FINAL REPORT
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SEISMIC SURFACE WAVE TOMOGRAPHY OF WASTE SITES

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Executive Summary

Because the Rayleigh waves generally have the largest amplitude of all waves generated by a vertical surface impact and because the near-surface shear-wave velocity primarily determines the Rayleigh wave velocity, the Rayleigh waves may be used to image shallow shear-wave structures. The Rayleigh wave group velocity can be measured from records of surface waves that have traversed a study area, typically, with a surface source on one side and an array of geophones along the opposite side. After data processing and noise suppression, group-velocity travel times from different source and receiver locations can be used in a tomographic inversion to image the distribution of group velocity within the study area. Then, vertical shear-wave velocity structure at any point can be interpreted from its dispersion curve.

The objective of this study was to develop analysis programs for surface-wave group-velocity tomography and apply these to three test areas. We succeeded by obtaining data covering two square areas that were 30 meters on a side and one that was 16 meters on a side, in addition to processing data from the Oak Ridge National Laboratory site, a collaborative effort. At all sites, usable group velocities were obtained for frequencies from 16 to 50 Hz using a sledgehammer source. The resulting tomographic images and velocity anomalies were sufficient to delineate suspected burial trenches (one 4-meters deep) and anomalous velocity structure related to rocks and disturbed soil. The success was not uniform because in portions of one area the inversion for shear-wave structure became unstable. More research is needed to establish a more robust inversion technique.

Research Objectives

The objectives of our contract (D-FG07-96ER14706) were to develop the computer programs and acquisition system for surface-wave group-velocity tomography and test these at three sites. An overview of surface-wave group-velocity tomography is given in our paper submitted to Journal of Environmental and Exploration Geophysics (JEEG). As described in the JEEG paper and summarized below, we have developed recording and analysis techniques to obtain the group velocity dispersion curves for a portion of a study area with a resolution theoretically limited only by the wavelengths of the surface waves.

Surface waves are uniquely suited for the estimation of near-surface shear-wave velocities. 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. In seismic tomography, waves crossing a study area are measured on its boundary in order to image the interior. The resolution of the image is limited by wavelength and imaging technique. Surface-wave group-velocity tomography has been used in seismology for over 30 years to study global crustal structure and recently to study regional structure and sedimentary basins (Kafka and Reiter, 1987; Kocaoglu and Long, 1993). In this project, we have applied the tomographic inversion of surface-wave velocities to areas with dimensions appropriate for near-surface structures that are often encountered in environmental problems.

The application of surface-wave tomography to near-surface structures has advantages and problems. The problems are introduced by the complexities of the structure and by the indirect and computationally intensive techniques that are inherent in surface wave interpretation. Structures in the near surface often do not satisfy the 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. The velocity contrasts may also be great at shallow depths, grading quickly from loose sands to unweathered granite. These conditions lead to wave modeling and resolution problems. However, the interpretation techniques presented in this paper were not significantly affected by converted waves and the computational complexity was easily within the capabilities of portable computers. The advantages of tomography are sufficient to warrant the use of surface waves in waste site evaluations. For example, an image of shallow structure can be obtained from the periphery of sites with limited access. In areas where trenches were used to dump wastes, the area of the trench will be revealed as an anomalous velocity. 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. The sensitivity of surface wave velocity to fluid content could eventually allow surface-wave tomography to track fluid movement with time.

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. These could include detection of the existence of dense fluids as contaminates.

To date we have limited our studies to shallow and small areas. With a larger source, the use of lower frequencies could increase the depth of effective imaging and allow applications with larger and deeper targets.

Surface-wave group-velocity tomography should be compared to those of SASW. However, the tomography should provide structures in three dimensions, not just average structure with depth. Tomography should improve the spatial resolution over that possible with multiple SASW tests and provide it with significantly less 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.

Few organizations other than Georgia Tech are currently investigating surface-wave, group-velocity tomography. With the exception of isolated attempts, such as the field trials reported through personal communication from Juhani Korkealaakso, chief research scientist in the Technical Research Centre of Finland (VTT), we know of few attempts to develop this technique for near-surface applications. The reasons for this are obvious. Execution of the technique is involved, requiring signal processing and multiple data inversions. Noise or errors in any one of these processes 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 not generally available to practicing environmental geophysicists and most would be reluctant to undertake development of the analysis programs without proof that the analysis works. During the course of the 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 simplest way to present the current state of knowledge is to condense and annotate our paper submitted to JEEG.

Methods and Results

The methods and results for this investigation are adapted from the paper titled "Surface-Wave Group-Velocity Tomography for Shallow Structures" by L.T. Long and A. H. Kocaoglu. Sections representing research not presented in the paper are inserted as appropriate.

Introduction

Surface waves are suited for the estimation of near-surface shear-wave velocities. 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 quarter wavelength, and their dispersion properties allow separation of different wavelengths for interpretation of velocity as a function of depth. When examining near-surface structures, these factors give the surface-wave method an advantage over the body wave methods used in seismic reflection and refraction. Most surface-wave methods used in the evaluation of near-surface velocity structure are based on measurements of phase velocity. When the signals are generated by single-frequency signal generators and measured in the field at discrete frequencies, the surface wave technique is generally referred to as SASW (Spectral Analysis of Surface Waves) testing in the engineering literature (Stokoe et al., 1989). The SASW test utilizes two (or more) sensors over the test zone and measures phase velocity in the frequency domain from the phase shift between two or more sensors. In order to examine the spatial variation in the near-surface shear-wave velocities, the SASW test would have to be repeated at many points over an area. Because the precision of phase velocity measurement is proportional to sensor spacing, the spatial resolution is limited. Park et al., 1999, improve the accuracy of phase velocity measurements by increasing the number of geophones in a multi-channel analysis of surface waves (MASW) technique and gain 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.

In contrast, seismic tomographic methods yield images representing the spatial variation of velocity with dimensions smaller than the array of geophones. In seismic tomography, waves crossing a study area are recorded at its boundary in order to image the interior. The resolution of the image is limited by wavelength and imaging methods, not just sensor spacing. Either phase velocity or group velocity can be measured. However, with large sensor spacing the dispersion shifts phases through a wide band of frequencies and the identification of phase velocity at discrete frequencies becomes more difficult. Group velocity measurements are confined to narrow frequency bands and are independent of phase identification. Hence, for areas large relative to the wavelength of the surface wave, group velocities are more appropriate for velocity determination. Surface-wave group-velocity tomography has been used in seismology for over 30 years to study crustal structure (e.g., Tarr, 1969) and recently to study regional structure and sedimentary basins (Kafka and Reiter, 1987; Kocaoglu and Long, 1993a). In this analysis, we apply the tomographic inversion of surface-wave velocities to an area with dimensions appropriate for imaging near-surface structures that are often encountered in environmental problems.

