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SEISMIC SURFACE-WAVE TOMOGRAPHY OF WASTE SITES

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Executive Summary

Surface-wave group-velocity tomography is an efficient way to obtain images of the group velocity over a test area. Because Rayleigh-wave group velocity depends on frequency, there are separate images for each frequency. Thus, at each point in these images the group velocities define a dispersion curve, a curve that relates group velocity to frequency. The objective of this study has been to find an accurate and efficient way to find the shear-wave structure from these dispersion curves.

The conventional inversion techniques match theoretical and observed dispersion curves to determine the structure. These conventional methods do not always succeed in correctly differentiating the fundamental and higher modes, and for some velocity structures can become unstable. In this research a perturbation technique was developed. The perturbation method allows the pre-computation of a global inversion matrix which improves efficiency in obtaining solutions for the structure. Perturbation methods are stable and mimic the averaging process in wave propagation; hence, leading to more accurate solutions. Finite difference techniques and synthetic trace generation techniques were developed to define the perturbations. A new differential trace technique was developed for slight variations in dispersion. The improvements in analysis speed and the accuracy of the solution could lead to real-time field analysis systems, making it possible to obtain immediate results or to monitor temporal changes in structure, such as might develop in using fluids for soil remediation.

Research Objectives

Tomography is an effective way to obtain images of Rayleigh wave group velocity covering a study area. The resolution of the image is theoretically limited only by the wavelengths of the surface waves. Because group velocity is a function of frequency, the images for all of the frequencies yield dispersion curves that may be used to infer the shear-wave structure. The paper by Long and Kocaoglu (2001) presents the technique for our development of surface-wave group-velocity tomography. In the inversion of the tomographic group-velocity measurements for S-wave structure, we assumed that the conversion of dispersion curves to shear-wave structure could be accomplished using well-known and "tested" techniques. These techniques were found to work for some of our areas, but became unstable in others. Our assumptions were wrong for complex structures and for structures with included low-velocity zones. The instability in these cases was related to the numerical difficulties in separating fundamental and higher modes and in determining the appropriate mode for the observed waves. While techniques exist to sort out the fundamental and higher modes, they are not practical for the automatic inversion of many dispersion curves (over 256 in each of our simple models). The conventional and existing inversion programs also contain a theoretical inconsistency because they are based on a model with constant-velocity layers. The approximation of soil structures by constant velocity layers may not be appropriate for the strong depth-dependence in velocities typical of soils and their transition to weathered and un-weathered rock. *Hence, the objective of this project was to improve the stability of the inversion techniques used in the interpretation of S-wave velocity structure and to develop interpretation methods for structures that are superimposed on a strong velocity gradient.*

This research addresses the limited availability of analysis programs that exactly model a gradient velocity structure. Most analysis programs that are currently used in surface wave interpretation approximate a gradient with a sequence of thin layers. Our objective is thus to develop a robust and accurate inversion method specifically for the velocity gradients of a soil. We proposed to base this inversion on exact solutions from finite difference simulations of dispersion. The inversion of group-velocity dispersion for shear-wave structure in this project is part of a larger objective to develop an analysis package for data acquisition, data reduction, and data interpretation that can be used to evaluate the three-dimensional structure and time variations in structure of near-surface soils. In the process of developing the analysis programs, we proposed to obtain and process data from 6 additional areas in order to test the robustness and accuracy of the interpretation.

The efficient and robust solution for S-wave structure from surface-wave group-velocity tomography is important because such techniques are required for routine application of the techniques by field workers. Surface wave tomography has the potential of becoming a powerful near-surface imaging technique for S-wave velocity structure. Surface waves are uniquely suited for the estimation of near-surface shear-wave velocities because they are usually the largest amplitude waves generated by a surface impact, their velocity is determined primarily by the shear-wave velocity of materials in a depth range of ¼ wavelength, and their dispersion properties allow separation of different wavelengths for interpretation of velocity as a function of depth. This research has attempted to develop a new approach to the inversion of dispersion curves that is theoretically correct and can include the effects of a velocity gradient. We have examined the question as to whether there is a significant difference between propagation in a velocity gradient and propagation in a layered media. We have found that the greatest impact of a gradient model is in the existence and character of the higher modes. The higher modes, which correspond generally to higher frequencies, in a layered model are equivalent to multiply reflected shear waves. A gradient eliminates reflections from discrete boundaries and replaces them with waves continuously refracted back to the surface, a process that significantly modifies the appearance of higher modes.

Surface-wave tomography could prove to be important because shear waves are very sensitive to the existence of fluids in soils when the fluids are at or near to saturation. Hence, the mapping of time

variations in the depth to the water table in soils may become possible without having to drill many wells to get single point values. The sensitivity of surface wave velocity to fluid content could eventually allow surface-wave tomography to track fluid movement with time. These measurements could include detection of the existence of dense fluids as contaminates. In areas where seepage from a waste site is controlled by structure, the structures may be defined and used as a guide for drilling and sampling. An added advantage of tomography is that waves crossing a study area are measured on its boundary, eliminating a need to physically occupy the interior of the study area. Hence, an image of shallow structures can be obtained from the periphery of sites with limited access.

To date we have limited our studies to shallow and small areas. A hammer source can image areas up to 50 meters on a side and interpret structure to depths of 3 to 5 meters, depending on the structure. With a larger source, such as a commercial weight drop, distances from 50 to 300m can be imaged and the lower frequencies could increase the depth of effective imaging to 20m. However, the resolution decreases in proportion to the increased wavelengths.

The structures obtained with surface-wave group-velocity tomography should be the same as those of SASW because the two techniques sample the dispersion of the same waves, the Rayleigh wave. However, the tomography provides images that can be inverted for structures in three dimensions, not just an average structure as a function of depth between two or more sensors. Tomography should improve the spatial resolution over that possible with a few SASW tests. However, many SASW tests covering a test area could be inverted for an equivalent shear-wave velocity structure, but with significantly greater field effort. Shear-wave velocity, or equivalently shear modulus, is a very important parameter in the design of foundations for structures. Additional evidence for the validity of surface-wave group-velocity tomography could help support the use of SASW and related surface wave techniques in providing estimates of shear modulus for construction.

Although phase and group velocity inversion for shear-velocity structure has been studied in depth, few organizations other than Georgia Tech are currently investigating surface-wave, group-velocity tomography. Execution of the technique is involved because it requires signal processing and multiple data inversions. Consequently noise or errors in any one of the processing steps can lead to unstable solutions and the final structure can be recovered only after successful completion of all data processing steps. Such techniques and skills are commonly available in research organizations, but not generally available to practicing environmental geophysicists. The lack of analysis programs inhibits the adoption or development of such analysis programs outside the research institutions without proof that the analysis works. The reasons for a lack of adoption of these methods are not all as obvious as those above. Our work had found that some features common in group-velocity analysis, in particular the determination of the travel time used to compute group velocity, might be discontinuous. Normally, phase velocity is continuous and a failure to recognize the discontinuities in the group velocity can lead to errors in the interpretation.

Park et al. (1999) improve the accuracy of phase velocity measurements by using many geophones in a multi-channel analysis of surface waves technique (MASW) and has achieved spatial resolution by repeating the measurement along a line, as done in conventional seismic reflection data acquisition. The phase velocity in MASW is the average phase velocity in the window defined by the dimensions of the array.

Louie (2001) has presented a passive recording technique to obtain cost-effective measurements of shear velocity, often to 100-m depths. The method uses a wavefield transformation data processing technique to detect phase velocities of Rayleigh waves, and a conventional inversion technique for shear-wave velocity versus depth. The results are comparable to those of SASW and the multi-channel analysis of surface waves, but still does not offer the three-dimensional resolution of tomography

A wavelet correlation analysis technique for resolving group velocity dispersion curves has been presented by Kritski et al. (2002). They claim that the technique is superior to traditional cross-correlation

and Fourier analysis for defining the phase velocity, particularly where higher modes may overlap. Their method has only been applied to marine sediments to date, but may also apply to near-surface soils.

The industry is generally reluctant to adopt and use (i.e. spend real dollars on) an unproven technique like surface-wave group-velocity tomography. Adoption of this technique will come only after a number of case studies are successfully demonstrated and after convenient (i.e. user friendly) packages are available. Hence, a natural extension of the proposed work would be to seek new "problem" areas to image and to use as demonstration data sets. Such areas could help to further develop the analysis programs and improve their ability to handle a wide variation in field conditions, as well as build confidence in the capabilities of the technique. In particular, the application to specific critical problem should be evaluated. Such problems could include assessment of permafrost degradation, flow of dense fluids, and a study of the relation between age of burial and ease of detection. The decrease in detection capability for older structures is expected because the disturbance of a burial will heal with time and the rate of this healing and its impact of seismic velocities is not well understood. There exist additional interpretation problems to evaluate, such as the impact of trees of various size on the passage of surface waves.

