APPLYING THE REFRACTION MICROTREMOR (ReMi) SHEAR WAVE TECHNIQUE TO GEOTECHNICAL CHARACTERIZATION

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ABSTRACT

The refraction microtremor (ReMi) technique provides a simplified characterization of relatively large volumes of the subsurface in 1-dimensional vertical (depth) profiles. Field data can be collected using seismic refraction equipment; ReMi and seismic refraction data can be collected using the same geophone array setups. Surface wave energy sources for ReMi can be ambient noise or range from jogging for short arrays to field vehicle for long arrays. ReMi profiles can be performed effectively in urban areas with considerable activity using ambient noise as the energy source. Shear wave (s-wave) velocities, the typical measured geologic material parameter, are a function of the moduli of the various material masses in the subsurface profile. Soil/rock contacts or contrasts between weaker and stronger geologic material horizons can be interpreted from ReMi data. Preliminary subsurface profiles can be developed from this information, and characterization of subsurface profiles between geotechnical borings, test pits and seismic refraction geophysical profiles can be accomplished. When performed in conjunction with seismic refraction, ReMi can characterize a lower velocity horizon underlying a higher velocity horizon (velocity reversal) condition that is missed using standard seismic refraction.

INTRODUCTION

The refraction microtremor (ReMi) method provides an effective and efficient means to obtain general information about large volumes of the subsurface in one dimension per setup, where appropriate setup length is related to desired the depth of investigation. ReMi is described by Louie (2001), where it is applied to obtain vertical s–wave profiles to depths up to 100 meters for earthquake seismic site characterization. The methods' theoretical basis is the same as spectral analysis of surface waves (SASW) and multi-analysis of surface waves (MASW). However, field data can be collected using modern standard small exploration seismic equipment. ReMi interpretation and analysis is performed using appropriate software that is available for desktop and notebook personal computers. For site seismicity characterization, appropriate low frequency geophones and relatively long geophone arrays are needed.

Figure 1. *Combined ReMi and seismic refraction setup in Sandia Mountains, NM. Equipment is set up on the back of the truck. Geophone spacing is 10 feet and the array length is 120 feet. The author is beginning to jog to generate surface waves for a ReMi data set; the sledgehammer seismic refraction energy source is in the foreground.*

This paper is intended to describe ReMi applications for geotechnical engineering work that can be applied to transportation and other facilities. ReMi capabilities have been available for only a short time; applications will increase as the method becomes more widely used and the geotechnical profession gains experience and confidence with it. The author has incorporated ReMi into the seismic refraction services for geotechnical characterization at his firm (Rucker and Keaton, 1998; Rucker, 2000). Projects completed that required a deep depth of investigation capability have included assisting in seismic site characterization at a state capitol and interpreting depth to bedrock to support gravity studies and interpret subsurface modulus profiles to help characterize and model differential ground subsidence and earth fissuring at flood control dams. More typical geotechnical applications have included characterizing foundation conditions at flood control dams, geotechnical site characterization at a major optical interferometry telescope facility and at wind turbine sites, and characterizing subsurface profiles for tunneling conditions for a people mover project through a major airport. ReMi has also been applied to interpret the bottom depth of an uncontrolled landfill. The ability to quickly, simply and effectively perform in situ s-wave characterization using this surface geophysical method could have a revolutionary impact on geotechnical site characterization.

REFRACTION MICROTREMOR (ReMi) SHEAR WAVE EQUIPMENT & PROCEDURES

The author began using ReMi in August 2002, and has developed typical procedures for it's use in geotechnical investigations. Surveys are performed in general accordance with the method described by Louie (2001) to develop vertical one-dimensional s-wave velocity profiles. The same equipment used for ReMi is also used for seismic refraction. When appropriate, both p-wave and s-wave data are collected in the same physical seismic line setup. In this manner, both the ReMi and seismic refraction data and interpreted results serve as complementary quality controls with each interpretation enhancing the other. Furthermore, weaknesses of each method are countered by strengths of the complementary method.

