993). Knowledge of the presence, extent and hardness of carbonate-cemented horizons is valuable to civil engineers. A fully developed carbonate-cemented deposit is a favorable bearing stratum for structural foundations because it can have strength and stiffness similar to that of concrete (Stone and Luke, 2001). Yet the same deposit would also be an expensive nuisance for excavations, especially if it is encountered unexpectedly.

Surface wave methods use the dispersive behavior of the waves in layered media to characterize shear wave velocity (V_S) variations in the subsurface. With advances in equipment and data analysis techniques, the use of surface waves for determining V_S has attracted interest in research and engineering practice (*e.g.*, Foti and Butcher, 2004). Several methods for developing one-dimensional (1-D) V_S profiles from surface wave data are in use today (O'Neill, 2005). In the current study, two widely used active-source methods for developing V_S profiles from Rayleigh surface wave data are considered. The two-channel method, best known as

the Spectral-Analysis-of-Surface-Waves (SASW) method (Stokoe *et al.*, 1994), uses geophones in pairs and spectral evaluation of phase differences to generate an "effective" dispersion curve (DC), which comprises a superposition of all recorded wave energy, including all modes of surface waves and other wave types. The multi-channel method, best known as the Multi-Channel Analysis of Surface Waves (MASW) method (Park *et al.*, 1999), uses a multi-channel linear array. Frequency-slowness ($f-p$) processing is applied to generate a dispersion image in which body wave energy and different modes of surface waves can be distinguished. One or more modes of the surface-wave DCs serve as the target ("observed") data for inversion.

Despite the proliferation of surface wave studies for subsurface profiling, difficulties remain in characterizing velocity reversals (decreases in velocity with increasing depth), especially when the impedance contrast is high. An embedded high-velocity layer (HVL) will partition energy to higher modes, the complex response of which can cause misleading results when test data are processed using fundamental-mode analyses (Gucunski and Woods, 1991). To illustrate this situation, in a precursor to this work, Jin and Luke (2006) and Jin *et al.* (2006) applied standard, fundamental-mode models to process MASW and SASW data collected at a site known to have a shallowly-buried carbonate-cemented layer. Even though the theoretical DC could be fit closely to the experimental DC, the HVL was not resolved with either method.

Calderón-Macías and Luke (2007) showed that highly anomalous layers could be found with surface wave data, provided that adequate prior (independent) information was available. The authors inverted for a background model, overprinted by a HVL. This process resulted in a more credible profile than when the inversion was performed without the prior information. The prior information that is required to correctly solve the problem might be in the form of either a geologic log or complementary geophysical data, such as a refraction survey. Even with this prior information, the ability to resolve a HVL also depends on its depth, thickness and velocity contrast (e.g., Xia *et al.*, 2007; O'Neill and Matsuoka, 2005; Luke *et al.*, 2006).

In this paper we consider V_S profiling by surface waves for the main purpose of discriminating and characterizing a HVL. We consider two approaches. The first involves improving the forward model. An approach that accounts for combined effects of multiple Rayleigh wave modes as well as possible body wave reflections and refractions is more descriptive than one that accounts only for fundamental-mode wave propagation. This has been addressed for the SASW method by Foinquinos-Mera (1991), Stokoe *et al.* (1994), and Joh (1996); and for the MASW method by Forbriger (2003) and O'Neill (2003). The second approach involves incorporating higher modes into the inversion. For the multi-channel method, Xia *et al.* (2000a, 2003) and Beaty (2000) developed dispersion images containing the fundamental mode and up to two higher modes, and then inverted for all modes simultaneously, modeling plane wave propagation.

In this paper, a synthetic profile having a 1.5-m thick HVL buried 2-m deep is studied. Two sets of synthetic tests are conducted, using target ("observed") dispersion curves computed differently. One set of target DCs is generated using numerical computations in the frequency domain. Another set of target DCs is derived from synthetic time histories generated through finite difference simulation. The tests are summarized in Fig. 1.

For both the SASW and MASW methods, two forward modeling methods are tested in the optimization process. For the SASW method, one approach models cylindrical wave propagation resulting from a vertical disk load. Combined effects of surface and body wave energy are manifested in a so-called "effective" dispersion curve. Because the approach addresses amplitude spreading and transmission with depth as well as with horizontal (radial) offset, it is known as the "3-D solution." This solution was developed at the University of Texas at Austin by Foinquinos-Mera (1991) and Roësset and coded into the program "SASWFI." This is the code embedded in "WIN-SASW", a computer program that is often used to invert

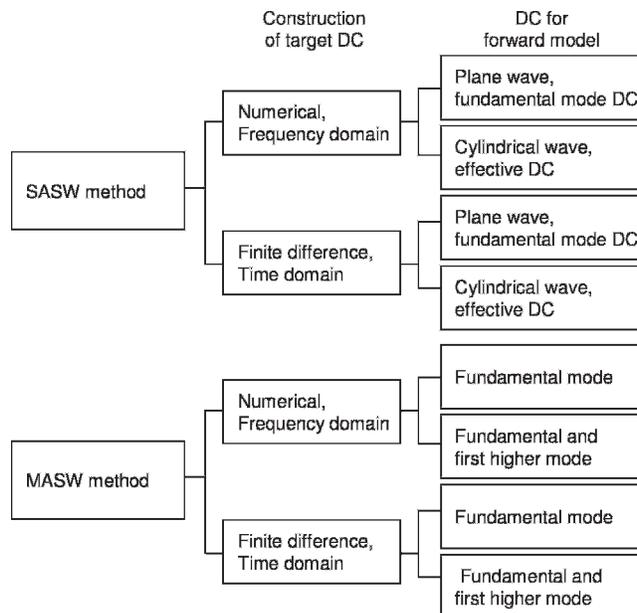


Figure 1. Summary of tests.

SASW data. The analyses presented here also test plane wave propagation of the fundamental mode. This solution is also incorporated in the SASWFI program.

For the MASW method, the analyses presented here consider multiple modes of surface wave propagation (fundamental plus first-higher), coded in the program "SWAMI" developed by Lai and Rix (1998). This code incorporates a reflectivity method that solves the homogeneous wave equation following procedures described by Hisada (1994). Outcomes of these analyses are compared to the case for strictly fundamental-mode wave propagation, also calculated using the SWAMI code.

