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CHARACTERIZATION OF ABANDONED MINE SITES BENEATH I-70 VIA CROSSHOLE AND SASW SEISMIC WAVE METHODS

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ABSTRACT

An approximately 2100-ft section of Interstate 70 (I-70) experienced a series of ground failures in 1994 and 1995 that were attributed to collapse of underground mine workings. Repair of the roadway consisted of construction of barrier walls of stiff grout to contain production grout pumped into the mines. Beginning in spring 1996, depressions were noted in the pavement surface over some of the grouted holes. As a consequence, a two-part investigation was initiated to determine whether the surface expressions reflect subsurface conditions that are a risk to the travel lanes and traveling public. In Phase I, Test Area Investigation, various field and analytical methods were tested and evaluated on a small scale prior to broad-scale implementation in Phase II. Crosshole and SASW seismic wave methods of subsurface characterization were included in the Phase I investigation. The paper describes the test methods employed in the field, and documents data and test results obtained from the test area. It is shown that quality geophysical measurements can be made in close proximity to the active interstate, and that no single technique will unambiguously detect voids or other anomalies over a wide range of depths. Based upon these results, specific recommendations for the Phase II investigation are provided.

INTRODUCTION

An approximately 2100-ft section of Interstate 70 (I-70) in Guernsey County, Ohio experienced a series of ground failures in 1994 and 1995 that were attributed to collapse of underground mine workings. The subsurface failures culminated in collapse of a section of pavement and development of a 10-ft deep, 10-ft diameter sinkhole in the eastbound travel lanes on March 4, 1995, resulting in closure of the interstate for approximately four months. Repair of the roadway began on March 23, 1995, and consisted of construction of barrier walls of stiff grout to contain production grout pumped into the mines.

Beginning in spring 1996, depressions were noted in the pavement surface over some of the grouted holes. As a consequence, a two-part investigation was initiated to determine whether the surface expressions reflect subsurface conditions that are a risk to the travel lanes and traveling public. In Phase I, Test Area Investigation, various field and analytical methods were tested and evaluated on a small scale prior to broad-scale implementation in Phase II. The objectives of the paper are to describe aspects of the Phase I investigation, and to summarize recommendations developed for Phase II.

BACKGROUND

Details of the project site, including geologic setting, mining history, ground failures, and subsequent repairs are well described by Hoffman, et al. (1995) and Guy et al. (2003). The following paragraphs provide a brief summary.

The site is approximately four miles east of Cambridge in east-central Ohio, 90 miles west of Pittsburgh, Pennsylvania and 100 east of Columbus, Ohio. The portion of the highway under study is a flat, tangent section approximately 9000 ft in length, within a broad, level valley that ends in steep sloping slides and drained by Mud Run.

According to Guy et al. (2003), the study area is in the unglaciated region of the Appalachian Plateau physiographic province, and the geology consists generally of relatively flat to mildly dipping Paleozoic sedimentary rocks with unconsolidated overburden materials that formed by periglacial erosion and deposition. The upper 5 to 15 ft of material beneath I-70 consists of silt and clay fill. Beneath this fill are silts and clays down to bedrock, with frequent interbedded lenses of sand and gravel. The total thickness of soil above bedrock ranges from 30 to 50 ft across the study area. Bedrock correlates as the Lower Mahoning Sandstone and Shale member in the Lower Glenshaw Group, is predominantly arenaceous shale in the study area, and ranges in thickness from 10 to 25 ft. Below the Lower Mahoning member is bituminous Upper Freeport Coal, 5 to 7 ft thick, underlain by claystone. The water table is above the coal seam, and water flows across the area through granular soils, fractures, and voids in bedrock and coal units.

As described by Hoffman, et al. (1995) and Guy et al. (2003), Murray Hill No. 2 mine complex underlies the study area and it was in operation from 1912 to 1935. In 1994 the abandoned, underground Kings coal mine down dip and south of the Murray Hill mine was intercepted by surface mining. For surface mining to proceed, water had to be pumped from the Kings mine, and, as a result, dewatering also occurred in the Murray Hill mine because the two complexes are connected by entries. Following dewatering, localized roof failure between coal pillars and soil piping above the mine workings occurred in the I-70 study area. Surface mining and dewatering ceased and water returned to previous levels. However, subsidence of the overburden soils continued, resulting in catastrophic failure of the eastbound lanes in March 1995.