ReMi Seismic Equipment

A multichannel seismograph capable of storing up to 16,000 samples per channel at sample intervals as long as 1 to 2 milliseconds in SEG2 or SEGY format can be used to collect ReMi data. The author performs ReMi surveys using a Geometrics S-12 Smartseis 12 channel signal enhancement seismograph. Geophone cables with 12 geophone takeouts at typical 10-foot or 20-meter spacings are used. Other spacings can be set from these cables. Vertical geophones with resonant frequencies of 28 Hz and 4.5 Hz are used to obtain surface wave data for s-wave vertical profile analysis. The high frequency geophones are used for shorter arrays with shallower depths of investigation, and the low frequency geophones are used for longer arrays with greater depths of investigation. Broad band ambient site noise may be used as a surface wave energy source. Controlled surface wave energy sources include jogging alongside shorter geophone arrays and driving a field vehicle alongside longer geophone arrays. The seismograph system is very portable. In areas where vehicular access is not possible, the equipment can be mobilized by various means, including backpacking, packhorse, helicopter and canoe.

ReMi Field Procedures

When the author performs surveys, ReMi seismic lines are generally laid out using the standard spacings on the geophone cables. According to Louie (2001), a depth of investigation of about 100 meters or more may be possible using a 200 meter array. For shorter lines with improved near-surface resolution, 10-foot spacings between geophones with a 120-foot array have a minimum depth of investigation of about 30 to 40 feet, although much deeper bedrock contact depths have been interpreted. Other geophone spacings can also be used.

Data collection consists of the system sampling the ambient or generated surface waves (a sampling event) at the geophone array for several to many seconds. Typical sampling times and intervals for a sampling event may be 6 seconds at 0.5 milliseconds, 12 seconds at 1 millisecond and 24 seconds at 2 milliseconds for array lengths of 60 feet, 120 feet and 240 meters, respectively. Several sampling events are collected at each ReMi setup. For shorter arrays where ReMi with surface wave energy generated by jogging is conducted in concert with seismic refraction data collection, four sampling events may typically be recorded. For longer arrays where urban ambient noise or a field vehicle generates the surface wave energy, six to ten sampling events may be recorded. Field notes, including line number and orientation, topographic variations and other notes as appropriate are made on hard copy of traces. Locations and other notes are made on site maps and in notebooks as appropriate. Sample data files may be transferred by 3.5-inch floppy to the notebook computer and preliminary interpretations made for immediate data adequacy verification as part of the quality control process.

Interpretation

Although preliminary or quality control initial ReMi seismic data interpretations may sometimes be performed in the field, full interpretations are completed in the office. Data files are transferred from the seismograph to the interpreting computer. The author performs Interpretation using the current SeisOpt ReMi software package (Optim, 2003). This software consists of two modules. The first module is used to transform data files into a spectral energy shear wave frequency versus shear wave velocity (or slowness) presentation for each ReMi seismic setup, as shown in the insert in Figure 2. The interpreter then selects a dispersion curve consisting of the lower bound of the spectral energy shear wave velocity versus frequency trend, shown as small squares in Figure 2, and that dispersion curve is saved. Tracing the lower bound (slowest) of the shear wave velocity at each frequency selects the ambient energy propagating parallel to the geophone array, since energy propagating incident to the array will appear to have a faster propagating velocity. The second module allows the interpreter to model a dispersion curve with multiple layers and s-wave velocities to match the selected dispersion curve from the field data. The modeler interactively varies layer velocities and depths until the resulting dispersion curve best matches the previously selected dispersion points. An interpreted vertical s-wave profile as summarized in Figure 2 is obtained through this process. It must be understood that this type of interpretation may not result in a unique solution.