During the course of this work, we have developed computer programs to carry out the unique aspects of surface-wave group-velocity tomography. We believe that our computer programs and preliminary results demonstrate that useful data can be obtained using surface-wave group-velocity tomography. The results of this project relate primarily to details and incremental advances in the interpretation techniques. The primary innovative aspect of the analysis is our formulation of the problem in terms of a perturbation. The perturbation approach mimics the way that surface waves are influenced by anomalous media. Hence, the perturbation formulation should provide accurate solutions that are not influenced by difficulties in inverting anomalous zones in the tomography image. We have also developed techniques that utilize whole waveforms generated via finite difference programs in order to generate the inversion relation for the perturbation type solution. The finite difference techniques require an unusually long operation time to generate observable dispersion of the surface waves. Most finite difference programs eventually become unstable; hence, we developed a frequency-domain implementation of a stable free surface condition in order to obtain clean synthetic seismograms. Interpretation of the phase velocity from synthetic traces was developed in time and frequency domain, including comparison with synthetic traces generated from dispersion curves. Of particular interest is the uniqueness of some interpretations of group velocity. Using the multiple filter technique it turns out that the straight line path through anomalous velocity zones may represent the observed group arrival times better than phases refracted around an anomalous zone. This can lead to discontinuities in the group velocity directly influenced by anomalous zones along the straight-line path. The minimum time path does not always correspond to the path of maximum energy. Finally, we have developed a new technique to utilize the difference between two traces to measure small differences in phase velocity.

Methods and results

Introduction

The surface-wave group-velocity tomography technique is used in this study to generate dispersion curves that can be inverted for S-wave structure. The technique will be summarized for background and to note factors that influence the inversion to shear-wave structure. Details are given in Long and Kocaoglu (2001). A preliminary accounting of the investigation of inversion methods was presented by Long (2002). These methods are significantly expanded in this report and are being considered for future publications.

The advantages of using surface waves for the estimation of near-surface shear-wave velocities include: their large amplitude when generated by a surface impact, the sensitivity of their velocity to the shear-wave velocity of materials in a depth range of one quarter wavelength, and the separation of

different wavelengths in time by dispersion. When examining near-surface structures, these factors give the surface-wave methods an advantage over the body wave methods used in seismic reflection and refraction. Also, seismic tomography yields images representing the spatial variation of velocity with dimensions that can be smaller than the separation of geophones in a recording array.

In seismic tomography, waves crossing a study area are recorded at its boundary in order to image its interior. The resolution of the image is limited by wavelength and imaging methods, not just sensor spacing. The group velocity image resolution directly determines the resolution of the shear-wave structure. In processing group-velocity data, the group velocity of a selected frequency is computed from the time it takes the energy of a single frequency to travel from a source to a geophone in an array. The multiple filter method (for details see Kocaoglu and Long, 1993) was used to identify the arrival times of the surface waves at selected frequencies. In the multiple filter technique, seismic data are filtered with a narrow-band filter. The group velocity for the arrival with a frequency at the center of the narrow-band filter is estimated from the arrival time of the peak instantaneous amplitude. The uncertainty of the arrival time of separate frequencies of energy is a factor in using tomography to generate images of the velocity.

In seismic tomography the area of study is generally divided into smaller areas (pixels of the image) and we estimate the slowness in each small area from the observed travel times of rays that sample the pixel. In tomography, ray theory is generally assumed in the computation of theoretical travel times for comparison with the observed travel times. Ray theory is correct for travel times in tomography where an exact travel time is observed independent of the amplitude of the wave. These ray paths follow the minimum-time paths, which are curved when traversing a medium with anomalous velocity structure. However, in media with slight velocity anomalies the deviation of the paths from a straight line will either be the same magnitude as the dimension of the blocks or will be less than one-quarter wavelength. Deviations smaller than the block size will not introduce significant errors and deviations less than one-quarter wavelength will be within the limits of image resolution. Elastic waves in general average material properties with dimensions smaller than a quarter of a wavelength and this effect limits the ability of elastic waves to resolve detail. Because surface waves penetrate to depth in proportion to their wavelength, this also implies that structures at depth will be resolved only if their dimensions are similar to or greater than their depth. Structure will be resolved with less detail with increasing depth.

We have assumed a straight-line approximation in the surface wave tomography. The straight-line assumption is not valid for conventional travel time tomography in media with large velocity anomalies; however, for reasons explained below it may remain valid for group-velocity tomography. Where the general ray theory inversion for travel time tomography is nonlinear, solution for nonlinear inversion is usually obtained through successive approximations and may not be stable. In group velocity tomography at each frequency, we use the observed travel times of the wave energy (not necessarily the minimum time path) in order to find a weighted and damped least squares solution for the group velocity, where the uncertainties in the group arrival times are incorporated in the weighting matrix.

The inversion of group velocity is analogous to inversion of maximum energy propagation. An example presented in figures 1 and 2 shows that minimum time and maximum energy paths are not necessarily the same. The delay for energy, and hence group velocity, may represent the straight line better as an approximation than the minimum time path. In particular, the arrival times of maximum energy can be discontinuous. An acoustic finite-difference program was invoked to illustrate this problem and to assist in interpretation. A plane wave was propagated across a zone of anomalously slow material. The traces are shown in figure 1.

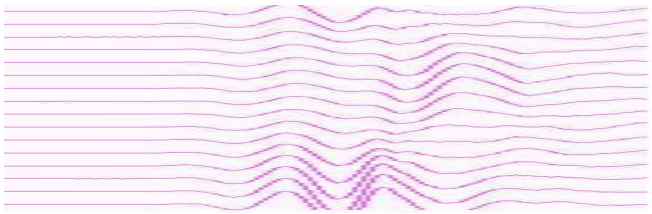

Figure 1. Synthetic traces for a plane wave crossing through a slow zone. See figure 2 for the location of the anomalous zone.

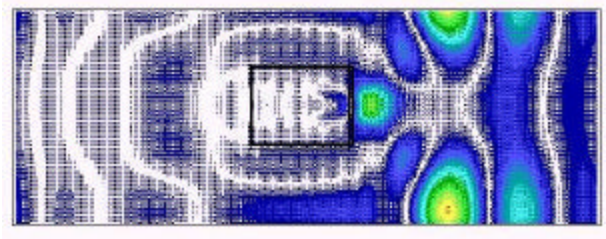

Figure 2. Snapshot of wave motion after wave has passed through the anomalous zone indicated by a square in the middle. Note the lower amplitudes of the center traces and delay of energy, shown as a shift to the left.

The wave front determined by the minimum time path is continuous and shows a measurable delay. However, the amplitudes are attenuated because this faster arrival was diffracted around the anomalous zone. The larger wave energy, the energy that propagated through the anomalous zone, arrives later for the center traces. This is the energy that would give the time for the measurement of group velocity. Hence, group velocity determinations would indicate multiple arrivals, with those waves traveling through the anomalous zone arriving later. This discontinuous behavior of the group velocity arrivals has been observed in some of our original data sets. In particular, it was observed is the data set from the Oak Ridge National Laboratory site and has contributed to the difficulty in interpreting some of that data.

The frequency dependence of group velocity at each pixel is the dispersion curve corresponding to the structure below the position of the pixel in the image. The shear-wave velocity versus depth at that point is determined from the group-velocity dispersion curves by fitting the observed dispersion curve to one computed from a layered model. However, because the resolution decreases with depth, in proportion to the wavelength of the waves sampling that depth, the resolution of the structure will similarly decrease. Hence, the shear wave structures at 2 meters depth will represent average structure over a length of about 2 meters, whereas at a depth of 10 meters, the average would be over a length of 10 meters. When a wave propagates across the area it averages the structure. A fundamental mode Rayleigh wave will remain a fundamental mode in each pixel and its velocity will be an average of the velocity of the pixels within a quarter wave length along the path of the maximum energy. Hence, interpretation of the structure is appropriately approached as a perturbation problem, rather than as a problem of independent inversion for structure at each pixel. The inversion method adopted in this project is based on determining the structure from perturbation analysis of an average velocity structure.