Hoffman, et al. (1995) describe in detail investigation and remediation activities following the 1995 collapse. In the end, repair of the roadway began on March 23, 1995, and consisted of construction of barrier walls of stiff grout to contain production grout pumped into the mines. However, beginning in spring 1996, depressions were noted in the pavement surface over some of the grouted holes. Exploratory drilling near the grout injection holes revealed not only grout, but also saturated clay and large voids. A second phase of grouting followed in 1997, and the roadway has shown no signs of further damage.

With good reason, concerns remain regarding stability of I-70. Thus, the Ohio Department of Transportation (ODOT) initiated a two-phase study in 1999 to determine if conditions exist that are a risk to the travel lanes and traveling public. In Phase I, Test Area Investigation, various field and analytical methods were tested and evaluated on a small scale prior to broad-scale implementation in Phase II, Project Area Investigation.

In Phase I, a detailed field mapping program consisting of a grid of surface and crosshole seismic and radar geophysical measurements was undertaken over a 200-ft length of highway to: 1) determine optimum field operating parameters for the methods, and 2) immediately investigate problems associated with the mine complex under I-70. The first phase of studies was central to planning for a more extensive geophysical and geotechnical survey of approximately 2100 ft of problem area in the second phase of the study.

Crosshole and SASW seismic wave methods of subsurface characterization were included in the Phase I investigation. The following sections will describe the test methods employed in the field, and document data and test results obtained from the test area. Based upon these results, specific recommendations for the Phase II investigation are provided.

CROSSHOLE TESTING

The crosshole research effort concentrated on three issues: 1) implementation of crosshole seismic testing alongside an active interstate with heavy truck traffic, 2) identification of voids, fractures, and other anomalies in the material profile, and 3) investigation of a new, simple crosshole seismic source capable of propagating shear waves polarized in the horizontal plane. This new source allows for determination of both vertically- and horizontally-polarized shear wave velocity profiles at a site, which is important in cases where depositional processes lead to significant anisotropy in soil properties.

Particulate materials such as soils are inherently anisotropic with respect to stiffness and strength properties. Depositional processes can clearly lead to material differences in vertical and horizontal planes, so-called structural anisotropy. Further, mechanical properties of these materials are significantly governed by state of stress. It is widely recognized that stresses in particulate materials are anisotropic, thus differences in stiffness and strength properties should be expected, i.e., stress-induced anisotropy. Anisotropic mechanical properties are not routinely assessed, yet differences in material properties can influence design-based calculations.

Recent studies into the understanding and importance of characterizing soil systems to include the influence of anisotropy (Roesler [1979], Yu and Richart [1984], Stokoe et al., [1985], and Zeng and Ni [1998]), particularly structural and stress-induced anisotropy, have produced a cross-anisotropic model that is characterized by five elastic parameters:

- M_H - constrained modulus in horizontal plane
- M_V - constrained modulus in vertical plane
- G_{HH} - shear modulus in horizontal plane
- G_{VH} - shear modulus in vertical plane
- C_{13} – a constant that is a function of M_H, M_V, and G_{HH}

Of particular importance for soils, the shear moduli, G_{HH} and G_{VH}, can be related to their respective shear wave velocities:

$$G_{HH} = \rho V_{SH}^2 \tag{1}$$

$$G_{VH} = \rho V_{SV}^2 \tag{2}$$

where V_{SH} is horizontally polarized shear wave velocity, V_{SV} is vertically polarized shear wave velocity, and ρ is mass density. With additions and modifications to typical test equipment, crosshole seismic wave methodologies can be employed to determine these important shear characteristics of an anisotropic particulate material.

The crosshole test has been well documented (Hoar and Stokoe [1978], Stokoe and Woods [1972], and Woods [1986]). Testing can be conducted with a minimum of two boreholes advanced to equal depths a known distance apart. However, the crosshole test method is optimized with use of three boreholes. The source is an impulse hammer that is advanced down one of the boreholes. Receivers are then placed in the remaining boreholes. These receivers are usually some type of transducer depending on the material being tested. Receivers then transfer body wave arrivals to a time recorder.

Vertical Shear Waves (SV)

Typically, crosshole seismic surveying is conducted in soil to obtain shear wave velocity with depth from vertical shear (SV) waves, i.e., waves that propagate perpendicular to particle motion and confined to the vertical plane. The test has been standardized, and specifications can be found in ASTM Testing Standard D 4428 Standard Test Methods for Crosshole Seismic Testing.