Here, these various solutions are assessed and compared qualitatively, considering accuracy and reliability in resolving the profile overall and the HVL in particular. The purpose of the assessment is to identify potential pitfalls and shed light on best practices for processing surface wave data in the presence of a HVL. The intent of this work is not to judge the relative merits of the MASW and SASW methods; each has important advantages with respect to the other. For example, the MASW method is used today to efficiently develop two-dimensional (2-D) vertical slices of V_S (Xia *et al.*, 2000b), and the SASW method is being applied with sophisticated, energetic sources to develop detailed V_S profiles to great depths (e.g., Stokoe *et al.*, 2004; Rosenblad *et al.*, 2007).

Inversion Procedure

A data-driven algorithm introduced by Liu *et al.* (2002) is used to generate the V_S profile that forms the

Table 1. Target profile.

Layer number	Thickness (m)	Shear wave velocity V_S (m/s)	Compression wave velocity V_P (m/s)	Poisson's ratio ν	Density (kg/m ³)
1	2.0	200	370	0.30	1700
2 (HVL)	1.5	1500/1000*	2600/1732*	0.25	2200
3	4.0	400	1500/748*	0.46/0.30*	1700
Half-space		600	2200/1122*	0.46/0.30*	1700

*Second numbers are for the finite-difference simulation of the effective dispersion curve.

starting model used for optimization in this work. In this process, several profiles are tested, each having different layer geometries that are obtained using a family of exponential functions. The DC is calculated for each profile, and compared to the target curve using the data difference (DD). The DD is defined as the root-square sum of the squared difference between dispersion datasets. Generally, the profile having the lowest DD is selected as the starting model (Luke and Calderón-Macías, 2007).

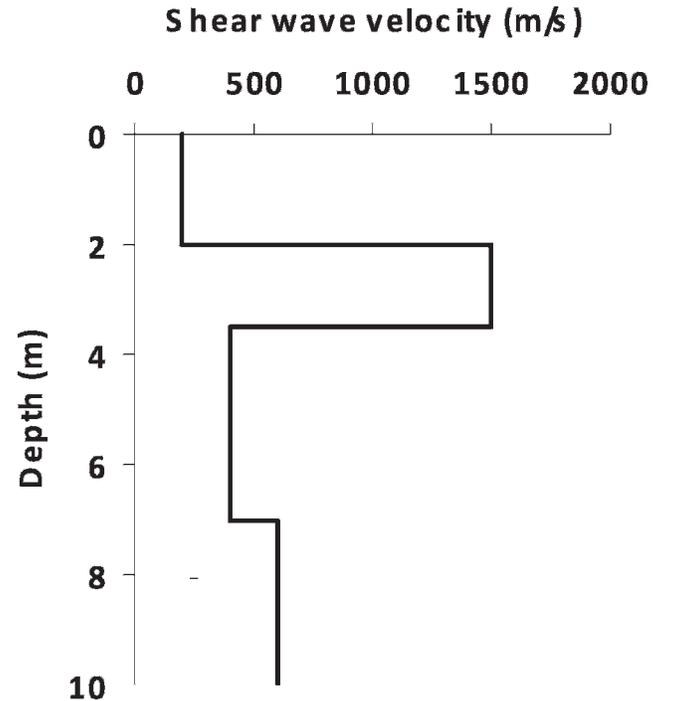
The inversion method used applies the global-minimum search method simulated annealing (SA) followed by linearized inversion (LI) (Calderón-Macías and Luke, 2007; Luke and Calderón-Macías, 2007). The SA method permits “uphill” moves in error space, which means that the DD is permitted to increase between iterations under the control of a probabilistic criterion. The intent is to prevent the solution from becoming trapped at a local minimum in the error space. The optimization framework is configured to guide the solution within expected ranges based upon independent knowledge of the site. The SA search incorporates a background profile overprinted with one or more HVLs. The layer geometry of the background profile remains fixed as in the starting model and the V_S of the layers is allowed to vary. Search parameters for the HVL are depth, thickness and V_S . In practice, the search ranges for each are set using all independent information available. The LI algorithm used is a linearized least-squares minimization process (*e.g.*, Xia *et al.*, 1999).

Because SA has a stochastic component, multiple optimizations using the same input parameters will yield different outcomes. It would be desirable to conduct a statistically-significant number of iterations and average the results (Luke *et al.*, 2006). However, this process would be very inefficient. For the studies in this paper, three runs of SA-LI, with identical parameters and search ranges, are performed for each inversion. In practice, a velocity-averaged version of several SA-LI solutions might be considered as the final inverted V_S profile, and the outer bounds of the solutions used as credible ranges (Luke and Calderón-Macías, 2007).

Target Profile and Dispersion Curves, Model Parameters

The target profile for this study, presented in Table 1 and Fig. 2, is derived from conditions that might be encountered in Las Vegas. The profile comprises three layers over a half-space. The second layer is the HVL; it represents a cemented layer. Its top is at 2-m depth and its thickness is 1.5 m. Assignments for its V_S , density and Poisson's ratio (Table 1) are based on laboratory tests (Stone and Luke, 2001) and a downhole measurement (Teclé *et al.*, 2003). The water table is set at 3.5-m depth, at the bottom of the HVL.

A set of target DCs is calculated directly using the layer parameters listed in Table 1 and the codes already introduced. Shown in Fig. 3, the set includes the effective Rayleigh wave DC from the SASWFI code, the fundamental-mode Rayleigh wave solution from the

**Figure 2.** Target profile.

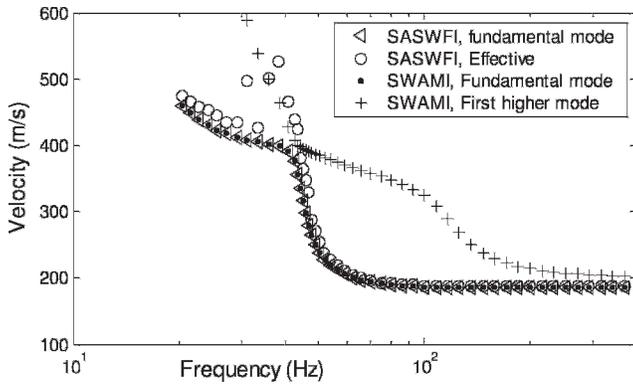


Figure 3. Target dispersion curves calculated numerically.