The inversion problem

The increase in technical complexity of the move from depth sounding techniques like SASW to three-dimensional tomographic imaging of shallow structure is analogous to the move from single reflection records to a three-dimensional seismic reflection survey. Instead of fitting an assumed layered model to limited data, the tomographic imaging gives a full picture of the three-dimensional character of near-surface structure. Three-dimensional structures can reveal complexities in the wave propagation that require computationally intensive three-dimensional techniques for modeling wave propagation. Many of these techniques are unique to surface wave interpretation and are not yet developed for three-

dimensional applications. Structures of real interest in the near surface rarely fit the uniformly flat layering of most analytical models developed originally for a predominantly layered earth. If the structure varies significantly within a wavelength of the surface wave, a conversion of wave motion to higher modes of propagation can interfere with interpretation of the fundamental mode and generate reflected and refracted, or scattered, surface waves. These scattered and refracted waves can be significant because velocity contrasts may be large at shallow depths. Also, in the near surface, the velocity typically grades quickly from loose sands at 0.1 km/s to granite at 6.0 km/s, almost two orders of magnitude, over distances that can be as short as a few meters. These conditions present difficult numerical modeling and resolution problems that often require approximations or simplifications to solve. In summary, the shear-wave structures in the near surface exhibit greater contrasts and steeper velocity gradients than are found in typical seismic interpretation problems. Their imaging may eventually lead to an entirely new interpretation method, capable of handling the unique properties of near-surface structure.

In this work we have examined certain problems related to the inversion of dispersion curves for shear-wave structure. In particular, we have examined problems unique to tomographic images of highly irregular structures and structures with gradients. Like any inversion problem, the inversion of tomographic data for the shear-wave structure requires one to combine observed data, represented by the dispersion curves, with prior knowledge of the velocity structure of typical soils and to use this information to find the parameters of a theoretical model. Inversion is a compromise between what is typically known and what the data can infer given the constraints of a theoretical model. The relation between prior knowledge that includes an understanding of certain constraints to the structure and the design of the theoretical model can be complex when the model is designed to be sensitive to the typical properties of the observed data and wave propagation constraints. In the case of an inverse model for soils, the inversion model will be most useful when the theoretical model is sensitive to the gradients in velocity that are typical of soils. By considering all components, one can converge to a reasonable solution, one that is optimal in some definable sense.

The elements of the inversion of group velocity that we have examined in this research are as follows:

(1) Prior knowledge of the character of soil velocities has been designed into the inverse problem. The shear velocity of a soil generally follows an exponential relation that depends on the relative concentrations of clay, sand and water. A typical soil column grades continuously from the unconsolidated materials at the surface to compact soils and weathered rocks at depth. Areas where un-weathered rocks exist near the surface are treated as highly inhomogeneous exceptions to a gradational velocity structure and are modeled as lateral anomalies in a velocity gradient.

(2) New techniques are used to generate theoretical dispersion relations consistent with a velocity gradient typical of soils. In order to compute the dispersion relations, a finite difference code was employed to generate synthetics traces. These were interpreted for phase and group velocity. We also compared these group velocity functions with those from a conventional analysis using thin layers. We use these theoretical group velocities to compute the inversion matrix for shear-wave structure.

(3) The inverse mechanism was defined to be computationally efficient and consistent with the limitations of surface wave imaging. We designed a set of orthogonal functions representing perturbations in the velocity versus depth function. These decrease in resolution with increased depth consistent with the decreased resolution of surface waves with depth. This is equivalent to designing a model with model parameters that have normalized eigenvalues. However, instead of defining a model with normalized eigenvalues, a process that is not practical when the structure varies laterally, we choose model parameters that have approximately equal eignevalues for a reference structure and that, hence, will be applicable to many similar structures. We find an average structure and perturbations from the average structure by solving for the contribution of the orthogonal perturbation functions in the group velocity curves, rather than performing an inversion, with its inherent error, at each pixel. We argue that this is a more realistic way to compute variations in velocity because the velocity of waves from an average velocity structure would be perturbed in a similar way.

Our starting point for this analysis is an observed dispersion curve and some measurement of its uncertainty as defined through tomography. We accept the dispersion curve as representative of the shear wave velocity directly below a single pixel, or, in practice, the weighted average of neighboring pixels. The dispersion curve represents the dispersion curve one would expect to observe if the media were layered and laterally homogeneous with a structure that is represented by the dispersion curve for that pixel. In what follows, the details of our investigation into the three elements above will be described.

Near-surface velocities

The typical shear-wave versus depth relation for a soil and its transition to weathered rock is a positive gradient. Theoretical relations and laboratory measurements have shown that soil velocities depend strongly on pressure and, hence, depth as well as other factors including age, cohesion, fluid saturation, clay content, porosity, and rock fabric. All of these properties affect the velocity and many, like fluid saturation and age, also, depend on depth. Our concern here is to define an approximate depth versus velocity relation that we can use to represent the depth dependence for shear-wave velocity, and ultimately to use perturbations in this relation to examine the influence of the above properties.

Sharp boundaries can exist, for example, with un-weathered rocks, buried cement slabs, and excavated or disturbed materials. The velocity contrast at the borders of these can be approximated with a sharp gradient in a continuous media. Perhaps, a sharp gradient is a more accurate approximation to the structure than the conventional approximation of a gradient by a thinly layered media. Hence, our approach is to formulate the inverse problem for shear-wave velocity in terms of a gradient. In order to define an appropriate starting gradient model for soils, we have examined both observed data and theoretical relations.

In our Oak Ridge National Laboratory (ORNL) data set for the surface-wave group-velocity tomography, data from seismic refraction lines were obtained for correlation with our tomography results. The average of all interpreted velocities for these data (Figure 3.0) when plotted as a Log-Log plot fall roughly on a straight line that suggests that the P-wave velocity satisfies a power law relation with depth with an exponent of 0.3 to 0.6. These data also show a velocity jump to un-weathered rock at depths of 20 to 40 meters. Others have documented similar exponential velocity versus depth relations. The well-known Foust law for velocity versus depth in seismic reflection data suggests a power law relation with an exponent of 0.166 (1/6). The increase in velocity with depth holds almost universally, but the absolute value of the velocity and the gradient varies strongly with soil type, age, composition, depth and other locally controlled factors.

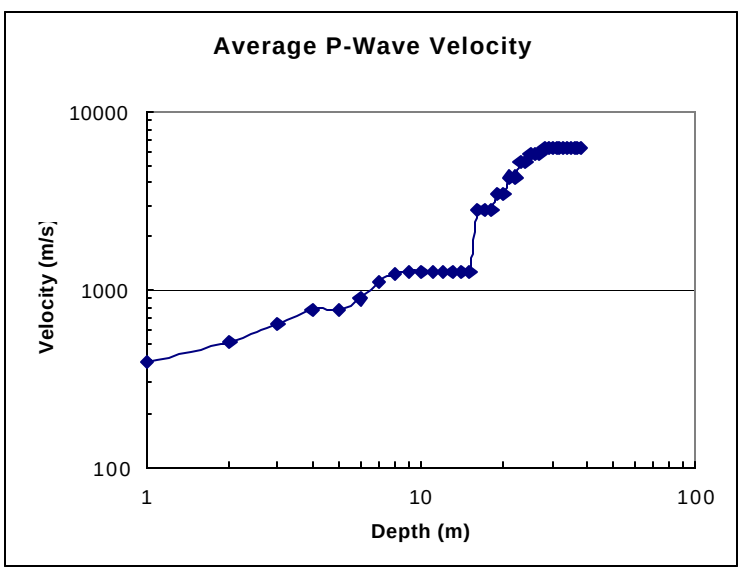

Figure 3. P-wave velocities from seismic refraction data at ORNL site.

A composite of observed shear-wave velocities and theoretical shear-wave velocity versus pressure equations from many sources (Fernandez, 2000) supports a power law relation with depth. Shear-wave velocity relations as a function of pressure for typical soils are often expressed as depth raised to some power consistent with a continuously increasing velocity with depth. In general the increase in velocity with depth is similar for a variety of soil compositions, but the absolute value of the velocities vary strongly with soil type, age, and factors controlled by soil composition and structure. A summary of these relations is presented in Figure 2.0. The sands dominate the low-velocity samples and the clays dominate the high-velocity samples in these trends.

