2009

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Repository Citation

Casto, D. W., Luke, B., Calderon-Macias, C., Kaufmann, R. (2009). Interpreting Surface-Wave Data for a Site with Shallow Bedrock. *Journal of Environmental and Engineering Geophysics*, 14(3), 115-127.
<http://dx.doi.org/10.2113/JEEG14.3.116>

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Interpreting Surface-wave Data for a Site with Shallow Bedrock

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ABSTRACT

The inversion of dispersive Rayleigh-wave data has been shown to be successful in providing reliable estimated shear-wave velocities within unconsolidated materials in the near surface. However, in a case where the multi-channel analysis of surface waves method was applied to a site consisting of clay residuum overlying basalt bedrock, inversion for the fundamental-mode Rayleigh wave resulted in shear-wave velocities within the rock that are less than half of expected values. Forward modeling reveals that the fundamental-mode dispersion curve is hardly sensitive to bedrock velocity perturbations over a practical range of wavelengths, leading to poorly constrained solutions. Standard surface-wave methods can fail because of a shortage of phase-velocity estimates at the low frequencies that are necessary to properly constrain shear-wave velocities at depth. The commonly used guideline that maximum investigation depth is roughly half of the largest recorded wavelength can be misleading. Data at much lower frequencies (*i.e.*, longer wavelengths) than typically acquired might be required to obtain a meaningful shear-wave velocity profile, particularly for a site with a high-velocity half-space beneath a low-velocity layer. For such cases, layer geometry appears to have a large impact on inversion results. Consequently, Rayleigh-wave methods can be effective in determining depth to bedrock in simple, layered geologies (*e.g.*, soft sediment over hard bedrock) when independent information of shear-wave velocity is available. Analysis techniques that address higher modes of Rayleigh-wave propagation may be useful for more accurately resolving depth and velocity of a high-velocity half-space. In the studied case, higher modes can theoretically reach the asymptotic high-velocity limits within the range of recorded frequencies.

Introduction

The inversion of dispersive Rayleigh-type surface-wave data has been shown to be successful in providing reliable estimated shear-wave velocity profiles for use in geotechnical investigations (*e.g.*, Stokoe *et al.*, 1994). Two methodologies that are used to provide shallow shear-wave velocity profiles are the spectral analysis of surface waves (SASW; Stokoe *et al.*, 1994) and the multi-channel analysis of surface waves (MASW; Song *et al.*, 1989; Miller *et al.*, 1999). In both cases, subsurface shear-wave velocity profiles are estimated through an inversion approach, such as least-squares minimization, to match simulated dispersion curves to dispersion curves extracted from the recorded seismic data. The surface-wave data presented here have been collected and processed using MASW methods.

The MASW method allows for rapid reconnaissance surveying over large areas. Typically with this method, a series of closely spaced one dimensional (1-D) shear-wave velocity profiles are created from data collected along survey lines and then contoured to provide a “2-D” cross-section of shear-wave velocity. The depth of investigation is largely a function of the geophone array length, source-receiver offset, and source and receiver characteristics. MASW data acquisition utilizes a fixed receiver array and an impact source (for active-source surveys). A multi-channel system with an active seismic source (*e.g.*, sledgehammer or accelerated weight drop) can typically be used to create shear-wave velocity profiles for the uppermost 30 m. A multi-channel coherency measure applied in the frequency domain is used to calculate the amplitude spectra of phase velocity with frequency from which a Rayleigh-

wave dispersion curve is extracted (Park *et al.*, 1998). An advantage of the MASW approach is the separation of Rayleigh-wave energy from other wave types (*e.g.*, body waves, backscattered waves and ambient noise).

For unconsolidated materials, numerous case studies have shown that shear-wave velocities derived from surface-wave data correlate well with velocities obtained using other methods (*e.g.*, cross-hole seismic and seismic cone penetrometer measurements). For example, in a comparison of MASW measurements and borehole measurements in unconsolidated materials, Xia *et al.* (2002) showed that MASW velocity models agree to within 15% of values derived from borehole measurements. To date, however, there has not been much published research evaluating surface-wave modeled velocities of hard rock buried beneath unconsolidated sediments.