Surface-wave tomography has advantages and problems when applied to the imaging of near-surface structures. The problems are introduced by the complexities of the structure and by the indirect and computationally intensive techniques that are inherent in surface-wave interpretation. Structures in the near surface often do not satisfy the 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. The velocity contrasts may also be great at shallow depths, grading quickly from loose sands to unweathered granite. These conditions lead to waveform modeling and resolution problems. However, the interpretation techniques presented in this paper were not significantly affected by converted waves and the computational complexity was within the capabilities of portable computers. The advantages of tomography are sufficient to warrant the use of surface waves in waste site evaluations. For example, an image of shallow structure can be obtained from the periphery of sites with limited access. In areas where trenches are used to contain wastes, the area of the trench may be revealed as an anomalous velocity. In areas where seepage from a waste site is controlled by structure, the structure might be defined and used as a guide for drilling and sampling.

Surface Wave Tomography

Surface-wave group velocity is used is this study in order to generate a tomographic image of the S-wave velocity structure. We measure group velocity of a selected frequency from the travel time of surface-waves traveling from a source to an array of sensors. In this analysis ray theory is assumed. That is, we assume that the structures vary only slightly within distances of a wavelength. Elastic waves in general tend to average material properties with dimensions smaller than a quarter of a wavelength and this effect limits the ability of elastic waves to resolve detail. Formally in ray theory, the travel time is computed from the integral of the slowness along a given raypath

$$t = \int s \; dl \tag{1}$$

where s is the slowness (reciprocal of velocity) and dl is the line element along the raypath. A common approach in seismic tomography is to divide the medium into small blocks (pixels of the image) and estimate the slowness in each block from the observed travel times. The minimum-time paths for waves traversing a medium with anomalous velocity structure are a function of slowness and are curved. 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 be less than a quarter wavelength. Deviations smaller than the block size will not introduce significant errors and deviations less than a quarter wavelength will be within the limits of image resolution. In media with large velocity anomalies, the general ray theory inversion becomes nonlinear. The iterative solution in this paper could accommodate a nonlinear solution by using numerical techniques (e.g. ray tracing) to identify those blocks that influence the propagation along each curved ray path. We solve linear discrete tomography problem by approximating Eq. (1) with constant slowness values in finite blocks. The discrete form of Eq. (1) is a matrix,

$$\mathbf{t} = \mathbf{Ls} \tag{2}$$

where $\mathbf{t}$ is the vector of observed travel times, $\mathbf{s}$ is the slowness of the blocks, and $\mathbf{L}$ is an $M \times N$ matrix of raypath segments, with M rays crossing the medium and N blocks in the model.

The problem of tomography is to solve Eq. (2) for the unknown group slowness, the reciprocal of group velocity. The measured group velocity at each frequency contains information about the underlying velocity structure to depths corresponding to approximately one-quarter wavelength of that frequency. The frequency dependence of group velocity is the dispersion curve corresponding to the structure below that position in the image. The dispersion curve is a direct indicator of the subsurface shear-wave velocity. 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.

Most geophysical inverse applications lack sufficient data to guarantee uniform coverage and to remove all the singularities in the least-squares solution. In geophysical applications, noise in measured travel times can degrade the solution and can produce spurious velocity anomalies. The generalized inverse, using damped least squares or singular value decomposition, and the conjugate gradient techniques are among many used in tomographic inversions to minimize the effects of noise. The advantage of a generalized inverse computed using these methods is that the model and data resolution matrices and the error covariance matrix can be computed. An inherent drawback of generalized inverse methods is that they require extensive computational resources (CPU time and memory) making it difficult to obtain detailed images in real-time under the field constraints commonly experienced in the acquisition of data for surface-wave tomography.

In order to obtain a solution to Eq. (2), we use iteration to find the damped least-square error solution. We start with a guess, an a priori solution, $s^{(k)}$, and find the new solution, $s^{(k+1)}$, using the alternate form for damped and weighted least squares (Menke, 1989, p. 55, Eq. 3.40),

$$s^{(k+1)} = s^{(k)} + W_b^{-1}\mathbf{L}^{\mathbf{T}}[LW_b^{-1}L^T + \varepsilon W_t^{-1}]^{-1}(\mathbf{t} - \mathbf{t}^{(k)}), \qquad (3)$$

where, W_b is weight assigned to each block. In this study the weight is the number of times a block is sampled by a ray. W_t is the covariance matrix for the observed times, and ε is the damping coefficient, which is chosen by trial and error to give the greatest resolution without causing instability in the inversion. For small damping, the solution approaches the weighted least-squares solution and for large damping the solution approaches the weighted minimum-length solution. The solution to Eq. (3) becomes the next guess and the iteration is repeated until the guess converges to the solution. Because the block weights and reading errors are generally independent, W_b and W_t, may be assumed to be diagonal and their inverse is trivial. However, the inverse to $[LW_b^{-1}L^T + \varepsilon W_t^{-1}]$ is difficult to compute for large data sets and we approximate this term by its diagonal. This approximation is justified when most of the elements of **L** are zero and tend to cancel out the off-diagonal elements. This is generally the case in tomography because each ray samples only a small subset of blocks comprising the model. A consequence of avoiding the large matrix inversions in the exact least-squares solution is the inability to directly compute the data and model resolution matrices. The lack of a resolution matrix is not generally a problem for surface wave tomography because the ray path coverage can be made arbitrarily uniform by the design of the shot and receiver positions. Also, the main function of the resolution matrix is to examine spatial variations in the ability to resolve individual cells. Because the data can be made arbitrarily dense, resolution is primarily limited by wavelength. The damped and weighted least-squares solution of Eq. (3) is computationally a more rigorous version of the simultaneous iterative reconstruction technique (SIRT) (see Lo and Inderwiesen, 1994, p. 36, Eq. (46)). In SIRT, the residuals between observed and predicted travel times are back projected to obtain average slowness perturbations to be used to update the latest slowness model.

Data Acquisition and Processing

Site Description

The site chosen for presentation in this study is located in east central Georgia, USA, in an unused portion of Hamburgh State Park. In the study area, the near-surface materials are sands and clays characteristic of the Coastal Plain sediments of Cretaceous age. The area is near the boundary between the coastal plane sediments and the crystalline Piedmont Province rocks. The test area is on a smooth slope down to the south with a drop of approximately 3.0 m over 30 m. The area is an open grassy field bounded by a young pulpwood pine forest.