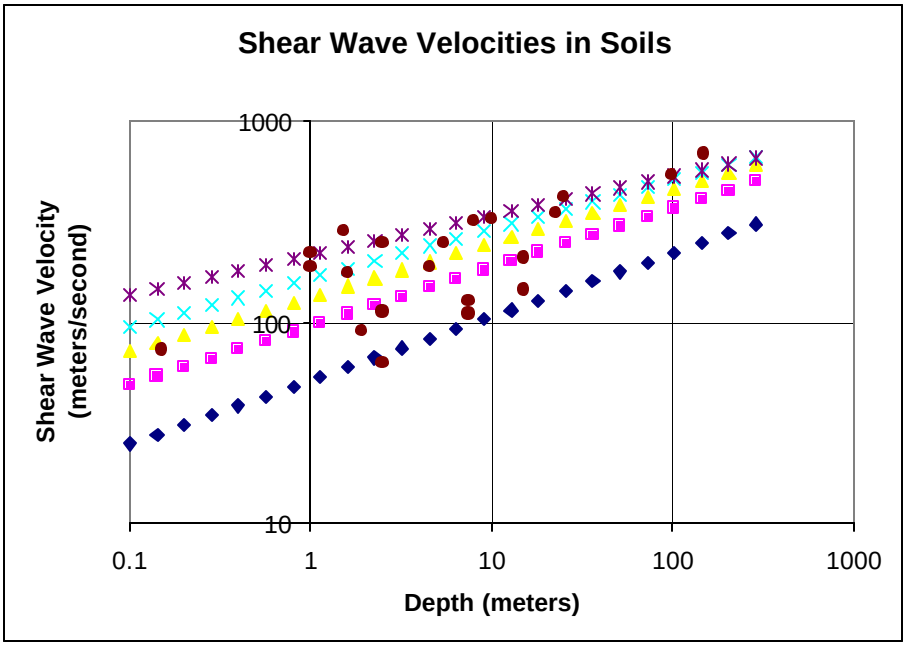

Figure 4. The lines of data points are from empirical relations for the shear-wave velocity of sands and clays as a function of stress converted to depth. The dots are observed velocities from a range of field studies.

We chose the middle of the velocity distribution from Figure 4.0 in this study as a reference velocity for the interpretation of dispersion curves for shear-wave structure. The relation corresponds to the approximate equation, $V_s(z) = a(s)^b$, where the median value for alpha is 40 m/s (the velocity at 1.0 kPa, or approximately 0.05 m depth) and a corresponding estimate for beta is 0.29. The value of 0.29 is higher than that typically observed for rocks buried at greater depths, but less than the 0.3 to 0.6 in the ORNL observed refraction P-wave velocities. However, we consider the ORNL depth dependence to be influenced by anomalous un-weathered rocks and changes in rock type that we wish to resolve. We approximate the stress, s, in kPa by $20z$, where z is in meters. The relation between depth and lithostatic stress depends on density, which may vary with depth; but for this study we assumed a constant density because density varies slowly in comparison with the elastic parameters. For numerical modeling of surface wave dispersion caused by structures below 1.0 meter, the layers above 1.0 meter were modified to asymptotically approach a velocity gradient given by the equation $V_g = V_0 + 20z$ where V_o is the surface value, in this case 80 m/s, corresponding to the average velocity of the top meter of soil. In field applications, the materials in the top meter of soil are likely to deviate significantly from these theoretical relations because they are compacted and rich in organic matter. Also, the high-frequency waves that would be confined to the low-velocity near-surface materials are strongly attenuated in soils and do not

propagate far. The shallow materials do not significantly influence the waves propagating through the deeper layers that are of primary interest in the inversion. The reference shear-wave velocity curve is indicated in Figure 3.0

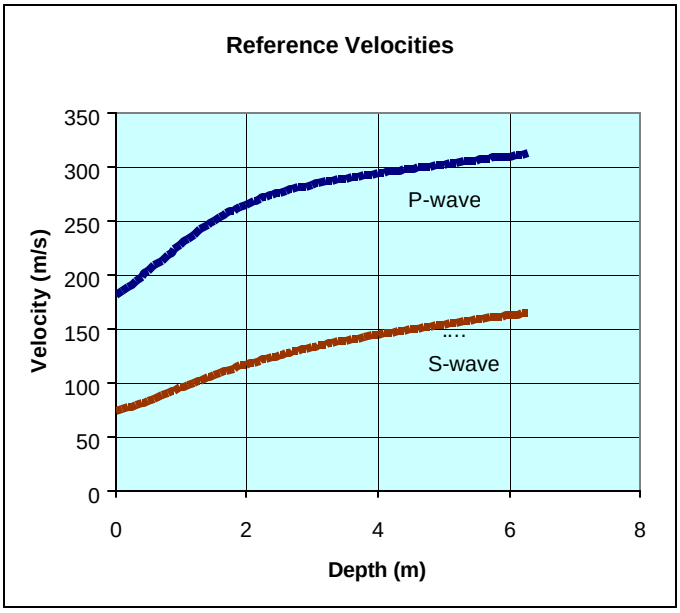

Figure 5. Reference S- and P-wave velocity structure for this study.

The corresponding P-wave velocity was computed by assuming a Poisson's ratio of 0.4 at the surface and an empirical relation σ=0.25+0.15/(1.0+z*z/25) that asymptotically approaches 0.25 with increased depth, z. At a depth of 5 m the Poisson's ratio is .325 and at 10 m it is 0.28. Poisson's ratio determines the P-wave velocity and has minimal effect on the determination of S-wave structure. The most significant contribution appears to be its affect on the stability of the finite difference algorithms, the generation of surface reflections and the creations of leaky P-waves trapped in the surface layer. While these affect the generation of synthetic traces, they have minimal effect on the interpretation of observed data because the near-surface high-frequency waves are typically highly attenuated and not observed in field data.

The finite difference method of simulating surface waves

The finite difference methods are convenient for simulating wave propagation in two-dimensional inhomogeneous media. Such media can be very difficult, or virtually impossible, to model analytically. In this study, we used the finite difference methods to model surface wave propagation in a media with a velocity gradient with depth and to examine the response of the media to anomalous structures. Traditional analytical techniques applied to the dispersion of surface waves search for phase velocities at a set of frequencies and match these to observed phase or group velocities to determine the structure. With locally anomalous structures, the phase velocities of fundamental and higher modes can be similar, causing misidentification errors in the interpretation. Furthermore, the analytical methods do not distinguish among solutions for modes that may carry little or no energy or that arrive at different times because their group velocities are different. In the finite difference simulation, the waves propagate in the same way as they propagate in the earth. The dominant waves, those that are excited by a weight drop, propagate as the fundamental mode of surface waves. As these propagate across a test site, the energy largely remains in the fundamental mode and anomalous velocity zones appear as perturbations in the velocity of the fundamental mode, rather than as converted higher modes. Hence, phase velocity and

group velocity measurements on finite difference waveforms should mimic the wave propagation in the ground and provide an accurate representation of velocity structure.

We used and refined two finite-difference computational codes. The first is the Fourier-spline method as developed by Kocaoglu (1995). The Fourier-spline method uses the velocity/stress formulation with the horizontal derivatives computed in the frequency domain. The vertical derivatives are approximated by the cubic spline method yielding a stable free surface condition and the capability of modeling two-dimensional velocity structure. The second is a conventional second order finite difference formulation of the equations of motion. However, we modified this code to apply the stable free-surface formulation of Vidale and Clayton (1986) in the frequency domain. The second-order finite-difference program is more flexible in approximating anomalous structure, but the Fourier-spline technique is more stable for large numbers of iterations and has less interference from the edges of the grid.

Snapshots of the rotational component of wave motion computed in finite-difference wave propagation illustrate the difference between propagation in a gradient and a layered media. Figures 6 and 7 give snapshots of the particle motion for a constant gradient and a single layer over a half space, respectfully.

Figure 6. Snapshot of rotational motion of surface waves propagating in a positive gradient with depth.

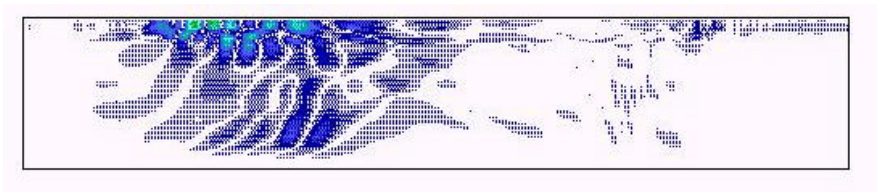

Figure 7. Snapshot of rotational motion of surface waves propagating in a low-velocity layer over a half space.

The principal difference is caused by reflections from boundaries that are lacking in the gradient model. The gradient shows a continuous sequence of surface waves extending to depths in direct proportion to the velocity. The layered media demonstrates the trapping of energy in a shallow layer by the reflecting boundary. The gradient is a more realistic representation of soils, as can be seen by comparing Figure 6 with Figure 8.

