DETERMINATION OF 1-D SHEAR WAVE VELOCITIES USING THE REFRACTION MICROTREMOR METHOD

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Abstract

Current commonly used techniques of estimating shallow shear velocities for assessment of earthquake site response are too costly for use in most urban areas. They require large sources to be effective in noisy urban settings, or specialized independent recorders laid out in an extensive array. The refraction microtremor (ReMi) method (Louie, 2001) overcomes these problems by using standard P-wave recording equipment and ambient noise to produce average one-dimensional shear-wave profiles down to 100m depths. 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. The slowness-frequency wavefield transformation is particularly effective in allowing accurate picking of Rayleigh-wave phase-velocity dispersion curves despite the presence of waves propagating across the linear array at high apparent velocities, higher-mode Rayleigh waves, body waves, air waves, and incoherent noise. 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, soil profile determination, mapping the subsurface and estimating the strength of subsurface materials, and finding buried cultural features, such as dumps and piers. In this paper we briefly discuss the method, data acquisition and interpretation of the data to yield one-dimensional shear-wave velocities.

Introduction

The refraction microtremor 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. Two essential factors that allow exploration equipment to record surface-wave velocity dispersion, with a minimum of field effort, are the use of a single geophone sensor at each channel, rather than a geophone “group array”, and the use of a linear spread of 12 or more geophone sensor channels. Single geophones are the most commonly available type, and are typically used for refraction rather than reflection surveying. 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.

Background Theory

As mentioned before, ReMi processing involves three steps: Velocity Spectral Analysis, Rayleigh Phase-Velocity Dispersion Picking, and Shear-Wave Velocity Modeling.

Velocity Spectral Analysis

The basis of the velocity spectral analysis is the p-tau transformation, or ``slantstack," described by Thorson and Claerbout (1985). This transformation takes a record section of multiple seismograms, with seismogram amplitudes relative to distance and time (x-t), and converts it to amplitudes relative to the ray parameter p (the inverse of apparent velocity) and an intercept time tau. It is familiar to array analysts as ‘‘beam forming’’ and has similar objectives to a two-dimensional Fourier-spectrum or ‘‘F-K’’ analysis as described by Horike (1985). Clayton and McMechan (1981) and Fuis et al. (1984) used the p-tau transformation as an initial step in P-wave refraction velocity analysis.

McMechan and Yedlin (1981) developed the p-f technique and tested it against synthetic surface waves, and reverberations seen on controlled-source multichannel seismic records. Park et al. (1998) applied the p-f technique to active-source MASW records. All phases in the record are present in the resulting (p-f) image that shows the power at each combination of phase slowness and frequency. Dispersive phases show the distinct curve of normal modes in low-velocity surface layers: sloping down from high phase velocities (low slowness) at low frequencies, to lower phase velocities (high slowness) at higher frequencies. Miller et al. (2000) examine p-f-domain power spectra of MASW records along a profile to define lateral variations in dispersion curves and thus in shear velocities.

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.

Rayleigh Phase-Velocity Dispersion Picking

This analysis adds only a spectral power-ratio calculation to McMechan and Yedlin's (1981) technique, for spectral normalization of the noise records. The ability to pick and interpret dispersion curves directly from the p-f images of spectral ratio parallels the coherence checks in the SASW technique (Nazarian and Stokoe, 1984) and the power criterion in the MASW technique (Park et al., 1999). Picking phase velocities at the frequencies where a slope or a peak in spectral ratio occurs clearly locates the dispersion curve. Picks are not made at frequencies without a definite peak in spectral ratio, often below 4 Hz and above 14 Hz where an identifiable dispersive surface wave does not appear. Often, the p-f image directly shows the average velocity to 30 meters depth, from the phase velocity of a strong peak ratio appearing at 4 Hz, for soft sites, or nearer to 8 Hz, at harder sites.

Picking is done along a ``lowest-velocity envelope'' bounding the energy appearing in the p-f image. It is possible to pick this lowest-velocity envelope in a way that puts confidence limits on the phase velocities, as well as on the inverted velocity profile.