Data

The test geometry selected for the surface-wave tomography experiment is a 29.3 m (96 ft) square on a side. The sensors were placed 1.8 m (6 ft) apart along the north (top) and west sides. The shots were symmetrically placed 1.8 m (6 ft) apart along the south and the east sides. The combination of 16 shots and sensors on opposite sides provided extensive coverage of the area (Fig. 1). The density of ray coverage for the study area ranges from 10 to 40 paths crossing imaging pixels of 0.9 m (3 ft) in size, and is sufficiently dense for this area geometry to allow pixels that are half the seismometer spacing in the interior of the rectangle. Along the edge the stability of the tomographic inversion is reduced because the pixels have a lower hit density and are primarily dependent on the adjacent shot or sensor locations. A refraction line was obtained to complement the tomography data. The 16 geophones were placed 3 m (10 ft) apart along a line striking N 60° W centered on the tomography square and passing 1 m south of its northwest corner. Shots were taken between the geophones, spaced at 3 m (10 ft) intervals, and extending 70 m from the center of the line in both directions. Field time to collect all data was approximately 4 hours.

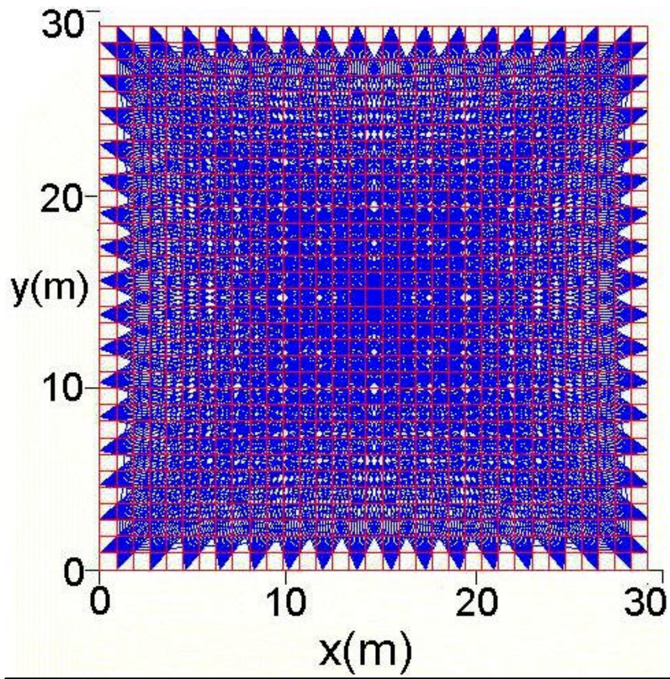

Figure 1. Ray geometry for a rectangular test area showing the density of ray paths.

At distances of less than 75 m, a sledgehammer provides sufficient energy for recording the surface waves. We used an eight-pound hammer with a trigger switch attached to the hammer's head. The strike plate was a block of wood which, unlike the rigid metal strike plate used in most shallow refraction studies, does not put as much high-frequency energy into the P and S waves and directs more of the energy into the lower-frequency surface waves. A typical recording (Fig.2) shows the moveout with distance expected for a shot point in one corner. The amplitude decay of coherent phases shows the consistency of the phase velocities. The dominant amplitudes correspond to the surface waves, principally the fundamental mode of Rayleigh waves, recorded on the 1.0 Hz vertical component seismometers used with our recording system. The 1.0 Hz seismometers have a flat response from 1.0 to 100 Hz. We recorded 16 channels at 6250 samples per second (sps) for 0.640 s. For analysis, the traces were filtered with a band-pass Butterworth filter extending from 5 to 170 Hz. The test area was isolated from electrical interference and no special filtering for 60-Hz electrical noise was needed.

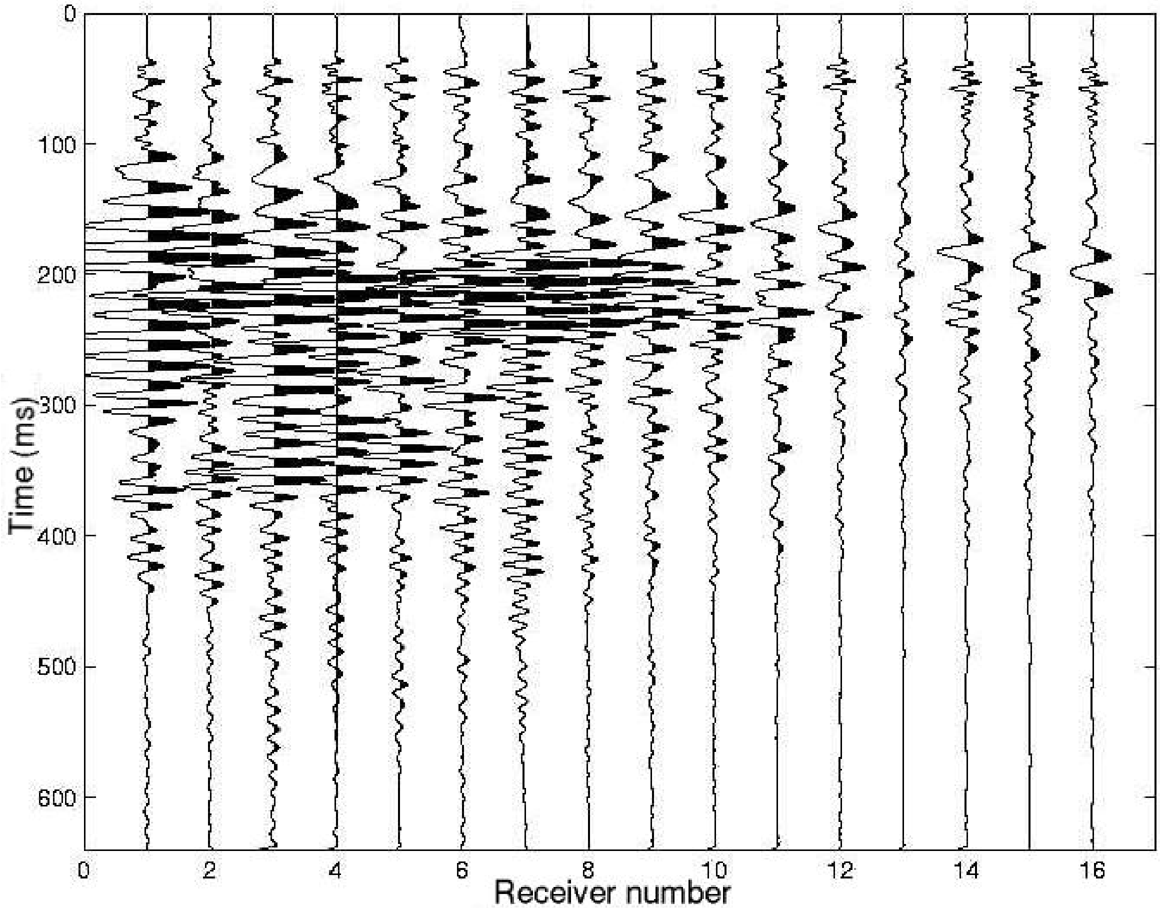

Figure 2 Seismic traces from a single shot located near the upper right-hand (northeast) corner of the square. The traces are recorded on the western border and extend from north (1) to south (16).