The MASW method has been used for evaluating depth to bedrock and locating anomalous bedrock conditions (Miller *et al.*, 1999; Ivanov, *et al.*, 2006). Topographic variations and discontinuities in the top-of-rock and/or within bedrock (*e.g.*, fault zones, fractures, weathered zones, voids, etc.) can be of great geotechnical concern. In many cases, the authors have observed an increased shear-wave velocity gradient with depth at the interface between the overburden (*e.g.*, soils, sediments and highly-weathered bedrock) and indurated bedrock. This higher gradient is usually a good indicator of the top-of-rock, as has been confirmed by boring information. However, the shear-wave velocities derived for the bedrock are often much lower than expected values.

The field data example discussed here illustrates underestimated shear-wave velocities derived from a MASW survey conducted at a site consisting of clay residuum over hard bedrock. The aim of this article is to highlight some of the complexities of developing shear-wave velocity profiles from surface-wave data, collected and processed using industry-standard techniques, that arise for sites with shallow bedrock. Most importantly, it reveals the problem of having insufficient low-frequency phase-velocity estimates to determine shear-wave velocities at depth. This study can serve as a reference to application geophysicists, as the lack of low-frequency data can be quite common in practice. This article expands upon a recent conference paper (Casto *et al.*, 2008) by incorporating additional numerical studies that better illustrate and explain our observations.

Inversion Method

The surface-wave data were collected using MASW field methods. Subsequent Rayleigh-wave dispersion curve extraction and shear-wave velocity inver-

sion were carried out using SurfSeis software (Kansas Geological Survey, 2006). An image of the amplitude spectra, referred to as an “overtone image”, is used to extract the dispersion curve of the fundamental-mode Rayleigh wave. The overtone image allows one to distinguish the fundamental-mode Rayleigh wave from other energy, such as higher-mode surface waves, body waves, backscattered waves, etc. The fundamental-mode dispersion curve that is manually picked from the image is run through an inversion to derive a shear-wave velocity profile. The inversion uses an iterative process known as the Levenberg-Marquardt least-squares algorithm (Xia *et al.*, 1999), which requires Poisson’s ratio, density and layer geometry to be fixed a priori. An appropriate initial earth model must be specified as a starting point for the iterative inversion process. Among body wave velocities, density, and layer thickness, shear-wave velocity is the parameter that has the most significant effect on the inversion result (Xia *et al.*, 1999). As a result, it is typical in practice to use a multi-layer model with fixed layer thicknesses and densities (generally within 25% of true values) and solve for shear-wave velocity. Initial shear-wave velocities are automatically calculated in SurfSeis on the basis of the fundamental-mode dispersion curve that the user has picked.

Field Data Case

Site Geology and Geophysical Data

The data set examined comes from a seismic survey conducted in the southern Panama Canal region, Pacific Ocean side. Several survey line-kilometers of MASW and seismic refraction data were acquired. The general geology in this region is composed of Miocene-age sedimentary and volcanic rocks covered by residuum overburden. The geology can be quite complex and the area is considered to be tectonically active. Late Miocene basalts are present and occur as sills, dikes, plugs, and flows with a hard, fine to medium-grained texture.

The MASW acquisition layout consisted of a Geometrics StrataVisor NZ seismograph and twenty-four 4.5-Hz geophones mounted in a landstreamer configuration. The geophones were spaced at 1.5-m increments for a total array length of 34.5 m. An elastic weight drop (EWD) was used as the source of seismic energy, and consisted of an 80-lb weight that was accelerated into the ground with a large elastic band. An optimal minimum source-receiver offset of 6 m was determined from a series of walkaway tests performed prior to the survey. This offset provided the best defined dispersion curve over the largest range of frequencies at the test location. The landstreamer was pulled along a

Figure 1. Shear-wave velocity model derived from the MASW survey (top) and P-wave velocity model derived along the same survey line using seismic refraction tomography (bottom). The surface wave data presented in this paper come from a single shot-gather located near boring TP1C-33. The P-wave model reveals general trends in the depth to top-of-rock (basalt).

survey line with a vehicle while maintaining a constant 6-m minimum source-receiver offset. For each shot record, the seismic data were stacked from three to five times to improve the signal-to-noise ratio. The survey line for the data discussed below was located along a gravel road. This road allowed for good seismic coupling between the earth and the geophones mounted on the landstreamer. Shots were spaced at 9-m intervals along each survey line. The seismograph recorded 1-s records for each shot point at a 0.5-ms sample rate.