Field testing was conducted for this study according to specifications for crosshole seismic surveying. Boreholes were drilled to a specified depth and cased with 4-inch diameter PVC pipe grouted in place. As suggested by ASTM, the source used in the investigation was a Bison hammer. The Bison hammer is an in-hole source, hydraulically coupled to the borehole, and produces SV-waves by creating a vertical traction in the source hole. Geophone packers were used as three-dimensional receivers. Packers are comprised of three velocity transducers oriented along the x, y, and z planes. The orientation of the transducers used is dependent on the direction of the polarized wave. For SV-waves confined to the vertical plane, the geophone aligned parallel to the z-axis was used to collect vertical shear wave data. In addition to velocity transducers, geophone packers also contain a rubber inner tube and airline. With the receiver at the desired depth, the tube is inflated with air against the borehole. Thus, the pneumatic tube enables coupling between soil, cased borehole, and transducer at a known depth. The recorder used in this study was a Hewlett Packard Dynamic Signal Analyzer (HP Model 3567A), which is capable of recording wave arrivals in the time domain.

The essential measurement of the crosshole test is interval travel time. Interval travel time is the time required for the shear wave to travel between two receivers and therefore eliminates need for precise triggering of the source and recording equipment. It is obtained by selecting the first arrival of the SV-wave at each receiver and is equal to the difference in arrival times. Vertical shear wave velocity is then computed as the distance between receivers divided by interval travel time.

Horizontal Shear Waves (SH)

Although crosshole seismic surveying is typically conducted to obtain profiles of vertical shear wave velocity with soil depth, these profiles do not present a complete assessment of a site's condition, as this standard test method only typifies the soil parameters pertaining to the vertical plane. To develop a comprehensive evaluation of site conditions, properties in the horizontal plane must also be characterized. In fact, parameters derived from in situ measurement of horizontal shear (SH) waves may be more appropriate for assessing certain soil dynamic problems, such as liquefaction potential. It is possible to obtain shear wave velocity profile with depth from horizontal shear waves, i.e., waves that propagate perpendicular to particle motion and are confined to the horizontal plane, by conducting crosshole seismic surveying.

In an attempt to ascertain the shear wave velocity in the horizontal plane, standard crosshole methods were used to conduct field testing using a trial energy source to produce horizontal shear (SH) waves. It is extremely difficult to create a pure SH-wave source without interference from compression (P) waves. The trial source must be rich in horizontal shear wave generation while simultaneously generating little compression wave energy. ASTM specifications state that in order to produce identifiable shear waves, the source must transmit energy to the ground primarily by directionalized distortion. Thus, a pure traction must be created by the source in the borehole to produce energy that propagates perpendicular to particle motion in the horizontal plane.

The required horizontal traction was produced by an encased solenoid, pneumatically coupled to the borehole and electrically triggered. Upon triggering, the solenoid fires horizontally producing the necessary propulsion to generate horizontal shear wave energy. Again, geophone packers were used as the receivers. For SH-waves confined to the horizontal plane, the velocity transducer aligned parallel to the x-axis was used to collect horizontal shear wave data. Orientation rods were connected to the solenoid hammer and receivers to ensure that alignment of polarized wave and receivers was maintained during testing at subsequent depths in the borehole. Horizontal shear wave arrivals were recorded in the time domain using a Hewlett Packard Dynamic Signal Analyzer (HP Model 3567A).

The essential measurement of the crosshole test is interval travel time. ASTM specifications state that for defendable shear waves, energy sources should be repeatable and, although not mandatory, reversible. It is well documented that shear waves typically show a reversal in wave arrival when the source is rotated 180 degrees. In this case, the travel time records illustrate the reversibility of the source and thus suggest the validity of the solenoid hammer.

I-70 Test Results

Crosshole testing was conducted at two sites near the edge of the eastbound lanes and at approximately project station 483+00, which is where the highway was repaired following collapse in 1995. The first site was on the south edge of the highway and employed project boreholes GC-213 (source), GC-214 (receiver #1), and GC-215 (receiver #2). Only SV testing was conducted at this first site. The second site was on the north edge of the highway and employed project boreholes GC-204 (source), GC-203 (receiver #1), and GC-202 (receiver #2). SV and SH crosshole testing was conducted at the second site. Both borehole arrays consisted of a 5-ft distance between source and first receiver, and a 10-ft distance between first and second receivers. The resulting shear wave velocity profiles are shown in conjunction with standard penetration test (SPT) N-values and a material profile in figures 1 and 2. The velocity profiles appear reasonable in that the shear wave velocity values are typical for the materials indicated, and appear to follow a pattern of behavior observed in the SPT results. It is reasonable to conclude that quality crosshole data can be obtained throughout the profile in close proximity to an active interstate. It is further noted that there are no apparent abnormalities in the data, suggesting that the overburden soils above the mine complex at this location are intact. Finally, in comparing the velocity profiles from the two different shear waves at the second site (figure 2), the SH-wave velocity is less than the SV-wave velocity, illustrating the presence of anisotropy in elastic shear stiffness parameters.

