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ABSTRACT

The refraction microtremor (ReMi) method uses standard P-wave, refraction recording equipment to record ambient noise and then uses a wavefield transformation to produce Rayleigh wave dispersion curves from which average one-dimensional shear-wave profile of the subsurface can be derived. The combination of commonly available equipment, simple recording with no source, a wavefield transformation data processing technique, and an interactive Rayleigh-wave dispersion modeling tool exploits the most effective aspects of the microtremor, spectral analysis of surface wave (SASW), and multichannel analysis of surface wave (MASW) techniques. It overcomes several of the problems afflicting other techniques for estimating shallow shear velocities that make them expensive or difficult to use in urban areas. For example, the refraction microtremor method requires no source, no drilling, and noise helps rather than hinder the data acquisition. It has been very effective for quickly and cheaply determining 30-m average shear wave-velocity (V_{30}) and thus the NEHRP (National Earthquake Hazard Reduction Program) soil classification. In addition, it has also been used for liquefaction analysis and finding buried cultural features, such as dumps and piers. In this paper we briefly discuss the method and present case studies showing its use in different geologic settings and engineering applications.

INTRODUCTION

The refraction microtremor (ReMi) technique is based on two fundamental ideas. The first is that common seismic-refraction recording equipment, set out in a way almost identical to shallow P-wave refraction surveys, can effectively record surface waves at frequencies as low as 2 Hz. The second idea is that a simple, two-dimensional slowness-frequency (p-f) transform of a microtremor record can separate Rayleigh waves from other seismic arrivals, and allow recognition of true phase velocity against apparent velocities. The Rayleigh wave dispersion curve is then picked and the picks (velocity, frequency pairs) are then modeled interactively to derive a one-dimensional shear-wave velocity model of the subsurface.

The advantages of ReMi from a seismic surveying point of view are several, including the following: It requires only standard refraction equipment already owned by most consultants and universities; it requires no triggered source of wave energy; and it will work best in a seismically noisy urban setting. Traffic and other vehicles, and possibly the wind responses of trees, buildings, and utility standards provide the surface waves this method analyzes.

The distinctive slope of dispersive waves is a real advantage of the p-f analysis. Other arrivals that appear in microtremor records, such as body waves and air waves, cannot have such a slope. The p-f spectral power image will show where such waves have significant energy. Even if most of the energy in a seismic record is a phase other than Rayleigh waves, the p-f analysis will separate that energy in the slowness-frequency plot away from the dispersion curves this technique interprets. By recording many channels, retaining complete vertical seismograms, and employing the p-f transform, this method can successfully analyze Rayleigh dispersion where SASW techniques cannot. Thus, the method is less expensive, faster and more effective than spectral analysis of surface wave (SASW), multi channel analysis of surface wave (MASW), and other surface seismic methods. ReMi provides NEHRP soil classification as accurately as drilling methods such as cone penetrometer and OYO logger, but is non-intrusive. Louie (2001) describes the theory in detail. In this paper we briefly discuss how to acquire ReMi data and then present some case studies showing the effectiveness of the method for various engineering and geotechnical applications.

REMI SURVEY DESIGN AND DATA ACQUISITION

The equipment needed to record refraction micrometer data includes a 12-, 24-, or higher channel digital refraction gear with 4.5-14 Hz single vertical geophones phones and recording cable. Most digital refraction seismographs built since 1990 should be adequate, digitizing 24-bit fixed-point or 21-bit floating-point samples. The recorder must have enough memory to hold 12- or 24-channel records with a length of at least 4 seconds or more. Generally, 15 to 30 seconds recording time is recommended. The total array length can vary from 300 ft to 600 ft. Arrays as short as 60 ft and as long as several kilometers have been used for recording ReMi data. The length of the array has an effect on the depth of sampling, that is, it determines the depth to which shear-wave velocities can be resolved and the accuracy of the shear-wave velocities. As a rule of thumb the maximum depth of resolution is about one-third to one-half the length of the array. But, there have been instances where velocities have been resolved down to depths as long as the array length. This is usually achieved by using low frequency phones (4.5Hz) and recording very low frequency noise records. A 300-ft assures an accuracy of 15% in the velocities. Amplitude or frequency-response calibration of geophones is not needed - as with refraction, ReMi uses only the phase information in the recorded wavefield