Figure 1 (top) shows the shear-wave velocity model resulting from a segment of one of the MASW survey lines. For the sake of simplicity, the data for this study come from analysis of a single shot gather (Fig. 2) recorded in the area next to boring TP1C-33, which is located approximately 10 m from the survey line (see Fig. 1). This shot gather is representative of other shot

gathers in the area. A geologic log from boring TP1C-33 shows clay overburden to a depth of 5.1 m above unweathered basalt. The overburden is described as residual, lateritic clay with very few gravel fragments, and shows Standard Penetration Test (SPT) blow counts ranging from 2 to 23 that generally increase with depth. The top-of-rock is described as a hard, strong, slightly weathered, coarse- to very coarse-grained igneous rock with some jointing present. The log indicates the presence of unweathered basalt to a total boring depth of 50 m.

Seismic refraction data were recorded along the same survey line as the MASW data using a similar land-streamer approach during data acquisition. The first-arriving energy along all of the shot records was chosen and then imported into SeisImager/2D software (OYO Corporation, 2006). An iterative, least-squares inversion routine was used to provide a tomographic

Figure 2. Shot record and calculated amplitude spectra of phase velocity as a function of frequency, or “overtone image”. A well-defined fundamental-mode Rayleigh-wave dispersion curve ranging in frequencies from 13 to 50 Hz was easily extracted from the image. Below 13 Hz, the perceptible dispersion curve becomes rather ambiguous.

model of compressional-wave (P-wave) velocity (Fig. 1, bottom).

The seismic refraction model (Fig. 1, bottom) shows some lateral variations in an interpreted top-of-rock elevation along the survey line. At the location of boring TP1C-33, there is no clear jump in velocity evident at the top-of-rock depth (5.1 m) reported in the boring log. While tomographic cross-sections such as this one provide a good representation of the overall subsurface bulk P-wave velocities, they smooth out distinct boundaries between layers of contrasting velocities (*e.g.*, soil-bedrock interface). Other refraction solutions, such as the generalized reciprocal method (GRM), might be superior for estimating bulk P-wave velocities and layer interfaces; however, such analyses are beyond the scope of this work. Near boring TP1C-33, the refraction model suggests that the depth to top-of-rock is close to 7.5 m, with P-wave velocities ranging from approximately 440 to 2,000 m/s within the overburden, and approximately 2,400 to 5,400 m/s within the basalt. The average modeled P-wave velocity of the overburden is approximately 900 m/s, while the average P-wave velocity within the basalt is approximately 3,600 m/s. According to Press (1966), P-wave velocities for basalt generally range from around 5,400–6,400 m/s. This range represents rock that has not been affected by weathering or significant stress perturbations (*e.g.*, fracturing, jointing and faulting). The lower velocities found in the refraction model are likely to be more representative of the true, in situ bulk characteristics of the shallow bedrock.

Velocity Models

The fundamental-mode Rayleigh-wave dispersion curve was picked manually from the overtone image that ranges in frequencies from approximately 13 Hz to

50 Hz (Fig. 2). The dispersion curve was defined using 50 points spaced at equal wavelength increments. Surface-wave phase velocities range from 260 m/s at the higher frequencies to 862 m/s at the lowest reasonably discernable frequency in the overtone image. At 13 Hz, the maximum resolvable wavelength is 66 m, based upon the defined phase velocity of 862 m/s; this is nearly twice the geophone spread length. In practice, the authors have often observed that the maximum definable wavelength is approximately twice the geophone spread length when using acquisition field parameters similar to those presented in this case study. Below 13 Hz, the dispersion curve becomes increasingly ambiguous, a result of the limitations that the geophone array length and the seismic source characteristics place on low-frequency data resolution.

