Beyond Rippability – A Case History Integrating Seismic Refraction, Electrical Resistivity Imaging, and Geotechnical Boring Logs

Jonathan B. Shawver [1] (jb@geovision.com), William Dalrymple [1] (will@geovision.com), and Robert M. Orr [2] (borr@wilbursmith.com)

[1] GEOVision Geophysical Services, Inc.
Corona, CA

[2] Wilbur Smith Associates
Kansas City, MO

Abstract

Geophysical investigations are best utilized to plan borehole locations and/or correlate geology between borehole locations. A geophysical survey was conducted along a portion of the southbound retaining wall of Missouri Highway 152 in Kansas City, Missouri. The purpose of the geophysical survey was to map bedrock geology, structure, and engineering properties of the shallow (upper 50 ft) subsurface. Geophysical methods used during this investigation included the seismic refraction and 2-D resistivity imaging techniques.

Borehole data alone is not an adequate measure of subsurface condition in karstic terrain. Geophysical techniques are not without fault. Seismic data at this site was affected by high ambient noise levels and steep topographic terrain prohibited the placement of far-offend shots, limiting depth of penetration. Interpretation of resistivity data is much more difficult than seismic interpretation independent of any correlating data. Resistivity imaging data are inherently more smoothed than seismic refraction data, therefore, sharp, easily definable geologic contacts are rarely observed in electrical resistivity data. However, an integrated approach combining all three methods was a successful (and cost-effective) means of characterizing subsurface geology as opposed to any singular technique.

Results from the geophysical investigation were used to better locate geotechnical borings. Preliminary boring information was used to refine both seismic and resistivity models. Geophysical data indicate that bedrock units strike in a southeasterly direction and dip to the southwest. Alternating shale and limestone sequences were observed in the refined resistivity models. Based on resistivity data models we were able to identify highly fractured zones within the bedrock and other potential areas of poor rock quality. The seismic refraction survey provided different and complimentary data. While not capable of differentiating between the different rock units, the seismic refraction survey provided was able to more accurately map sediment thickness, bedrock velocity, and degree of weathering.

Introduction

A geophysical survey was conducted in Kansas City, Missouri in February 2006. The purpose of the investigation was to map bedrock geology and structure along a proposed retaining wall for the southbound lane of Missouri Highway 152. Geophysical methods used during this investigation included the seismic refraction, refraction microtremor, multi-channel analysis of surface waves and 2-D electrical resistivity imaging techniques. Seismic refraction was utilized to determined bedrock depth and rippability. 2-D resistivity was used to differentiate geological layers and to detect subsurface features, such as karst structures, that were expected to be in survey area. These methods were also used to correlate subsurface geology between existing geotechnical borings, as well as to locate potential areas for future borings. The refraction microtremor and MASW data were used to estimate global properties of the material along the arrays.

Figure 1 shows the approximate locations of the geophysical traverses. Seismic refraction data was acquired along three lines (Lines SL-1, SL-2, and SL-4) on the slope and one line (Line SL-3) transverse to Lines SL-1, SL-2, and SL-4. Resistivity profiles were acquired along 4 lines (RL-1 to RL-4) overlapping seismic lines SL-1 to SL-4, using stationing information from the seismic line.