The geophone cable is laid out on straight stretch of flat ground at the site and should be centered on the desired target. It is best to avoid known underground cavities 10 ft or more in diameter - pass beside but not over them. Geophones can be placed on thin pavements as long as they can be set so that there is good coupling with the ground. An easy urban layout is to run the array along the sidewalk, with the geophones planted into the parking strip or cracks in pavements. If the seismic cable must cross a street or driveways that cannot be blocked during the survey, put it between 2x4s nailed to the pavement. For recording noise records, a deviation in the line of 5% of the total length will not affect the stated 15% velocity accuracy of the method. This accuracy applies to elevations as well - in fact the line can have a constant inclination that can safely be ignored, as long as geophone elevations do not deviate more than 5% from the incline. The geophone locations need to be surveyed in only if the array deviates more than 5% of the total length from a straight line or if the elevation changes more than 5% from a constant include.

<u>Recording Data</u>

Acquire 5 to 10 records of background noise, 15 to 30 seconds long each. Set the record to have 12 or 24 channels or more if the recorder allows more. A sampling interval of 2 milliseconds works well for shallow shear-wave studies. Turn off any filtering before digitizing or plotting. If the recorder does not allow this, set the lowest possible low-cut filter frequency (hopefully 4 Hz or less) and a high-cut frequency equal to half the sampling frequency. For example, with 2 ms samples, sampling frequency is 500 Hz, so a high-cut filter at 250 Hz is OK as a reasonable anti-aliasing filter. It helps to wait for the passage of a good noise source like a train, heavy trucks, or low-flying jet. Do not stack records in the seismograph's memory. Clear the stack memory before triggering each record and save each record separately to the seismograph's hard disk, or floppy. If the site is quiet, activate some sort of source during each record by driving up and down the geophone line in a truck, running or walking up and down the line, striking a hammer or dropping heavy (greater than 50lbs) objects. No timing or locating of the source is needed.

REMI DATA PROCESSING

There are three steps to processing the data. The first is to perform a p-f (slowness-frequency) transformation of the noise records to create "velocity spectrum". The second step is to pick the dispersion curve revealed in the p-f image and the third is to model these picks to derive a one-dimensional shear-wave velocity profile of the subsurface.

<u>Generating A Velocity Spectrum And Picking The Dispersion Curve</u>

The first step is to generate a p-f image ("Velocity spectrum) from the recorded noise data. This process involves computing a surface-wave, phase-velocity dispersion spectral-ratio image by p-tau and Fourier transform across all vectors. This is described in detail in Louie (2001). The resulting image will be in the slowness-frequency (p-f) domain (Fig. 1). The p-f transformation separates the Rayleigh waves from other types of waves contained in the data. The normal-mode dispersion will trend down from the right starting from the upper left and is distinct from the aliasing and wavefield-transformation truncation artifact trends, which are down to the left (Fig. 1).

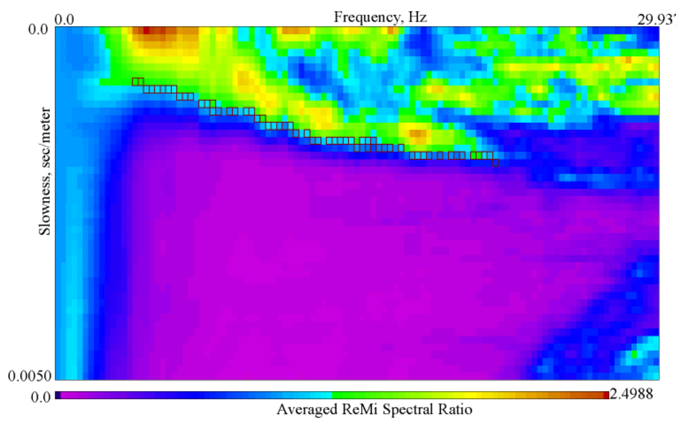

Fig. 1. Velocity spectrum (p-f) image derived from the noise records show the Rayleigh wave dispersion curve. Picks are made along the lowest energyenvelope (squares).