Picking a surface-wave dispersion curve 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.

Spatial aliasing will contribute to artifacts in the slowness-frequency spectral-ratio images. The artifacts slope on the p-f images in a direction opposite to normal-mode dispersion. The p-tau transform is done in the space and time domain, however, so even the aliased frequencies preserve some information. The seismic waves are not continuously harmonic, but arrive in groups. Further, the refraction microtremor analysis has not just two seismograms, but 12 or more. So severe slowness wraparound does not occur until well above the spatial Nyquist frequency, about twice the Nyquist in most cases.

Shear-Velocity Modeling

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. 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.

Survey Design and Data Acquisition

The refraction microtremor method, as the name implies, makes use of standard refraction equipment to determine one-dimensional S-wave velocities.

Equipment Used

The equipment needed includes a 12- or 24-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.

Recording Data

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. Running or walking alone will create shear-waves, but the p-f transform will ensure that they do not interfere with the Rayleigh wave dispersion curve.

A combination of these noise generation techniques is preferable to any one method of doing the same.

Data Processing and Interpretation

We use the data collected at the Los Angeles County Fire Station in Newhall, California to demonstrate the data processing and interpretation of refraction microtremor data. The refraction microtremor experiment at Newhall employed a 200-m-long array of 24 8-Hz refraction geophones along the asphalt-paved access road at the side of a 4-m-deep concrete-lined flood channel. The 200m array was centered 4 m from the ROSRINE hole. Noise records 30 and 60 seconds long were recorded.

As explained in the “Background Concept” section, the first step is to create a “velocity spectrum (p-f image) from the noise records (Figure 1). From 3-12 Hz, the p-f image shows a clear energy cutoff at a minimum-velocity envelope. The energy of obliquely-propagating waves is broadly distributed across high apparent velocities above this envelope. Arrivals at many different apparent velocities form a broad ramp in spectral ratio, but the cutoff of high spectral-ratio values against the true phase-velocity envelope is clear from 3-12 Hz. At frequencies below 3 Hz, and in the area of F-K aliasing, this envelope is not as clear. There are a few spectral-ratio peaks in these areas still aligned with the dispersion envelope.

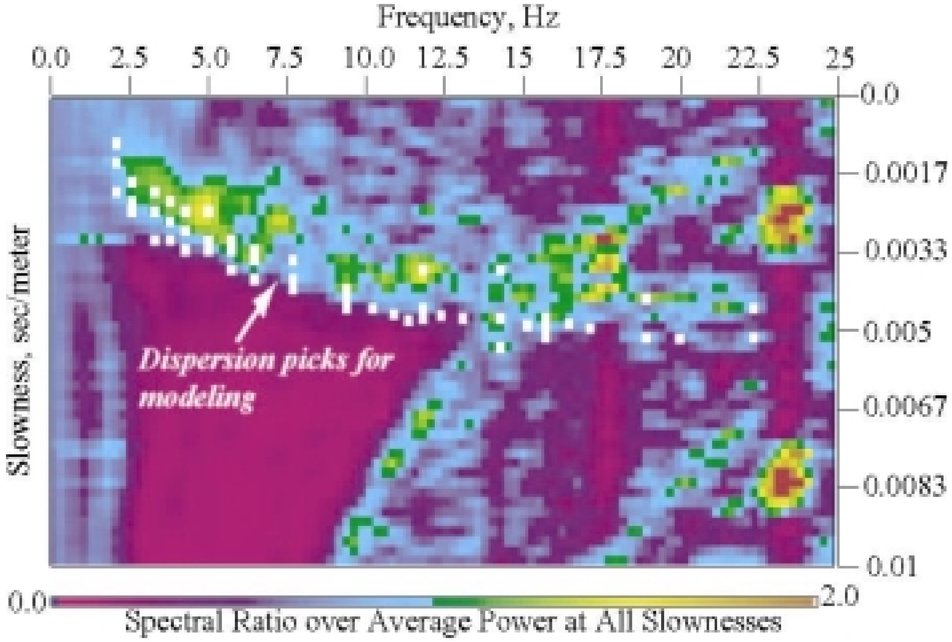

Figure 1: Velocity spectral analysis of the refraction microtremor recordings at Newhall site, California. The low energy envelope of the p-f image is picked for modeling.

