BLIND TESTS OF REFRACTION MICROTREMOR ANALYSIS AGAINST SYNTHETICS AND BOREHOLE DATA

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ABSTRACT

Two investigations of new applications for the refraction microtremor (ReMi) technique have been carried out to further develop the method. The first application involved creating a dozen synthetic elastic array recordings using a finite-difference code. The test models span the range of Vs profiles seen for rock sites in southern Nevada, plus models including velocity inversions. Vs profiles were then interpreted from the synthetics in a blind test, following standard ReMi procedures. Between the models and the blind results, we compared Vs30 and the depth to the shallowest interface Z0, as indicators of the precision of the analysis. Only one of the test models yielded as much as 20% error, in Z0. The maximum error in Vs30 was 12%, and ten profiles resulted in an error margin of ≤10% for Vs30. Seven of the profiles generated errors ≤10% for Z0. For the second application, we completed blind analyses of refraction microtremor data taken at a site with multiple borehole profiles in southern Nevada. Across this one-square-kilometer area, Vs30 as measured by sixteen downhole profiles varied from 442-764 m/s; and adjacent boreholes show the existence of high degrees of lateral velocity heterogeneity. ReMi measurements provided average velocities from this highly heterogeneous site that are useful for assessing potential seismic shaking.

Introduction

The refraction microtremor (ReMi) process, originated by Louie (2001), has recently become popular in engineering investigations; and new applications and benefits of the method are frequently found. We conducted two programs of blind tests using the ReMi technique in order to better utilize the method. As recognized by Pullammanappallil et al. (2003a) the advantages of ReMi measurements include: requiring only typical seismic refraction equipment; needing no triggered source; and working best in urban settings that are seismically noisy. Pullammanappallil et al. (2003a) also point out that ReMi measurements analyze a larger volume of the subsurface than do downhole or crosshole measurements. ReMi results represent average shear-wave velocities over volumes as extensive as 300 m. Lateral inhomogenetiy of subsurface

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geology over 300-meter distances is not uncommom, and is well-observed by transects of multiple ReMi measurements (e.g., Scott et al., 2004).

Pullammanappallil et al. (2003b) compared ReMi results with borehole measurements and other surface methods such as refraction, MASW, and SASW. They found that ReMi was often able to reach greater depths of investigation than boreholes or other surface surveys. ReMi results also correlate well with velocity trends in cross-hole measurements. A case study in Pullammanappallil et al. (2003b) from western France demonstrates the correlation of interfaces in a ReMi shear-velocity profile with logged cores, and gave the same soil classes as the boreholes.

In 2001 and 2003, ReMi investigations of over 300 locations total were undertaken intending: (1) to correlate shear-wave velocity averaged to 30 m depth (Vs30) measurements with geologic map units, soil map units, and stratigraphic models; and (2) to find the scales of heterogeneity in Vs30, and how it varies along transects crossing urban basins (Scott et al., 2004; Scott et al., 2005; Thelen et al., 2005). The three transects were through the Reno basin, the Las Vegas basin, and San Gabriel Valley and Los Angeles Basin, respectively. By measuring Vs30, these experiments evaluated the National Earthquake Hazards Reduction Program (NEHRP) classification at each of the 300 sites.

Scott et al. (2004) found that gravity-derived alluvial-thickness modeling can reasonably match ReMi Vs30 measurements in the Reno basin, but existing mapping cannot predict hazard classification with sufficient accuracy for engineering application. Scott et al. (2005) attempted to correlate soil map units, as well as a stratigraphic model derived from 1145 water-well logs, against Vs30 measurements in the Las Vegas transect area. Neither model can predict measured hazard class well, but the stratigraphic model is at least conservative, more often predicting velocities below those later measured.