SASWFI and SWAMI codes, and the fundamental- and first-higher-mode Rayleigh wave solutions from the SWAMI code. The two solutions for the fundamental-mode Rayleigh wave are indistinguishable. The fundamental- and first-higher-mode DCs nearly intersect at 41 Hz. The location of this near-intersection has been termed an “osculation point” (Forbriger, 2003). In a composite dispersion curve, it is indicative of a transition to higher modes due to a large velocity contrast or reversal (e.g., O’Neill, 2003). The velocity difference between the effective DC and the fundamental mode is negligible at high frequencies. However, the effective DC has notably higher velocities within a narrow frequency band at and below the osculation point, 30 to 45 Hz. Here, the effective DC displays a kink and significant scatter. This band is diagnostic of the presence and location of the HVL (Jin and Luke, 2007). Note that the frequency band corresponding to the kink occurs over the wavelength range 9 to 15 m. If the effective sampling depth is assumed equal to one-third of the wavelength (Stokoe and Nazarian, 1983), the depth range associated with the jump in the curve is 3 to 5 m. This approximation overestimates the depth and thickness of the HVL, which appears from 2- to 3.5-m depths. Use of a multiplier for depth of one-fourth, instead of one-third, places the HVL at 2.25 to 3.75 m. This revised approximation correctly estimates thickness and errs by only 0.25 m in depth.

As stated above, the search ranges permitted in SA would be set using prior information of the site. For the tests described here, the search range for the HVL is as follows: depth, 1 to 5 m; thickness, 0 to 2 m; V_S , 1,000 to 2,000 m/s; and probability of encountering a HVL, 80%. The probability of encountering the HVL, which relates to the reliability of the independent information (Huynh *et al.*, 2003), is addressed by incorporating a factor that permits a controlled number of solutions that lack the overprinted HVL. The V_S for each layer in the background profile is permitted to range from one half to twice the V_S of the starting model. In the inversion of

multiple-mode DCs, fundamental- and first-higher modes are weighted at 0.75 and 0.25 respectively, reflecting increased uncertainty in accurately picking higher modes (e.g., Beaty *et al.*, 2002). The densities and Poisson’s ratios for all layers are fixed at the true values.

Inversion of Target Dispersion Curves

In this study, the various DCs representing the target profile, including those computed numerically and those derived from synthetic time histories, are inverted using both SASW and MASW methods. For each case tested, results are presented in the form of comparisons between estimated and target DCs, and between inverted and target V_S profiles.

Inversion of DCs Computed Numerically

This section addresses inversion of target DCs computed directly from the SASWFI and SWAMI codes. For the SASW method, the target data are inverted using the (a) cylindrical wave (three-dimensional (3-D)) solution; and (b) fundamental-mode plane wave solution. For the MASW method, inversion is conducted using (a) fundamental- and first-higher mode, jointly; and (b) fundamental mode alone.

SASW method. For the SASW method, the effective DC is considered as target. Results when the same 3-D solution used to generate the target DC is also employed for forward modeling in the inversion are shown in Fig. 4. Overall there is a good fit between the computed DCs and target DC, which is challenging considering the fluctuations in the target DC. One of the three runs has a poor fit at high frequencies. All runs yield a solution that includes a HVL. All inverted V_S profiles match reasonably well with the background of the target profile, but the depths, thicknesses, and V_S of the HVL are different. The run having the poor DC fit at high frequencies had the poorest V_S fit overall.

When the same target DC is fit using the fundamental-mode dispersion curve from the SASWFI code, results are significantly poorer (Fig. 5). Fits between the estimated and target DC are poorer, particularly below 40 Hz. One run correctly identified the depth and thickness of the HVL but overestimated its velocity by 43%. The other two runs failed to match the target DC at high frequencies. These runs yielded unacceptably poor V_S profiles overall and neither identified the HVL.

MASW method. For the MASW method, the multi-mode data are considered as target. Results when both modes are considered in the inversion, using the same code and algorithm used to generate the target DC, are shown in Fig. 6. The accuracy of results is very good.

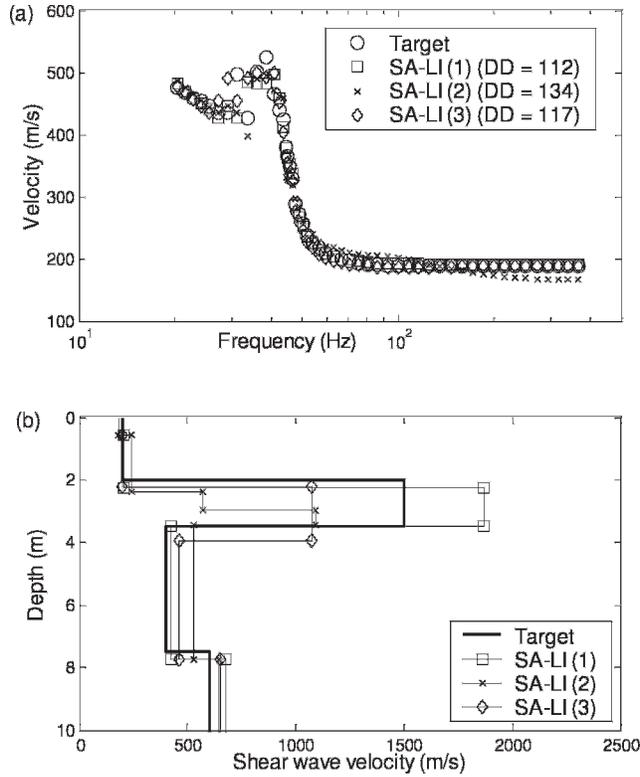


Figure 4. Numerical computation procedure, SASW method, inversion with 3-D solution: (a) dispersion curves, and (b) shear wave velocity profiles.

The DC fit is near-perfect for all three runs. The depth and thickness of the HVL are closely captured, within 5% in two of the runs and 20% in the third.

When the same target data are estimated using the fundamental mode alone (Fig. 7), results are poorer. One theoretical DC has a near-perfect fit and yields an inverted V_S profile having a reasonable match to the target. The HVL is well-resolved, but resolution of layers below the HVL is only fair. For the other two runs, the DC fit is poor and the HVL is not recognized.

Summary for inversion of DCs computed numerically.

Tests run on DCs computed using the same numerical processes that are incorporated in the inversion process yield expected outcomes. For the SASW method, results are improved by enhancing the forward model. Predictably, the 3-D solution yielded a better result than the fundamental-mode solution, due to model compatibility. For the MASW method, results are improved by inverting for multiple modes. Of the four cases studied, the MASW method with the multiple-mode solution yielded the best results.