SASW TESTING

Traditionally, measurement of the shear modulus of soil required an intrusive type test such as the crosshole test. With the advent of fast, portable computers, non-intrusive testing methods such as SASW have been developed that allow determination of shear modulus without the damage and expense of drilling boreholes (Hiltunen [1988]). SASW testing involves the use of velocity transducers and a spectrum analyzer along with computer data acquisition and storage to measure dynamic signals in the field. With the raw data collected using the instrumentation system, variation of shear modulus with depth in soil can be determined.

The SASW research issues were similar to those previously discussed for crosshole testing: 1) implementation of SASW seismic testing alongside an active interstate with heavy truck traffic, 2) identification of voids, fractures, and other anomalies in the material profile. Of particular importance for SASW testing was investigation of an adequate energy source. The source must create seismic waves of sufficient magnitude to be reliably measured in the presence of heavy truck traffic. Also, the source must produce low frequency/long wavelength energy to resolve the material profile to a depth of at least the top of the coal seam.

A typical SASW test can be divided into two major parts, the actual field test and collection of data, and analysis of data. These components are summarized and illustrated in the following sections.

Equipment and Testing

Basic components of the SASW test are a fast fourier transform (FFT) spectrum analyzer (in this study a Hewlett Packard Dynamic Signal Analyzer Model 3567A), two or more geophones (Mark Products L-4), and an energy source such as a sledgehammer, heavy weight, or virbrator. The field set-up of the test is based on an imaginary centerline from which two geophones are equally spaced. An energy source is then placed the same distance from one geophone (S) as the distance between the geophones (X). Energy is created at the source location and arrivals of waves through the soil are recorded at the two geophones using the spectrum analyzer. A series of vibrations are conducted and the average is stored as the results for a given receiver spacing. The test is repeated for various receiver spacings and is done in the forward and reverse directions (the source is moved from one side of the centerline to the other).

Shear modulus can be determined from shear wave velocity as follows:

$$G_s = \rho V_s \tag{3}$$

where G_s is shear modulus, ρ is mass density of soil, and V_s is velocity of the shear wave. A surface test such as SASW will create what are known as Rayleigh waves that travel along the surface of a soil deposit and to a depth of approximately one wavelength. Velocity of Rayleigh waves is closely correlated to velocity of shear waves allowing for determination of shear modulus using a non-intrusive surface test. Variation of the weight of the source will create waves of different wavelengths (frequencies) in soil. A lighter source will create a range of higher frequencies. The longer the wavelength, which corresponds to a heavier weight, the deeper into the soil profile shear modulus can be determined.

A geophone is a transducer that will produce a voltage proportional to the velocity of movement. The movement of a magnetic mass inside a coiled spring within the geophone will create a measurable voltage in the coil. In SASW, geophones transmit this voltage to the recording device in response to arriving surface waves.

In the case of an SASW test, the recording device is a dynamic signal analyzer or spectrum analyzer. Dynamic signals recorded in SASW, while produced by system responses as a function of time, are often better analyzed in terms of variation with frequency. A spectrum analyzer is capable of performing conversion of an input signal as a function of time into a signal as a function of frequency almost instantaneously using a FFT algorithm. Once the signal has been transformed into a function of frequency, a number of spectral analyses can be done on the signal. A spectral analysis is typically a statistical operation comparing signals with themselves or with other signals. The spectral analysis of interest in SASW is a cross power spectrum that compares the signals from two geophones. It can be used in determining differences in signals caused by time delays, propagation delays, or varying wave paths between receivers. As the spectrum analyzer receives the signals from the geophones it calculates the cross power spectrum of the incoming signals and stores it for further analysis.