Using synthetic data as a test, the effects of different types of velocity profiles on ReMi analyses can be better recognized. Sheriff (1991) sets out four canonical types of earth resistivity profiles, which we can apply to velocity profiles: A-type, where Vs increases with depth at all interfaces; H-type, with a low-velocity layer; K-type, with a high-velocity layer above a velocity inversion; and Q-type, where Vs decreases with depth at all interfaces. In collecting Vs profiles to 30-to-100-meter depths at hundreds of sites, we have never observed a Q-type profile. So we ignore that type here. This study models synthetically developed seismic records derived from shear-velocity profiles similar to those measured at rock sites in southern Nevada. Ten of the synthetic models (Figure 1) have A-type profiles as described by Sheriff (1991), with widely-varying interface depths and velocity contrasts, and the two remaining consist of an H-type and a K-type profile.

We also compare downhole logs taken from a well-studied and highly heterogeneous site in southern Nevada against ReMi measurements we collected. The object of the comparison is to test the averaging property of ReMi measurements, and how the analysis is affected by high degrees of lateral heterogeneity. The differences in shear-wave velocity sampling techniques should be noted: ReMi is a velocity average over a volume; while a downhole log is a measure of velocity at a single location point.

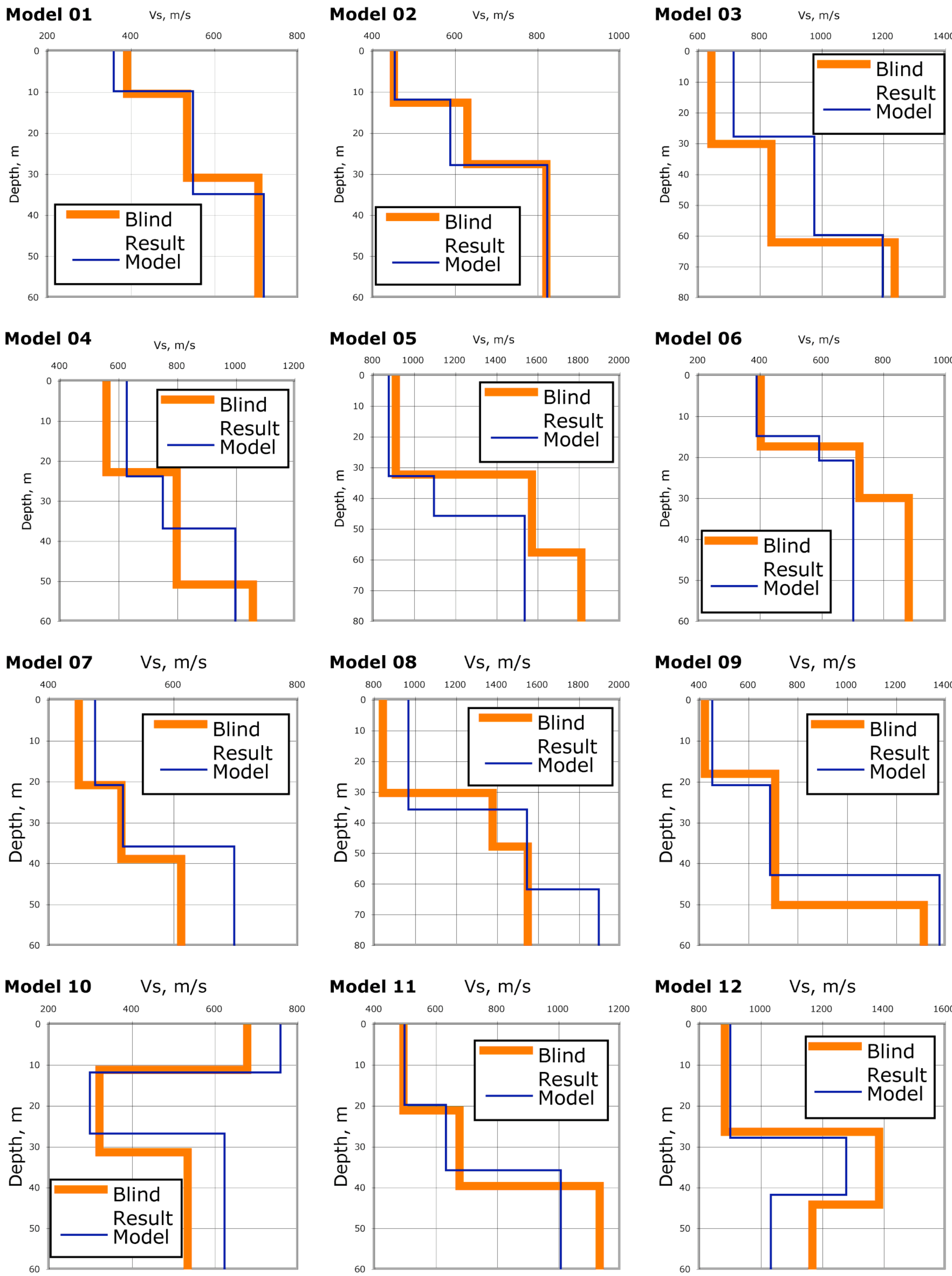

Figure 1. Model shear-velocity versus depth profiles for the synthetic ReMi analyses. Ten of the twelve profiles represent Sheriff's (1991) A-type section of increasing velocity with depth. The remaining two profiles correspond to an H-type section and a K-type section. The H-type section (Model 10) has a low-velocity layer, while the K-type section (Model 12) has a high-velocity layer.

The main parameters used in these examinations are Vs30 and the depth to the shallowest interface (here denoted as Z0). Vs30 is a key factor in prediction of earthquake ground-motion amplification and site response in sedimentary basins (Field et al., 2000). The NEHRP-Uniform Building Code (UBC, 1997) uses Vs30 as the main site characteristic for categorization of shaking hazard. It had been estimated that the average shear-wave velocity of unconsolidated sediments is a function of sediment thickness when assuming that a quarter-wavelength relationship governs the relationship between resonant period, sediment thickness, and average shear-wave speed (Bodin et al., 2001). Therefore, the depth of the top interface, Z0, is an important parameter for accurately calculating the effect of resonances on seismic shaking hazards, which is why we incorporated it in this study.