Inversion of DCs Derived from Synthetic Time Histories

To increase realism, new target DCs were developed through extraction from synthetic seismograms,

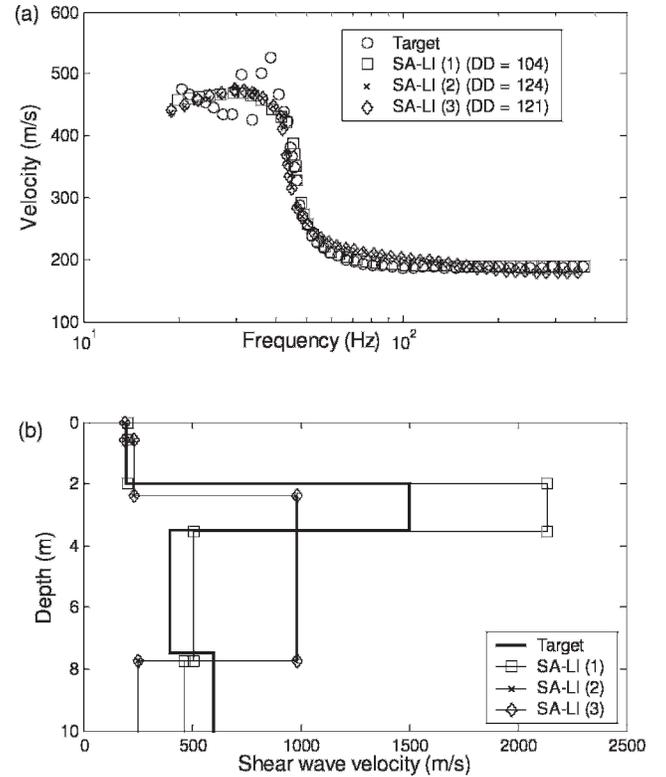


Figure 5. Numerical computation procedure, SASW method, inversion for fundamental mode: (a) dispersion curves, and (b) shear wave velocity profiles.

which were computed by finite difference (FD) analysis. The same modeling and inversion procedures described in the preceding section were applied to the interpreted DCs.

Computational models and parameters. For the FD computations, the computer program E3D (described by Larsen and Schultz, 1995) was used. The model is elastic. A free-surface condition is applied at the top boundary and Clayton and Engquist boundary conditions (Larsen and Schultz, 1995) are invoked to absorb wave energy. To simulate the MASW method, a 2-D model is used. To simulate the SASW method, a 3-D model is used. Special modifications were required for the 3-D simulations. First, the high Poisson's ratio of the saturated sediments (Table 1) violated the stability conditions of the program. Therefore, the target profile was modified to remove the water table. Second, the V_S of the HVL was decreased from 1,500 to 1,000 m/s. This was done to save computation time and to satisfy the Courant condition, which is needed to ensure the stability of the solution and which is stricter for 3-D models than for 2-D models (Larsen and Schultz, 1995). The modifications to the profile for the 3-D computations are documented in Table 1. Other parameters

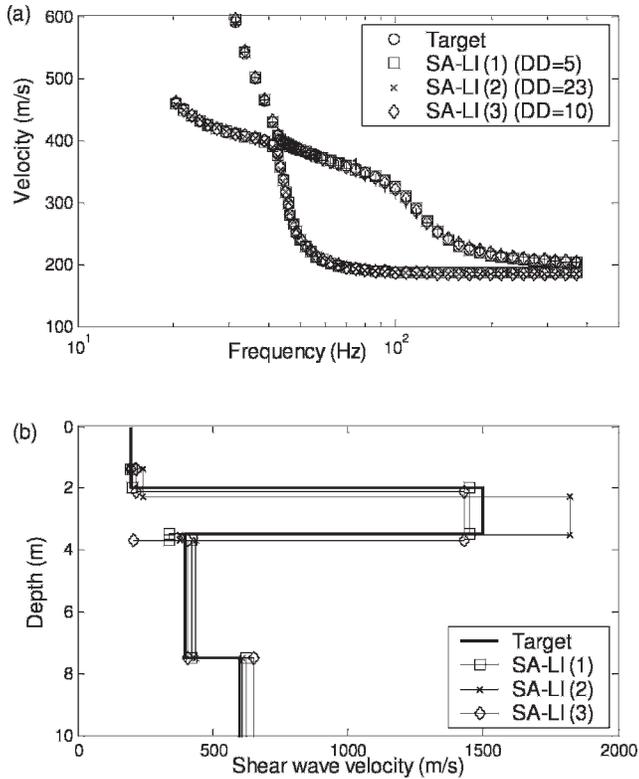


Figure 6. Numerical computation procedure, MASW method, inversion for first two modes: (a) dispersion curves and (b) shear wave velocity profiles.

needed to define the profile, which include grid dimension, grid spacing and time step, are provided in Table 2. The dispersion curves are extracted through frequency-phase velocity transformations (Jin, 2006).

SASW method. An SASW measurement is normally performed with different receiver spacings. Here, four spacings are simulated: 2, 4, 8 and 16 m. For spacings 2, 4 and 8 m, a Ricker wavelet (*e.g.*, Sheriff, 2002) with central frequency of 100 Hz is applied as a vertical point force at the center of the grid surface. For the 16 m spacing, a central frequency of 10 Hz is used. From the authors' experience, these central frequencies are reasonable values for the field experiment configuration. Following procedures traditionally used for processing SASW data (Stokoe *et al.*, 1994; Rix, 1988), the effective dispersion curve for each receiver spacing is computed from phase differences between receiver pairs as functions of frequency. Figure 8 shows the contribution of each test spacing to the composite DC. The target DC is a condensed version of the composite, developed by computing average velocities for bins that are equally spaced on a scale that is logarithmic with respect to wavelength. Unfortunately, coverage in the frequency band where the fluctuations caused by the HVL are

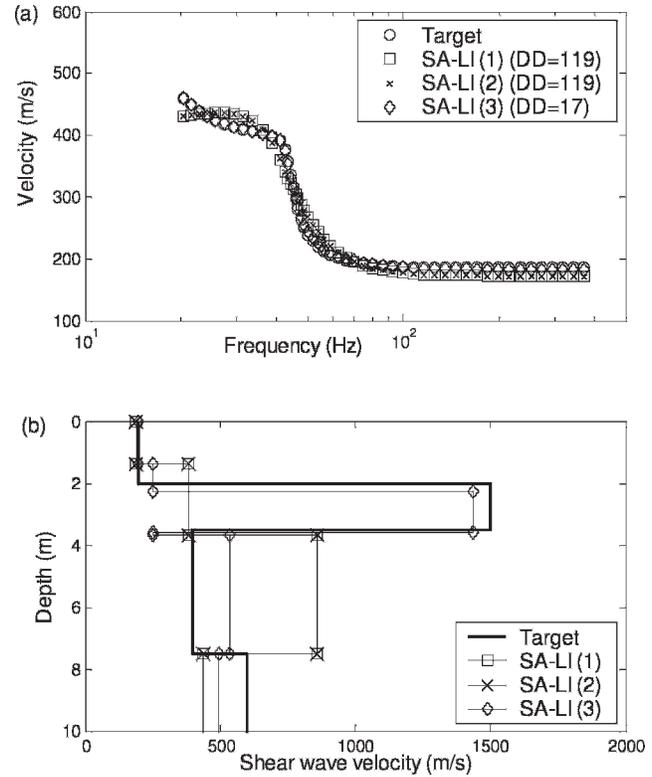


Figure 7. Numerical computation procedure, MASW method, inversion for fundamental mode only: (a) dispersion curves and (b) shear wave velocity profiles.

most significant is sparse. This is not unrealistic; with the SASW method, data density normally decreases as frequency decreases.