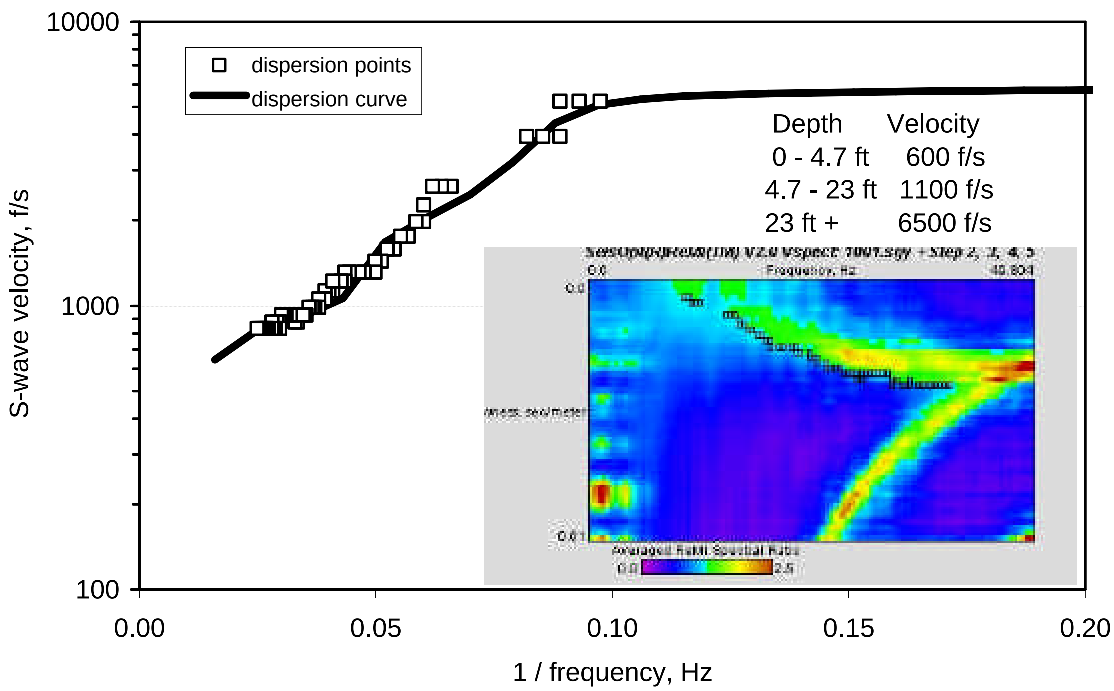


Figure 2. *Example ReMi interpretation. Note bedrock velocity interpretation at 23 foot depth. The color insert plots spectral energy as a function of frequency and wave propagation velocity.*

EXAMPLE APPLICATIONS

Subsurface Profiling for Tunneling at Airport Terminals (Noisy Urban Setting)

ReMi was included as part of a subsurface investigation for the geotechnical baseline report for a proposed people mover transit system at Terminals 3 and 4 of the Phoenix Sky Harbor International Airport. Tunneling is a proposed alternative for this project, and tunnels would be advanced in coarse grained sand-gravel-cobble (SGC) deposits underlying the airport along the edge of the Salt River. Upper, younger portions of these SGC deposits are typically dese to very dense but cohesionless. They would have a tendency to be unstable, with little or no stand up time, if tunneling is performed in them. Lower, older portions of these SGC deposits typically include small amounts of clays or cementation in the pore spaces. Those clays or cementation provide that SGC with sufficient cohesion to have stand up time for effective tunneling. Drilling and sampling in these coarse deposits with cobbles and occaional boulders is very difficult. Reverse circulation drilling with air (Becker hammer, ODEX methods) severely disturbs samples and typically strips them of fines, including clays. Rotosonic drilling can provide complete recovery of very disturbed samples for fines and clay identification, but is very expensive and relatively slow. The investigation was further complicated by the proposed alignment being alongside or under the terminals in areas where passengers load and unload from cars, buses and other transport. Drilling was severely constrained to short nighttime shifts in limited areas.