Methods for Blind Synthetics Test

A dozen shear-velocity profiles (Figure 1) were created by randomly altering the interface depths and shear velocities of measured profiles from southern Nevada rock sites (not shown). All of the profiles use three-layer models, among which 10 of the profiles follow the A-type resistivity section as described by Sheriff (1991). The A-type section is defined as an increasing shear velocity as the interfaces become deeper. Vs30 for the A-type profiles varies from 466 m/s (Model 01) to 975 m/s (Model 08), and Figure 1 shows the large degree of variation in interface depths and velocities between these models. The two remaining profiles represent the H-type section (Figure 1, Model 10) and the K-type section (Figure 1, Model 12). The H-type section is signified by the second interface of the profile being a low velocity zone, while the K-type section can be identified by the high velocity zone of the second interface. These models have Vs30s of 424 m/s and 920 m/s, respectively.

The synthetics were created with the E3D code (Larsen and Schultz, 1995; Larsen and Grieger, 1998) from Lawrence Livermore National Laboratory (LLNL). E3D is a 2D/3D elastic finite-difference wave propagation code used for modeling seismic waves. Each shear-velocity profile was entered into the E3D program as a laterally-homogeneous 2D grid 500 m wide and 130 m deep, with a node spacing of 0.5 m. A Ricker-wave vertical source impulse with 6 Hz dominate frequency was placed near one end of the grid to create shear waves that after a 100 m developed the Rayleigh waves needed for ReMi analysis, recorded at 100-285-meter distances from the source. The seismic records are composed of a linear array of 20 traces spaced 15 m apart, which is a typical layout of the southern Nevada sites. Synthetic recording was for 4 seconds, much less time than is needed to record a ReMi record in the field. In order to create a blind test the synthetic records were randomly renamed by one author, with their origin unknown to the author who processed the synthetics.