Picking of the surface-wave dispersion curve is done along an envelope of the lowest phase velocities having high spectral ratio at each frequency has a further desirable effect. Since higher-mode Rayleigh waves have phase velocities above those of the fundamental mode, the refraction microtremor technique preferentially yields the fundamental-mode velocities. Higher modes may appear as separate dispersion trends on the p-f images, if they are nearly as energetic as the fundamental. Picking the "lowest energy" envelope ensures that the resulting model has velocities close to the true velocity. Apparent velocities due to waves coming from directions other than inline will have amplitudes that will lie above this lowest energy envelope (Louie 2001).

Shear Wave Modeling

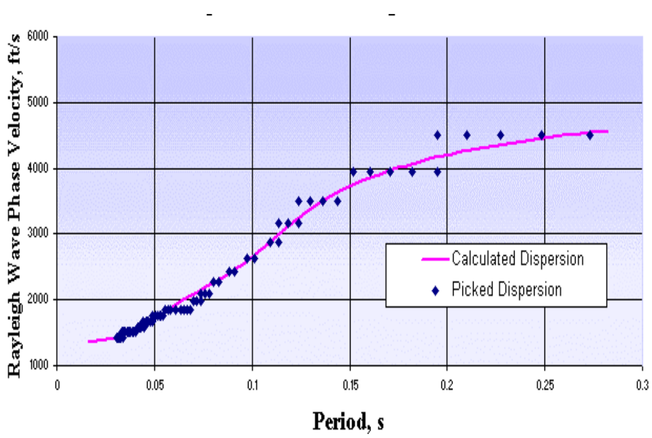

Fig. 2. The picks made in Fig 1 are interactively modeled to derive a one-dimensional shear-wave velocity profile.

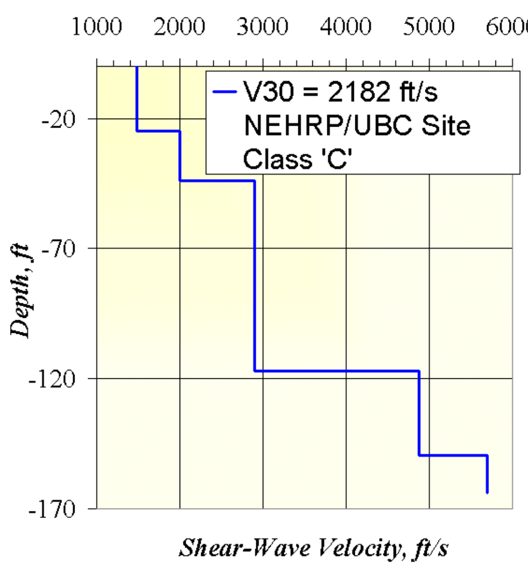

Fig. 3. One-dimensional shear-wave velocity profile determined by interactively modeling the picks shown in Fig 1.

The refraction microtremor method interactively forward-models the normal-mode dispersion data picked from the p-f images with a code adapted from Saito (1979, 1988) in 1992 by Yuehua Zeng (Fig. 2). This code produces results identical to those of the forward-modeling codes used by Iwata et al. (1998), and by Xia et al. (1999) within their inversion procedure. The modeling iterates on phase velocity at each period (or frequency), reports when a solution has not been found within the iteration parameters, and can model velocity reversals with depth (Fig. 3).