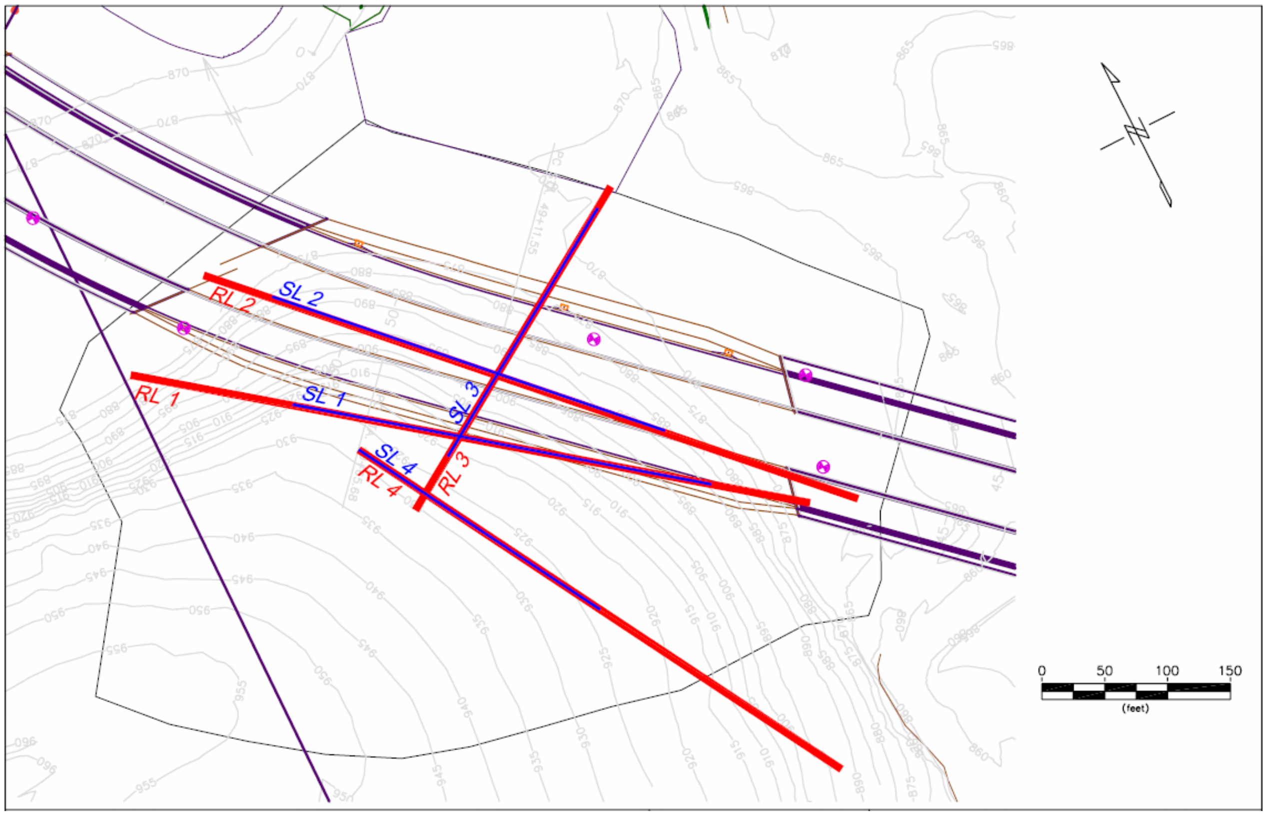

Figure 1: Approximate Seismic Line (SL), Resistivity Line (RL), and Existing Boring Locations and Line Overlap

Geophysical Methods

During seismic refraction surveys, acoustic energy is input to the subsurface by an energy source such as a sledgehammer impacting a metallic plate, weight drop, or explosive charge. The acoustic waves propagate into the subsurface at a velocity dependant on the elastic properties of the material through which they travel. When the waves reach an interface where the density or velocity changes significantly, a portion of the energy is reflected back to the surface, and the remainder is transmitted into the lower layer. Where the velocity of the lower layer is higher than that of the upper layer, a portion of the energy is also critically refracted along the interface. Critically refracted waves travel along the interface at the velocity of the lower layer and continually refract energy back to surface. Receivers (geophones) laid out in linear array on the surface, record the incoming refracted and reflected waves.

The seismic refraction method involves analysis of the travel times of the first energy to arrive at the geophones. These first arrivals are from either the direct wave (at geophones close to the source), or critically refracted waves (at geophones further from the source). Seismic refraction equipment used during this investigation consisted of a Geometrics Geode signal enhancement seismograph, 8 Hz vertical geophones, refraction cable with 15-foot takeouts, a Betsy Seisgun™ downhole percussive firing rod (DPFR) with 500-grain industrial blank charges, a sledgehammer and an aluminum striking plate. Each seismic line consisted of one or two overlapping spreads of 24 geophones nominally spaced 10 feet apart for a total spread length of 230 ft (slope distance). Seven or more shot point locations were used per spread, with off–end shots located at a distance far enough to image the deepest refractor.

Picking of first arrival times of the seismic data and processing of the seismic refraction data were processed using a combination of commercial and in-house software. The seismic refraction data were processed using the GRM computer modeling technique according to the procedures outlined in Lankston and Lankston (1986) and Redpath (1973). After phantoming was completed GRM processing was conducted.

The 2-D electrical resistivity survey was conducted using an Advanced Geosciences, Inc. (AGI) SuperSting™ R8/IP memory earth resistivity meter with 56-channel external switch box, electrode cables with 5 m takeouts, and stainless steel electrodes. Each 2-D electrical resistivity line consisted of a single spread of 56 (or fewer) electrodes nominally spaced 10 ft apart for a maximum total line length of 550 ft or less.

During a resistivity survey, electrical current is applied to a pair of current electrodes, and the potential difference (voltage) is measured between one or more pairs of potential electrodes. For a 2-D resistivity survey, the current and potential electrodes are generally arranged in a linear array. Common array types include pole-pole, dipole-dipole, Schlumberger, and the Wenner array. The dipole-dipole, Wenner and a modified Schlumberger array were evaluated during this investigation. The apparent resistivity is the bulk average of all soils and rock influencing the applied current. It is calculated by dividing the measured potential difference by the input current and multiplying by a geometric factor specific to the array being used, as well as electrode spacing.

2-D resistivity data was modeled using a combination of commercial and in-house software. A least-squares inversion of the resistivity data was conducted using a finite element mesh with surface topography to generate a 2-D model of resistivity versus depth/elevation. The data were then outputted into Geosoft's Oasis Montaj™ mapping system for gridding, contouring and final presentation.

The refraction microtremor (REMi) and multi-channel array surface wave (MASW) methods are in-situ seismic methods for determining shear wave velocity (V_S) profiles [Stokoe et al., 1994; Stokoe et al., 1989; Park et al., 1999a and 1999b; Louie, 2001]. Surface wave techniques are non-invasive and non-destructive, with all testing performed on the ground surface at strain levels in the soil in the elastic range (< 0.001%).

The basis of surface wave methods is the dispersive characteristic of Rayleigh waves when propagating in a layered medium. The phase velocity, V_R, depends primarily on the material properties (V_S, mass density, and Poisson's ratio or compression wave velocity) over a depth of approximately one wavelength. Waves of different wavelengths, λ, (or frequencies, f) sample different depths. As a result of the variance in the shear stiffness of the layers, waves with different wavelengths travel at different phase velocities; hence, dispersion. A surface wave dispersion curve, or dispersion curve for short, is the variation of V_R with λ or f.

For the MASW method, ground motions were recorded by 24 geophones aligned in a linear array spaced 1m apart and connected to a seismograph. Data was recorded along a single array. A 3 lb hammer and 20 lb sledge hammer were used as energy sources for each shot point. Shot points were located 0, 1, 5 m from the end geophone locations. A wavefield transform, such as the f-k or τ-p transform is applied to the time history data to isolate the surface wave dispersion curve. The dispersion curve is then modeled to obtain the variation of shear-wave velocity with depth.