Analysis of Data

When a signal is transformed into a function of frequency (the frequency domain) it is composed of two components, a real (Re) component and an imaginary (Im) component. The magnitude of these components can be considered the amplitude (Amp) of the signal, while the inverse tangent of the ratio of the two components represents what is called the phase angle (ϕ):

$$Amp = \sqrt{(\mathrm{Re}^2 + \mathrm{Im}^2)} \tag{4}$$

$$\phi = \tan^{-1}\left(\frac{\mathrm{Im}}{\mathrm{Re}}\right) \tag{5}$$

A cross power spectrum analysis calculates the difference in phase angles for waves of various frequencies and displays these relative angles as a function of frequency. This data is displayed on, and stored in, the spectrum analyzer for each hammer impact in the field. The phase angles are then unwrapped (plotted as increasing) to show true phase angles for each frequency. Each test will generate an unwrapped phase plot.

The next step in the data analysis is to use these relative phase angles to calculate the velocity of the Rayleigh wave at each frequency. The following series of equations represents the relationship between phase angle, Rayleigh wave velocity, and Rayleigh wave wavelength:

$$\Delta t = \frac{\phi}{360} * \frac{1}{f} \tag{6}$$

$$V_r = \frac{X}{\Delta t} \tag{7}$$

$$\lambda = \frac{V_r}{f} \tag{8}$$

where Δt is travel time between receivers, ϕ is phase angle, f is frequency, V_r is Rayleigh wave velocity, X is receiver spacing, and λ is wavelength. Once Rayleigh wave velocity or phase velocity is determined, it can be plotted versus frequency or wavelength to create a dispersion curve. Data from each receiver spacing will produce a dispersion curve, and an average or composite dispersion curve can also be created by adding together and averaging phase velocities at overlapping frequencies from the different tests at various receiver spacings.

Inversion

Once variation of phase velocity versus frequency (i.e., the dispersion relationship) has been determined, correlation between Rayleigh wave phase velocity and shear wave velocity can be used to determine the shear wave velocity profile. To complete this analysis an assumed shear wave velocity profile is used to compute a theoretical (model) dispersion curve. The model dispersion curve is then compared with the experimental dispersion curve. If the difference between the curves is small, the assumed profile, updated to minimize the difference in fit, can be taken as that of the test site. If the theoretical and experimental dispersion curves do not match satisfactorily, the profile is updated and shear wave velocity profiles are altered until a match is found.

In the simplest of terms, inversion can be described as an iterative "guessing" procedure. Field testing provides an experimental dispersion curve. In order to determine a shear wave velocity profile a user must "guess" a shear wave velocity profile that is then used to calculate a theoretical dispersion curve. The two curves are then compared to see if they match adequately, and the decision must be made to continue guessing or accept the profile. This process continues through several iterations, each building on the previous guess, until an acceptable profile is found.

I-70 Test Results

Fourteen SASW tests were conducted near the eastbound lanes of the 200-ft test section investigated in Phase I (project station 483+00 to station 485+00). Three sources of energy were employed: 1) a series of hand-held hammers for characterization of the shallow (<15 ft) subsurface, 2) a "Mini-Vib" vibration shaker, and 3) a "half-vibroseis" vibration shaker.

The tests can be grouped as follows:

- Tests 1, 2, 4, and 14: conducted parallel to eastbound lane along outside edge of outside shoulder, test 4 outside of remedied area at station 489+71
- Tests 3 and 5 through 8: conducted parallel to eastbound lane at station 484+00 at various offsets on sloped right-of-way
- Test 9: conducted parallel to eastbound lane at station 484+00 at center of median
- Tests 10 through 13: conducted from a common source location at station 483+50 near outside edge of outside shoulder of eastbound lane, and along receiver lines 0, 15, 30, and 45 degrees from the longitudinal axis of the eastbound lanes.

Dispersion curves generated from the fourteen test arrays are grouped into three figures and displayed in figures 3-5. The dispersion data from figure 3 (south edge of eastbound lanes) were inverted to produce a shear wave velocity profile that is shown in figure 1 in conjunction with crosshole results obtained from the same location. Comments on the SASW test results include:

- High quality SASW test records were obtained despite the high levels of vibration noise created by heavy truck traffic.
- The vibration shaker sources were adequate to sample the overburden soil and give a strong indication of the depth to the underlying rock layer. A stronger source (e.g., full vibroseis) would be required to delineate the rock properties (e.g., shear wave velocity), including any low-velocity zones.
- The dispersion data for the 14 test sets depict similar subsurface characteristics: a thick layer of overburden soil overlying high-velocity rock-like material.
- The data are very consistent among the locations along the edge of the shoulder (1, 2, 4, and 10-14). The overburden soil is approximately 30 ft thick, with a shear wave velocity profile that is curvilinear in shape: 700 fps near the surface, 550 fps at about 15 feet, and increasing to 900 fps near the rock interface.
- The data for the test locations on the median and right-of-way slope (3, 5-9) are more variable than along the shoulder, and the soil near the ground surface is of lower velocity (350-500 fps). The data indicate a depth to bedrock that is also more variable as a result of the tests having been

conducted at locations of varying surface elevation.
- As with the crosshole test results, there are no apparent abnormalities in the data, suggesting that the overburden soils above the mine complex at this location are intact.