ReMi provided a means to obtain basic subsurface profile information on an essentially continuous basis across the site. The upper cohesionless SGC has typical s-wave velocities less than about 1,200 feet/second (f/s), while the lower SGC has typical s-wave velocities of about 2,500 to 3,500 f/s. A typical ReMI setup at a loading curb is shown in Figure 3. A test program utilizing Becker and Rotosonic drilling, seismic refraction and ReMi in a quieter and more accessible area was initially completed to test the various methods for site characterization.

Figure 3. *Typical field setup for ReMi data collection along loading and unloading curbs at airport terminals. Note cinder blocks used to assist with geophone placement on pavement. Geophones were placed on hollow cinder blocks set on the pavement in a 12-geophone array with 10-foot spacing. Each ReMi data set was 12 seconds long at 1 millisecond sample intervals. Twenty-eight Hz geophones are set up on the cinder blocks, and 4.5 Hz geophones are collected on the sidewalk next to the seismograph. The ReMi test is being performed on a street section consisting of a minimum of 5-inches of asphaltic concrete pavement over an aggregate base course. Although the site was hopelessly noisy for seismic refraction as well as being paved, the ambient noise served well as a source for the ReMi method.*

Typical ReMi results for a setup are shown in Figure 4. For this project, both high and low frequency geophones sampling ambient noise were used. Data sets were first obtained using the 4.5 Hz low frequency geophones, and then the 28 Hz high frequency geophones were placed into the array. Interpretations were based primarily on the low frequency results.