Estimation of Group Travel Times by Multiple-filtering

The multiple filter method (for details see Kocaoglu and Long, 1993b) was used to identify the arrival times of the surface waves at selected frequencies. The selected frequencies were limited by the energy in the recorded traces and by their wavelength. In this study reliable energy was observed for frequencies from 16 to 50 Hz. These frequencies provided appropriate wavelengths for imaging the top 1 to 8 m. Frequencies below 15 Hz had wavelengths greater than 20 m and were limited in their ability to resolve structures within the shallow depths of the study area. Higher frequencies are attenuated in the near-surface soils and obscured by interfering scattered body waves.

In the multiple filter technique, seismic data are filtered with a narrow-band filter. The group velocity for frequencies at the center of the narrow-band filter is estimated from the arrival time of the peak instantaneous amplitude. The center frequency of the narrow-band filter in our analysis is changed successively from 16 to 50 Hz at 1 Hz increments to allow tracking of group velocity as a function of frequency. The narrow-band filtering is performed in the frequency domain with a Gaussian filter whose bandwidth is proportional to the center frequency. In order to obtain the instantaneous amplitudes for each filtered trace, we compute the analytic signal, which is a complex signal with its real part defined by the actual trace and its imaginary part defined by the Hilbert transform of the real part. The instantaneous amplitude of the output is the magnitude of the complex trace in the time domain. The results of multiple filtering are shown for frequencies of 16 (Fig. 3a) and 24 Hz (Fig. 3b). The trace-to-trace variation in arrival times of the peak instantaneous amplitudes for a given frequency indicates the group velocity anomaly along the ray-paths of the particular source-receiver geometry. Anomalous travel times of the surface wave are determined by comparing arrival times at adjacent geophones.

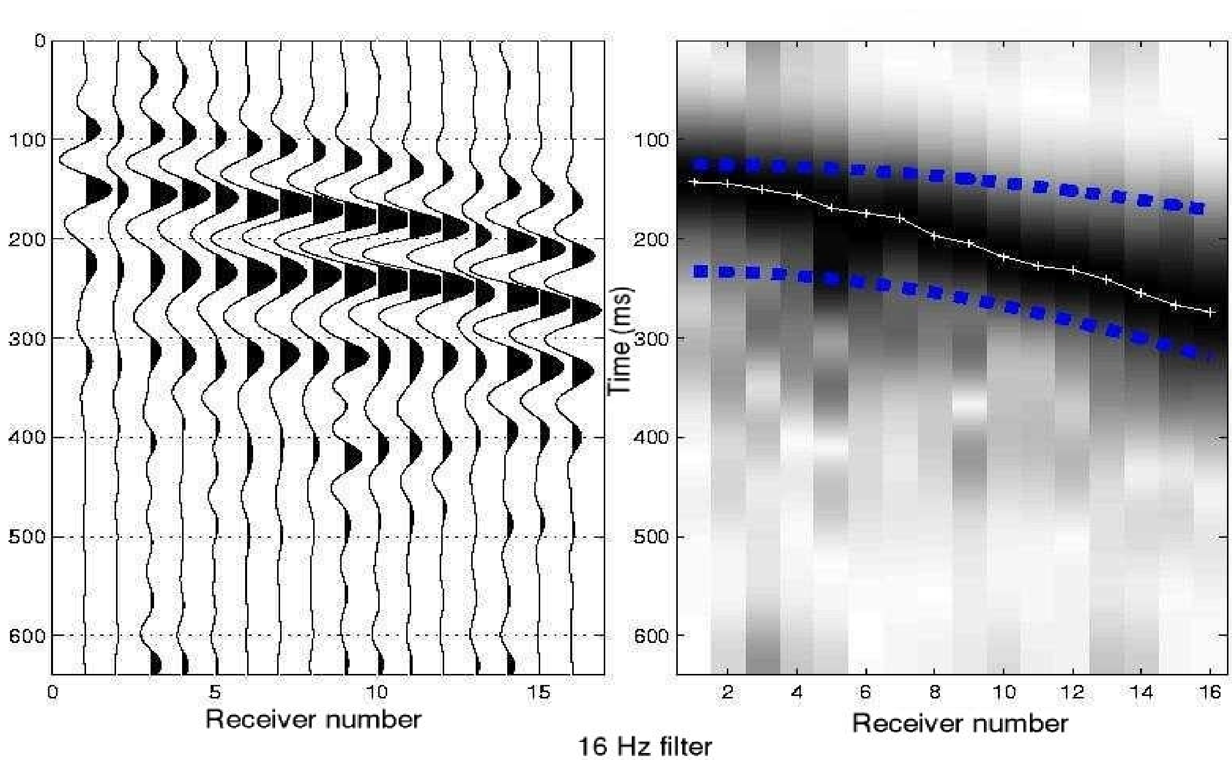

Figure 3a Filtered traces (left) and analytic signal (right) for 16 Hz. The line indicates the interpreted arrival time.