Processing took place using exactly the same procedures as for the field data, holding to Louie's (2001) refraction microtremor analysis, and using SeisOpt®ReMi™ version 2 software. ReMi processing produced a shear-wave velocity versus depth profile for each of the 12 synthetic seismic records. Fig. 2 shows an example of a synthetic seismic record and a slowness-frequency spectrum from another similar synthetic record. Fundamental-mode Rayleigh-wave dispersion-curve points were picked along a minimum velocity envelope of energy in the slowness-frequency spectrum image. Typically dispersion progresses from small slowness values at low frequencies down and to the right in the direction of larger slowness values at higher frequencies. The fundamental-mode Rayleigh dispersion curve was interactively forward-modeled to attain a shear-wave velocity versus depth correlation. The interactive forward-modeling included analyses of the depth to which shear-wave velocities could be resolved from the Rayleigh dispersion picks, as illustrated by Louie (2001). The Vs30 measurements were calculated by arithmetically averaging slownesses to 30 m depth.

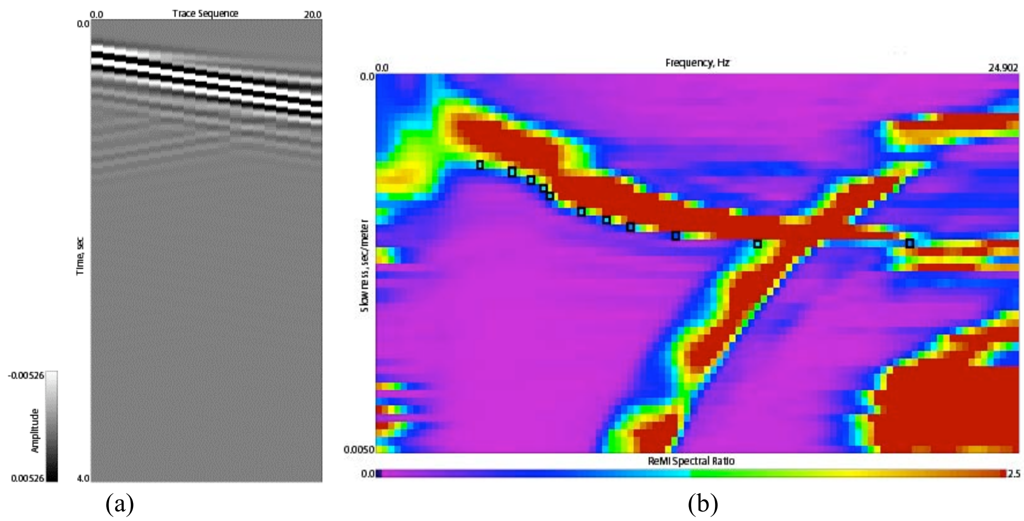

Figure 2. (a) Four seconds of example 20-trace E3D synthetic-seismogram record from a model array extending 285 m. (b) Example image of slowness-frequency (*p-f*) spectrum. The warmer colors of the image represent increased spectral ratio in the manner of Louie (2001); the ratio of spectral power at a particular *p* and *f* over the average spectral power for all slownesses at that *f*. The small squares indicate analyst's picks of the fundamental-mode Rayleigh-wave phase velocity.

Results of Blind Synthetics Test

Figure 1 shows the blind ReMi results (thick orange profiles) plotted atop the original model profiles (thin blue profiles) for all twelve synthetic models. The synthetic ReMi results are contrasted according to our tests of Vs30 and Z0 against the corresponding original input profiles in Figure 3. Only one of the test models yielded as much as 20% error, for Z0, the depth to the shallowest interface. That model was "test006" or Model 06, and it had a relatively thin intermediate layer, only 6 m. The maximum error in Vs30 was 12%, for Model 08, which was the model with the highest velocities, having a Vs30 of 975 m/s. Ten profiles resulted in an error margin of ≤10% for Vs30. Seven of the profiles generated errors ≤10% for Z0 (Figure 3).

