

# GEOTECHNICAL AND GEOPHYSICAL CASE STUDIES INVOLVING THE REFRACTION MICROTREMOR (ReMi) METHOD FOR SHEAR WAVE PROFILING

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## ABSTRACT

The Refraction Microtremor (ReMi) method is being used widely by the geotechnical and geophysical community to determine one-dimensional (1D) and pseudo two-dimensional (2D) shear-wave profiles of the subsurface. ReMi uses standard refraction equipment, simple noise recording with no source needed (source can be used if necessary), a wave field transformation data processing technique, and an interactive and automatic Rayleigh-wave dispersion-modeling tool to reveal 1D and pseudo 2D shear-wave velocity structure. 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. In this paper we present several examples that show the versatility of the method. With the proper array design one can produce shallow high-resolution profiles that reveal soil compaction beneath concrete basements that are a few inches thick or map velocities down to depths of 1 km. Examples from off-shore surveys done as part of pier extension studies will also be presented. . Thus, in addition to routine soil classification (Vs100' or Vs30m) surveys, ReMi has also been used for liquefaction analysis, soil compaction control, mapping the subsurface and estimating the strength of subsurface materials, and finding buried cultural features, such as dumps and piers. ReMi becomes extremely powerful when used in conjunction with refraction tomography. Since the same array setup can be used to record ReMi and refraction data, one can use the shear-wave and compression wave velocities obtained from each method to generate more complete images of the subsurface. We present case studies wherein ReMi gives the deeper velocities and maps low-velocity horizons that are missed by refraction, while refraction tomography provides higher resolution at shallower horizons and accurately maps lateral variations along the profile.

## 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 (even lower if low frequency phones are used). 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 analyses (Louie, 2001, Pullammanappallil et. al, 2003).

In this paper we present case studies that show applications of the ReMi method in different geologic conditions. The examples show the scalability of the method and how it can be used in conjunction with refraction analysis to reveal detailed velocity variations within the subsurface. Since both refraction and ReMi data can be recorded using the same layout, they play off each others mutual strengths to provide complementing information. This approach is increasingly being adopted by the geotechnical community to enhance the value of their seismic projects.

## CASE STUDIES

### Combined ReMi and Refraction at 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 work that was performed by Siemens and Associates of Bend, Oregon and 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 10% 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.

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 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.

Figures 1a and b shows the dispersion curve obtained from the ReMi analysis and the fits produced to the picks by the model shown in Figure 2a. The shear-wave profile (Figure 2a) 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.

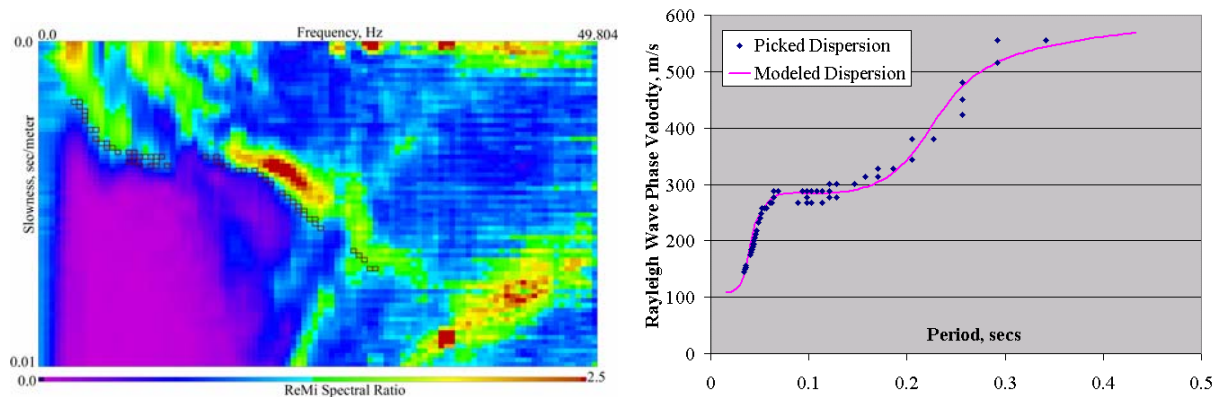


Figure 1a (left): Velocity spectrum derived from Oregon State University data. Note the "kink" in the dispersion amplitudes, indicating presence of velocity reversal at depth. Figure 1b (right): The dispersion picks are interactive fit (pink line) to derive a 1-D shear-wave profile of the site.

Since the ReMi survey uses essentially the same array as a refraction survey, refraction data was acquired along the 36-receiver array.

