CHARACTERIZING POTENTIAL ‘BRIDGING GROUND’ CONDITIONS USING THE REFRACTION MICROTREMOR (ReMi) SURFACE SEISMIC TECHNIQUE

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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. ReMi can characterize a lower velocity horizon underlying a higher velocity horizon (velocity reversal) condition that is missed using standard seismic refraction. In a situation where more competent ground is bridging over a weaker zone due to subsidence or collapse of underlying geologic materials or abandoned spaces, ReMi has the capability to detect the weaker underlying material s-wave velocity. It is also effective as a rapid general subsurface characterization method, especially in conjunction with seismic refraction. 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. For operation adjacent to or near highways, passing vehicles can serve as an 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. Several characterization examples are presented.

INTRODUCTION

The refraction microtremor (ReMi) method provide 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 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 laptop 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 ad 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, with an emphasis on identifying potential weaker zones or openings in a subsurface profile. 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 in it. The author has incorporated ReMi into the seismic refraction services for geotechnical characterization at his firm (Rucker and Keaton, 1998; Rucker, 2000; Rucker, 2003). Projects using 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

Figure 2. *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.*

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 (Figure 2). 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 upon 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 as well as seismic refraction data. High frequency geophones are used for very short arrays with very shallow depths of investigation, and low frequency geophones are used for typical geotechnical application 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 extremely 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 completed using both seismic refraction and ReMi 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. Arrays with 5-foot and 1-foot spacings have been used effectively; 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 and 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 laptop computer and preliminary interpretations made for immediate data adequacy verification as part of the quality control process.

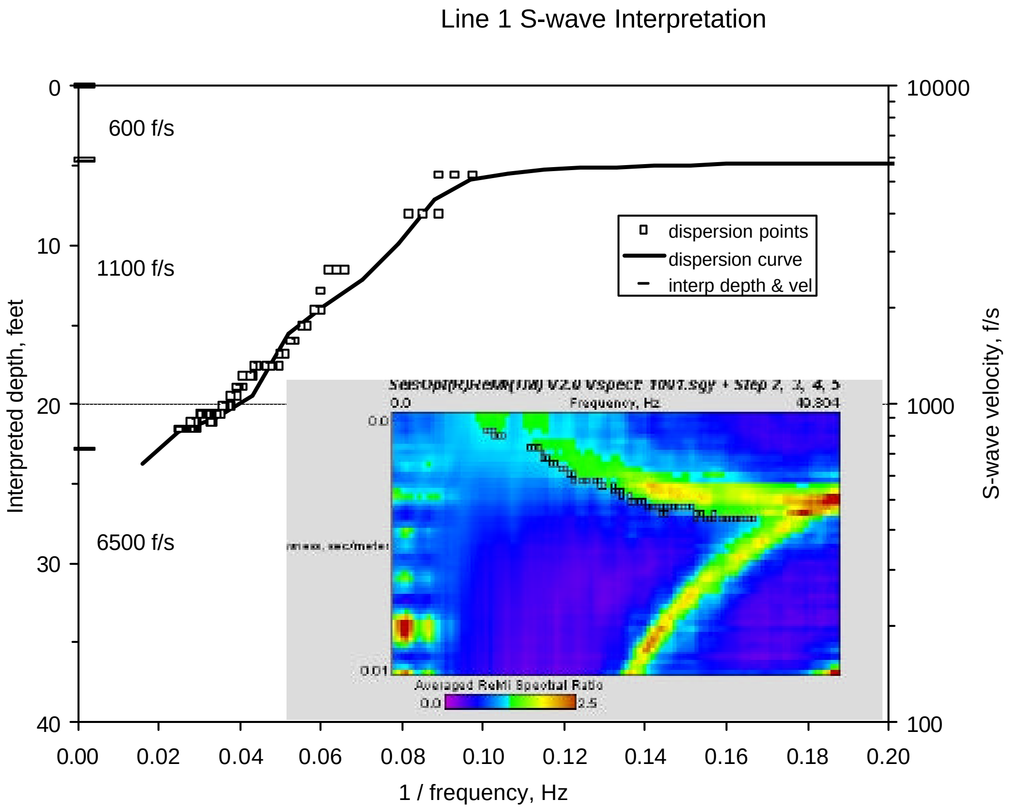


Figure 3. *Example ReMi interpretation. Note bedrock velocity interpretation at 23 foot depth.*

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 3. 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 3, 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. An interpreted vertical s-wave profile as shown in Figure 3 is obtained through this process. It must be understood that this type of interpretation may not result in a unique solution.