Four separate data inversions (Cases 1 through 4) were run. The following conditions are common to all four inversions: 1) the shear wave velocity profile geometry is defined by nine model blocks (layers) with fixed thicknesses increasing 25% with depth, plus a model half-space; 2) the depth to the model half-space is 23 m, corresponding to approximately one-third of the maximum resolvable wavelength; 3) a maximum of 10 iterations is possible, and an option exists to stop the inversion process early when some pre-programmed convergence criteria are met; and 4) densities are set to 2.0 g/cm³ for all layers. The choice of inverting a multi-layer model instead of a simple two-layer model (overburden over rock) arises from the aim of the investigation, which was to study industry-standard data processing techniques that more often than not incorporate multi-layer models with fixed geometries. In addition, while a two-layer model may fit well very close to the logged borehole, it may not necessarily fit elsewhere along the several line-kilometers of data where the site geology is

Figure 3. Shear-wave velocity model resulting from using SurfSeis default modeling parameters (Case 1).

too complex to warrant such a simple assumption for stratigraphy everywhere. Furthermore, there is value in knowing the velocity gradients in the overburden and shallow bedrock.

The four data inversions differed from one another through their starting model shear-wave velocities and/or Poisson's ratios. Case 1 utilizes initial shear-wave velocities derived directly from the observed dispersion curve and a starting Poisson's ratio of 0.4. These parameters yielded the shear-wave velocity model shown in Fig. 3. Eight iterations were performed and resulted in an RMS error of 34.2 m/s. The theoretical dispersion curve matches the measured data fairly well at higher frequencies, but does not show a good fit at the lower frequencies where there is a clear jump in surface-wave phase velocity at around 16 Hz. Model shear-wave velocities in the overburden material range from 137 m/s to 436 m/s, while shear-wave velocities within the basalt range from 380 m/s to 982 m/s, with a model half-space shear-wave velocity of 1,452 m/s.

Case 2 utilizes fixed P-wave velocities with the same starting shear-wave velocity model. The P-wave velocities were set to the average velocities within the overburden and basalt taken from the refraction model data, and remained fixed throughout the inversion. These inversion parameters yielded the shear-wave velocity model shown in Fig. 4. Eight iterations were performed and resulted in an RMS error of 49.9 m/s. The theoretical dispersion curve matches the measured data fairly well at higher frequencies, but, again, does not show a good data fit at the lower frequencies where there is a clear jump in surface-wave phase velocity at around 16 Hz. Model shear-wave velocities in the overburden material range from 146 m/s to 416 m/s,

while shear-wave velocities within the basalt range from 560 m/s to 935 m/s, with a half-space shear-wave velocity of 1,954 m/s. Considering these shear-wave velocity ranges with respect to the P-wave velocities modeled, Poisson's ratios ranged from 0.36 to 0.49 in the overburden and 0.46 to 0.49 in the bedrock. The Poisson's ratios for the bedrock are unreasonably high (Press, 1966).

Case 3 utilizes starting Poisson's ratio values that are more representative of the subsurface materials. Values of 0.3 and 0.24 are used for the overburden and the basalt, respectively. The starting shear-wave velocities correspond again to the ones derived from the target dispersion curve. These inversion parameters yielded the shear-wave velocity model shown in Fig. 5. Ten iterations were performed and resulted in an RMS error of 20.8 m/s. The theoretical dispersion curve matches the measured data fairly well at high frequencies. The match below 15 Hz is better than in the first two cases, but still leaves room for improvement. Model shear-wave velocities in the overburden material range from 146 m/s to 531 m/s, while shear-wave velocities within the basalt range from 423 m/s to 985 m/s, with a model half-space shear-wave velocity of 1,965 m/s.