The dispersion picks follow the lowest-velocity envelope at the base of the high spectral ratios in the image (Figure 1).

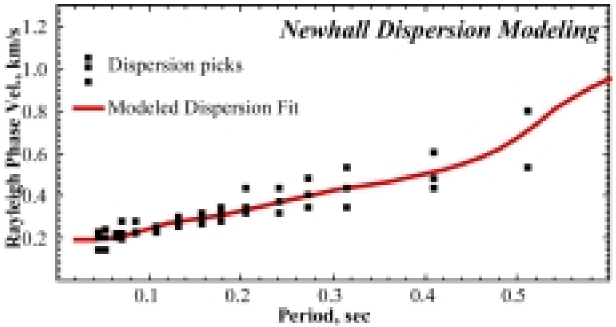

Figure 2: Rayleigh-wave phase-velocity dispersion picks made in Figure 1 and the calculated curve through the velocity model shown in Figure 3.

The three phase-velocity values at one frequency constitute the dispersion pick (filled squares in Figure 2) and its uncertainty within extremal values. Dispersion picking is possible where an F-K analysis would spatially alias (right of the thick dashed line in Figure 1), although the p-f artifacts produce larger uncertainties there. Figure 2 shows just the dispersion curve with increasing velocity uncertainty at larger periods, interactively modeled with the velocity profile of Figure 3 (bold line). The modeled profile is an excellent match to the ROSRINE logged shear velocity (thick gray line). The 8-m-thick shallowest layer with 210 m/s shear velocity compares well with the log, which starts at 2 m depth and varies from 178-238 m/s to 8 m depth. The 370 m/s modeled layer from 8-34 m depth averages across a strong gradient in the log from 219-685 m/s over the same depth range. Below 34 m, the shear-velocity log has about 10% variability with a standard deviation of 77 m/s, but maintains to the 105.2 m maximum logged depth a 741 m/s average. The 34-125-m-depth model layer has a velocity of 620 m/s, which are just 16% low.

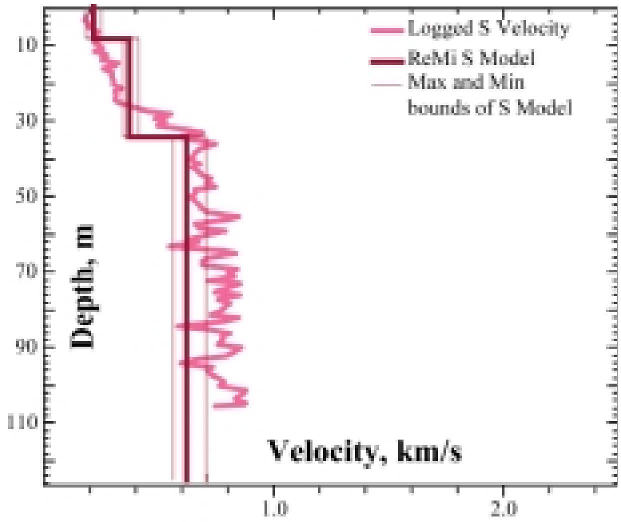

Figure 3: Shear-wave velocity profile obtained by modeling the phase-velocity picks. The profile matches the suspension-logger shear-velocity results from the ROSRINE borehole.

The bias of the interactive modeling process toward fewer layers 7-100 m thick is clear in this comparison. Since the phase-velocity dispersion data effectively integrate velocities over substantial depth ranges, modeling results could never match the detail of the shear-velocity log. In the log velocities can change by 30% over a few meters. This lack of detail in the modeled velocity profile is no impediment to site-response evaluation, however. The amplification of earthquake waves by site conditions is also an integrative process. As long as the velocity results are accurate in terms of averages over 5-100 m depth ranges, accurate prediction of linear site amplification effects is assured (Borcherdt and Glassmoyer, 1992; Boore and Brown, 1998; Brown, 1998).