EXAMPLE APPLICATIONS

Practical applications of the ReMi method to geotechnical investigations will be used to further present capabilities and limitations of the method in practice. It should be noted that results from seismic refraction data has the potential to provide very useful information concerning ground conditions that may be related to the presence of abandoned underground spaces or differential subsidence. Unusual changes in seismic refraction signal amplitude (anomalous attenuation) and sudden increases in refraction signal travel time could indicate the presence of subsurface ground distress.

Seismic Characterization at Culvert Site (Combined ReMi and Seismic Refraction)

The author used a culvert in a roadway fill east of Phoenix, Arizona to verify that the ReMi method can be used to indicate the presence of an open space underlying ‘bridging ground’ in a subsurface profile. If the method could not distinguish such a known open space, ReMi would have limited application in locating unknown underground spaces. The culvert was an 8-foot diameter corrugated metal pipe, the crown of which was buried at a depth of about 6 feet in the embankment, which was about 10 feet high at that location. Native ground in the embankment vicinity includes a cemented horizon with p-wave velocities of about 3,400 to 7,000 feet per second (f/s), s-wave velocities of about 2,000 f/s, with a thickness of several to perhaps 15 feet beginning at a few feet below the surface. An underlying less competent horizon has s-wave velocities of about 1,600 f/s, and a deeper more competent material with s-wave velocities of about 2,800 f/s begins at depths of about 40 feet. Three combined ReMi and seismic refraction line arrays, each 60-feet long, were performed end to end along the embankment. The center array was centered over the culvert, and the outer arrays were outside of the influence of the culvert.

Seismic refraction data was completely interpreted for the center and one outside line. Below the second (f/s) at the culvert line and 2,100 to 2,500 f/s at the adjacent line to the east. At a depth of about 12 feet at the culvert line, p-wave velocities increased to about 4,000 f/s. At a depth of about 7 to 12 feet at the adjacent line, p-wave velocities increased to about 3,300 f/s. These depths and velocities were consistent with the embankment material and height and with the native cemented horizon present in the area. There was no indication of a culvert in the seismic refraction p-wave results.

Results of the ReMi s-wave data from the three lines are presented in Figure 4. S-wave velocities in the embankment fill were 1,000 to 1,100 f/s, which was about half of and consistent with the embankment p-wave velocities of 2,100 to 2,500 f/s. Below the embankment, a cemented horizon in the shallow native soils with s-wave velocities of 1,700 to 2,100 f/s was interpreted in the lines on either side of the culvert (Figure 4B, 4C). These velocities were consistent with analogous p-wave velocities of 3,300 to 4,000 f/s in the embankment p-wave results and other nearby seismic line results.