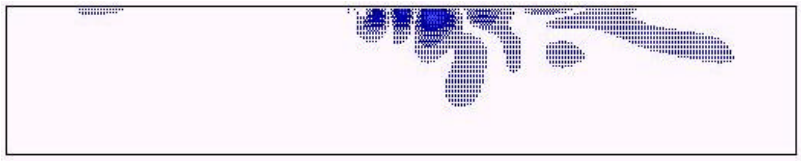

Figure 8. Snapshot of rotational motion for surface waves propagating in the reference soil velocity structure.

Figure 9.0 demonstrates waveforms generated by one of the finite difference techniques. The source is a vertical force, with a time history corresponding to a Ricker wavelet with a center frequency of 20 Hz. The dispersion is typical. The minimum in the group velocity for this structure is near 20 Hz and these waves arrive last. The 10 to 15 Hz waves arrive first, followed by the 30 to 40 Hz waves which propagate along the one-meter thick surface zone.

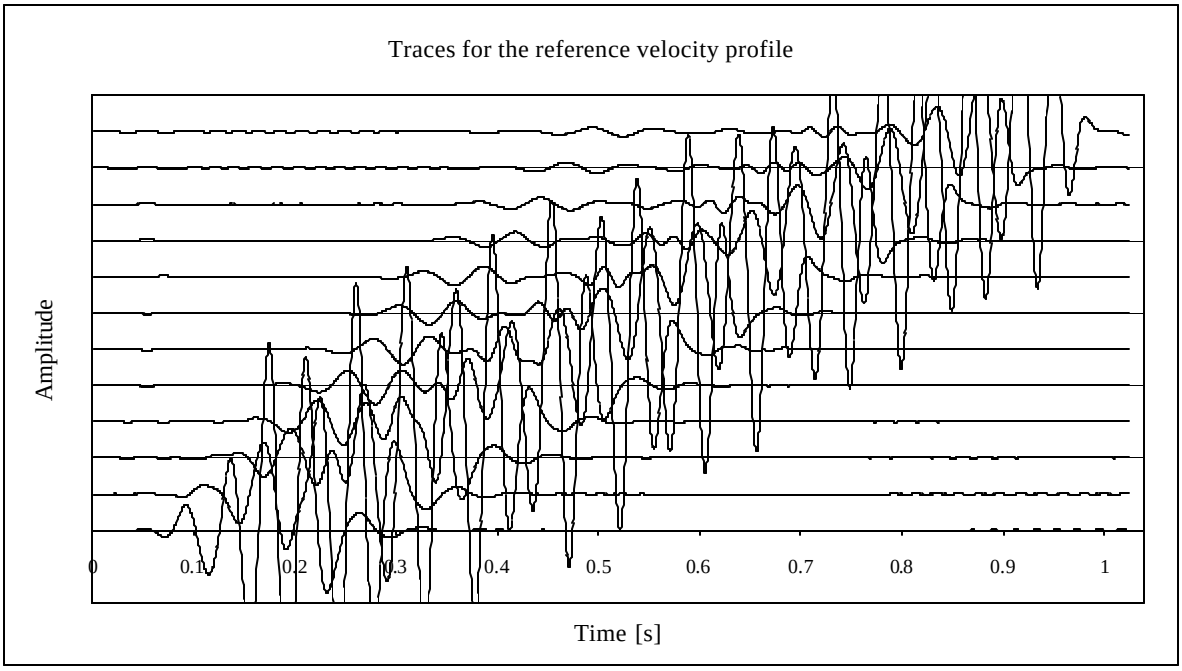

Figure 9. Traces generated by the Fourier spline finite difference method for the reference soil velocity gradient.

Interpretation of phase velocity from synthetic traces

We used the finite-difference wave simulation to generate traces at successively greater distances along a line from the source. In the line format the phase velocity can be directly measured in a comparison of successive traces. The group velocity can then be computed directly from the phase velocity. This is more precise than using the group velocity methods used in the tomography field array. The array design for group velocity tomography does not provide for closely spaced traces in line from the source. Figure 10 is a set of closely spaced traces near the top traces shown in Figure 9.

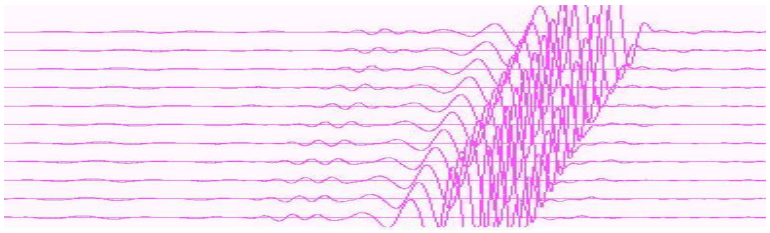

Figure 10. Set of closely spaced traces

Once the traces are generated, the phase velocities can be observed and computed. The method used in this study is a frequency domain direct observation of the phase difference. The first step is to select a set of group velocities that span the observed dispersion range of the surface wave. For each group velocity in the set, we time shift the traces to follow the energy of a given small range of frequencies. The time shift guarantees that the phase shift between traces will be minimal and that

interpolating skips of a cycle between traces will not introduce uncertainty. The traces in Figure 10.0 were windowed with a width of 6 wavelengths and truncated by using a Cosine taper. The windowed traces were Fourier transformed into the frequency domain. The amplitude of the Fourier spectra indicates the range of frequencies for which the analysis is appropriate, that is the phase measurements should be good for frequencies with relatively high amplitude. We assumed 50 percent of the peak value. Prior to computing phase differences, the phases of the traces are unwrapped if necessary to remove jumps of 2p. The phase differences between all traces were then averaged and the average value converted to phase velocity as shown in Figure 11.

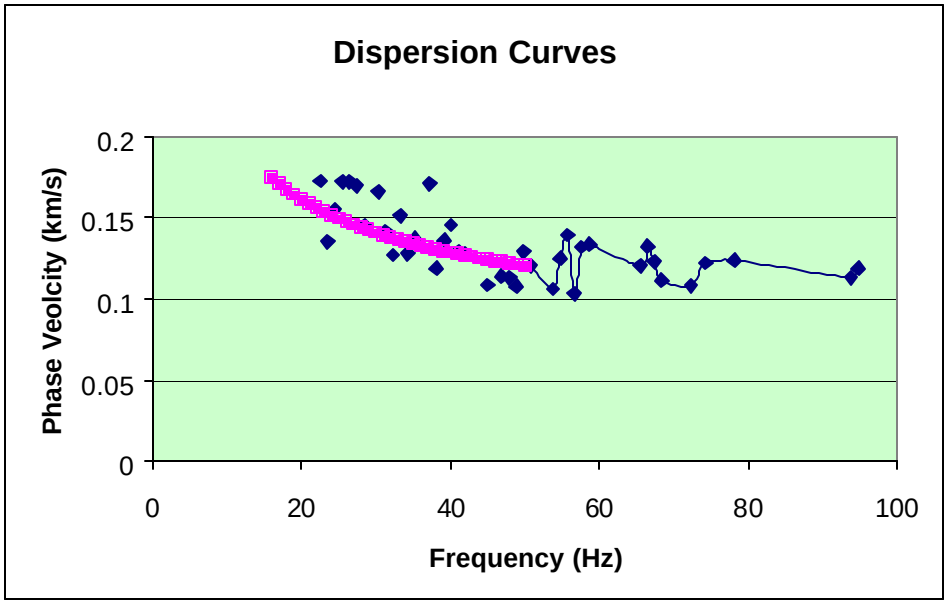

Figure11. Phase velocity curve from synthetic data for gradient (dots) and from layered approximation to gradient (solid line)

The phase velocity for a layered approximation to the reference soil velocity structure can be computed using conventional methods. The results of such computation are also shown in Figure 11. Conventional matrix methods provide dispersion relations at lower frequencies because they do not depend on observation of the longer period waves.

The inversion method

The conventional technique for the inversion of dispersion curves for shear-wave structure starts with a guess in the form of a layered structure. The group (or phase) velocity is a function principally of the shear wave velocities of the layers. Therefore, the first two terms in a Taylor's series expansion are used to compute corrections for the initial guess of layer velocities. Because the equations are nonlinear, the process is repeated until no additional corrections are required. In our analysis, we start with a gradient velocity structure. The perturbations will not be layers, they are linearly independent functions of velocity versus depth. We maintain a gradient by using continuous functions to represent the perturbations in velocity as a function of depth. In our solution the elements of the Jacobian matrix are the derivatives (as a function of frequency) of the group velocity with respect to the functions, instead of with respect to the velocity of a layer as in the conventional method. If the initial guess is a gradient and is close to the final solution, then the elements of the Jacobian matrix will change slowly and the derivative equations would only need to be computed once. This solution has the advantage of being a perturbation solution; hence, the solution should mimic the media response to a propagating fundamental mode of surface waves. In this solution, we compute a velocity versus depth relation that satisfied the average dispersion, and measure structure as a perturbation from the average.