The refraction microtremor technique is a passive surface wave technique developed by Dr. John Louie at University of Nevada, Reno. The refraction microtremor method differs from the more established array microtremor technique in that it uses a linear receiver array rather than a triangular or circular array. Unlike the SASW and MASW methods, which use an active energy source (i.e. hammer), the microtremor technique records background noise emanating from ocean wave activity, construction, noise, traffic, industrial activity, etc.

The refraction microtremor field procedure for this investigation consisted of laying out a single linear array of 24, 4.5 Hz geophones with a 4m receiver spacing and recording twenty, 30 second noise records using a 2 ms sample rate.

Results

Line 1

Three distinct velocity units were apparent on the seismic refraction model corresponding to an upper low velocity sediment layer, an intermediate velocity sediment layer and higher velocity sedimentary rock unit. The upper low velocity layer had an average compressional-wave velocity 1,100 ft/s and thickness ranging from about 6 to 8 ft. This unit was probably associated with unconsolidated soil deposits. Underlying the upper soil unit was a slightly more consolidated sedimentary rock layer with P-wave velocity averaging about 2,750 ft/s. This rock unit was considered very low velocity and was interpreted as being highly weathered and rippable for planning purposes. The sedimentary rock unit underlied the sediment layers and was modeled as having an average P-wave velocity of 9,100 ft/s and was about 20 ft beneath the seismic profile. There appeared to be a diffuse velocity boundary between the weathered rock unit and the underlying competent bedrock; however bedrock was definitely becoming much shallower under the central portion of the line.

Four layers were observed in the electrical resistivity data. The first layer was a moderately conductive soil layer that correlated well with the low velocity sediment layer observed in the seismic data. This layer was interrupted by a thin weathered limestone layer ("Upper Limestone") observed between stations 100-280 beneath the line. This layer was underlain by a more conductive shale sequence ("Upper Shale") 30 to 45 feet thick. Beneath the Upper Shale unit was second resistive unit identified as Lower Limestone and is about 50 ft beneath the central portion of the line. This top of this unit appeared to be at or around the expected water table observed in geotechnical boring logs (approximate elevation 860 ft). There was a conductive zone in the Lower Limestone located between stations 410-460. As this anomaly was located below the water table, this anomaly was interpreted as being caused by fluid-filled fractures or a possible saturated clay or fluid-filled void. This anomaly could have been caused by highly-weathered (saturated) rock; in any case this zone was considered to be very poor-quality rock.