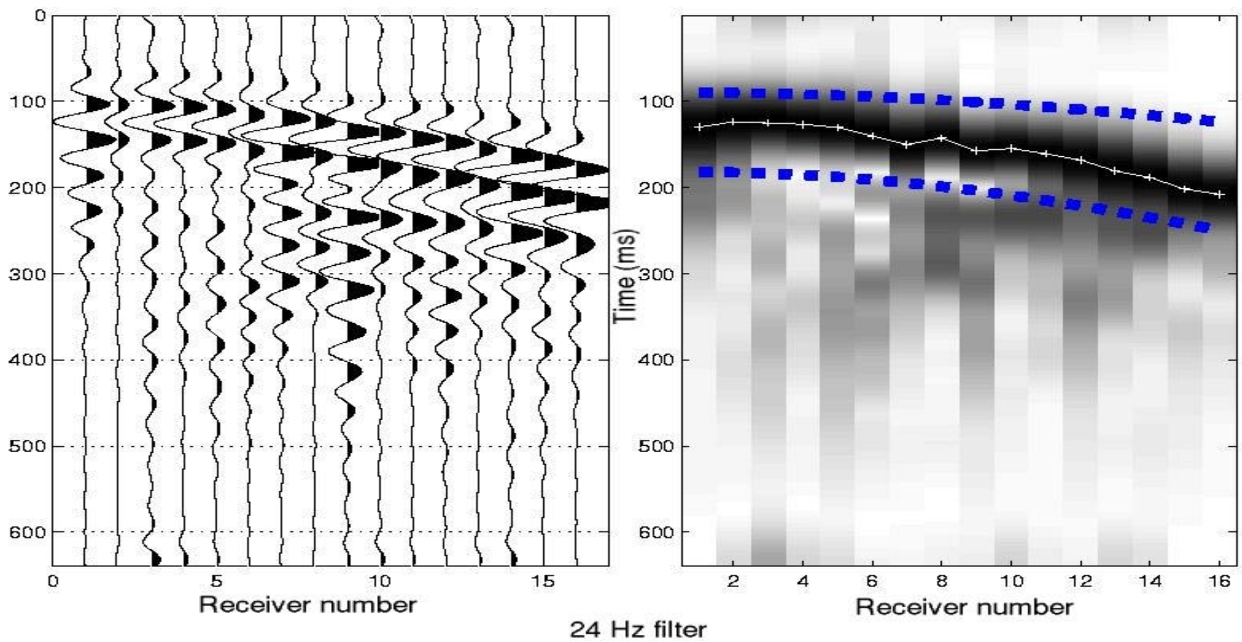

Figure 3b Filtered traces (left) and analytic signal (right) for 24 Hz. The line indicates the interpreted arrival time.

Unlike non-dispersive P-wave arrivals and other phases for which the trace correlates directly with the arrival, the picking of arrival times for determination of group velocity is achieved through the indirect multiple filter process. Along a line, the arrival of the wave group may shift across phases as can be seen in Fig. 3a at 16 Hz.

The amplitude peaks in the filtered record may be altered by noise. Slight noise may only introduce scatter in the location of the peak amplitudes, but noise that is large relative to the surface wave amplitude could cause peaks at extraneous times. Also, when waves are focused or scattered by anomalous structures and arrive at anomalous times, the interfering waves may introduce peaks at extraneous times. In order to minimize the picking of arrival times of peaks corresponding to interfering waves, such as the shear wave, the P-wave, the acoustic air wave or other sources of noises, we limited the picking of peaks to times close to the expected group arrival time of that frequency. The expected group velocity for a set of traces was found by stacking all filtered trace amplitudes with respect to group velocity. When a strong dispersed surface wave exists, the peak of this stack indicates the expected group velocity and the width indicates reasonable limits for expected variations in the group velocity. Alternatively, the range of acceptable time picks could be determined interactively through direct observation of the filtered traces. We applied an accept/reject condition to eliminate arrival times that fell outside the range of expected variations in the group velocity or that were inconsistent with neighboring arrival times. For some traces, particularly those that are at higher frequencies and at greater distances, no obvious peak may exist in the instantaneous amplitude and these spurious values are also eliminated with the accept/reject condition. The times corresponding to peaks in the

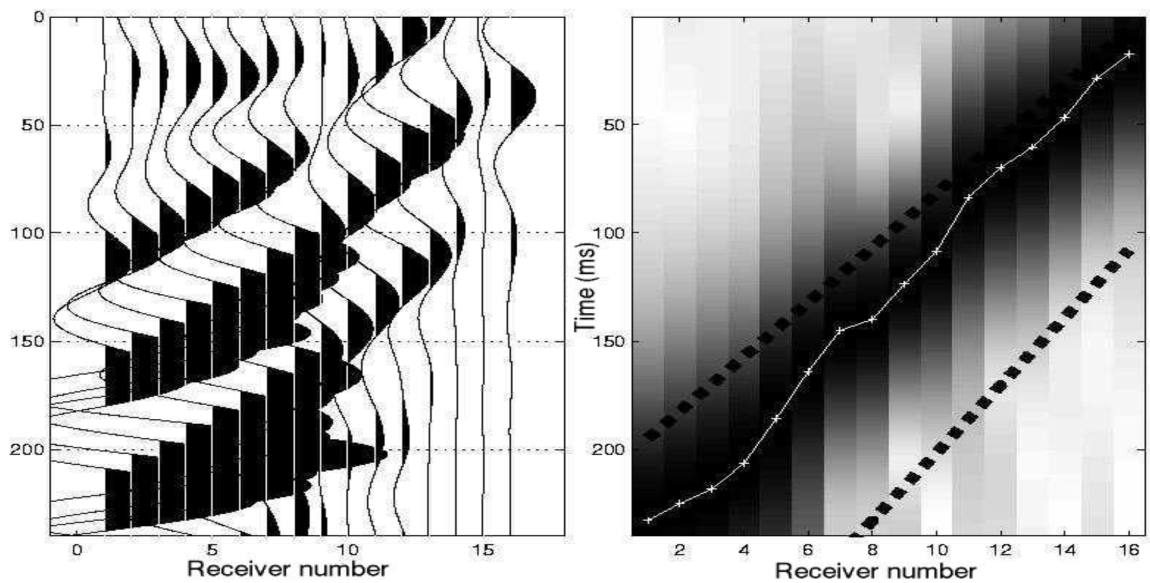

Figure 4. Filtered traces and analytic signal from the refraction line showing the offset and its interpretation.

amplitudes provide the basic data for the tomographic image at each frequency. However, these arrival times must first be corrected for group delays related to source function, instrument response, and ground coupling of the instrument. We have determined that the instrument and its coupling to the ground can impart measurable delays to the group arrival time. If left uncorrected, the velocities can be in error by 10 to 25 percent, particularly for frequencies near the geophone's natural frequency. While the instrument group delay can be determined exactly from the instrument's impulse response, the coupling of the instrument to the ground, and the source function delays depend on the properties of the ground. The coupling of the geophone generally resonates at frequencies one to two orders of magnitude higher than the geophone's natural period, but on soft ground it can be lower and significant for the higher frequencies measured. Average group delays that include all source and geophone effects can be measured directly from field data if data from a refraction line are available. Refraction line data (Fig. 4), from an area of assumed uniform structure, are processed for group delays with the multiple filter technique, thus including any group delays possibly introduced by the analysis technique. As the surface waves cross the survey area, the group arrival times at each frequency can be extrapolated back to the source and a delay time determined. These delay times are then removed from the observed times prior to further processing.