CASE HISTORIES

In this section we present some case histories demonstrating the effectiveness of the refraction microtremor method under various geological conditions. It also shows how the ReMi method can be used for soil classification, identifying low velocity zones, faults, and other subsurface characteristics useful in a geotechnical investigation. Comparisions between the shear-wave velocities derive from the ReMi method and other methods are also shown where available.

Geotechnical Field Research Test Site, Oregon State University

The Field Research Site at Oregon State University represents an area where the University and private consultants have practiced and/or tested various geophysical methods among other activities.

The ReMi work that was performed there was intended to illustrate the effectiveness of the ReMi analysis as a means of rapidly measuring the shear-wave velocity with little effort to develop results similar (within about 20% or better) to other, more detailed methods. Since the signal is simply random background noise and associated microtremors, the work can be readily performed in noisy urban environments where traffic and other disturbance can cause interpretation difficulty for procedures relying on a 'timed source' such as a hammer to induce the seismic signal to a down-hole geophone.

The depth of ReMi investigation (typically 30 meters or more) meets or exceeds recommendations of the IBC 2000 (International Building Code) that is being adopted in many parts of the country. The site-specific shear-wave velocity profile is useful for proper assignment of the correct UBC or NEHRP site classification. We anticipate that this knowledge will justify a basis for improved construction economics for better than average sites (typically 'assumed' UBC Site Classification D) and an increase in safety for very soft sites where conservative design and construction should be appropriately applied.

Standard refraction seismic equipment was used to measure background 'noise' enhanced at this quiet site by inducing background noise; in this case, by driving 1 ton truck along the array as the records were recorded. The equipment includes a Geometrics R-48 Strataview digital seismograph capable of storing record length up to about 60 seconds. The ReMi analysis presented here was developed from a 36 receiver (10 Hz. geophones) set along a straight-line array with 10-foot receiver spacing for a total line length of 350 feet. Unfiltered, 20 second records were recorded of the relatively quiet background (no activity) and 'noise' created by driving the 1 ton rubber tired truck near the array. Aside from initial reconnaissance, the fieldwork to conduct the ReMi survey, including setup, acquisition and breakdown took less than 1½ hours with a two-person crew.

The p-f image derived from the noise records is shown in Fig. 4. The “kink” in the amplitudes is indicative of velocity reversals at depth. The picks were made and modeled (Fig. 5 and Fig. 6) to get a shear-wave profile.

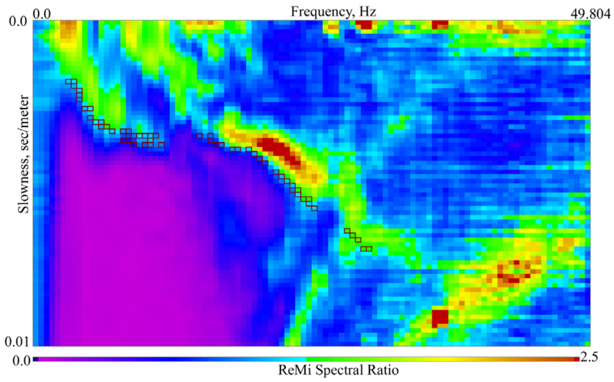

Fig. 4. Velocity spectrum derived from Oregon State University data. Note the “kink” in the dispersion amplitudes, indicating presence of velocity reversal at depth.