In Fig. 9, the DC obtained from simulated seismograms is compared to the effective and fundamental-mode DCs obtained from the numerical computation procedure. Note that the DCs are not identically spaced in frequency; this is because the SASWFI code computes the DC by wavelength instead. The DCs are not expected to be identical because of the differences in the target profiles. Despite those differences, the DC from the simulated seismograms agrees closely with the effective dispersion curve from the numerical computation procedure.

Table 2. Discretization for finite difference models.

Test approach	Grid dimension	Grid spacing	Time step
SASW	150 m \times 150 m (lateral) \times 50 m (vertical)	0.25 m	0.05 ms
MASW	150 m (lateral) \times 50 m (vertical)	0.125 m	0.025 ms

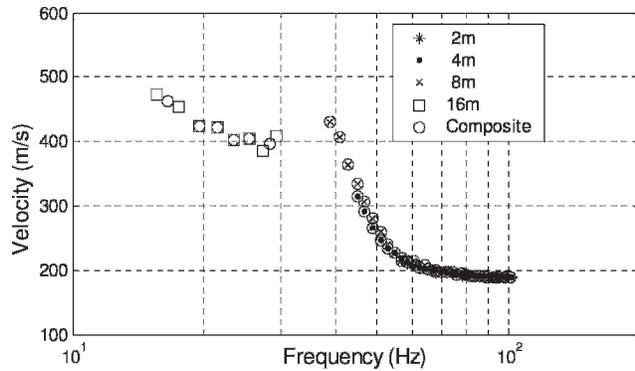


Figure 8. Finite difference simulation procedure, SASW method: illustrating construction of composite effective dispersion curve.

Results of inversion using the effective DC as the forward model are shown in Fig. 10. All DC fits are good. The V_S profiles fit the background of the target reasonably well. The fit for the top layer of the profile is near-perfect. However, none of the runs properly resolve the HVL. If the primary goal of the investigation had been to discern the presence of a HVL, the observer would likely conclude that it did not exist.

Results of inversion using the fundamental mode from the SASWFI code are shown in Fig. 11. Again, the DC fits are good. As for the previous case, the fit for the top layer of the profile is near-perfect. All three runs successfully identify the HVL. The depth to the top of the HVL is near-perfect, while the thickness and V_S are overestimated by averages of 41 and 29%, respectively. The layers below the HVL are less well resolved than when the effective DC was used as the forward model. These findings can be compared to a study by Luke *et al.* (2006) in which a statistically significant number of inversions were performed using SA for a synthetic profile containing a shallowly buried HVL. In both studies, the depth to top of the HVL was well resolved, the V_S was overestimated, and the HVL and layers just beneath it had the poorest resolution. However, in the

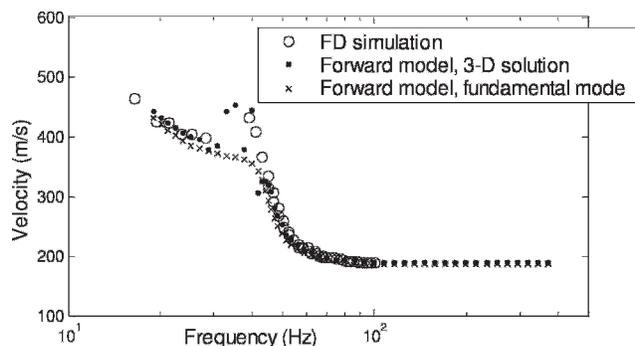


Figure 9. Effective dispersion curve: comparing finite difference simulation to numerical computation solutions.

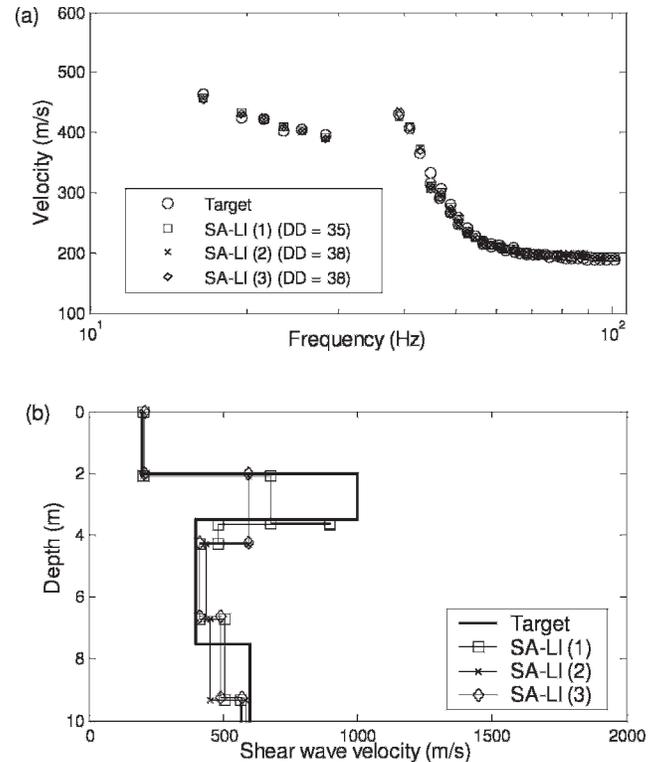


Figure 10. Finite difference simulation procedure, SASW method, inversion with 3-D solution: (a) dispersion curves and (b) shear wave velocity profiles.

previous study, the thickness of the HVL was consistently underpredicted, not overpredicted. This contradictory finding warrants further parametric study.