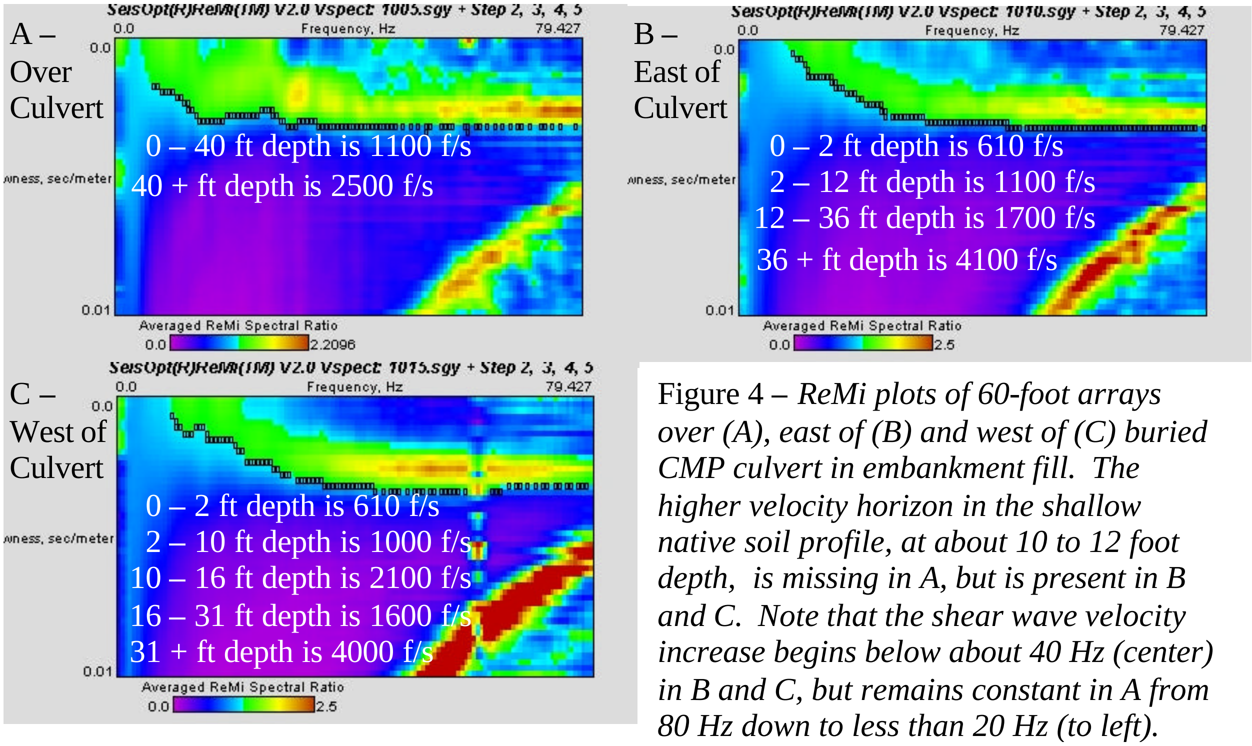


Figure 4 – *ReMi plots of 60-foot arrays over (A), east of (B) and west of (C) buried CMP culvert in embankment fill. The higher velocity horizon in the shallow native soil profile, at about 10 to 12 foot depth, is missing in A, but is present in B and C. Note that the shear wave velocity increase begins below about 40 Hz (center) in B and C, but remains constant in A from 80 Hz down to less than 20 Hz (to left).*

However, no cemented horizon in the shallow native soils was indicated in the ReMi line overlying the culvert (Figure 4A). This was in spite of a horizon with a p-wave velocity of 4,000 f/s at a depth of 12 feet in the seismic refraction data at the same array. An anomalous condition at the culvert line was thus indicated when the ReMi and seismic refraction results were compared. Furthermore, an anomalous condition at the culvert line was indicated when the ReMi results for all of the lines in the area were compared.

Seismic Characterization at Cemented Soil Site (Combined ReMi and Seismic Refraction)

Cemented soil horizons or relatively competent rock layers provide geologic settings where 'bridging ground' can develop when underlying open spaces are present or softer ground subsides or is eroded out. Combined seismic refraction and ReMi data can assist in reasonable characterization of these complex conditions. Seismic refraction data, including unusual attenuation and/or time delay in first arrival signals, can indicate the presence of significant or continuous discontinuities (Figures 5 and 6) or localized lower material strength. Concurrent ReMi data can investigate below a relatively high velocity near surface horizon to indicate the presence of significantly lower strength or missing material underlying a cemented soil or rock cap. Seismic refraction generally cannot quantify conditions below a 'velocity reversal,' where lower velocity material underlies a higher velocity horizon. Thus, as demonstrated in the previous example, a potential subsurface problem might be masked if seismic refraction alone is used.