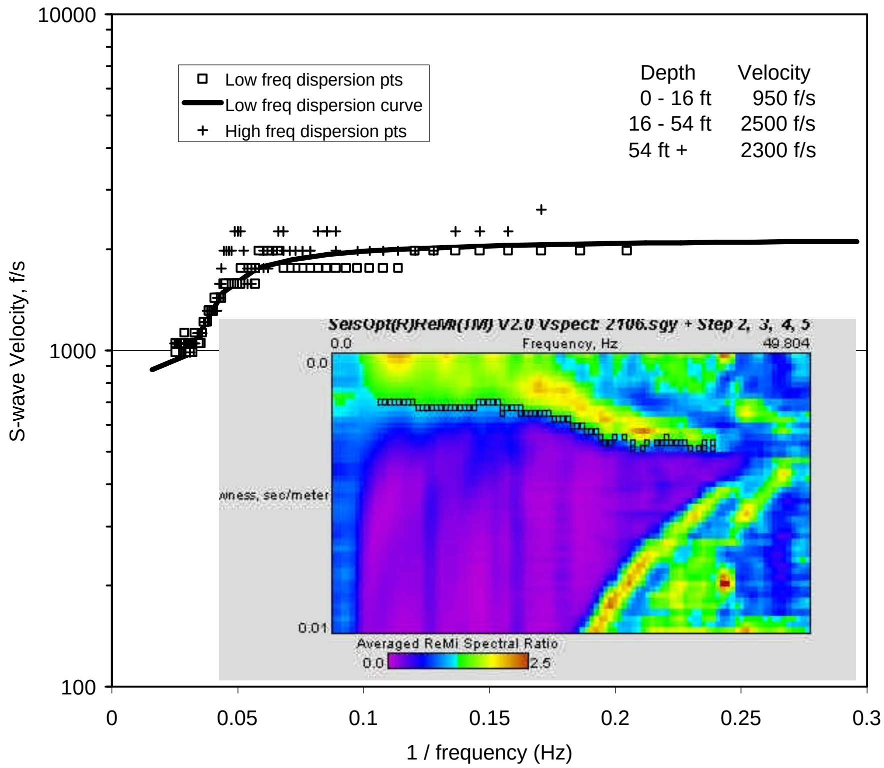
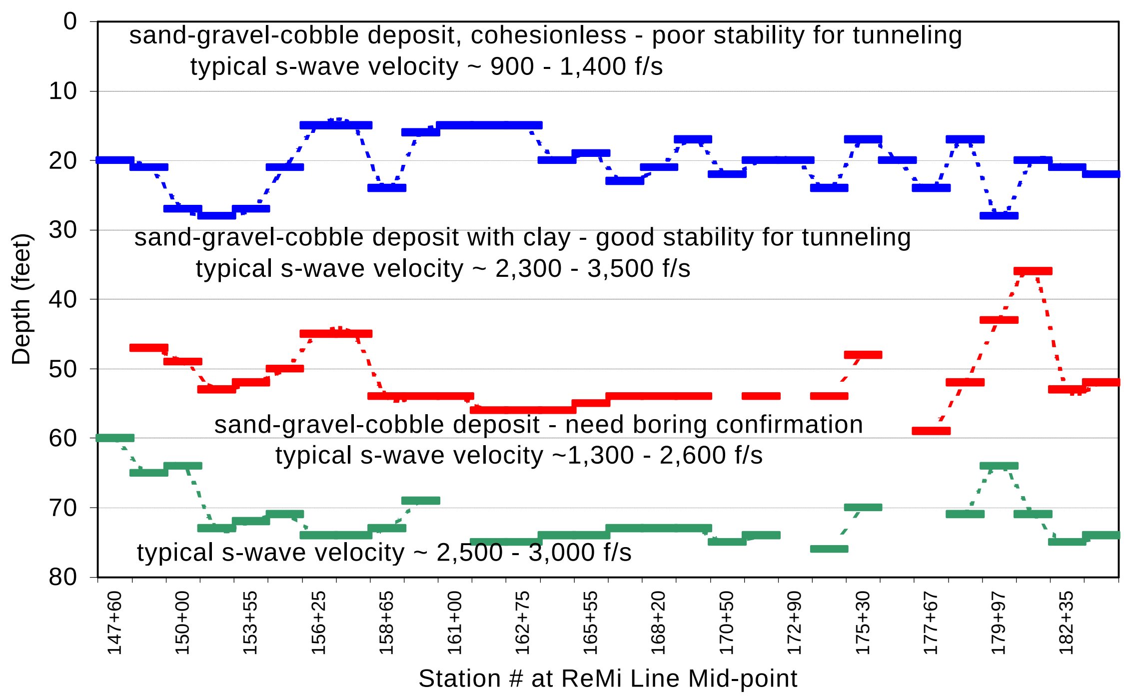


Figure 4. *Example ReMi results using 120-ft array with ambient noise at loading/unloading curb with both low and high frequency geophone arrays.*

Figure 5. *Summary of 30 ReMi surveys completed for preliminary 3,600 foot-long profile along airport terminal. Setups were as shown in Figure 3; ambient noise was used as source.*



A simplified summary of the resulting profile for part of the project site is presented in Figure 5. As can be seen from the figure, useful subsurface information for planning and design was obtained inexpensively and with minimal disturbance to airport operations. In addition, twenty-one borings were completed along the entire profile and sixty-one 120-foot long ReMi lines provided nearly continuous profile coverage to assist in characterization for tunneling. Seismic refraction was performed at seventeen ReMi setups where it was practical to do so.

Geotechnical Characterization at Telescope Site (Combined ReMi and Seismic Refraction)

Twenty-five combined seismic refraction and ReMi lines were completed as part of the geotechnical investigation at a proposed optical interferometry telescope site on top of a high-altitude volcanic ridge in central New Mexico. Seismic program goals included presence, depth and geometry of the bedrock profile between borings, excavation conditions and determining the dynamic modulus characterization.