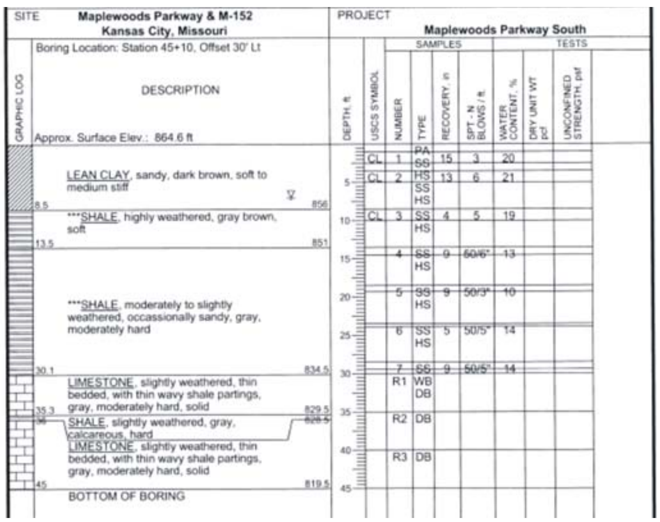

Figure 2: Sample Boring Log from Previous Geotechnical Investigation

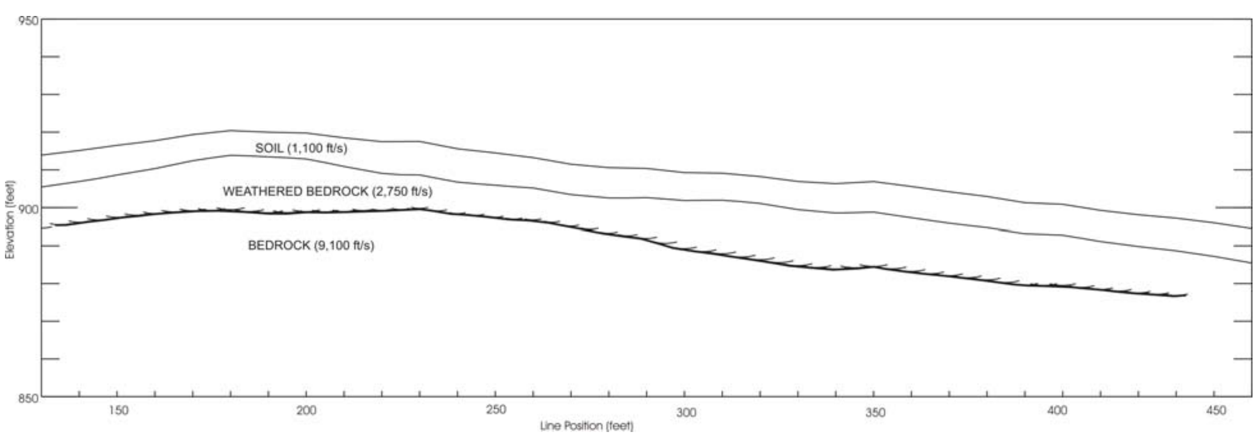

Figure 3: Seismic Refraction Depth Model SL-1

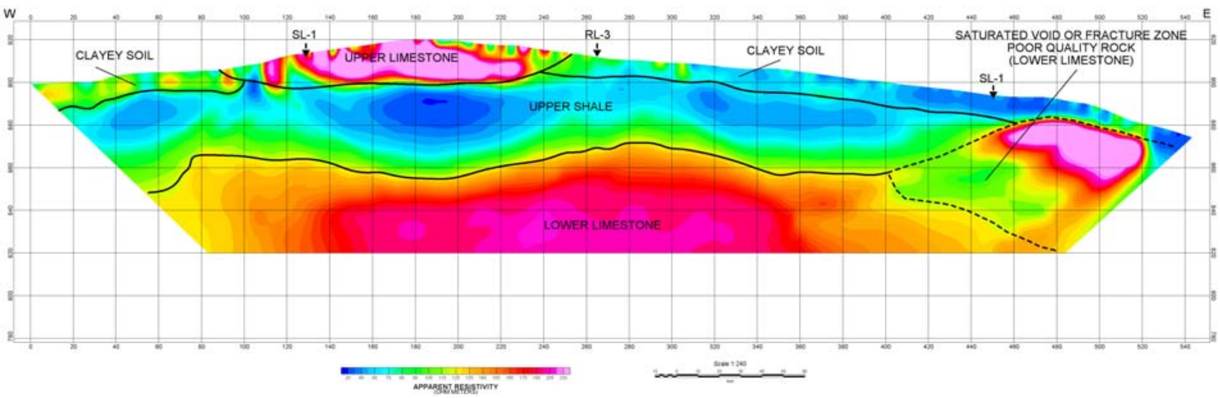

Figure 4: Modeled Electrical Resistivity Section RL-1. Wenner Array with 56 Electrodes at 10 ft spacing shown

Line 2

Three distinct velocity units were apparent on the seismic refraction model corresponding to an upper low velocity sediment layer, an intermediate velocity sediment layer and higher velocity sedimentary rock unit. The upper low velocity layer had an average compressional-wave velocity 1,100 ft/s and with an average thickness of 6 ft. This unit was probably associated with unconsolidated soil deposits. Underlying the upper soil unit was a slightly more consolidated sedimentary rock layer with P-wave velocity ranging between 4,000 and 5,000 ft/s. This rock unit was considered low velocity and was interpreted as being weathered and rippable. The sedimentary rock unit underlies the sediment layers and was modeled as having an average P-wave velocity of 8,400 ft/s and was about 25-35 ft beneath the seismic profile. This rock unit was considered to be not rippable for planning purposes. The bedrock contact could not be mapped to the ends of the seismic line as surface topography and vegetation limited the placement of off-end shot points.

Three layers were observed in the electrical resistivity data. The first layer was a moderately conductive soil layer that correlates well with the low velocity sediment layer observed in the seismic data. This layer was underlain by the resistive Lower Limestone observed beneath RL-1. The water table was interpreted at an elevation of approximately 860 ft, as confirmed by boring logs. The conductive anomaly in the Lower Limestone unit between stations 120-180 was interpreted as being caused by fluid-filled fractures or saturated, highly-weathered, poor quality rock. Beneath the Lower Limestone unit was a less-resistive unit identified as “Lower Shale” and was about 50 ft beneath the central portion of the line. The top of this unit appears to be at or around the expected water table (approximate elevation 860 ft). There was a resistive zone in the Lower Limestone located between stations 340-400. This anomaly was interpreted as being caused by a localized less-weathered or hard zone within the shale sequence, and would be considered better rock quality than the surrounding Lower Shale. Fluid-filled fractures or saturated weathered zones would be expected to be more conductive than the surrounding country rock.