The uncertain longest-period picks of the dispersion curve (Figure 2) suggest a velocity increase at an interface below the 100m maximum logged. However, the low-frequency dispersion picks cannot control the trade-off between the depth and velocity of this interface. Experimentation shows that many models could match the dispersions in Figure 2. Both the depth and the velocity of the deepest layer are highly non-unique and very poorly determined at this site by the dispersions down only to 2 Hz. In this case, at least the ROSRINE log shows that the interface is deeper than 100 m. This fact suggests the refraction microtremor method could estimate velocity accurately to 100 m at this site.

A “top-down" approach is most effective, matching phase velocities with layer velocity adjustments, starting at the surface layer (e.g. fitting the picks on Figure 2 below 0.1 second period first). Cusps and increases in slope of the dispersion curve (as at 0.12 s, 0.25 s, and 0.45 s in Figure 2) are matched by adjusting layer thicknesses. Following such a procedure, it is possible to model velocities. Here the extremal velocity limits are found by fitting not only the “best picks” (filled boxes on Figure 2) but also, separately, the highest-velocity picks, and the lowest-velocity picks of the confidence limits. This procedure results in three models, one central and two that represent the upper and lower-velocity extremes of confidence in the pick of the central model. The thin lines on Figure 3 show the velocity profiles that result from this procedure.

Summary

Several tests have shown 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 1.5 Hz, and as high as 35 Hz. It is to be noted that the frequency range is a function of the frequency of the geophones used and the subsurface conditions. Presence of hard rock allows deeper penetration while thick alluvial fill will attenuate frequencies. Figure 4 is an example of a p-f image generated using 4.5 Hz geophones along the San Gabriel River in southern California. One can see that dispersion picks can be easily made at frequencies less than 1Hz, allowing velocities to be resolved to depths of 100m. Figure 5 shows dispersion image generated on a rock site in Oregon. In this case picks can be made all the way out to 45 Hz allowing detailed resolution of shallow velocities.

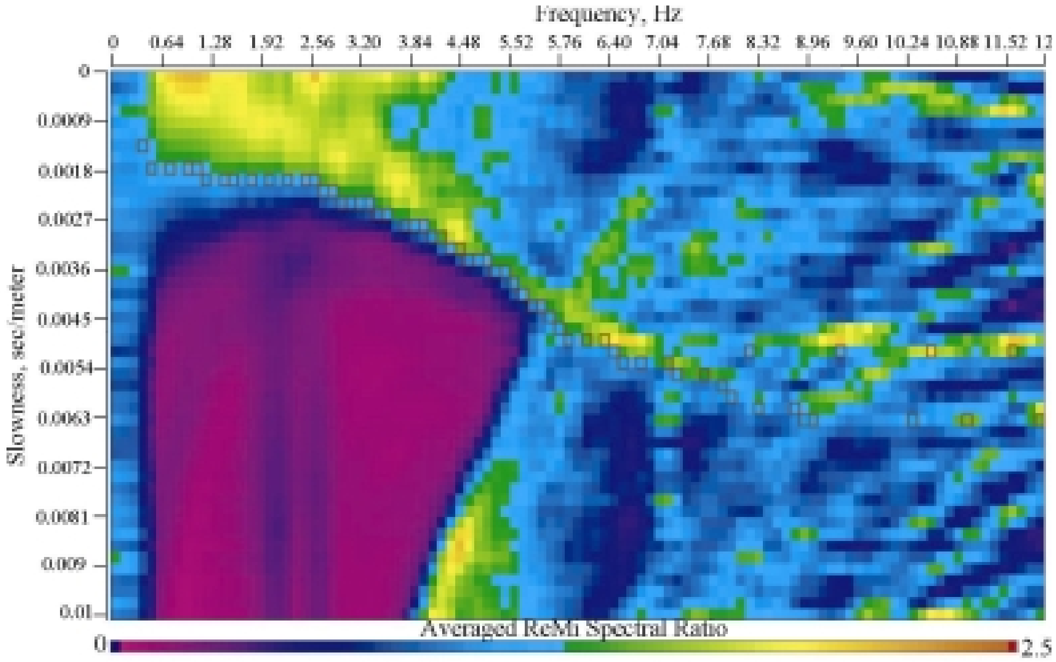

Figure 4: Velocity spectral analysis (p-f) of the refraction microtremor recordings at San Gabriel River site, California. Use of 4.5Hz frequency geophones allows dispersion picks of less than 1Hz frequency, allowing determination of shear-wave velocity to depths of 100m