Design of perturbation functions

This analysis starts with a gradient velocity structure that approximates a typical soil or the average structure in a study area. We maintain a gradient by using continuous functions to represent smooth perturbations in velocity as a function of depth. Hence, we choose an appropriate set of linearly independent perturbation functions, $O_i(z)$, to approximate the perturbation in the velocity structure, $V(z)$, relative to the reference soil velocity structure, $\overline{V}(z)$,

$$V(z) = \overline{V}(z) + \sum_{i=1}^{N} k_i O_i(z), \tag{1}$$

where k_i is a constant measuring the contribution of each independent function, $O_i(z)$, to the perturbed velocity structure. Generally, the constants are unknown and are to be found so that perturbations in the velocity structure predict the observed perturbation in dispersion. The reference velocity structure has a corresponding reference dispersion function defined by $\overline{U}(w)$. Likewise, each independent perturbation function generates a perturbation in the dispersion curve. This change, for a unit k_i, can be obtained from theoretical computations and designated as $\Delta U_i(w)$. Using the reference dispersion relation and our observed dispersion, $U_{obs}(w)$, we find the anomalous dispersion relation, $\Delta U(w) = U_{obs}(w) - \overline{U}(w)$, and can express this as,

$$\Delta U(w) = \sum_{i=1}^{N} k_i \Delta U_i(w). \tag{2}$$

Given perturbations in group velocity observed at a set of discrete frequencies, equation 2 is solved for certain values of k_i and by direct substitution of the k_i into equation (1) an estimate of the perturbation of the velocity structure is obtained. The inverse problem is reduced to that of finding the relative contribution of each independent perturbation function in the observed dispersion function.

If the reference dispersion corresponds to the average soil structure, then the analysis gives the structure. In this solution the elements of the Jacobian matrix are the derivatives (at each frequency) of the group velocity with respect to perturbations in the amplitude of the independent functions, instead of a layer velocity as in the conventional method. If the initial guess is a gradient and is close to the final solution, then the elements of the Jacobian matrix will change slowly with a change in velocity structure and the elements of the Jocobian matrix would only need to be computed once in order to obtain an image of the perturbations to the average structure.

The linearly independent set of perturbation functions can be arbitrary. However, they should allow easy computation of the associated perturbation in the dispersion and fit the resolution capabilities of surface waves. The objective is to define a set of independent functions that can approximate any reasonable velocity function. Surface waves do not resolve velocity variations at depth in the same detail as they do shallow velocity variations. Hence, any model perturbation function used to determine soil velocity structure from surface waves decreases in resolution exponentially with depth of the structure. These functions will define a range of valid dispersion curves. By fitting the perturbation in dispersion to the observed dispersion, only dispersion relations that have a realistic velocity structures are considered. This limits the influence of noise in the dispersion curves and contains most of the near-singularities that plague the inversion of dispersion curves. One restriction in using surface waves is that their ability to resolve velocity structure decreases exponentially with depth. In order to give smooth variations in the velocity perturbations, we propose using a set of Gaussian, or normal, distributions in which the standard deviation increases exponentially with depth. Although not unique, the relation could take the form,

$$F_i(z) = \exp[-\frac{(z-a^i)^2}{(ak)^{i-1}}], i \geq 1 \tag{3}$$

$$F_0(z) = 3\exp[z^2] \ .$$

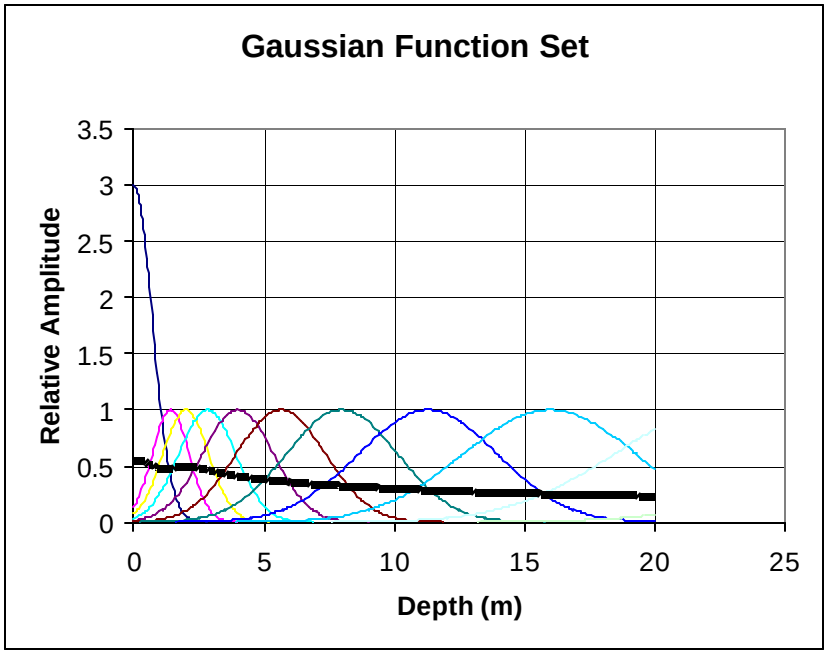

Figure 12. The Gaussian function set for *a*=1.4 and *k*=1.1. The solid line is the sum of the functions showing their ability to fit a smooth velocity function. These functions are also estimates of resolution of the technique.

The curves in Figure 12 define the depth resolution typically available from surface wave studies. Lateral resolution would be equivalent; that is structures at 5 m depth would be smoothed over a range of approximately 3 meters. The lateral resolution would also be a function of acquisition technique, with those methods using tomography giving the greatest resolution.

The group velocity perturbations corresponding to the velocity perturbations in Figure 12 are shown in Figure 13. Group velocities are more complex than the corresponding phase velocities and their perturbations function.

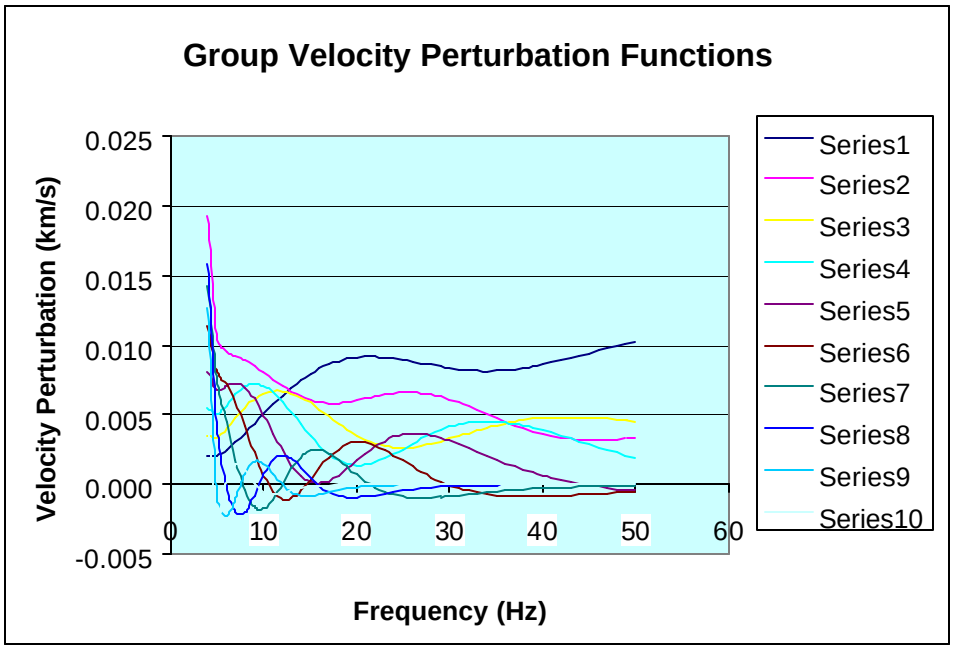

Figure 13. Perturbation functions of group velocity corresponding to velocity perturbations in Figure 12.

A complete reevaluation of our Oak Ridge National Laboratory data set is currently under study using this analysis technique and a consideration of the revisions noted above concerning interpretation of discontinuities in group velocity.