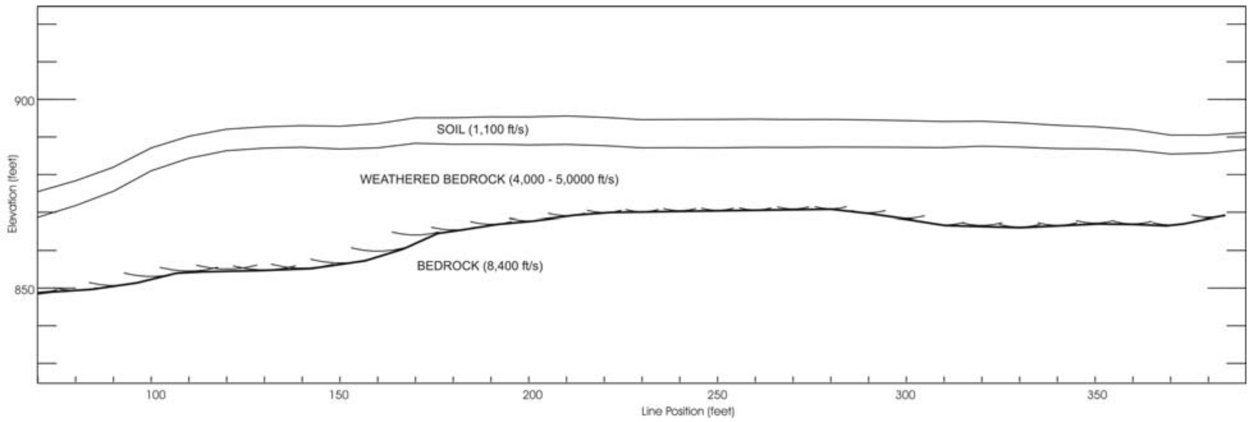

Figure 5: Seismic Refraction Depth Model SL-2

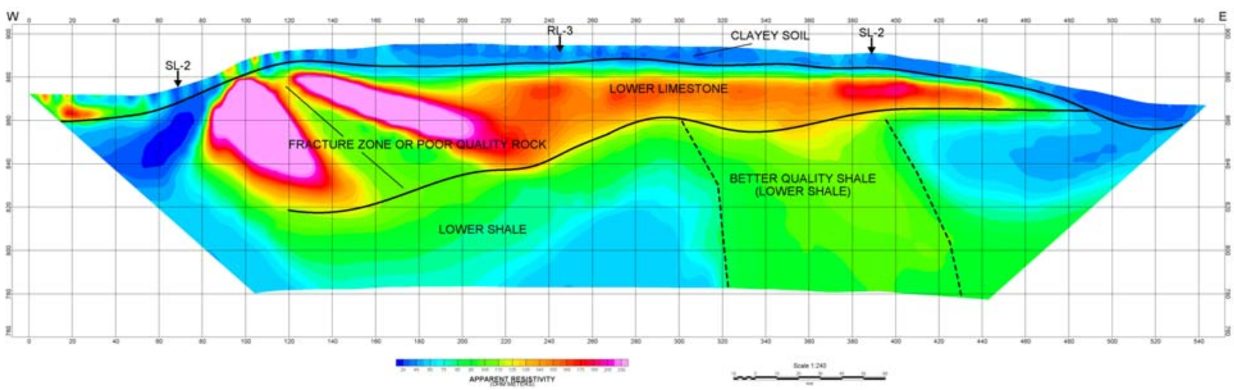

Figure 6: Modeled Electrical Resistivity Section RL-2. Wenner Array with 56 Electrodes at 10 ft spacing shown

Line 3

Three velocity units were apparent on the seismic refraction model corresponding to an upper low velocity sediment layer, an intermediate velocity sediment layer and higher velocity sedimentary rock unit. The upper low velocity layer had an average compressional-wave velocity 1,100 ft/s and with an average thickness of 6 ft. This unit was probably associated with unconsolidated soil deposits and correlates well with a thin, relatively resistive layer in the resistivity model. Underlying the upper soil unit was a slightly more consolidated sedimentary rock layer with P-wave velocity ranging between 2,000 and 3,500 ft/s. This rock unit was considered low velocity and was interpreted as being weathered. The sedimentary rock unit underlied the sediment layers and was modeled as having an average P-wave velocity of 8,200 ft/s and was about 20-30 ft beneath the seismic profile. The velocity boundary for the second layer was difficult to model. There may be a diffuse velocity contrast between the second and third layers in the model. Bedrock velocity was considered to be increasing with depth and this rock unit was considered not rippable for planning purposes.

Five layers were observed in the electrical resistivity data. These units correspond to a clayey coil layer and four rock units. Two resistive limestone units (Upper and Lower) and two low resistivity shale units (Upper and Lower) were interpreted in the data. These appeared to be subhorizontal in lines RL-1, RL-2 and RL-4 (strike direction) and dipping in the cross-line RL-3. The dip angle shown in the resistivity profile was approximate. Three-dimensional effects do not allow for true dip angle measurements.

The slightly more conductive zone within the Lower Shale unit was interpreted as being caused by weathered or unsaturated fracture zone. We recommended that this anomaly be drilled for confirmation should it be problematic for the construction of the retaining wall structure.