Even though the forward model that produces an effective DC is the more technically appropriate choice for a SASW-type measurement, inversion using the fundamental mode was more successful in detecting the HVL. One contributing factor is illustrated in Fig. 12, where the three DCs of Fig. 9 are plotted against the fundamental-mode DC from the SASWFI code for a background profile lacking the HVL. In this latest analysis, the material properties for the depth range that would otherwise have contained the HVL are set equal to those of the layer below. The three DCs for the profile containing the HVL, including the fundamental-mode solution, differ from the DC for the background profile below 50 Hz. Clearly, the shape of the fundamental-mode DC carries the imprint of the HVL. This enables resolution of the HVL using a forward model that addresses only the fundamental mode.

Considering the more technically correct approach (effective DC as forward model), we suspect that the shortcomings of the inversion are caused by inadequate resolution in the vicinity of the kink. Particularly because the data are sparse in this critical portion of the dispersion curve, the influence of the HVL is not

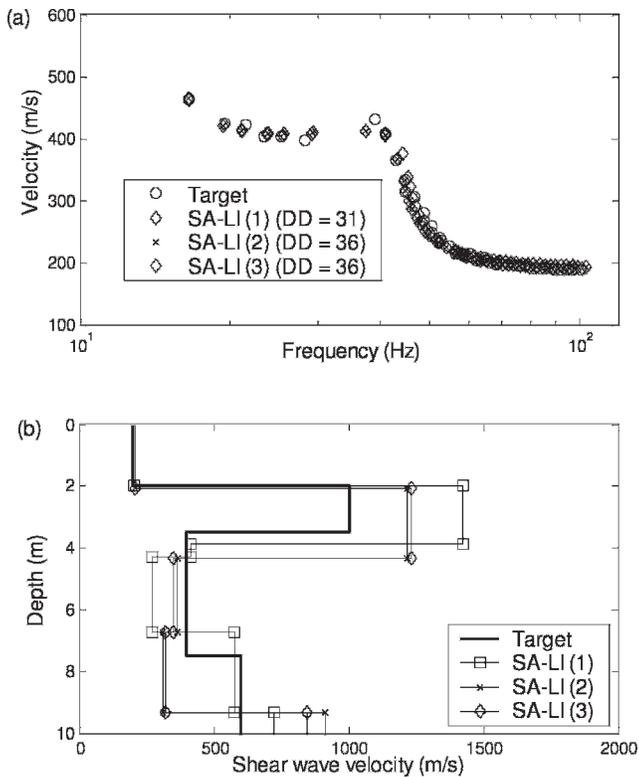


Figure 11. Finite difference simulation procedure, SASW method, inversion for fundamental mode: (a) dispersion curves and (b) shear wave velocity profiles.

sufficient to distinguish the effective DC from the fundamental-mode DC. The implications of this data gap for testing and data processing warrant further study.

MASW method. To simulate a MASW test, time histories were computed for 81 receivers at 0.5-m spacing (Fig. 13). The source pulse consisted of two superimposed Ricker wavelets with central frequencies

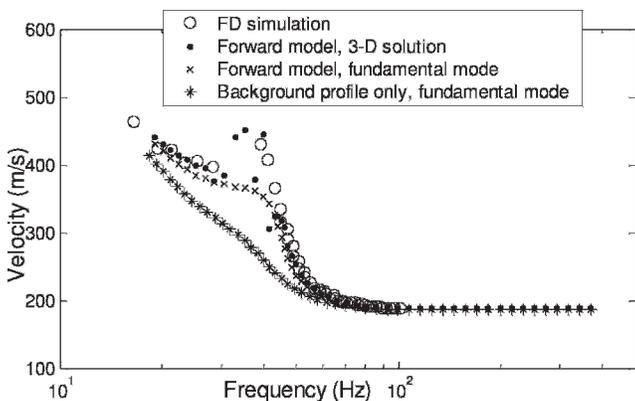


Figure 12. Comparison of dispersion curves with case lacking a high-velocity layer.

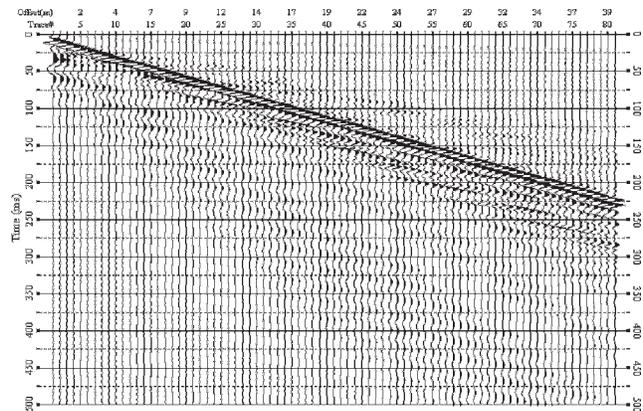


Figure 13. Finite difference simulation procedure, MASW method, time histories.

of 25 and 100 Hz, applied in the downward direction at the center of the grid surface. To generate the dispersion image, an f - p transform is applied (Sacchi and Ulrych, 1995). Figure 14 shows the p - τ (slowness-time) and f - p images. Fundamental and higher modes can be distinguished in the f - p image.

The DC is picked manually (Fig. 15(a)). Judgment developed through experience and knowledge is required to correctly pick the DC. The fundamental mode loses resolution below 40 Hz. The first higher mode loses resolution below 80 Hz. The f - p image is superimposed with the dispersion curve obtained from the numerical computation procedure in Fig. 15(b). The numerical solution matches well with the f - p image. As observed previously, the solutions for the first two modes nearly cross at 40 Hz. The fundamental-mode portion of the DC below 40 Hz would be nearly impossible to discern from the f - p image alone.

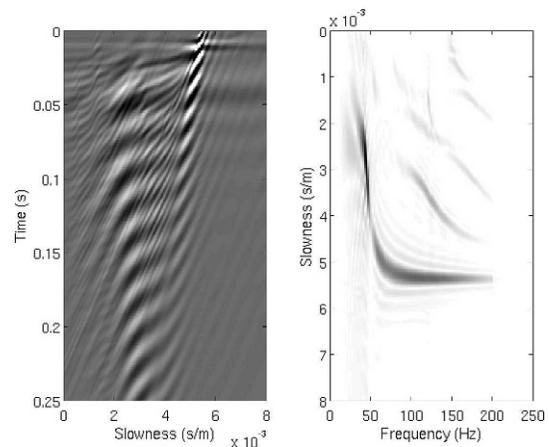


Figure 14. Finite difference simulation procedure, MASW method: (a) p - τ and (b) f - p images for the target profile.