In this study, the precision of the observed group arrival times was generally less than 10 percent of the arrival time anomalies caused by the velocity structure, making it possible to compute a tomographic image. The uncertainty in picking a group arrival time depends, among other things, on the filter used in the multiple filter technique. A narrow filter, one that would be desirable for resolving the arrival time of a single frequency, gives a broader peak and a larger uncertainty in the time domain. A wider filter would give a narrower peak and more precise pick, but would yield an average velocity for a wide range of frequencies. Because the objective in this study is to determine the frequency dependence of group velocities, we use a narrow filter. For a narrow filter, the uncertainties of the picks can be large compared to the time one would expect for a surface wave to propagate from an adjacent station. We added a constraint in order to suppress the noise in the image introduced by the scatter in the group arrival times. The constraint is that the difference between the times of arrival at adjacent stations is given by the difference in travel time along the two expected propagation paths. The uncertainty is estimated from the uncertainty in the direction of wave front propagation for an inhomogeneous medium. The weight for the constrained least-squares reduction is inversely proportional to the uncertainty of the measurements of observed arrival time and the derived uncertainty in the time difference for similar travel paths. A constrained and weighted least-squares reduction is then used to determine the optimal arrival times by combining the amplitude picks and expected time differences between traces that follow similar paths. In this way, the different lines are tied together and random deviations in picks of arrival times are suppressed. The details of this reduction depend on the geometry, the number of similar paths included in the reduction and number of sides of the study area along which data were obtained.

Results and Discussion

We obtained 36 images at 1.0 Hz increments from 15 to 50 Hz (see Fig. 5 for selected frequencies). The images are 30 by 30 pixels, each slightly less than 1.0 m^2, corresponding to 900 unknown velocities at each frequency covering an area of 894 m^2. These images show a pattern of anomalies that changes gradually with frequency. In Fig. 5, the group velocity ranges from a low of 100 to a high of 300 m/s. For the lower frequencies, there is a distinct difference between the higher velocities in the north and the lower velocities in the south. For the intermediate frequencies, the anomalies are less distinct at an average of 225 m/s. Above 35 Hz the surface waves are most strongly affected by the top two meters. The images show a pattern that is related to surface features but may also include noise at the highest frequencies. For example, the lowest velocities at the higher frequencies are along the north edge. The north edge bordered a young pine forest where the near-surface soil would contain more humus accumulations than in the open field. The study area included a structure consisting of a 1.0-m deep cement base topped with a 1.0-m high cement block enclosure. This structure covered approximately a 2.0 by 3.0-m area located at 23-m north and 21-m east in Fig. 5. A high-velocity anomaly associated with this location is most pronounced at 16, 20 and 48 Hz (see Fig. 5). This structure is close to the resolution limits for the recorded wavelengths. Resolution limits for anomalous velocity structures depend on many factors, such as velocity contrast, object size, wave propagation path, and noise. However, a quarter wavelength limit suggests an average resolution of 2 m for most frequencies, with maximum resolution of 1 m at 50 Hz and 2 m to 5 m at 15 Hz.

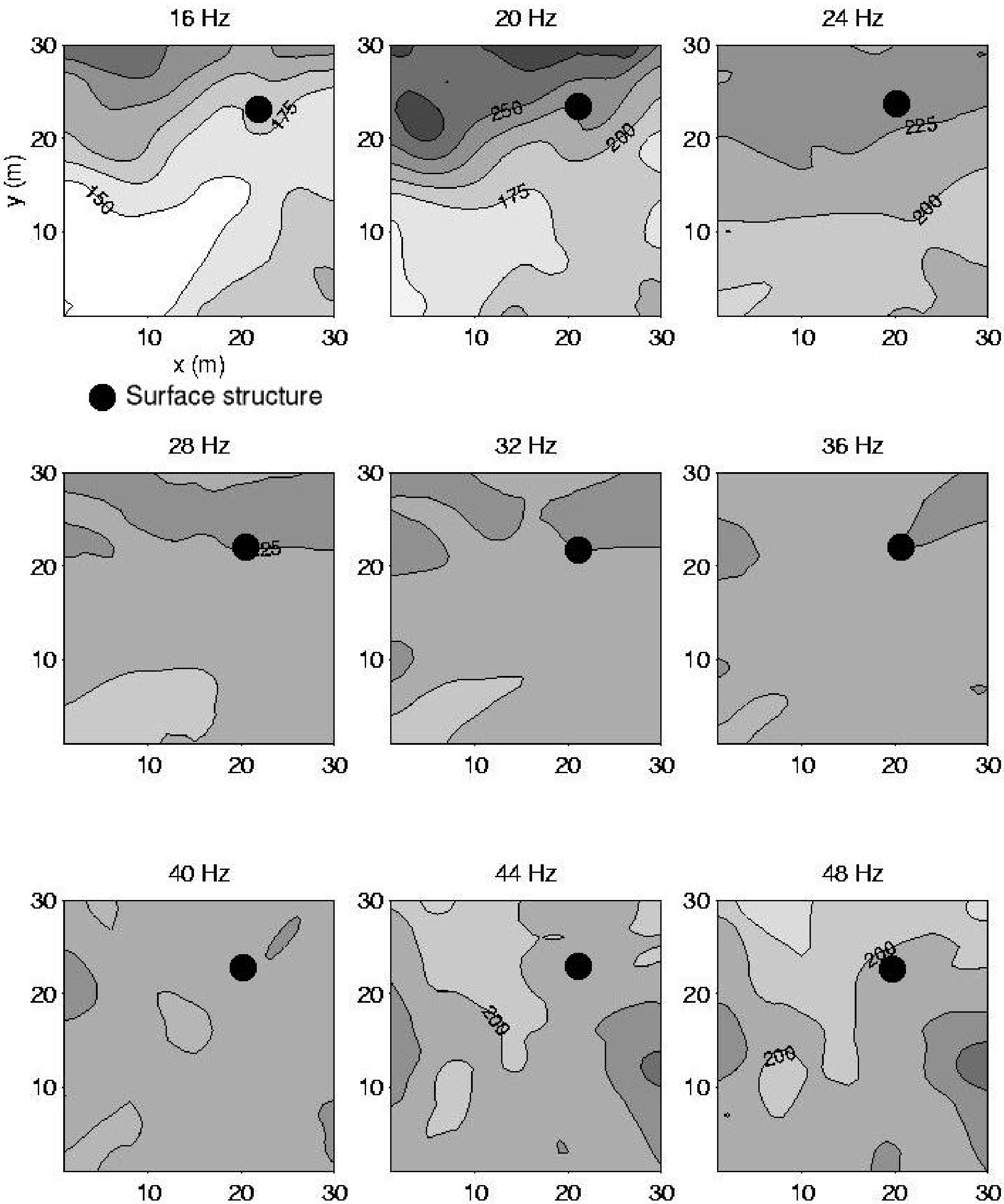

Figure 5 Tomographic images for 16 Hz to 48 Hz at 4.0 Hz intervals. Contour lines are group velocity in m/s. The solid square is the small cement block

With dispersive group velocities, the tomographic images of individual frequencies do not translate directly to shear-wave structure. In general with phase velocities the low frequencies are sensitive to the average of shallow and deep structure, while the higher frequencies reflect only structures at shallower depths. With group velocities, changes in phase velocity can lead to a group velocity minimum at some frequencies that can be deceptively low relative to the shear-wave velocity structure. Hence, interpretation of anomalous group velocity requires examination of structure as well as observed velocity anomalies.