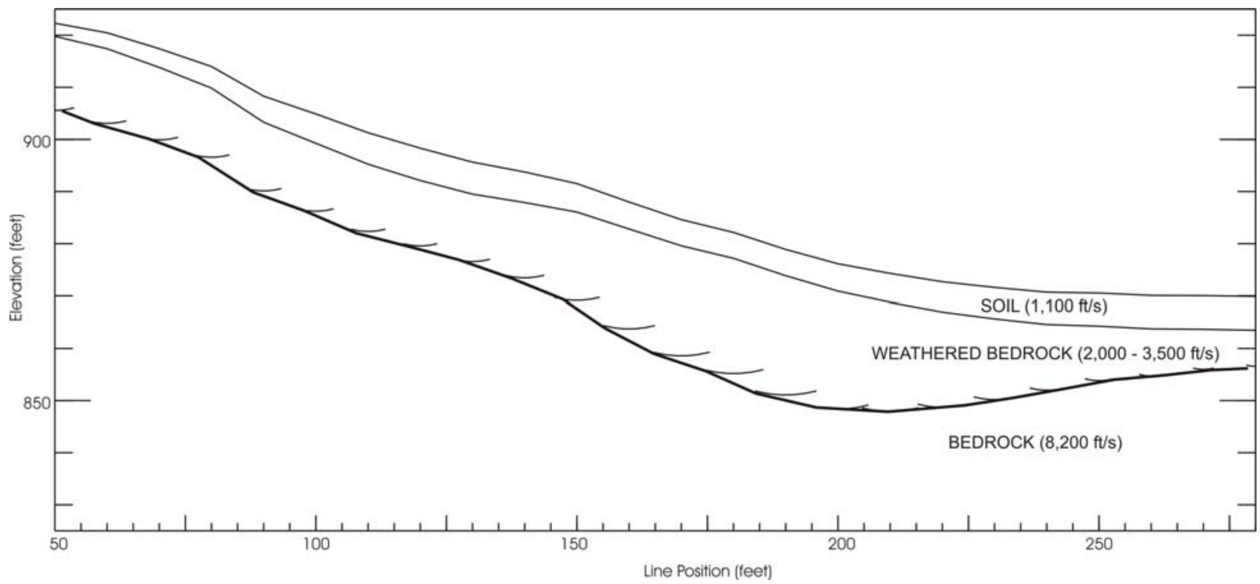

Figure 7: Seismic Refraction Depth Model SL-3

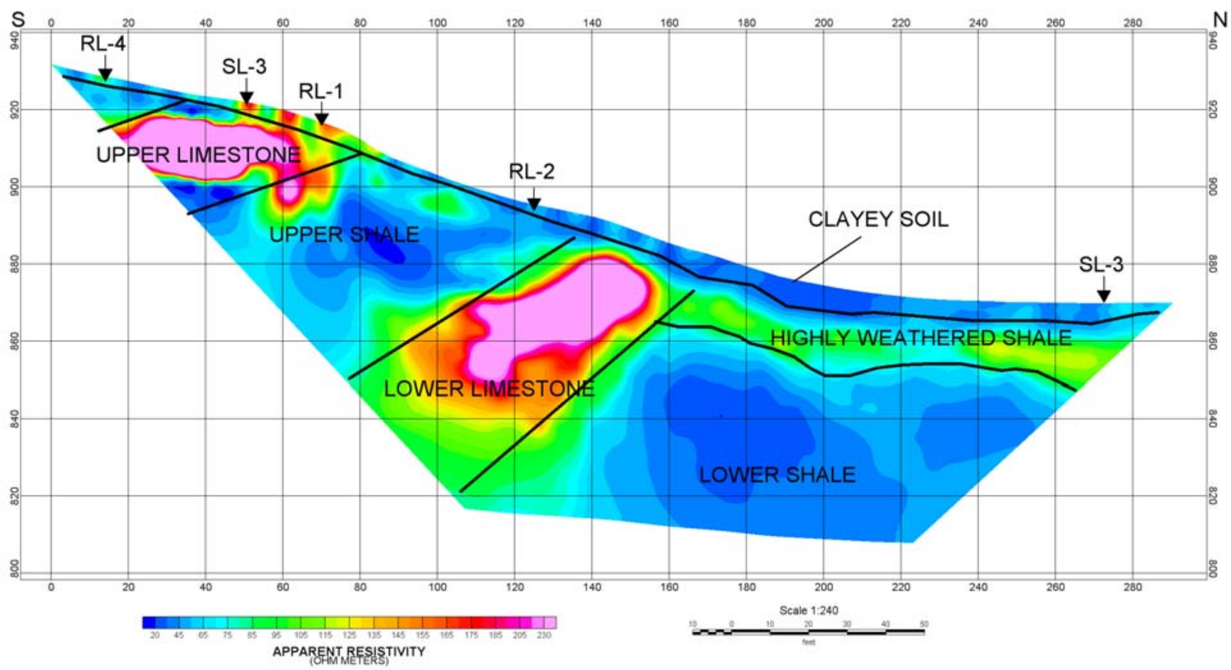

Figure 8: Modeled Electrical Resistivity Section RL-3. Dipole-Dipole Array with 30 Electrodes at 10 ft spacing shown

Line 4

Three distinct velocity units were apparent on the seismic refraction model corresponding to an upper low velocity sediment layer, an intermediate velocity sediment layer and higher velocity sedimentary rock unit. The upper low velocity layer had an average compressional-wave velocity 1,100 ft/s and thickness ranging from about 5 to 7 ft. This unit was probably associated with unconsolidated soil deposits and correlated well with a thin, relatively resistive layer in the resistivity model. Underlying the upper soil unit was a slightly more consolidated sedimentary rock layer with P-wave velocity averaging about 6,000 ft/s. The modeled velocity for this layer was consistent with saturated soils or soft rock. For the most part this sediment unit correlates with a highly resistive unit. The lower apparent resistivity values relative to the overlying layer were interpreted as not consistent with saturated sediments; this rock can therefore be interpreted as being weathered rock. The sedimentary rock unit underlied the sediment layers and was modeled as having an average P-wave velocity of 8,400 ft/s with depths ranging between 37 and 60 ft beneath the seismic profile.

The electrical resistivity model indicates a simple three-layer model consistent with the results of the seismic refraction interpretation. The first layer was a moderately conductive soil layer that correlated well with the low velocity sediment layer observed in the seismic data. This layer was underlain by the resistive Upper Limestone observed beneath RL-1 and RL-3. The water table was interpreted at an elevation of approximately 860 ft, as confirmed by boring logs. Beneath the Upper Limestone unit was the less-resistive saturated unit identified as “Upper Shale” observed beneath RL-1 and RL-3. There were no anomalies in the electrical resistivity data that were of particular concern under this profile and no additional borings were recommended for this area.