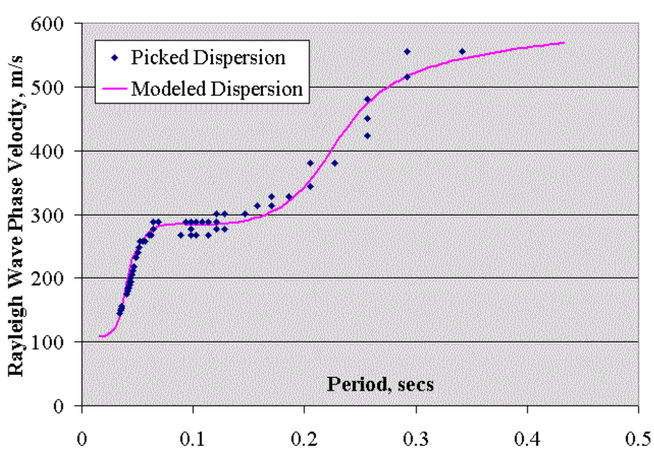

Fig. 5. The dispersion picks are interactive fit (pink line) to derive a 1-D shear-wave profile of the site.

The shear-wave profile describes a thin low velocity surficial soil to a depth of about 6 feet. A moderate velocity stratum extending to a depth of about 35 feet where the velocity profile reverses (decreases) underlies these surficial soils. The stratum in the 6 to 35 foot zone could contain at least one thin, low velocity layer. The primary velocity reversal is likely due to the presence of either a very low strength granular soil or more likely a silty, clayey material extending to a depth of about 70 feet where the velocity gradually increases to speeds indicative of a transition into soft bedrock at 80 feet or so. Hard rock is likely a bit deeper than 80 feet. The 36-receiver array provided confident data no deeper than about 100 feet.

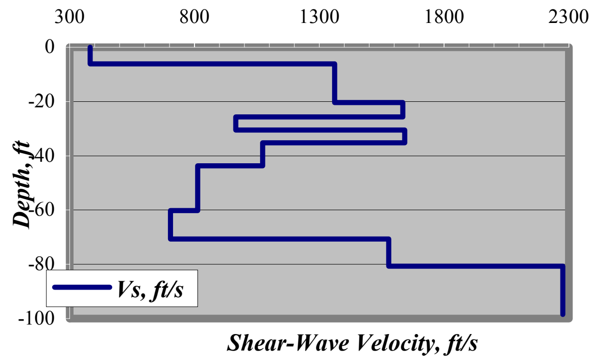

Fig. 6. 1-D shear wave velocities derived using the ReMi method.

Since the ReMi survey uses essentially the same array as a refraction survey, refraction data was acquired along the 36-receiver array. For refraction a Betsy Seisgun detonating 400-grain charges as our seismic source spaced at intervals of 30 feet along the array. However, to extend the effective survey depth of investigation we extended the shots 55 feet outside of the array on the first receiver side.

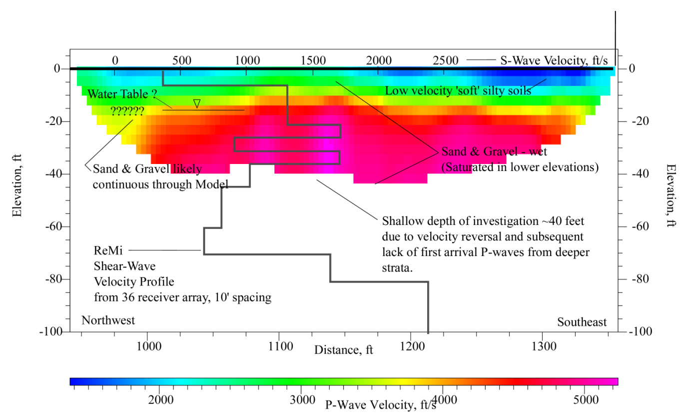

Fig. 7. P-wave velocity model derived from a refraction survey at the same site correlates well with results of the ReMi data. The survey set up for ReMi and refraction were identical allowing the user to derive information about both S- and P-wave velocities with minimal additional effort to what was expended for the refraction survey.

Figure 7 shows the velocity model derived from the refraction data with annotations to describe various features. For correlation, the ReMi shear-wave velocity profile is plotted as an overlay on the P-wave data. The P-wave velocity model is fairly simple and describes essentially two strata; a thin, slightly undulating (~3 to 8 foot thick) lower velocity material likely to be unconsolidated sand and silt underlain by a distinctly higher velocity material offering velocity in the range commonly associated with a reasonably dense sand and gravel (3000 to 5000+ fps).