New developments

Instead of mapping variations in structure as detailed above in differential surface-wave interpretation we noticed that it is possible to look slight variations in the dispersion curves (as indicated by time variations in the seismic trace). Such variation could be induced, perhaps, by changes in stress and/or fluid pressure. The reference or average structure would not be critical to this analysis so long as a reasonable approximation is available to generate appropriate theoretical differences in dispersion induced by known perturbations in the structure. We have noted that the reference does not need to be the pre-test velocity structure, which is generally unknown in detail, but could be the seismic trace from the unperturbed structure, which is generally available from an earlier survey. We noted that we can measure the differences in the dispersion for waves traveling the same path by direct comparison of two seismic traces recorded at different times. We next use the Jacobian matrix to map the areas that are influenced, perhaps, by perturbations in the fluid concentration or hydrostatic pressure.

While the difference approach would work with tomography, it is simpler to examine it through a measurement of perturbations in phase velocity along a refraction line. We modeled an arrangement where a linear array of geophones is located above an anomalous zone, corresponding to a zone of perturbation. Figure 14 illustrates this geometry. For an example we ran a theoretical model corresponding to figure 14 using a finite difference code developed in this study. The traces with the perturbation are shown in figure 15.

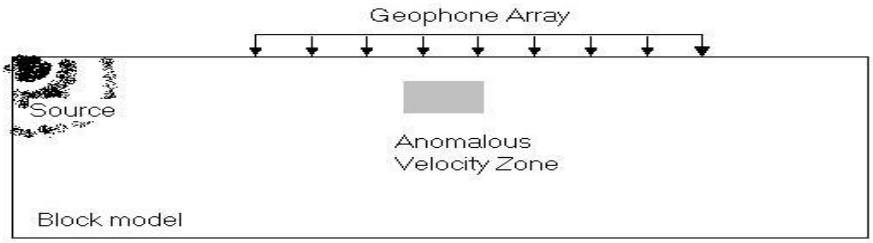

Figure 14. Model for refraction line geometry used in detection of anomalous velocity.

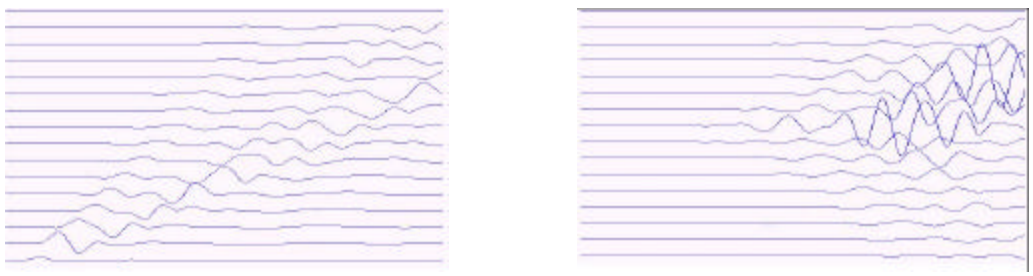

Figure 15. (a) Left block shows traces with the anomalous structure. (b) The right block (gain x 20) represents the difference.

The phase velocity perturbation at any point along the line is a cumulative function of phase velocity perturbations between the source and that point. We are interested in directly observing differences in phase velocity and must first find the perturbations in phase velocity at any position. The travel time, t, of a phase at given frequency traveling from a reference or reference position, x_r, to the observed position at distance, x, under the condition that the phase velocity is a function of distance can be expressed as:

$$t = \frac{f(w,x) - f_{ref}(w,x)}{w} = \int_{x_r}^{x} \frac{dx}{c(w,x)} \qquad (4)$$

A similar equation can be written for the travel time, *t`*, for a phase in a perturbed velocity structure. Expressing the perturbed velocity as, *c(w,x)+ Dc(w,x)*, that time is given as,

$$t' = \int_{x_r}^{x} \frac{dx}{c(w,x) + \Delta c(w,x)}$$

The difference in these two times is then measured directly by the difference in the phase spectra of the arrivals and the difference in the integrals.

$$\frac{\Delta f(w,x)}{w} = \int_{x_r}^{x} \frac{\Delta c(w,x)dx}{c(w,x)(c(w,x)+\Delta c(w,x))} \qquad (6)$$

In this application, *Dc(w,x)* is small and will vary about zero when compared to a relatively large and positive value for c(ω,x) and, thus, we can use the mean value theorem to pull c(ω,x) out of the integral. The equation we have to solve at each frequency is thus,

$$\frac{\Delta f(w,x)}{w} = \frac{1}{\bar{c}(w)^2} \int_{x_r}^{x} \Delta c(w,x)dx \qquad (7)$$

Equation (7) is solved either by differentiating the observed phase differences or by a numerical approximation to the integral. The preferred solution would depend on the efficiency by which the data in each can be smoothed to minimize noise.

By obtaining high-quality repeated measurements, a difference seismogram may be obtained that represents the response to the anomalous structure. We can obtain phase differences that are representative of all expected changes in the seismograms, although they should be dominated by changes in phase velocity of surface waves. This is the case in figure 4 where the difference in amplitude of the traces from the two conditions is too small to be observed without computing a difference trace. In real data, the traces would be composite traces, the sum of multiple shots to reduce noise, and the amplitude would be normalized. Alternatively, the difference in the traces may be minimized outside the area of expected perturbation to find an optimal normalizations factor for each set of traces. In the theoretical example, the greatest changes are observed in region of the maximum amplitudes of the surface waves starting at the position of the anomalous block. The major contribution to the difference traces comes from a phase shift, not a change in amplitude.

The Fourier transform of the difference of two traces with identical sources and recording sites will give an estimate of the phase shift caused by the anomalous velocity. To show this, the Fourier transform of the difference, *d(t)*, of two traces, *a(t)* and *b(t)*, can be written as,

$$d(t) = \sum_{w} |A(w)| e^{i(f+\Delta f/2)} e^{iwt} + |B(w)| e^{i(f-\Delta f/2)} e^{iwt} \qquad (8)$$

where f is the average phase shift. The real part of equation (8) can be written in terms of the sum and difference in the amplitude spectra as,

$$d(t) = \sum_{w} (|A| - |B|) Cos(wt + f) Cos(\Delta f/2) + (|A| + |B|) Sin(wt + f) Sin(\Delta f/2) \qquad (9)$$

By normalizing the amplitude of the traces, the difference in the amplitude spectra, the first term in equation (9) is minimized. The result for small changes in velocity is that the spectra of the difference in the traces will be dominated by the phase shift. Hence, under condition of minimum difference in the amplitude spectra of the two traces, the phase shift is approximated by,

$$\Delta f \approx 2 Sin^{-1}\left(\frac{|D(w)|}{|A(w)| + |B(w)|}\right) \quad . \qquad (10)$$

Hence, the Fourier transform of the differences of the normalized traces near the surface wave arrivals will approximate the phase shift. These phase shifts are total system responses including the influence of converted waves as well as the dominant effect of changes in phase velocity of the surface waves. These phase differences are then used to solve for perturbations in phase velocity in equation (7).

The phase perturbations computed by equation (10) provide sensitive estimates of the phase velocity perturbations. In conventional methods a change in phase velocity is computed by first computing phase velocities in each of two sets of traces. In each, the phase velocity is obtained by comparison of adjacent traces, typically in the frequency domain. Generally this requires, first, a removal of the mean velocity, second, a transformation to the frequency domain, and, third, an unwrapping of the phases or the difference in the phases to determine the dispersion relation. These processing steps can add uncertainty to the analysis process. The difference method minimizes the uncertainty by normalizing the traces and computing the difference in the time domain.

Conclusions

The research has developed a perturbation method of inversion of surface waves for shear-wave structure. The perturbation method is stable and relevant to the perturbation character of the wave propagation. Primary innovation is the formulation of this inverse problem in the form of a perturbation is in the introduction of orthogonal functions of velocity with respect to depth. The perturbation approach mimics the way waves sense velocity perturbations in the earth. The choice of orthogonal velocity

perturbation functions provides a consistent inversion for all pixels in an image generated by surface-wave tomography. In particular, the influence of a local inhomogeneity may be to perturb the velocity of the surface wave, rather than to cause a major change in the distribution of energy in higher modes.

The inversion in this research is based on a reference velocity structure that is typical of soils. We compiled data on the variation of soil velocity versus depth (equivalently pressure) to define the reference velocity structure. The orthogonal velocity perturbations to the velocity structure were designed to be consistent with the resolution of surface waves.

The inversion method is compatible with the steep gradients found in soils. We have used finite difference programs to generate synthetic wave forms for a gradient structure and used these waveforms to generate dispersion relations and compared these to those generated by using conventional matrix equations for layered media. The most significant difference between a gradient in velocity and a layered velocity structure appears to be in the existence and character of higher modes.