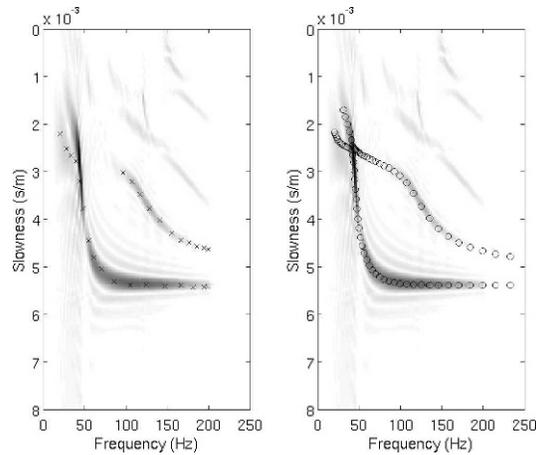


Figure 15. Finite difference simulation procedure, MASW method, f - p images superposed with (a) manual picks of the first two modes and (b) solution from the numerical computation.

Difficulties in correctly identifying modes in DC images have been reported previously. O’Neill and Matsuoka (2005) illustrated a case similar to the one shown here, where the dispersion curve that a user would logically pick as the fundamental mode actually transitions smoothly to the first higher mode at low frequencies. Wathelet (2005) observed that misidentification of modes in interpreting dispersion curves “introduces bias” in the results. For profiles including a low velocity layer, the author concluded that incorporation of prior information was key to correct interpretation of the profile from the dispersion curve. Zhang and Chan (2003) used a synthetic dataset to demonstrate that incorrect or inaccurate DC identification has a dramatic influence and usually produces misleading results. Dal Moro *et al.* (2006) used numerical simulation to demonstrate that reflection events and their multiples could be misinterpreted as higher-mode DCs. They suggest using synthetic data analysis to guide interpretation of experimental data. O’Neill (2003) demonstrated the use of full-wavefield inversion to reduce dependency on accurate mode identifications. Other potential solutions appear in recent work by Park and Rydén (2007) and Neduzca (2007). These authors recommend enhancing resolution of the f - p images by discriminating offsets and frequencies. This approach is used successfully in SASW data processing (Stokoe *et al.*, 1994).

The manual DC picks were interpolated using a cubic spline to increase the number of points and to smooth the curve. The manually-picked DC and its spline fit are shown in Fig. 16, along with the DC from the numerical computation procedure. Comparing the DC derived from simulated seismograms to the DC computed numerically, the fundamental mode has lower

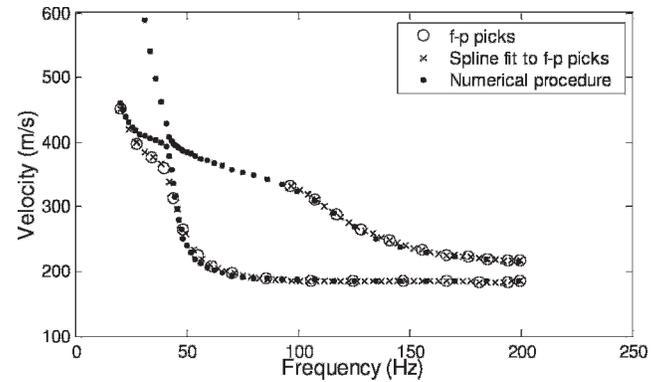


Figure 16. Comparing dispersion curve picked from f - p image to that computed numerically.

velocities in the 30 to 40 Hz range, and the first-higher mode is not resolved at high frequencies. These differences result from challenges in resolving and interpreting the f - p image.

Results of inversion for both modes, using the spline fit as the target DC, are shown in Fig. 17. The DC fits are good, and all three runs identified a HVL. However, the results are much poorer than the excellent outcomes from the numerical computation approach (Fig. 6); the DC fits are poorer and neither the HVL nor the background profiles are as well resolved. This

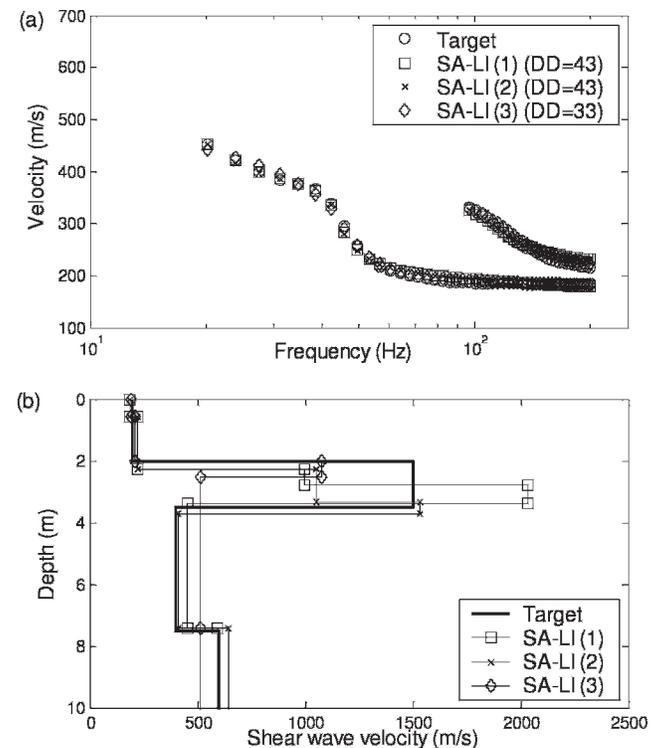


Figure 17. Finite difference simulation procedure, MASW method, inversion for first two modes: (a) dispersion curves and (b) shear wave velocity profiles.

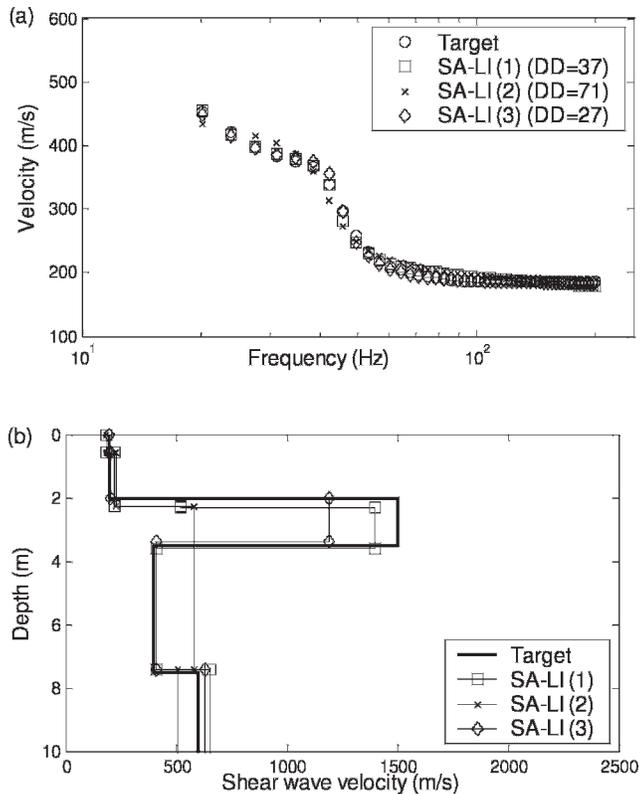


Figure 18. Finite difference simulation procedure, MASW method, inversion for fundamental mode alone: (a) dispersion curves and (b) shear wave velocity profiles.

reduction of quality in outcomes can be attributed to the difficulties noted above in picking the DC accurately and completely from the f - p image.