The sand and gravel velocity is also in the same neighborhood as groundwater (typically 4300 to 5200 fps) and as such, the water table is not well distinguished. We have estimated the depth to the phreatic surface to be around 15 feet corresponding to the velocity increase at that same depth.

The 350 foot long, 36-receiver array would normally provide depth of investigation somewhere between 70 and about 110 feet below grade. However, due to the apparent reversal in velocity (both P-wave and S-wave), wave arrivals from strata deeper than about 35 feet were not the first arrivals and therefore the 'best model' does not define conditions any deeper than about 35 feet. The absence of data below this depth provides a strong indication of velocity reversal with the unfortunate consequence of not defining the depth to bedrock. This also shows how refraction microtremor (ReMi) can be combined with a standard refraction result to provide valuable additional information.

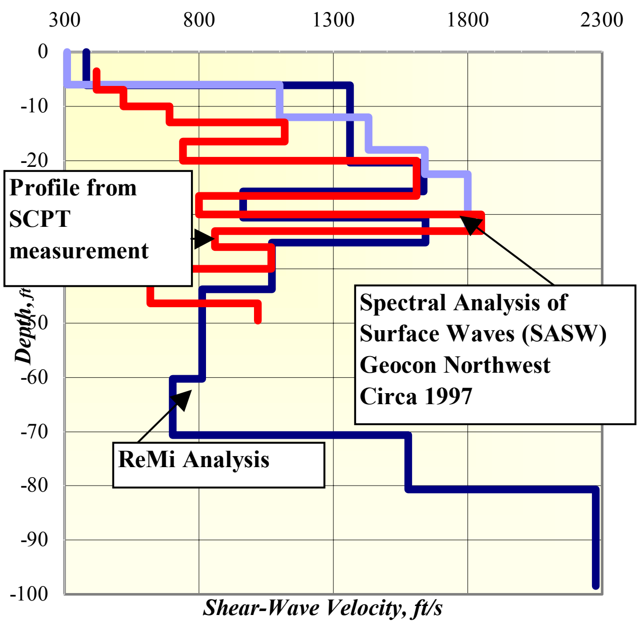

Fig. 8. Comparision fo ReMi results to 1-D shear wave velocities derived using SASW and SCPT at the Oregon State Unviersity site.

Figure 8 shows comparison of one-dimensional shear-wave velocities derived using the refraction microtremor (ReMi) method to those obtained from SASW and SCPT. Overall the profiles compare very well. The significant advantage on using the ReMi method is the depth of analysis. ReMi samples the subsurface down to 100ft, almost twice as deep as SCPT and three times the depth of SASW. At this site both SASW and SCPT fail to sample the bedrock at 70 feet.

<u>Wickiup Dam, Deschutes National Forest, Oregon</u>

The objective of performing the ReMi survey at this site was to determine how effective the method would be in detecting the change in shear-wave velocities before and after completion of the jet-grout columns being constructed to improve subsurface characteristics at the dam site. The follow-up analysis is proposed as a measure of project success since we expect the average shear wave velocity to increase through the treatment zone.

A Geometrics R-48 Strataview digital seismograph was used to record background noise along a 24 receiver spread laid out on 25 foot spacing for a total line length of 575 feet. Receivers were Marks Product 10 Hz geophones. Unfiltered records with length ranging from 20 to 60 seconds were recorded during dozer activity, relatively quiet background (no activity) and noise created by driving a 1 ton rubber tired truck near the array. Subsequent analysis of the records revealed essentially the same profile from each record type.

Figure 9 shows the ReMi results along with data interpreted from cross-hole analysis from BH-99 located about 650 feet west of the ReMi center survey. As indicted on the depth profile, shear wave velocity was interpreted to be well constrained to a depth of about 300 feet.