PHASE I INVESTIGATION SUMMARY

Details of crosshole and SASW testing conducted in Phase I have been presented. The following will provide an overview of all testing activities in Phase I, and recommendations produced for Phase II. Based primarily on data quality achieved at the site, and an analysis of the data under the severe conditions imposed by the site, including traffic noise and preexisting site drilling and in-filling of material in the subsurface, it was concluded (Daniels, et al. [2000]) that several of the methods tested can be combined to provide a good indication of the presence and location of voids and disturbed zones beneath the highway. Specific statements are as follows:

- There is no single technique that will unambiguously detect voids over a wide range of depths.
- The subsurface and surface (traffic) complications are not an overwhelming obstacle to making quality geophysical measurements along the highway.
- Surface ground penetrating radar (GPR) using both co-pole and cross-pole orientation of antennas can provide an indication of disturbances in the very near surface (less than five feet), and can be used to guide drilling searches for voids.
- Surface seismic shear wave measurements can be used to investigate disturbed zones that cannot be detected with surface GPR.
- Crosshole shear wave seismic and GPR will provide detailed information on the subsurface conditions that are indicated as anomalous by the surface GPR and seismic measurements.

Based upon these conclusions, the following surveys are recommended for characterization of the entire 2100 ft of roadway in Phase II (Daniels et al. [2000]):

- Surface seismic shear wave measurements can be used as a reconnaissance tool for locating slump zones in the subsurface that might be associated with mine collapse that has propagated to the overburden/bedrock interface.
- Surface GPR can be conducted along closely-spaced lines to detect voids in the very near surface.
- Crosshole GPR and seismic shear wave measurements can be conducted in holes drilled to investigate anomalies that are located by surface seismic and GPR measurements.

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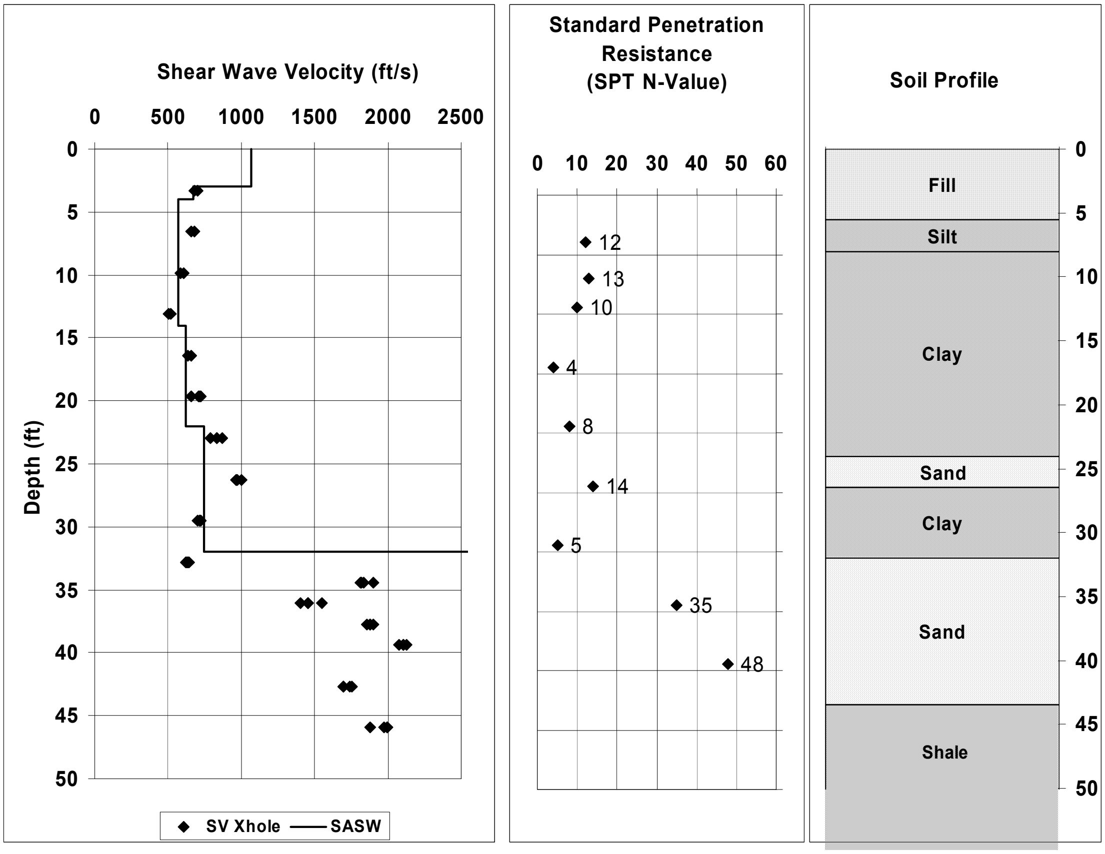