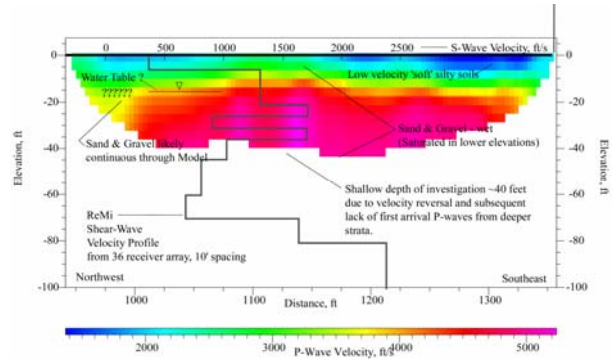
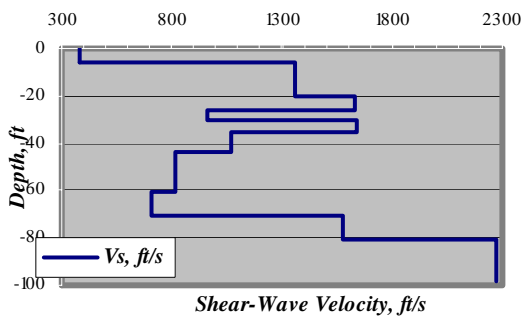


Figure 2a (left): One-dimensional shear-wave velocity profile derived using the ReMi method. Figure 2b (right): P-wave velocity model derived from a refraction survey at the same site correlates well with results from the ReMi survey. In addition, the shear-wave velocities from the ReMi survey allow deeper depth of reconnaissance.

Figure 2b 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.

### Two-dimensional ReMi analysis at Phoenix Airport

ReMi survey was conducted as part of the geotechnical investigations for runway expansions at Phoenix Sky Harbor Airport, Arizona (Figure 3, data and results courtesy of Mike Rucker, AMEC). As the photograph shows, there was no need to close down the airport or disrupt normal operations during the survey, making ReMi attractive option in urban and congested areas.



Figure 3: Vertical P-wave geophones were laid out along the curb to record noise for ReMi analysis. There was no need to close down the airport or disrupt normal operations during the survey, making ReMi attractive option in urban and congested areas.

ReMi data from 30 adjacent 120 ft long 12, 4.5 Hz geophone ReMi lines were put together to create a 2D profile (Figure 4). The contact between cohesionless and cohesive soils in the upper portion of the profile is very clear. This is crucial for tunneling since cohesionless ground may 'run' and cause severe stability problems for tunneling, while cohesive ground probably has good 'stand up' capability and can be tunneled effectively with much less risk.

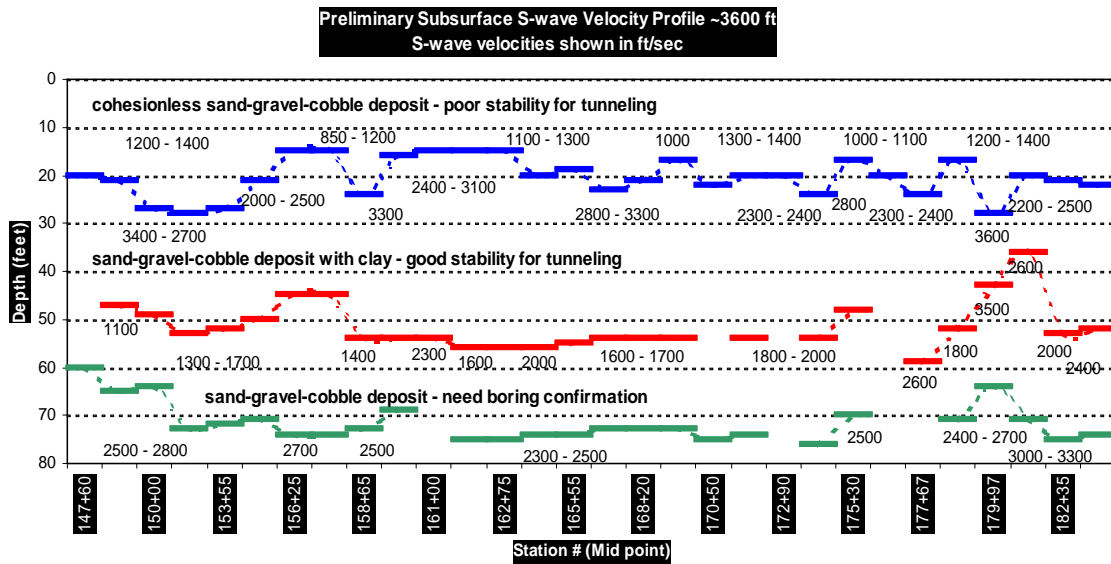


Figure 4: Two-dimensional profile constructed from a series of 1D ReMi analysis, showing the variations of soil beneath the proposed runway expansion study.