Case 4 uses starting model shear-wave velocities set close to expected values. As a rough approximation, shear-wave velocities are equal to about 0.4 times the P-wave velocities within unconsolidated materials, and 0.6 times the P-wave velocities within crystalline rocks (Press, 1966). Using the average P-wave velocities within the interpreted overburden and basalt obtained from the refraction model, starting model shear-wave velocities of 360 m/s and 2,160 m/s are used for the layers that lie within the overburden and basalt, respectively. These

Figure 4. Shear-wave velocity model resulting from using fixed P-wave velocity constraints (Case 2). The P-wave velocities for the overburden and the basalt were set to average velocities obtained from the seismic refraction tomography model.

inversion parameters yielded the shear-wave velocity model shown in Fig. 6. Ten iterations were performed and resulted in an RMS error of 15.8 m/s, the lowest of the four trials. The theoretical dispersion curve matches the measured data very well at all sampled frequencies, including where there is a clear jump in surface-wave phase velocity at around 16 Hz. Model shear-wave velocities in the overburden material range from 180 m/s to 657 m/s, while shear-wave velocities within the basalt range from 2,163 m/s to 2,175 m/s, with a model half-space shear-wave velocity of 2,206 m/s.

Discussion of Field Data Outcomes

Figure 7 compares all inverted shear-wave velocity models. Most models show a gentle increase in shear-wave velocity beginning at depths between 7 and 10 m. This corresponds well with the seismic refraction data, and reasonably well with the lithology log that shows clay overburden to a depth of 5.1 meters above unweathered basalt. However, with the exception of Case 4, which used the expected site conditions as the starting model, all of the inversions failed to converge

Figure 5. Shear-wave velocity model resulting from using a starting Poisson's ratio of 0.3 for the overburden and 0.24 for the basalt (Case 3).

Figure 6. Shear-wave velocity model resulting from using a starting model with expected shear-wave velocities (Case 4). Expected values were calculated using average P-wave velocities from the seismic refraction tomography model.

upon a solution that comes close to the expected site model (*i.e.*, a distinctive sharp jump in shear-wave velocity at around 7.5 m). Altering Poisson's ratios and/or P-wave velocities resulted in different values of data fit, but did not produce a more realistic model. A starting model that comprised shear-wave velocities resembling expected values resulted in a more accurate data fit and a more plausible shear-wave velocity profile.

The MASW Cases 1–3 show relatively low-velocity material for the upper 7.5 meters, but the values vary between one another by as much as 260 m/s. Less

variation is observed between the models below 10 m. Also, in all models, the shear-wave velocity of the half-space is virtually the same as the shear-wave velocity used in the starting model. This result suggests that the solution is insensitive to the shear-wave velocity of the half-space.

Changing the starting Poisson's ratios to values more representative of the subsurface materials (Case 3) resulted in the best data fit out of the three inversion attempts that used starting shear-wave velocities derived automatically from the dispersion curve values. The theoretical dispersion curve fits particularly well at lower frequencies (*i.e.*, less than 16 Hz) where a clear jump in surface-wave phase velocity can be seen in the data (Fig. 5). The best MASW data fit, however, comes from Case 4 (Fig. 6), where starting model shear-wave velocities were set to expected values. This shows that the outcome is very dependent upon the starting model. This will frequently be problematic in practice, because one does not often have the benefit of a priori information, and the shear-wave velocity is the very parameter sought from the investigation.

Numerical Studies

2-Layer Forward Modeling

To further explore the influence that shear-wave velocity and depth of bedrock have on Rayleigh-wave phase velocities, a series of simple two-layer models representing clay of varying thickness overlying basalt having different shear-wave velocities was examined. A forward modeling scheme by Schwab and Knopoff (1972) was used to produce theoretical fundamental-mode dispersion curves for the two-layer models (Fig. 8)

Figure 7. Comparison of all shear-wave velocity models.