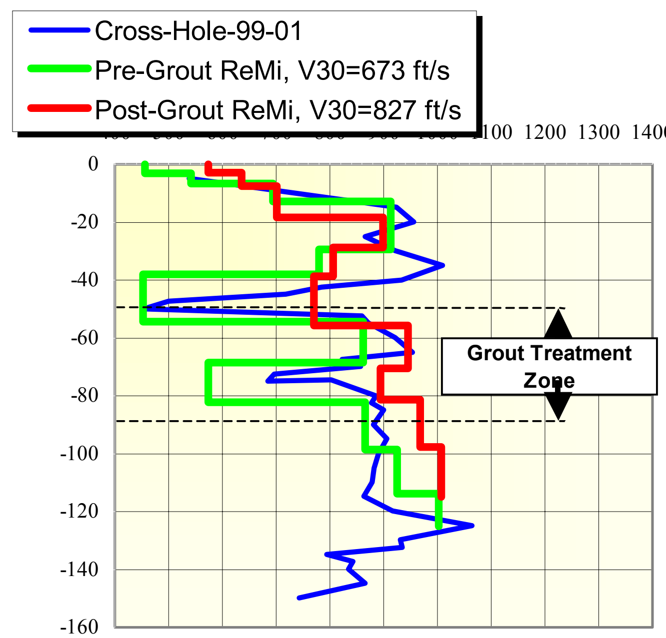

Fig. 9. Shear-wave profiles derived from ReMi pre- and post grout treatement. The blue line shows the shear-wave velocities derived from cross-hole analysis at the same site.

The average shear-wave velocity increased from 673 ft/s before grouting to 827 ft/s after grouting, indicating ReMi might be a good tool to measure the effectiveness of grouting. The ReMi profiles also compare very well the shear-wave velocities derived from the cross-hole analysis.

Offshore ReMi Study

The objective of this study was to demonstrate the effectiveness of the refraction microtremor method under water. The project was performed or a port authority of west of France as part of their harbor extension plans.

Data was collected using 24-channel (5m spacing) hydrophone streamer cable. The frequency of the phones was about 2Hz. Instead of collecting noise, air gun (40cu/in) shots were set of at intervals while the boat was moving. The hydrophone streamer and the air gun were towed along the seabed at approximately 2 knots speed. The water depth varied between 5 meters to 15 meters along the profile.

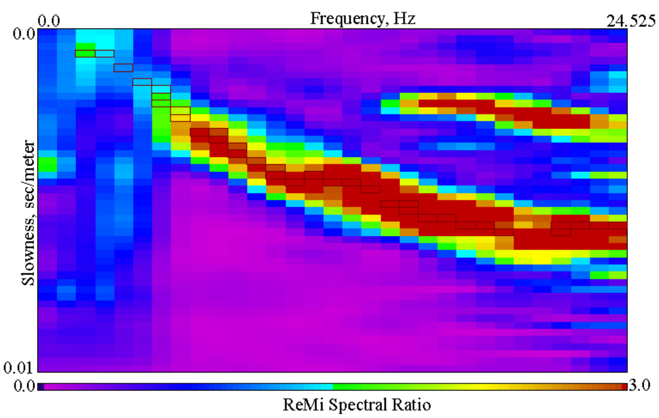

Fig. 10. P-f image derived from analysing air-gun records collected during the offshore ReMi study. Picks are made along the peak amplitude since this is an active source data.

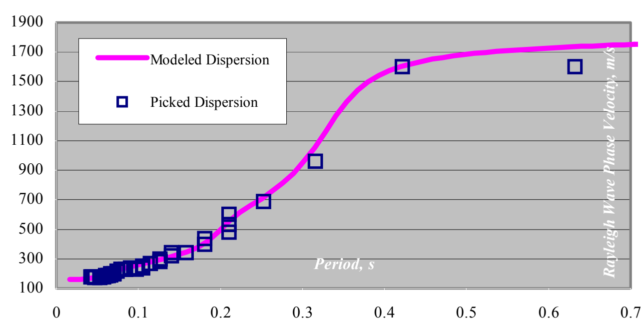

Fig. 11. The dispersion picks are fit to obtain the 1-D shear wave model shown in Fig. 11.