Figure 5 – *Fracture discontinuity in cemented soil horizon west of Phoenix, Arizona. This fracture passes through the cemented horizon in a zone of ground tensile strain caused by differential ground subsidence. Although of small aperture, it caused an anomalous seismic refraction signal as shown in Figure 6; the interpreted seismic signal led to the discovery of the fracture through test trenching. Should differential subsidence due to groundwater pumping continue, this crack could develop into an earth fissure located in the foundation of a flood control dam.*

In this seismic characterization example, seismic refraction signals and results identified the presence and location of discontinuities in a cemented horizon that, although of small aperture, were sufficiently continuous to indicate the presence of ground tension that could be a potential future hazard at a flood control dam. In the case of bridging ground over an abandoned space or very weak subsurface zone, similar fractures or discontinuities could be anticipated in zones of tension in the ground surrounding the abandoned space or weak zone. In this example, ReMi was used to verify that a lower velocity softer horizon was underlying the cemented zone. In the case of bridging ground, ReMi would be used to indicate the presence of an underlying abandoned space or very weak subsurface zone.

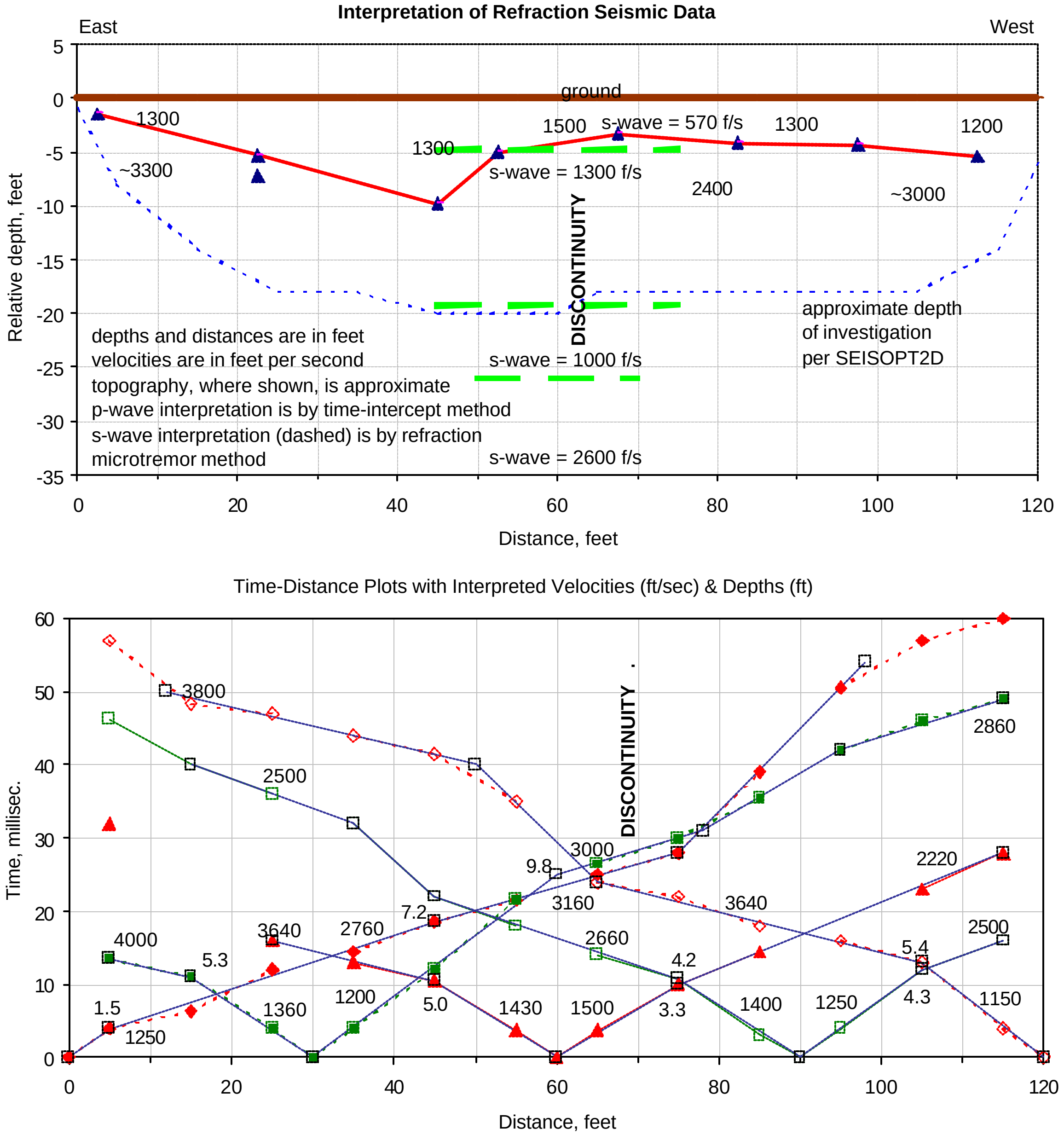
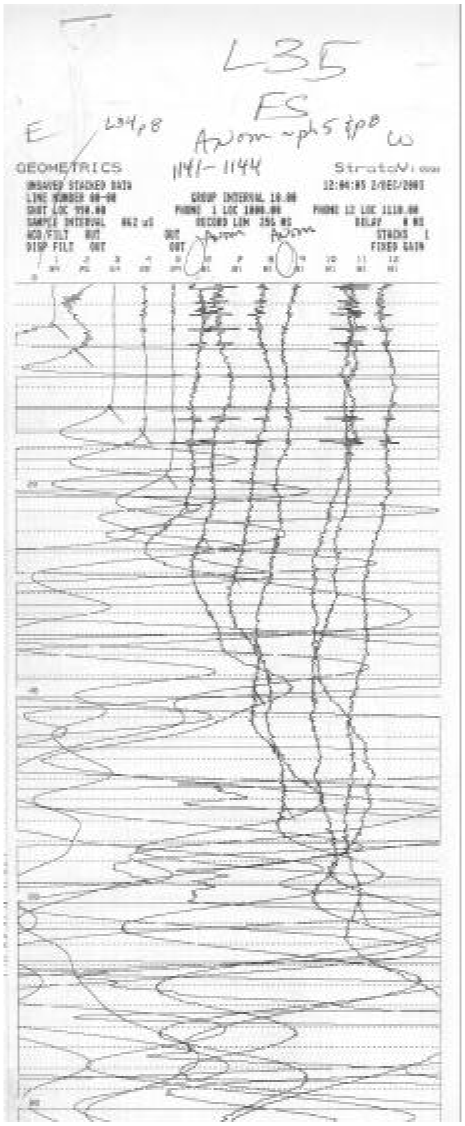