Figure 8. Theoretical fundamental-mode dispersion curves for an overburden thickness of 2.5 m (top), 5 m (middle) and 10 m (bottom) and varying half-space shear-wave velocities.

having shear-wave velocities for basalt of 1,000 m/s, 2,000 m/s and 3,000 m/s, and overburden thicknesses of 2.5 m (Fig. 8, top), 5 m (Fig. 8, middle) and 10 m (Fig. 8, bottom). The shear-wave velocity of the overburden is constant for all models (284 m/s), and is obtained from the observed surface-wave phase velocities at higher frequencies (*i.e.*, the average velocity of the asymptote observed in the overtone image). It becomes clear in Fig. 8 that, for an overburden thickness (*i.e.*, depth to bedrock) greater than 5 m,

there is little observable change in surface-wave phase velocity within the range of measured wavelengths (maximum of 69 m). In other words, the wavelength at which the fundamental-mode dispersion curves stop exhibiting sensitivity to the overburden is larger than the maximum wavelength sampled in our field data test. This suggests why, given a fixed layer geometry, models having a broad range of shear-wave velocities in the second layer can all provide a good fit to the fundamental-mode dispersion curves defined over the measured wavelengths.

Figure 9. Theoretical fundamental-mode dispersion curves for a range of overburden thicknesses (*i.e.*, half-space depths) and a half-space velocity of 2,160 m/s.

For a simple layered model, the low-frequency limit of the fundamental-mode Rayleigh-wave phase velocity will asymptotically approach a value slightly less than the shear-wave velocity of the half-space (*e.g.*, Xia and Xu, 2005). For the model that best represents our field study, this would require data at frequencies much lower than the observed limit of 13 Hz, perhaps even less than 5 Hz (see Fig. 8). For the assumed phase velocities, this corresponds to wavelengths greater than 400 m, which are far greater than the maximum achieved with the survey equipment and geometry used.

Solving for Depth

Figure 9 illustrates that surface-wave phase velocities for the same two-layer model are highly affected by depth to bedrock. The curves in Fig. 9 represent the theoretical fundamental-mode dispersion curves with phase velocity as a function of wavelength for a fixed-velocity half-space ($V_s = 2,160$ m/s, based upon the modeled P-wave values) at depths ranging from 2.5 to 20 m. Within the range of the measured wavelengths from the field data case (those less than 69 m), there is a clear separation in phase velocities among the various depth models.

To exploit the sensitivity of phase velocities to layer thickness, an inversion of the field data was performed in SurfSeis using a general Monte-Carlo

approach. The Monte-Carlo approach coded in SurfSeis uses the overtone image directly to find the best-matching solution through a random search. The purpose of this test was to determine how effective the MASW method can be in determining depth to bedrock using a simple, fixed velocity structure. The shear-wave velocities for the first layer and half-space were set to 284 m/s and 2,160 m/s, respectively, based upon the data and the average modeled P-wave velocity displayed in Fig. 1. Poisson's ratios of 0.3 and 0.24 were fixed for layer 1 and the half-space, respectively. Density was held constant at 2.0 g/cm^3 . The inversion was directed to match the overtone image, with data weighting proportionate to the relative spectral amplitude at each frequency. Figure 10 shows the shear-wave (top) and P-wave (bottom) velocity models presented in Fig. 1 with the derived half-space depths overlain. There is excellent correlation between the reported depth to the top of unweathered basalt in the boring logs and the calculated depths. This outcome demonstrates that a combination of surface-wave studies utilizing fundamental-mode Rayleigh-wave dispersion with supplementary geological or geophysical data, such as borehole lithologic data or seismic refraction data, would provide a more accurate characterization of shallow bedrock than would the use of fundamental-mode surface-wave data alone.

Figure 10. Shear-wave (top) and P-wave (bottom) velocity models (from Fig. 1) showing the half-space depths (bold dashes) derived using the Monte-Carlo inversion approach in SurfSeis. Note the excellent correlation to the top of unweathered basalt shown in the boring log summaries.

Examining Higher Modes

Figure 11 illustrates the effect of varying basalt velocities on the higher modes of Rayleigh-wave propagation when using parameters similar to the case studied here (*i.e.*, simple two-layer model) with a bedrock depth of 10 m. Within the range of wavelengths (frequencies) sampled, the second and third higher modes are much more sensitive to layer velocity than the two lowest modes of propagation. The change in shear-wave velocity of the bedrock yields a more pronounced separation in the phase velocities at the shorter wavelengths (higher frequencies) that are resolvable with the test. At the 3rd higher order mode, the dispersion curve values at low frequencies approach their asymptotic limits within the range of measured wavelengths at velocities below approximately 2,500 m/s.