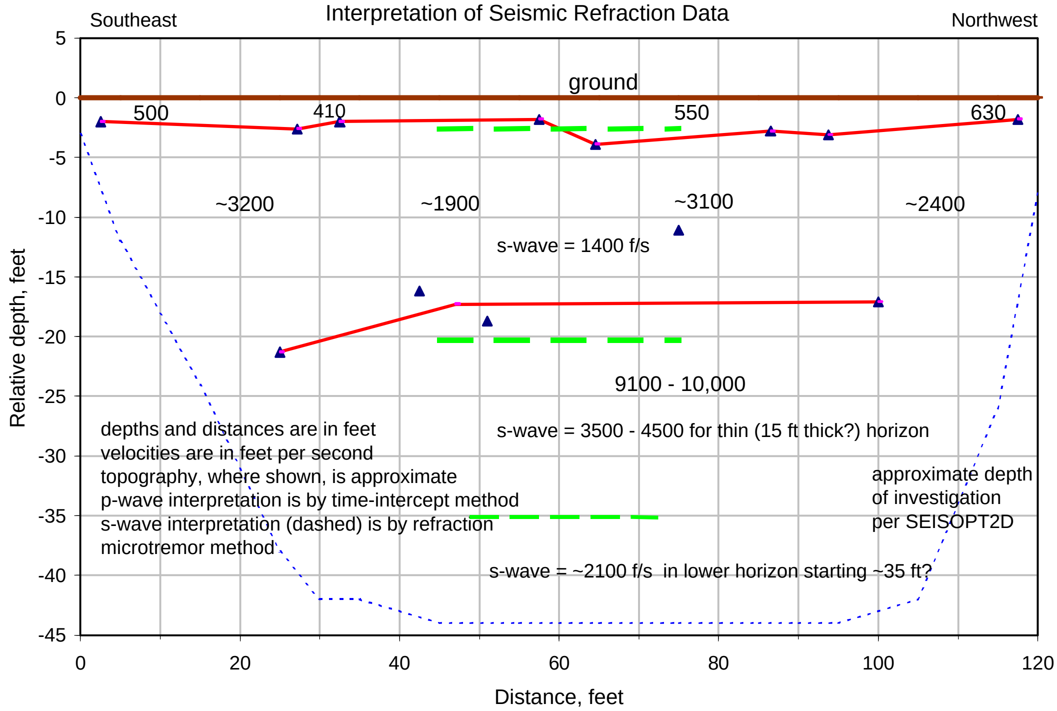


Figure 6. *Results of seismic refraction and ReMi interpretations at a select line in a volcanic setting. Seismic refraction interpretation implies bedrock contact at about 17 to 22 feet; bedrock p-wave velocity is apparently about 9,000 to 10,000 f/s. However, ReMi interpretation indicates a deep s-wave velocity of only about 2,100 f/s, significantly less than the about one-half the p-wave velocity that would be anticipated for the bedrock. A ReMi interpretation is shown in Figure 7 that includes a high s-wave velocity horizon overlying a lower velocity horizon that is also consistent with the seismic refraction interpretation.*

Complete interpretation of the seismic data involved iterating between both the seismic refraction and ReMi interpretations. In the example shown in Figure 6, both strengths and weaknesses of each seismic method are demonstrated. The horizon at a depth of about 3 feet to 17 feet has interpreted p-wave velocities of 3,200, 1,900, 3,100 and 2,400 f/s, and an interpreted s-wave velocity of 1,400 f/s. As presently implemented as a 1-dimensional characterization method, this ReMi result does not interpret horizontal changes in seismic wave velocity as can be done with seismic refraction. Below a depth of about 17 feet, the p-wave velocity increases to about 9,000 to 10,000 f/s, while the highest s-wave velocity in the ReMi dispersion curve does not exceed about 2,100 f/s. By using the results of the p-wave interpretation to force a higher s-wave velocity horizon at a depth of about 20 feet, a ReMi interpretation now includes a high s-wave velocity horizon of about 3,500 to 4,500 f/s as shown in Figure 7. However, this horizon is also interpreted to have a thickness of only about 15 feet. Furthermore, this high velocity horizon overlies a deeper horizon with an interpreted s-wave velocity of about 2,100 f/s. The velocity reversal condition is not interpreted in the seismic refraction p-wave interpretation. Given the extreme subsurface variability that can be present in a volcanic setting, an alternative geologic interpretation for the high velocity horizon may be that it is a flow or intrusion rather than a typical bedrock condition. A combination of both ReMi and seismic refraction data, collected using the same field setups, provides the opportunity to enhance interpretations and better characterize subsurface conditions than either method alone.