Once the tomographic images are developed, a dispersion curve for selected areas may be generated. We generated the group velocity curves by using a distance-weighted average of the image. We used the weight function $w[r] = 1/[1+[a/r]^n]$, where r is the distance from the selected area, a is the distance where the weight is half its maximum value, and n controls the decay with distance. This arbitrary weight function was chosen because it is efficient in computer programs and allows adjustment of the radius of averaging and relative weights of near and distant values. Choosing $n=10$ in this study gives nearly equal weight to values at distances less than a and very little weight to values at distances greater than a. We generated an average dispersion curve for the entire area ($a=30$) in order to find an appropriate initial starting model for the determination of structure (Fig. 6).

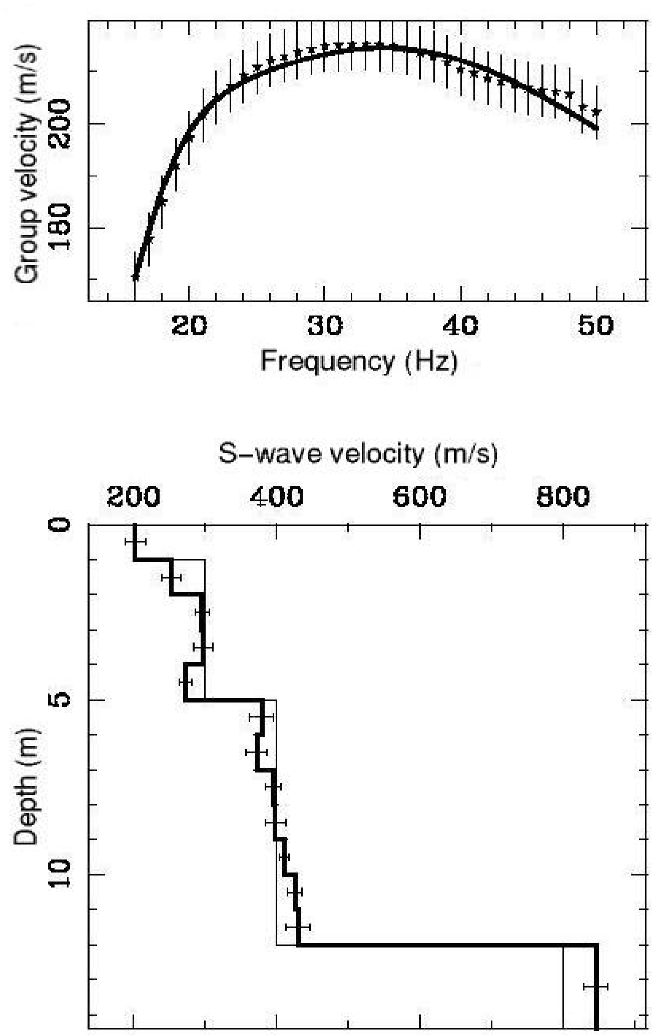

Figure 6 The dispersion curve is for the average group velocity of the entire area. The initial estimate is the light curve. The heavy line indicates the average model and its dispersion curve for the entire study area.

For a starting model, we chose a three-layer model with velocities of 200 m/s, 300 m/s and 400 m/s, respectively 1.0 m, 4.0 m, and 7.0 m thick, over an 800 m/s half space. The P-wave first arrivals from the refraction line indicate a two-layer model with velocities of 500 m/s, and 1300 m/s, respectively 1.0 m and 11.0 m thick, over a 2300 m/s half space. These are consistent with the initial shear-wave velocity model, considering the high Poisson's ratio of near-surface soils. For modeling shear-wave velocities at each pixel, we used a model with 12 one-meter thick layers over a half space. In general, the model parameters include layer thickness, shear-wave velocity, P-wave velocity and density. In this study we solve only for shear-wave velocity, fixing the layer thickness and using assumed values for density and Poisson's ratio. The inverse method outlined in Kocaoglu and Long (1993a) was used to solve for the model. Given an initial estimate of the model, the initial estimate of the group velocity dispersion curve can be computed directly from the model parameters. Then, by using the first two terms of a Taylor's expansion, corrections to the initial estimate of the model can be obtained by iteration until convergence is achieved at values within the estimated error of the measurements. The Jacobian matrix is computed numerically by using a finite difference approximation. For all iterations, singular value decomposition is used to provide stability in the generalized inverse.

The group velocity images suggest that the principal structure in this area is two-dimensional with an east-west strike. In order to illustrate this structure, we generated group velocity dispersion curves at 1.0-m intervals along a north-south line passing through the center of the study area. The half width used to generate an average group velocity curve for each of the 30 observation points along the profile was set at a width of 1.0 pixel (approximately 1.0 m). Although not needed for this study, a dispersion relation created for a larger half width (*a* > 5 pixel lengths) would suppress noise and produce a smoother image. The tradeoff for a smoother image is reduced resolution of the structure. The model for the average dispersion curve from Fig. 6 was used as a starting model for all points on the profile. The resulting structure (Fig. 7) indicates that the high velocities that are most obvious at 20 Hz (Fig. 5) are caused by a shallow high-velocity structure. There is a distinct 2.0-m vertical displacement of the velocity structure across a line near the 18-m point. The character of the anomaly with depth suggests a thrust fault or, alternatively, the existence of an area near the10-m point that has been disturbed to a depth of 4.0 m.

Conclusions

The tomographic inversion of travel times for images of group velocity is an effective way of identifying shear-wave structure. In the study area, the interpreted shear-wave velocity varied from 200 m/s at the surface to 450 m/s at 4-m depth and the image shows considerable detail. The structure suggests a possible thrust fault or edge of a buried trash dump. The resolution at a one-quarter wavelength dimension was sufficient at the high frequencies to