Discussion and Conclusions

For a site with a high shear-wave velocity contrast at shallow depth (unconsolidated material over hard

bedrock), standard Rayleigh-wave methods failed to accurately capture the shear-wave velocity of the bedrock due to an inability to resolve the fundamental-mode dispersion curve at sufficiently low frequencies. The use of more realistic Poisson's ratios during data inversion resulted in a marginally better data fit. However, only when the starting model shear-wave velocities were set close to expected values did the shear-wave velocity predictions improve. Numerical modeling of a simple two-layer system representing site conditions observed in this study showed little or no change in the fundamental-mode dispersion curve with variation in deep-layer shear-wave velocity over a practical range of wavelengths. To obtain the correct shear-wave velocity of the half-space, the dispersion curve must be defined at much lower frequencies than are obtained with typical methods. This would require the acquisition of data at wavelengths greater than 400 m for the case studied.

A commonly used guideline states that the maximum depth of investigation for the inversion of

Figure 11. Theoretical dispersion curves for an overburden thicknesses of 10 m and varying half-space shear-wave velocities for the 1st higher order (top), 2nd higher order (middle) and 3rd higher order (bottom) modes of Rayleigh-wave propagation.

fundamental-mode Rayleigh waves is roughly equal to half of the largest recorded wavelength. However, our study of a high-velocity layer beneath a low-velocity layer shows that the guideline does not ensure that shear-wave velocity estimates will be accurate to this depth. While it may be possible to predict the depth of an interface up to the anticipated maximum depth, based upon an observed increase in velocity gradient,

data at much lower frequencies (*i.e.*, longer wavelengths) may be required to resolve the shear-wave velocity profile.

This study also demonstrated that the inversion results are highly sensitive to choices for layer geometry in the case of a high-velocity half-space beneath a low-velocity layer. Numerical studies and tests on the field data suggest that surface-wave methods can resolve

depth to bedrock in simple, layered geologies (*e.g.*, soft sediment over hard bedrock) when bulk velocities can be inferred from supplementary data.

Practitioners of surface-wave techniques should be aware of the constraint that the low-frequency limit imposes upon resolution of both layer boundaries and shear wave velocities at depth. The lack of low-frequency data is common in practice. The lower frequency, fundamental-mode data necessary to accurately model shear-wave velocities to desired depths might be acquired using longer geophone arrays with stronger sources, or possibly by adding passive-source techniques (Park *et al.*, 2005; Park *et al.*, 2007).

Dispersion data from higher modes of Rayleigh-wave propagation, if available, may have been useful for resolving depth and velocity of the high-velocity half-space in the studied case, because the higher modes theoretically reach the asymptotic high-velocity limits within the range of recorded frequencies. Some relatively recent published literature show that higher-mode phase velocities of Rayleigh-waves appear to be more sensitive to shear-wave velocities at greater depths for a given frequency, and incorporating higher-mode dispersion data in the inversion improves the accuracy of inversion results (Beaty *et al.*, 2002; Xia *et al.*, 2003; Luo *et al.*, 2007; Supranata *et al.*, 2007). The greatest benefit from multiple-mode inversion techniques may be realized with irregular subsurface velocity profiles (*e.g.*, where stiffer layers are underlain by softer layers) (Supranata *et al.*, 2007). Nevertheless, interpretation of higher-mode phase velocities poses some challenges, as they are not always easy to separate from the fundamental mode and possibly from other scattered energy (*e.g.*, Zhang and Chang, 2003). In practice, the occurrence of a high-velocity half-space beneath lower-velocity materials or the presence of stiff layers (Luke and Calderón-Macías, 2007) is commonly encountered. Consequently, there is a real need by practitioners for the availability of improved processing and inversion techniques that incorporate higher-mode dispersion data.

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Casto et al.: Interpreting Surface-wave Data for a Site with Shallow Bedrock

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