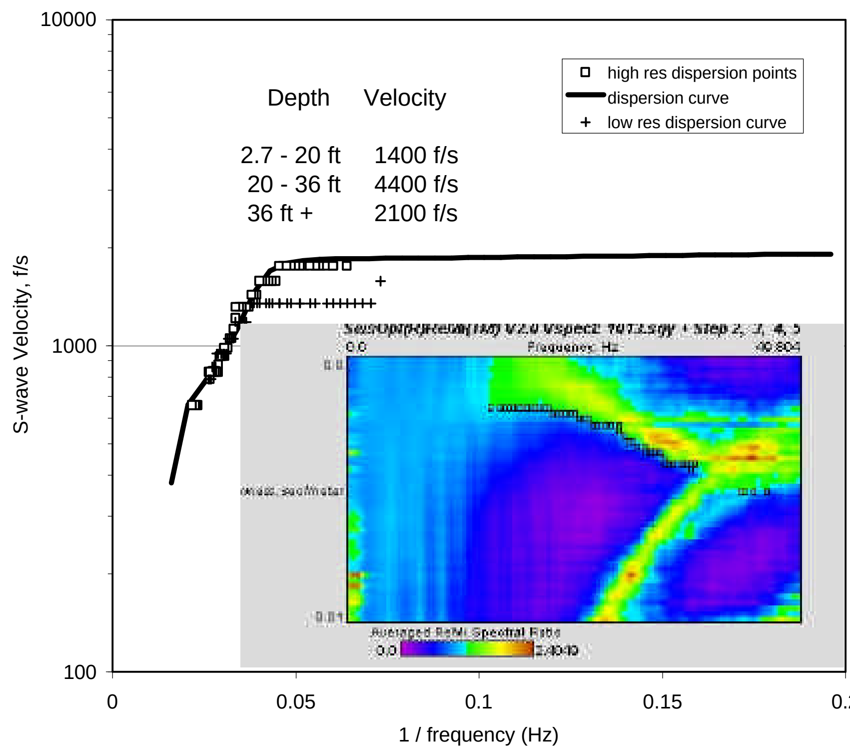


Figure 7. *ReMi interpretation at the line shown in Figure 6. Dispersion curves at higher and lower resolution are presented. 'Lower resolution' data was processed to enhance the lower frequency portion of the data since jogging at this site was a poor generator of lower frequency data. However, that enhancement compromise reduces resolution at higher s-wave velocities. Interpretation at his line was based on the data processed at 'higher resolution.'*

Characterization of Fill Under Distressed Concrete Slab

An unusual application of the ReMi method was to characterize a subsurface fill and native soil profile under a distressed concrete floor slab in a residence. Concrete slab cracking was evident through ceramic tile mortared to the slab around some edges of the room. As shown in Figure 8, the scale of this work was very small, with geophone spacings of only 1 foot and a total array length of 11 feet. High frequency (28 Hz) geophones were deployed using large binder clips attached to the geophone spikes for vertical mounting on the tiles. No permanent marks or other evidence of the work were made on the floor surface. Soft shuffling of feet on the floor alongside the array served as a suitable energy source.