Figure 6 - *Results of seismic refraction and ReMi interpretations at select line in cemented soil setting. Seismic refraction interpretation indicates cemented soil contact at about 1 to 10 feet. ReMi interpretation indicates an s-wave velocity reversal at a depth of about 20 to 26 feet. Anomalous arrival times through time-history plot indicate presence of a subsurface discontinuity in several of the time-history traces.*

Figure 7 – *Original forward shot traces at Figure 6 seismic line showing significant signal attenuation and time delay across discontinuity eventually found by trenching (Figure 5). Significant first arrival signal degradation has occurred by geophone 6, indicating the presence of a significant discontinuity in the vicinity of that geophone. Such anomaly interpretations are made in the field and staked immediately to mark locations for later test verification by test trenching.*



In this example, seismic refraction results provided a means to characterize the subsurface in a lateral manner that could identify vertically oriented discontinuities and/or zones of lower seismic velocity, while ReMi results served to provide characterization below the cemented soil horizon. Zoghi and others (2000) report that, among various geophysical methods attempted for subsurface reconnaissance in an area of abandoned coal mines in eastern Ohio, that seismic refraction was quite useful.

DISCUSSION

ReMi provides a means to obtain s-wave profiles for subsurface characterization using simple and flexible surface procedures concurrent with seismic refraction. Used concurrently with seismic refraction, the two complementary seismic methods can identify subsurface anomalous conditions that could include abandoned spaces and subsidence effects otherwise obscured by bridging ground. 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. 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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