### Mapping low velocity zones beneath concrete with ReMi

This case study shows the application of ReMi for basement analysis. The survey was done in Alabama (courtesy of PSI, Inc.) with geophones laid out, using sand bags, (Figure 5) on top of a concrete basement that cut into limestone. Presence of high and low velocity reversals in the subsurface results in a complicated dispersion curve as shown in Figure 6a. Modeling the picks (Figure 6b) results in the velocity profile shown in Figure 7.



Figure 5: Geophones were placed inside sand bags and placed on top of concrete.

The velocity model derived from ReMi analysis not only maps strata beneath concrete (showing possible failure) but also images some low velocity zones (possible sink holes) within the limestone rock. The ease of ReMi data acquisition allows the practitioner to quickly and efficiently collect several lines at a project site and perform an initial study to see where might be the problem areas. ReMi can thus be used as a powerful reconnaissance tool to cut down the number of drill holes that might otherwise be required.

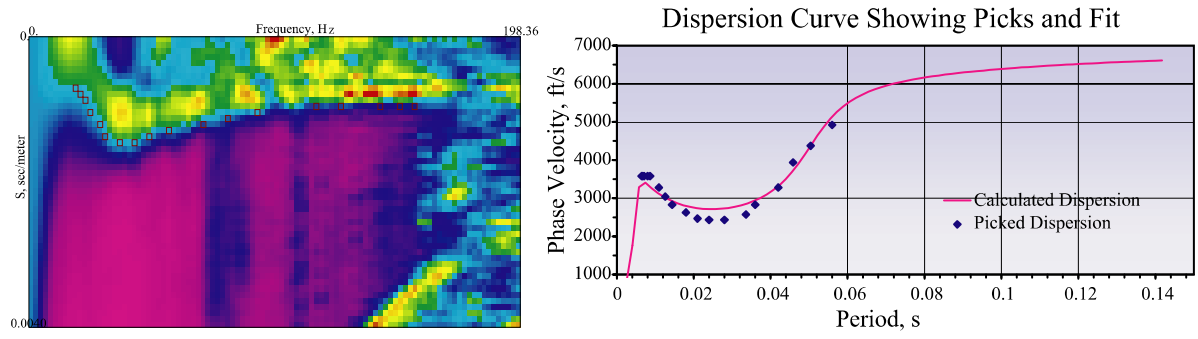


Figure 6a (left): Dispersion curve showing with the picks. The complicated dispersion curve reflects the complex velocity variations within the subsurface. Figure 6b (right): The picks are modeled to reveal the velocity model shown in Figure 7.

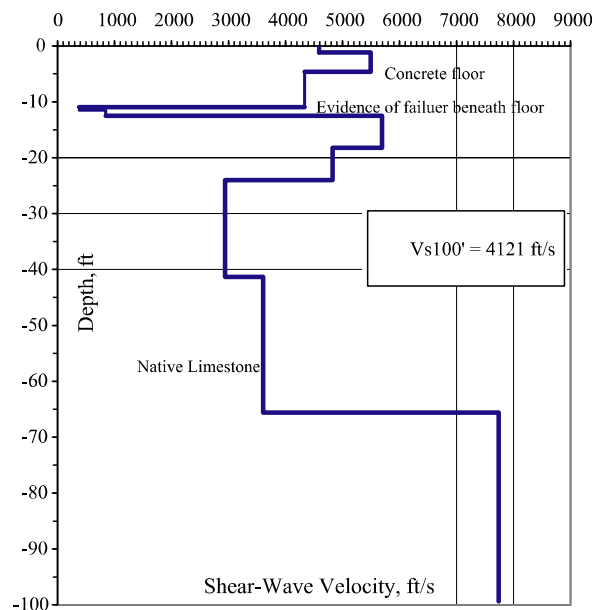


Figure 7: Velocity model derived from analysis of the dispersion curve shown in Figure 6b. ReMi was able to map evidence of probably failure beneath the concrete as well as map low-velocity zones (sinkholes) within the native limestone rock.