Fig. 1. Composite Material Profile: South Edge of Eastbound Lanes

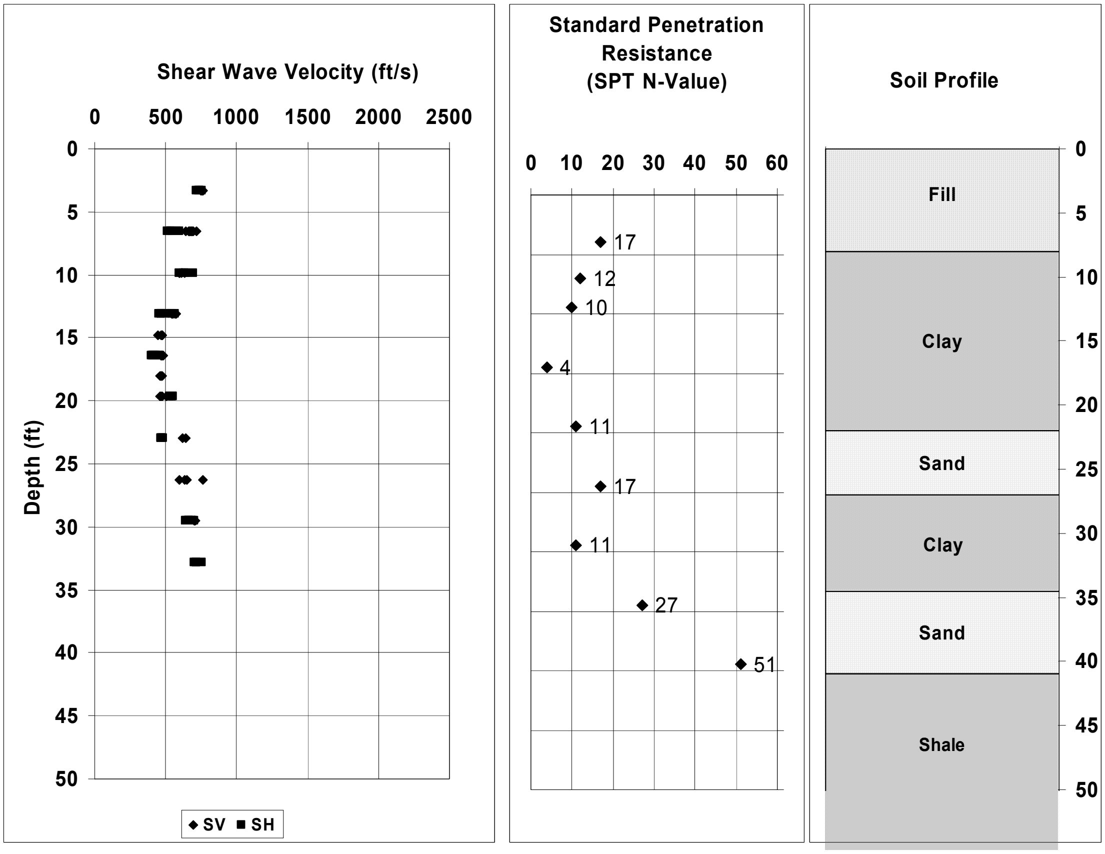

Fig. 2. Composite Material Profile: North Edge of Eastbound Lanes

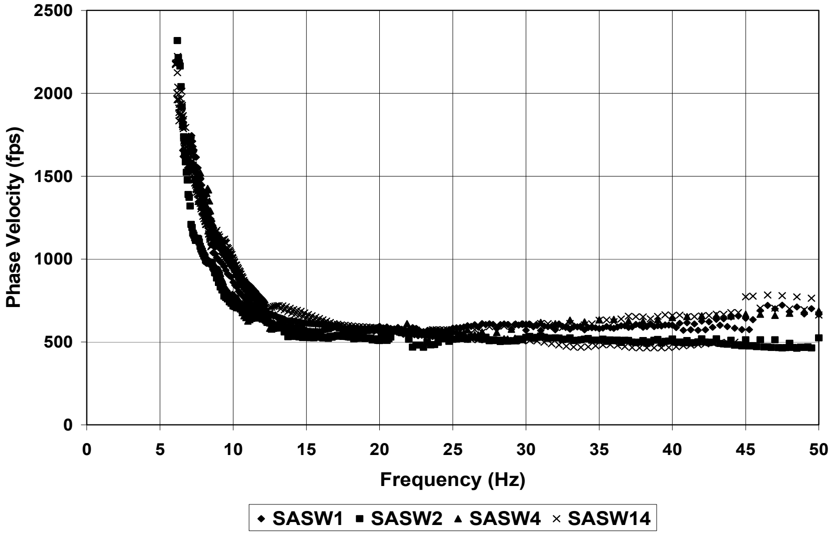

Fig. 3. SASW Dispersion Curves: Edge of Outside Shoulder, Eastbound