We developed a few notable innovations in the FD programming. These include the frequency domain implementation of a stable free surface condition and the use of a finite difference code to confirm interpretation of apparent discontinuities in the group velocity.

Group velocity interpretation differs significantly form phase velocity. The minimum time path is associated with the phase velocity, may refract around an inhomogeniety. The group velocity measurements can sense the larger energy groups traveling through the anomalous structure. The minimum time path does not always correspond to the path of maximum energy.

Finally, in this research we recognized a potential for a differential interpretation technique that promises to provide real-time analysis of minor perturbations in structure. By using the actual seismic traces as a reference, rather than a reference velocity model, very slight perturbations in velocity can be measured. Future studies will be testing the sensitivity and usefulness of this new technique.

Relevance, impact and technology transfer

This project addresses critical DoE environmental Management problems related to identifying structures in soils, such as trenches where waste has been buried. By evaluating the temporal variation in velocity structure, the method may prove useful in monitoring water and/or organic contaminants in soils. Most importantly, the tomography aspect of the technique allows measurements at distance, avoiding hazards associated with access to the surface above a contaminated zone.

The application of surface-wave group-velocity tomography could potentially reduce the costs for technologies and cleanup approaches by minimizing the number of drill holes needed to test an area for suspected hazardous waste. It could also assist in extrapolating information from limited test wells to a larger area with detail not possible without drill holes every 2 to 4 meters. The new development of rapid perturbation inversion of surface waves could allow real-time monitoring of some remediation processes relate to fluids in shallow soils.

This project is attempting to apply theoretical techniques used in regional and global seismology to the scale of a 100 meters. There is a significant gap between these global studies and the engineering test methods, like Spectral Analysis of Surface Waves (which give interpretation at one point and require access directly above the site). Alternative methods, such as those that use surface waves along a refraction line, are also under development but still require access to the surface above the structure.

The shear-wave velocity is an important parameter in many studies, not just the location of waste and monitoring of fluid flow. It is important in foundation and building design. For these applications seismic refraction or cross-hole velocity studies are usually performed. Shear-wave velocity structure is important in analysis of structures for resistance to damage in an earthquake and for estimating the risk of

damage in an earthquake. The technique could also be useful in analyzing the potential for liquefaction during shaking.

The method should be tested for application to a variety of problems. The primary deficiency of the method at this time is a lack of experience in applying the method to a variety of conditions. The main impediment to more general application at this time is access to sites and continued development of analysis programs for improved efficiency.

The move from SASW and seismic refraction to surface-wave tomography is equivalent to the move from seismic reflection profiles to three dimensional seismic processing. The advantages of a three dimensional image are significant improvements in the ability to visualize the structure and processes in the near-surface soil environment. The move to tomography also requires reevaluation of many conventional interpretation techniques.

Project productivity

The objectives of this contract were to investigate the inversion of tomographic images of surface wave velocity for shear wave structure and to test the method in the field. The inversion techniques were developed and extended to significant new applications, exceeding the goals of the project. However, the new data sets could not be obtained. The development of the inversion methods took longer than expected and when we were ready to go to the field, the computer in the acquisition system failed. The acquisition computer has been repaired and the acquisition program installed so that new data sets can be obtained in the near future.

Personnel supported

Principal Investigator:

Dr. Leland Timothy Long, Professor of Geophysics, School of Earth and Atmospheric Sciences, Georgia Institute of Technology.

Graduate Research Assistants:

Ms Tatiana Totiva, graduate student, was responsible for computer modeling of synthetic waves and the development of phase velocity measurements. She also assisted in field data acquisition.

Post Doctoral Assistants:

none

Electronics and Computer Assistance:

Roberto Stuart and Mark Keever provided assistance in computer system management and repair.

Student Assistants:

none

Publications and Presentations

Long, L.T. and Tatiana Toteva (2002). Differential surface-wave interpretation of temporal changes in velocity, Expanded Abstract, Society of Exploration Geophysics Meeting, Salt Lake City, October, 2002.

Long, L.T., (2002) Group Velocity Inversion Using Synthetic Surface Waves in *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems*, The Environmental and Engineering Geophysical Society, February, 2002. (SAGEEP02)

This presentation gave the basis of the inversion technique studied in this research.

Long, L.T., and A. Kocaoglu (2001) Surface-Wave Group-Velocity Tomography for Shallow Structures, *Journal of Environmental and Engineering Geophysics, Vol. 6, No. 2*, pp. 71-82.

Uses the data from Hamburgh State Park to illustrate the technique and describe the resolution of surface-wave tomography.

Jeffrey Martin, L. Timothy Long, and Toshiro Kubota. Imaging near-surface buried structure with high-resolution surface-wave group-velocity tomography. Proceedings of the IEEE Signal Processing Society, International Conference on Image Processing, Vancouver, Canada, September 10-13, 2000

This paper presented the theory for the inversion of tomography data that we used in this research. It reports on a test of High-Resolution surface-wave tomography for detection of buried waste and ordinances. It emphasizes the use of Surface wave tomography for small object at a site where the target positions are known. The test range is located at the Cobb Co. offices of the Georgia Tech Research Corporation.

Long, L.T., and Kocaoglu, A. (1999). Surface-Wave Group-Velocity Tomography for Shallow Structures, in Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Environmental and Engineering Geophysical Society, March, 1999 (SAGEEP99)

Presented the analysis and results from a small square of data from the Oak Ridge National Laboratory site.

Long, L.T.(1999). Seismic Surface Wave Tomography at Waste Sites, Research Note in: Fast Times, The EEGS Newsletter, February.

Presented the method in abbreviated form, non-technical description of the data and its interpretation from Hamburgh State Park.

Long, L.T., A. Kocaoglu, W.E. Doll, X.Q. Chen, J. Martin. Surface-Wave Group-Velocity Tomography for shallow structures at a waste site, SEG Expanded Abstract, Annual Meeting, Houston, October 1999.

Long, L.T., A. Kocaoglu, J. Martin, and F. Williamson. Analysis package for in-field group-velocity tomography measurements using a portable computer.

(internal document currently under revision and development of an install program. This program is to be made available through on web page or distributed by some other arrangement to be determined later)

Interactions and meetings

Society of Exploration Geophysics, Salt Lake City, October 2002. (see reference to expanded abstract above) At this meeting, the new theory on differential analysis of surface waves was presented.

Environmental and Engineering Geophysical Society, February, 2002. (SAGEEP02) in Las Vegas (see reference to Long 2002 above). This presentation gave the basis of the inversion technique presented in this research.

The PI attended a February, 2002 meeting on Inversion methods sponsored by Army Research Office, Waterways Experiment Station, Vicksberg MS.

The PI has acted as a consultant and advisor on numerous proposals relating to the detection and monitoring of underground facilities. He is currently acting as an advisor and possible participant on a development program for an instrument package that can be deployed in remote areas to monitor underground facilities. This work is in collaboration with researchers in the Georgia Tech Research Institute.

The PI is currently on the Ph.D. thesis committee for a Civil and Environmental Engineering student studying aspects of surface wave inversion.

Transitions

We are currently investigating various avenues to distribute the surface-wave group-velocity tomography analysis techniques developed under this contract. We are continuing discussions of the possibility of developing a commercial package in cooperation with major instrument manufacturer. The analysis package would be marketed as part of a seismic acquisition system and we would jointly run training workshops for equipment operators. A commercial package would require a robust dispersion inversion program, such as developed in this project. Alternatively, we could make the analysis programs available through Georgia Tech and provide support and documentation, perhaps through workshops.

The industry is generally reluctant to adopt and use (i.e. spend real dollars on) an unproven technique like surface-wave group-velocity tomography. Adoption of this technique will come only after a number of case studies are successfully demonstrated and after convenient (i.e. user friendly) packages are available. Hence, a natural extension of the proposed work would be to seek new "problem" areas to image and to use as demonstration data sets. Such areas could help to further develop the analysis programs and improve their ability to handle a wide variation in field conditions, as well as build confidence in the capabilities of the technique. In particular, the application to specific critical problem should be evaluated. The potential of differential techniques to image slight variations in velocity could prove critical in assessing fluid flow in porous soils. Also, such problems could include the assessment of the relation between age of burial and ease of detection. The decrease in detection capability for older structures is expected because the disturbance of a burial will heal with time and the rate of this healing and its impact of seismic velocities is not well understood. There exist additional interpretation problems to evaluate, such as the impact of trees of various size on the passage of surface waves.

Patents

No patents applied for at this time.

Future work

The future work will examine and evaluate the prospect of using the differences in waves to detect slight changes in structure and create a transportable package for acquisition and analysis.

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