Figure 8. *Small scale ReMi array setup to evaluate fill conditions under concrete slab. Binder clips were set on spikes and then taped to the geophone bodies for mounting on the floor.*

Results of the ReMi work are shown in Figure 9. Analysis and interpretation included frequencies up to 300 Hz that are considerably higher than the frequencies used in normal geotechnical work. Interpretation under these extreme conditions was more approximate than in the other examples, but general trends were incorporated into the dispersion data and interpreted curve. An interpretation including a roughly 3-foot thick relatively competent higher s-wave velocity horizon overlying a 3- to 4-foot thick lower velocity horizon defined the fill underlying the slab. One possible explanation for the slab distress is that the bottom 3 to 4 feet of fill was not compacted as well as the upper 3 feet of fill. Footings around the room extended through the fill into the underlying native material (s-wave velocity of about 2,400 f/s). As the lower fill settled, the wall footings around the room did not settle, and differential settlement and distress occurred.

SUMMARY

ReMi provides a means to obtain s-wave profiles for subsurface characterization using simple and flexible surface procedures. Seismic refraction equipment can be used to collect data, increasing the effectiveness and application of that equipment. Noisy sites that are difficult to evaluate using seismic refraction can be effectively profiled using ReMi. Several geotechnical applications have been presented in this paper. It must be emphasized that effective characterization may require multiple exploration methods to obtain suitable information to sufficiently understand relevant subsurface conditions for a particular project or situation.

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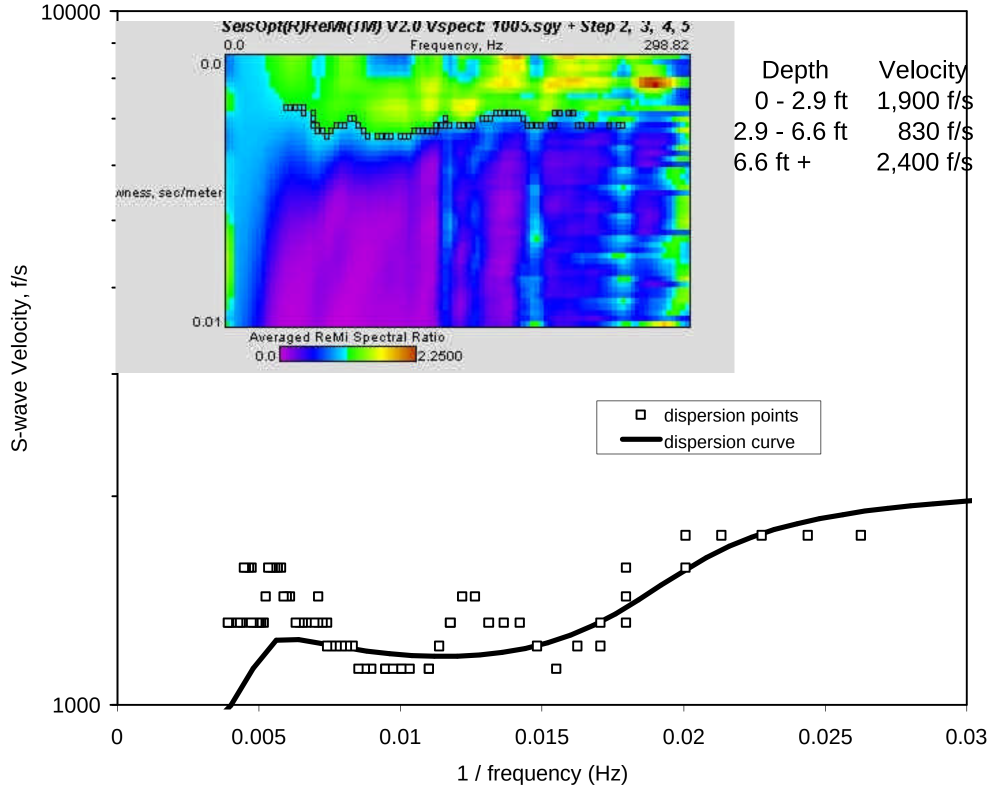

Figure 9. *ReMi interpretation at distressed concrete slab. Note interpretation of velocity reversal condition in the approximately 6 to 7 foot fill profile.*