### Deep ReMi at Mount St. Helens, Washington

The following case study demonstrates the application of ReMi for mapping deep structures. The survey was conducted by on Mount St. Helens, Washington (data courtesy Wes Thelen, University of Washington, Thelen et. al., 2005). The transect consisted of 39 vertical component stations at 100 m spacing, which alternated between 1 Hz and 4.5 Hz sensors to enhance the recording of low frequencies across the transect. During the deployment, earthquakes as well as coherent energy from rock fall sources were recorded across the entire array (Figure 8). ReMi analysis performed on this data revealed velocities down to 4 km (Figure 9) and was used to constrain models to existing models derived from

refraction analysis. This improved velocity model I snow being used to greatly improve the absolute accuracy in earthquake locations.

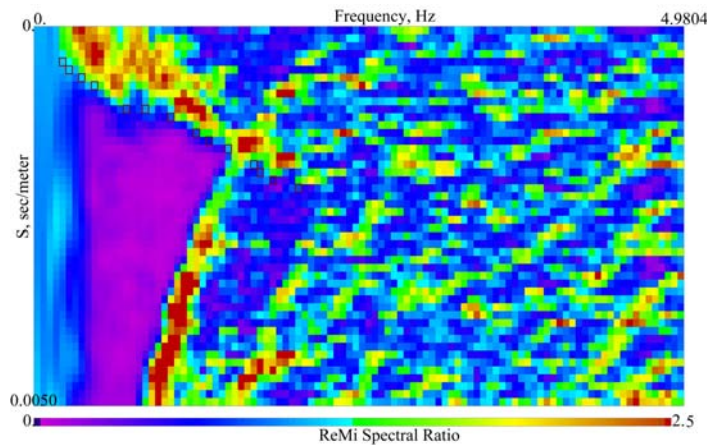


Figure 8: Dispersion analysis of the noise data reveals information at very low-frequencies allowing for resolution of deep structure (Figure 9).

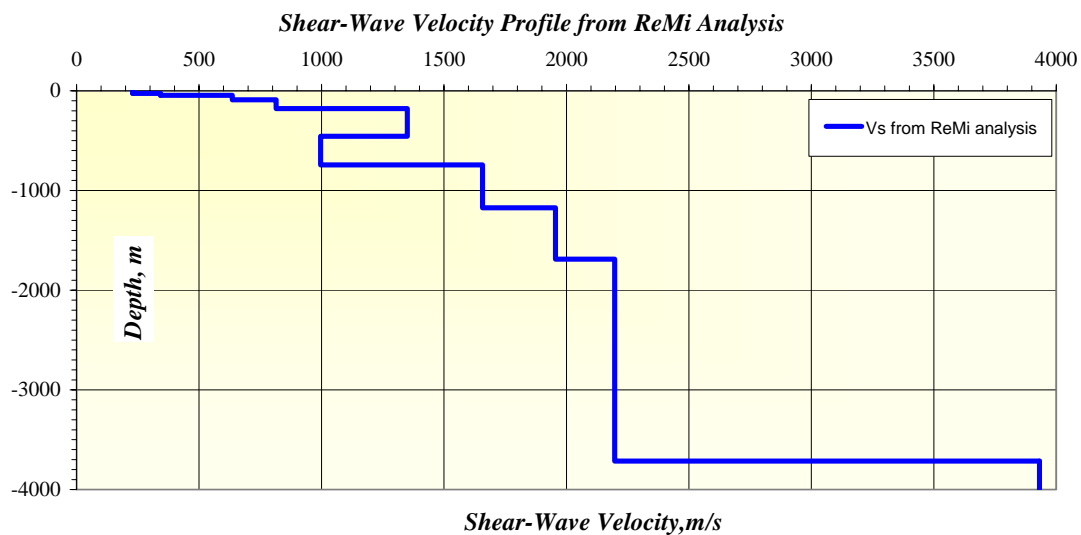


Figure 2: Shear-wave velocities down to a depth of 4 km were obtained, thus demonstrating the scalability of the ReMi method.

## CONCLUSIONS

This paper presents some case studies highlighting the effectiveness of the Refraction Microtremor (ReMi) method for various geophysical and geotechnical applications. It is being used for routine Vs100 surveys as part of IBC site classification work to more involved, high-resolution one-dimensional and two-dimensional shear-wave profiling. The examples show the scalability of the method and how it can be used in conjunction with refraction analysis to reveal detailed velocity variations within the subsurface. Since both refraction and ReMi data can be recorded using the same layout, they play off each others mutual strengths to provide complementing information. Whatever the application, the ease of data acquisition and processing makes ReMi very attractive to geotechnical and engineering companies worldwide.

## REFERENCES

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- Thelen, W. A., Malone, S.D., Qamar, T., and Pullammanappallil, S., 2005, Improvements to absolute locations from an updated velocity model at Mount St. Helens, Washington, presented at the American Geophysical Union Fall Meeting, San Francisco, USA.