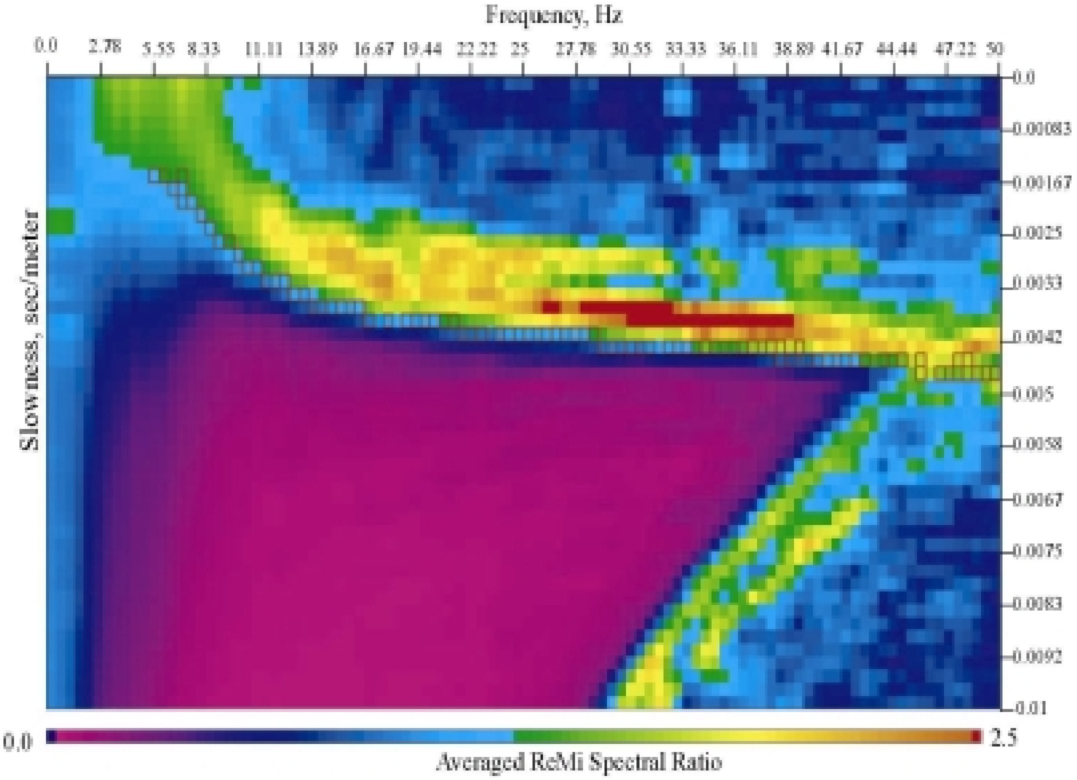

Figure 5: p-f image generated from microtremor recordings in Oregon. 10Hz geophones were used and dispersion picks can be made as high as 45Hz enabling detailed resolution of shallow velocities.

Thus the depth of constrain will vary depending on the frequencies that can be resolved, but for most cases velocities down to 30m can be resolved. If conditions allow a depth of 100m can be achieved.

If the goal is to get an average shear-wave profile, 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 can also be fine-tuned to offer detailed look at the subsurface structure. For example, shorter geophone spacing and higher-frequency phones can resolve shallow structure (< 30m) in great detail (4 to 5 layers). Lateral changes along the profile can also be investigated by selecting fewer traces (from the 12 or 24 channels recorded) to analyze. A 1-D profile can be derived for each section and then put together to get a 2-D image. D

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.

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