Results of inversion for the fundamental mode alone are shown in Fig. 18. The DC fits are good. Two runs resolved the entire profile quite well. The other, which had the poorest DC match of the three, did not identify the HVL. Counter-intuitively, the DC fits and V_S profiles for this analysis are improved with respect to the corresponding analysis using the numerical computation procedure for fundamental mode alone (Fig. 7).

Summary for inversion of DCs from synthetic seismograms. Tests run on DCs derived from synthetic time histories yield outcomes that are counter to expectations. For the SASW method, results from inversion using the fundamental-mode solution are better than those employing the more technically correct 3-D solution. For the MASW method, the DC proved challenging to pick from the f - p image. Results are not improved by inverting for two modes as opposed to one. Considering all four tests, the best results would derive from the MASW method, inverting for fundamental mode alone, providing that the outcomes having better fits to the target dispersion curve are favored.

Discussion

The outcomes from all tests are summarized in Table 3. As expected, the best results from the simulations that incorporated synthetic seismograms were not as good as the best results from the numerical computation procedure. When the most straightforward processes are tested (target DC computed numerically), results are as expected; improving the forward model and inverting for multiple modes improves outcomes. However, when the target dispersion curves are developed from synthetic seismograms, the simpler forward models yield better inversion results.

Reasons for the counter-intuitive results from the tests using synthetic seismograms might be as follows. For the SASW method, the HVL induces sharp fluctuations for a few points in the curve, which are not resolved well through inversion. The fundamental-mode solution for the same profile is smoother and therefore it is less influenced by the scatter caused by the HVL, yet this solution still reflects the imprint of the HVL (Fig. 12). For the MASW method, the higher mode could be picked from the f - p image only for high frequencies; this additional data did not appear to contain significant independent information about the target profile. This observation reinforces the research of Wathelet (2005), who found that in the frequency range where the higher modes are most likely to be observed, they contain redundant information. Further study of the nature and extent of the contribution of the higher modes to resolution of the V_S profile is warranted.

Our analytical tests using synthetic seismograms indicate that for a complex profile, more sophisticated forward models might not yield improved results. A true experimental DC from a site containing a HVL will include complex responses caused not only by the HVL but also by noise sources, which were not simulated in these tests. These further complications reinforce the hypothesis that the simpler forward models might be more successful in resolving complex profiles in practice.

Our analytical tests using synthetic seismograms did not indicate that one method, MASW or SASW, was better suited than the other for characterizing the target profile.

Conclusions

The main purpose of the research is to evaluate surface-wave methods in common use today for V_S profiling at a complex site. The most important anticipated outcome of the survey is discrimination of an HVL. Two surface wave data processing methods,

Table 3. The eight cases studied and their outcomes.

Procedure to develop target DCs	Numerical computation		FD simulation (synthetic seismograms)	
Test method	SASW	MASW	SASW	MASW
Approach to generate target DC	SASWFI, cylindrical wave	SASWFI, plane wave	Spectral computations of phase difference between receiver pairs, from synthetic time histories	Picked from f - p image, fundamental mode only
Modeling approach for inversion	Cylindrical wave (SASWFI)	Fundamental mode (SWAMI)	Cylindrical wave (SASWFI)	Fundamental mode (SWAMI)
Figure number	5	7	10	17
Outcome: DC fit	Reasonably good, especially at the kink	Near-perfect	Good	Good, variable
Outcome: V_s profile, with emphasis on resolution of HVL	Good overall. HVL resolution is fair.	One run places HVL correctly, but overestimates V_s . Two runs fail to resolve the HVL and have poor fit overall.	One run resolves HVL not resolved, but background profile good. Lowest layers not resolved well.	All runs match HVL depth, but thickness and V_s are overestimated. Background profile good.
				An HVL is resolved by all runs, but resolution is low. Background profile very well, one does not.

SASW and MASW, were tested synthetically for a one-dimensional synthetic profile containing a 1.5-m thick high velocity inclusion buried 2-m deep. This profile yields an irregular dispersion curve that is challenging to interpret. Two processes were used to generate target dispersion curves: a numerical computation procedure and a procedure involving generation of synthetic seismograms through finite difference analysis. Shear wave velocity profiles were developed through inversion by simulated annealing followed by linearized inversion. The forward models used had different degrees of complexity. For the SASW method, the more technically correct “effective” dispersion curve was compared to the fundamental-mode solution; for the MASW method, the effect of inverting for a second surface-wave mode was investigated. Overall, eight cases were considered.

When the more straightforward numerical computation procedure was followed to generate the target dispersion curves, results were as expected; using more technically correct and more detailed models yielded the best results. However, when the dispersion curves were derived from synthetic seismograms, inversion using the simpler forward model (fundamental mode only) was more successful at identifying the HVL.

Considering the test based on synthetic seismograms, for the SASW method, the improved outcomes encountered with inversion using the fundamental mode might be attributed to the facts that this approach ignores the complexities of scattering, and basic characteristics of the complex system are retained even in a smoothed, composite DC. The case studied suggests that the fundamental mode can be used successfully to invert SASW data for a complex profile when it is applied in the context of a well-informed search parameterization. For the cases studied, depth to the anomalously high-velocity layer was resolved reliably, whereas the velocity and thickness of that layer were consistently overestimated.

Considering the MASW method, the reduction in resolution with the test incorporating synthetic seismograms compared to the direct numerical computations is attributed to difficulty in picking dispersion curves. For the seismogram-based test, incorporation of the first higher mode did not improve results, perhaps because the higher mode could be resolved only for high frequencies. In this range, the higher mode may contribute little new information to the resolution of the V_S profile.

Implications of this study for real-world testing are that the simpler forward models tested might yield adequate and potentially more satisfactory results than their more complex counterparts in the presence of complex site conditions.

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