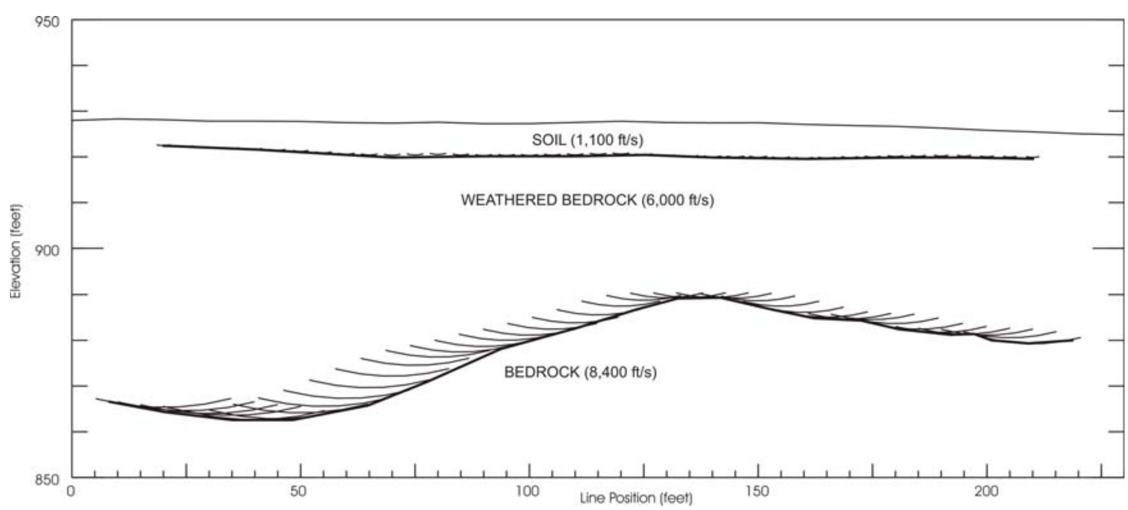

Figure 9: Seismic Refraction Depth Model SL-4

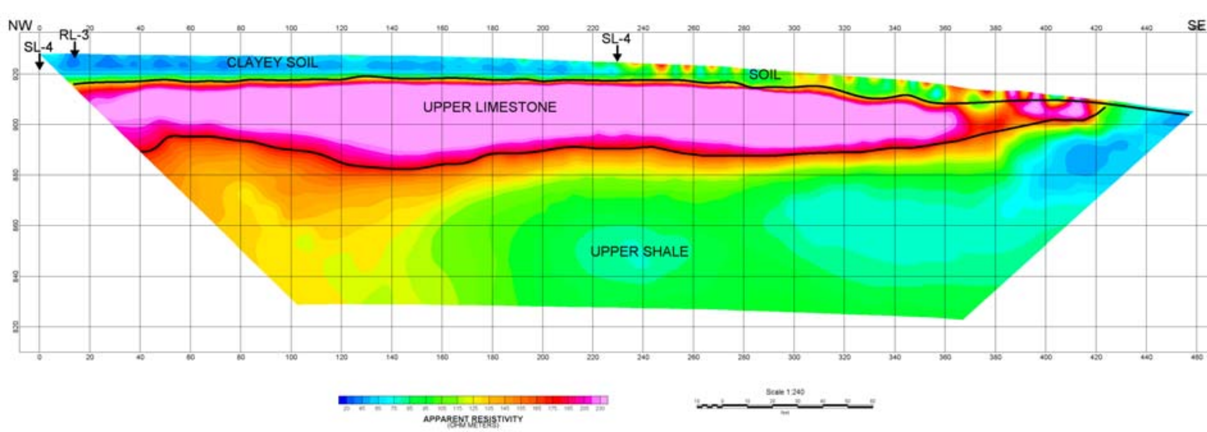

Figure 10: Modeled Electrical Resistivity Section RL-1. Wenner Array with 56 Electrodes at 10 ft spacing shown

Surface Wave Models

MASW and refraction microtremor data were reduced using the Optim™ Software and Data Services SeisOpt® ReMi™ v2.0 data analysis package and processed using WinSASW V1 and WinSASW V2 were used to model the data, whereby through iterative forward and/or inverse modeling, a V_S profile is found whose theoretical dispersion curve is a close fit to the field data. The final model profile is assumed to represent actual site conditions. The resolution decreases gradually with depth because the dispersion curve is less sensitive to changes in V_S at greater depths. Several options exist for forward modeling: a formulation that takes into account only fundamental-mode Rayleigh wave motion (called the 2-D solution), and one that includes all stress waves and incorporates receiver geometry (3-D solution) [Roesset et al., 1991].

The theoretical model used to interpret the dispersion assumes horizontally layered, laterally invariant, homogeneous-isotropic material. Although these conditions are seldom strictly met at a site, the results of MASW testing provide a good "global" estimate of the material properties along the array. The results may be more representative of the site than a borehole "point" estimate. Based on our experience at other sites, the shear wave velocity models determined by surface wave testing are within 20% of the velocities that would be determined by other seismic methods [Brown, 1998]. The average velocities, however, are much more accurate than this, often to better than 10%, because they are much less sensitive to the layering in the model.

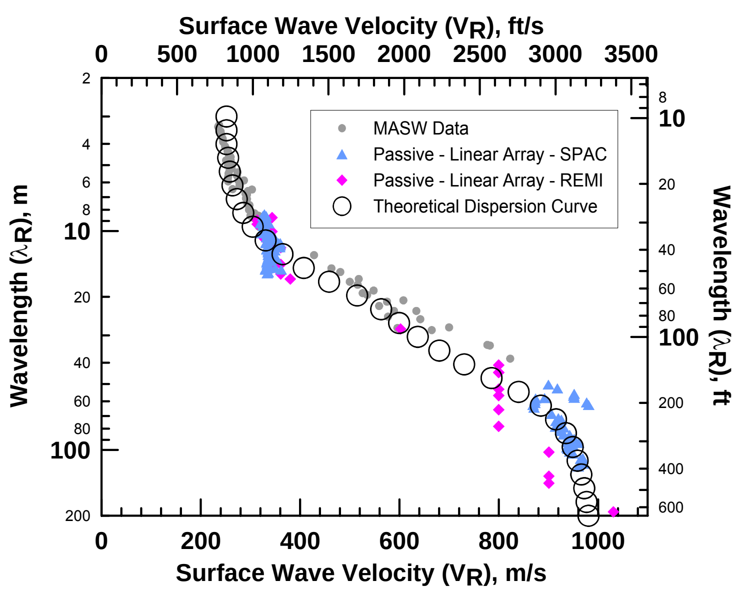

Figure 11: Comparison of Theoretical and Experimental Dispersion Curves from MASW and REMi Arrays