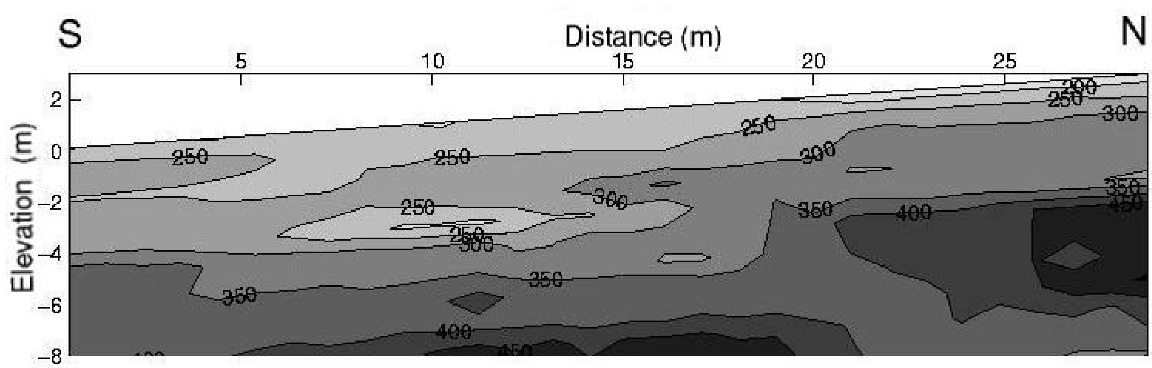

Figure 7. Structural cross-section extending south to north in the center of the study

resolve anomalous features to within 1.0 m, the size of the resolution pixel and half the geophone spacing. Usable dispersion curves were obtained for square areas with sides on the order of a single 1.0-m square pixel. These could be interpreted reliably for variations in velocity to a depth of 8.0 m. The analysis is designed so that images, dispersion curves, and interpretations of structure could be obtained during acquisition of the data in the field.

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Relevance, Impact and Technology Transfer

This project addresses 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.

Application of surface-wave group-velocity tomography could potentially minimize 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.

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 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 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 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.

Project Productivity

The objectives of our contract (D-FG07-96ER14706) were to develop the computer programs and acquisition system for surface-wave group-velocity tomography and test these at three sites. The project results, which met or exceed these objectives are reported in papers, expanded abstracts, and talks (see Publications). Complete inversion of one area was not accomplished because the surface wave inversion to shear wave velocity proved to be unstable for certain conditions. An unfounded extension was requested to initiate the study of the inversion technique. These studies led to a proposal for more detailed study of the inversion of surface waves in soils.

Personnel Supported

<u>Principal Investigator:</u>

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

<u>Graduate Research Assistants</u>:

Dr. XiuQi Chen. Dr. Chen was responsible for field acquisition assistance, data reduction and data analysis.

<u>Post Doctoral Assistants</u>:

Dr. Argun Kocaoglu. Dr. Kocaoglu was responsible for the development of the programs for group-velocity analysis and tomographic inversion.

Dr. Jeffrey T. Martin. Dr. Martin was responsible for field acquisition and programming of the noise reduction algorithms.

<u>Electronics Assistance</u>:

Mr. Frank Williamson. Mr. Williamson was responsible for interfacing the seismometers with the computer and programming the data acquisition system.

<u>Student Assistants:</u>

Mr. Thomas F. Collins assisted in the field acquisition and equipment maintence.

Ms. Heather S Nisbet assisted in the preliminary data processing and determination of velocity profiles.

Mr. R. Brook Miller assisted in the programming of the data acquisition system.

Publications

Long, L.T., and A. Kocaoglu (in press, June 2001) Surface-Wave Group-Velocity Tomography for Shallow Structures, Journal of Environmental and Engineering Geophysics,

Uses the data from Hamburgh State Park to illustrate the technique and describe the resolution of the method.

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.

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

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 at Cobb Co. Georgia Tech Research Corporation.

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, to be placed on web page or distributed by some other arrangement to be determined later)

Interactions and Meetings

DOE Atlanta meeting, April, 2000. Presented poster and discussion on the surface-wave group-velocity inversion method.

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, Talk and presentation at SEG Annual Meeting, Houston, November 1-3, 1999.

Presented a preview of surface-wave group-velocity inversion.

DOE Chicago meeting, 1998. Presented preliminary results from analysis.

Long, Leland Timothy, Surface-Wave Group-Velocity Tomography, (a power point presentation), Earth and Atmospheric Sciences Departmental Seminar.

Long, L.T. and Argun Kocaoglu, 1999. A tomographic inversion method for near-surface structure, (Abstract and talk, Eastern Section Seismological Society of America, Annual meeting October 16-20, 1999, Memphis, TN.

Present inversion details.

Transitions

We are currently investigating various avenues to distribute the surface-wave group-velocity tomography analysis techniques developed under this contract. For example, we are discussing 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 proposed 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. 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.

Patents

No patents applied for at this time.

Future Work

In this work we assumed that the conversion of dispersion curves to shear-wave structure could be accomplished using well-known and "tested" techniques. Our assumptions were wrong. These techniques were found to work for some of our areas, but became unstable in others, particularly those with low-velocity zones at depth. The instability in these cases is related to the numerical difficulties in distinguishing fundamental and higher modes. 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 models). Also, the existing inversion programs are based on constant velocity layers; an approximation that may not be appropriate for the strong depth-dependence in velocities typical of soils and their transition to unweathered rock. Programs to exactly model a gradient velocity structure do not currently exist (except as an approximation with a sequence of thin layers). Future work should be directed toward developing a robust and accurate inversion method specifically for the velocity gradients of a soil. These could be based on exact solutions from finite difference simulations of dispersion. The complete objective would be to develop an analysis package for data acquisition, data reduction, and data interpretation in terms of shear-wave structure 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 program, data from additional areas are needed.

Literature Cited

Lo, T., and Inderwiesen, P., 1994, Fundamentals of seismic tomography: Geophysical Monograph Series, 6, Society of Exploration Geophysicists, Tulsa, Ok, 178pp.

Kafka, A. L., and Reiter, E. C., 1987, Dispersion of Rg waves in southeastern Maine: Evidence for lateral anisotropy in the shallow crust: Bulletin of the Seismological Society of America, **77,** 235-238.

Kocaoglu, A. H., and Long, L. T., 1993a, Tomographic inversion of Rg wave group velocities for regional near-surface velocity structure: Journal of Geophysical Research, 98, B4, 6579-6587.

Kocaoglu, A. H. and Long, L.T., 1993b. A review of time-frequency analysis techniques for estimation of group velocities: Seismological Research Letters, 64, 2, 157-167.

Menke, W., 1989, Geophysical data analysis: discrete inverse theory: Academic Press, Inc., New York, New York, 289pp.

Park, C. B., Miller, R. D., and Xia, J., 1999, Multi-channel analysis of surface waves: Geophysics, 64, 800-808.

Stokoe, K.H. II, Rix, G. J., and Nazarian, S., 1989, In situ seismic testing with surface waves: Proceedings of 12th International Conference on Soil Mechanics and Foundation Engineering, Rio De Janeiro, 12-18 August, 331-334

Tarr, A. C., 1969, Rayleigh-wave dispersion in the North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico: Journal of Geophysical Research, **74**, 1591-1607.