Figure 10 shows the p-f image derived from the records. Since the data collected used an in-line active source, the peak rather than the lower envelope of the dispersion amplitudes are picked (Louie, 2001). The picks are modeled to obtain the shear-wave velocity profile (Fig. 12).

Figure 12 has the layer interfaces determined from drill logs plotted on top of the ReMi profile. ReMi seems to have determined the layer depths quite accurately. It is important to note that using surface waves was the only way to obtained information about the bedrock at this site. The first seabed layer was not completely saturated and so the refraction velocities derived were that of velocity of seismic wave propagation in water (1,500 m/s), rendering the refraction data not very useful.

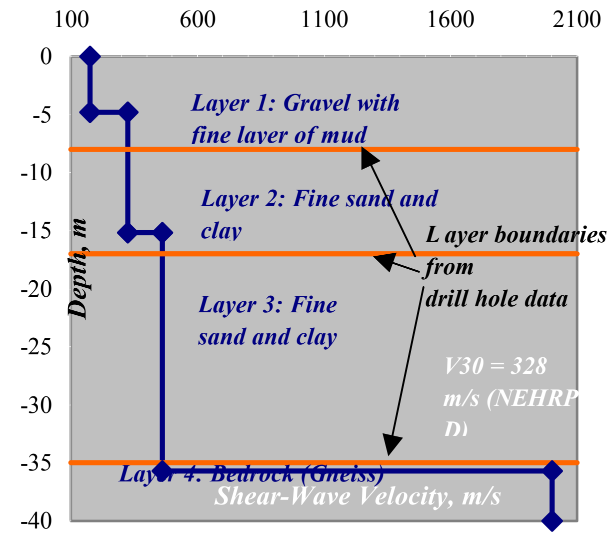

Fig. 12. One-dimensional shear-wave profile derived from the offshore ReMi data. Layer boundaries from drill logs are plotted on top of the profile for comparison.

SUMMARY

The case studies presented in this paper show that common seismic refraction equipment can yield accurate surface-wave dispersion information from microtremor noise. Configurations of 12 to 48 single vertical, 4.5-14 Hz exploration geophones can give surface-wave phase velocities at frequencies as low as 2 Hz, and as high as 35 Hz. This range is appropriate for constraining shear velocity profiles from the surface to 100-m depths. The heavy triggered sources of seismic waves used by the SASW and MASW techniques to overcome noise are not needed, saving considerable survey effort. This microtremor technique may be most fruitful, in fact, where noise is most severe. Proof of this technique suggests that rapid and very inexpensive shear-velocity evaluations are now possible at the most heavily urbanized sites, and at sites within busy transportation corridors.

The ReMi method offers significant advantages. In contrast to borehole measurements ReMi tests a much larger volume of the subsurface. The results represent the average shear wave velocity over distances as far as 200 meters. Because ReMi is non-invasive and non-destructive, and uses only ambient noise as a seismic source, no permits are required for its use. ReMi seismic lines can be deployed within road medians, at active construction sites, or along highways, without having to disturb work or traffic flow. Unlike other seismic methods for determining shear wave velocity, ReMi will use these ongoing activities as seismic sources. There is no need to close a street or shut down work for the purpose of data acquisition and a ReMi survey usually takes less than two hours, from setup through breakdown. These advantages sum to substantial savings in time and cost.

The refraction microtremor method can be used to economically derive 30-m average velocities V_{30} and thus be used in site classification studies. In addition it has been used for offshore studies, soil classification and finding buried objects like dumps and piers.

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