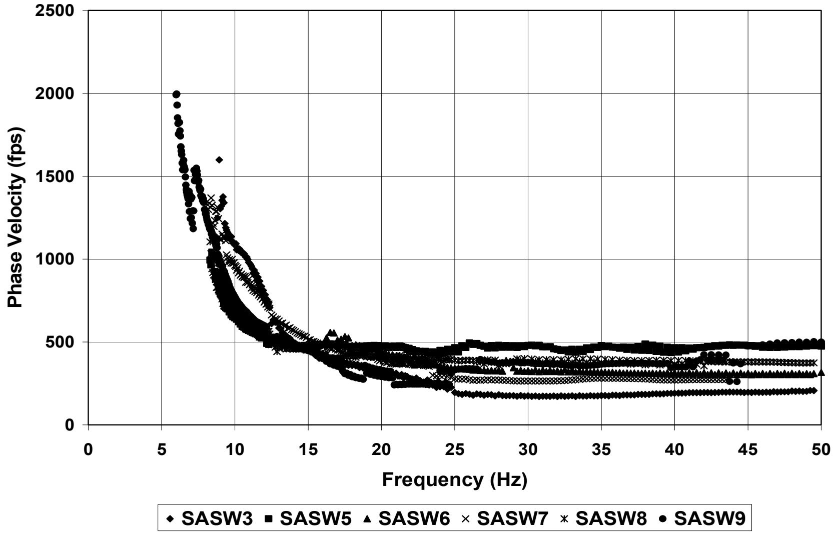

Fig. 4. SASW Dispersion Curves: Median and Eastbound Right-of-Way

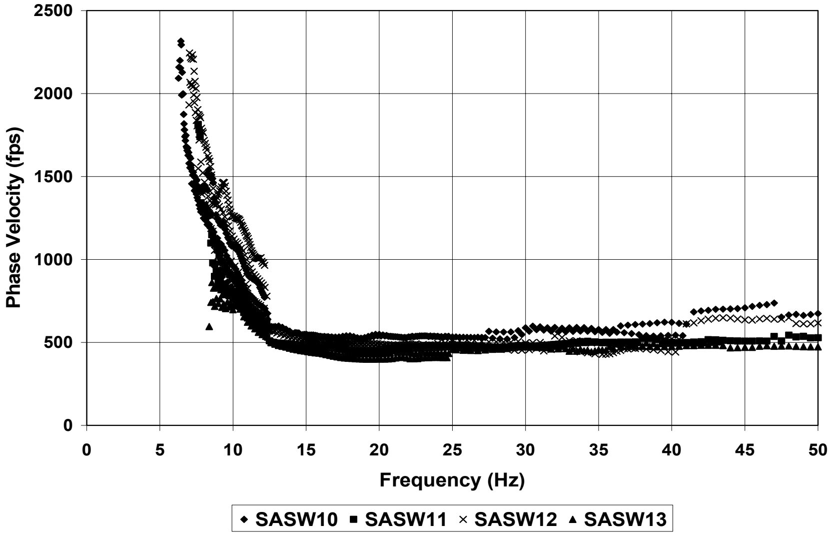

Fig. 5. SASW Dispersion Curves: 0, 15, 30, and 45 Degrees at Station 483+50