Conclusions

Seismic data was affected by high ambient noise levels and steep topographic relief which prohibited the placement of far off-end shots, limiting the ability to image bedrock beneath all but the central portion of the line. Interpretation of the resistivity profile is much more difficult than seismic interpretation independent of any correlating data. Resistivity data is inherently more "smoothed" than seismic refraction data, as the measurements include a bulk resistivity of all materials the current encounters between the potential electrodes. There is not necessarily any direct correlation between seismic velocity and electrical resistivity. Data obtained during a resistivity survey indicates the electrical properties of a soil or rock, which may change within a particular unit. Therefore, sharp, easily definable geologic contacts are rarely observed in DC resistivity data. A priori information from the seismic refraction survey was used to model the DC resistivity data.

It was assumed that subsurface bedrock units at the site consist of limestone and shale with a thin clayey soil cover. Two resistive potential limestone units and two low resistivity potential shale units were interpreted in the data. Resistivity models indicate that bedrock units strike in a southeasterly direction and dip to the southwest.

The seismic refraction survey provided different and complimentary data. The refraction survey was not able to differentiate between the different rock types but does provide information of weathering and rippability of the bedrock. The upper portion of bedrock seems to be weathered and is rippable. Weathering decreases with depth and rock typically becomes non rippable at depths of 20-35 ft. Apparent resistivity values calculated using the electrical technique have no direct correlation on rippability but are capable of imaging highly fractured zones provided the fractures are fluid or clay-filled. Electrical resistivity is very helpful in determining rock quality, especially in karstic geology. The higher resistivity at the upper portion of the shale layers identified on line RL-3 may be caused by increased weathering/fracturing or by the upper part of the units being unsaturated and the lower portion saturated. The limestone units may be locally fractured or weathered as indicated on RL-1 and RL-2.

Geophysical investigations are best utilized to plan borehole locations and/or correlate geology between borehole locations. These borings were not directly coincident with any of the geophysical traverses; however, information from the boring logs was used to refine the geophysical interpretation. In particular, groundwater levels and lithologic information were most useful in the sense that they allowed for differentiation between saturated and unsaturated zones, which aided interpretation of various anomalies observed in the geophysical data.

Seismic refraction, resistivity data, and geotechnical borehole logs provide complementary information to each other. The existing geotechnical boring logs refined the seismic refraction and 2-D resistivity models. The combination of the seismic refraction method and the resistivity method was a cost-effective means to correlate the areas between existing boreholes and to constrain locations for future borings.

References

Brown, L.T., 1998, "Comparison of V_S profiles from SASW and borehole measurements at strong motion sites in Southern California", Master's thesis, University of Texas at Austin.

Hales, F. W., 1958, An accurate graphical method for interpreting seismic refraction lines: Geophysical Prospecting, **6**, p 285-294.

Hawkins, L. V., 1961, The reciprocal method of routine shallow seismic refraction investigation: Geophysics, **26**, p. 806-819.

Lankston, R. W., 1990, High-resolution refraction seismic data acquisition and interpretation, in Ward, S. H., ed., Geotechnical and Environmental Geophysics, Volume I: Review and Tutorial: Society of Exploration Geophysicists, Tulsa, Oklahoma, p. 45-74.

Lankston, R. W., and Lankston, M. M., 1986, Obtaining multilayer reciprocal times through phantoming: Geophysics, **51**, p. 45-49.

Louie, J.N., 2001, "Faster, Better: Shear-Wave Velocity to 100 Meters Depth from Refraction Microtremor Arrays", Bulletin of the Seismological Society of America, vol. 91, no. 2, p. 347-364.

Palmer, D., 1980, The generalized reciprocal method of seismic refraction interpretation: Society of Exploration Geophysics, Tulsa, Oklahoma, 104 p.

Palmer, D., 1981, An introduction to the field of seismic refraction interpretation: Geophysics, **46**, p. 1508-1518.

Park, C.B., Miller, R.D. and Xia, J., 1999a, "Multimodal analysis of high frequency surface waves", *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems '99*, 115-121.

Park, C.B., Miller, R.D. and Xia, J., 1999b, "Multichannel analysis of surface waves", Geophysics, Vol 64, No. 3, 800-808.

Redpath, B. B., 1973, Seismic refraction exploration for engineering site investigations: U. S. Army Engineer Waterway Experiment Station Explosive Excavation Research Laboratory, Livermore, California, Technical Report E-73-4, 51 p.

Roesset, J.M., Chang, D.W. and Stokoe, K.H., II, 1991, Comparison of 2-D and 3-D Models for Analysis of Surface Wave Tests, Proceedings, 5th International Conference on Soil Dynamics and Earthquake Engineering, Karlsruhe, Germany.
Stokoe, K.H., II, Wright, S.G., Bay, J.A. and Roesset, J.M., 1994, Characterization of Geotechnical Sites by SASW Method, ISSMFE Technical Committee 10 for XIII ICSMFE, Geophysical Characteristics of Sites, A.A. Balkema Publishers/Rotterdam & Brookfield, Netherlands, pp. 146.
Stokoe, K.H.,II, Rix, G.L. and S. Nazarian, 1989, In situ seismic testing with surface waves Proceedings, Twelfth International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, Rio de Janeiro, Brazil, pp. 330-334.
Yang, X., 1999, Stochastic inversion of 3D ERT data: PhD thesis, the University of Arizona, Tucson, Arizona, USA.