The comparisons of summary Vs30 values, and of the crucial Z0 depths, are excellent. Noteworthy are the close matches of the model H-type and K-type profiles (Figure 1, Models 10 and 12) that involve velocity inversions. Other details of the comparisons that can be made in Figure 1 are adequate, but show room for improvement of the analysis. The deepest, half-space velocities are off by ~15% where velocity inversions are involved (the H- and K-type models, Models 10 and 12). For the A-type models, half-space velocities match as well as better than 1% for Model 02, while Model 06 shows a blind underestimate of 27%. The thickness and velocity of the intermediate layer, just below Z0, is another model parameter that is not well recovered. Models 04, 05, and 06 have intermediate layers that are not well matched on Figure 1.

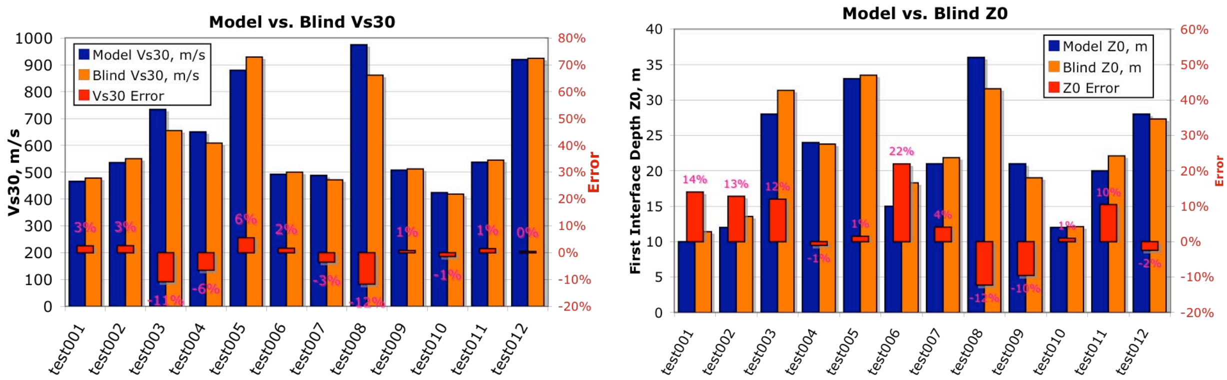

Figure 3. Comparisons of original-model Vs30 (left) and Z0 (right) against corresponding results from blind ReMi analyses of synthetic data records.

Methods for Evaluating Borehole versus ReMi measurements

Leubbers et al. (2002) report downhole measurements of 16 boreholes sites in southern Nevada, near Yucca Mountain, in the location of a planned nuclear-waste handling building (Figure 4). The ReMi data collected at this site were effectively blind tests, since the author doing the ReMi data gathering and analyses did not view the borehole data before ReMi results were reported. We gathered the southern Nevada ReMi data in July of 2004 using 20 Ref Tek RT-125 "Texan" seismographs mated to 4.5 Hz vertical geophones. The linear instrument arrays had 15 m spacing, extending approximately N-S and W-E from strong motion stations Midway Valley (MDVS) and Exile Hill (EXHS). Daily the internal clocks of the seismographs were synchronized and programmed to record twenty-four 2-min records per hour with a sample rate of 200 Hz. At least twelve 2-min records were recorded for each array.

Results of Borehole versus ReMi measurements

Figures 5 and 6 display the shear-wave versus depth profiles of the southern Nevada borehole and ReMi measurements. The profiles presented in Figure 5 exhibit a great range of interface depths, and velocities ranging from 130 m/s to 1177 m/s within 30 m of the surface. Vs30 values from the downhole profiles range by 73%, from 442 m/s at RF#26 up to 764 m/s at RF#28. The drillhole profiles at the extemes of this variation, RF#28 and RF#26, are only separated by 150 m, on the cut and fill sides of the pad, respectively (Figure 4). The ReMi Vs30 results range from 570 m/s at MDVS EW, to 708 m/s at EXHS NS, a 24% variance, thus encompassing some of the variance seen among the borehole Vs30 results. Figures 4 and 5 show that the boreholes near the higher-velocity EXHS results show higher downhole velocities.

Figure 6 shows only borehole RF#19 and the nearby MDVS ReMi results. The RF#19 downhole log shows a Vs30 of 586 m/s, just 3% above the MDVS EW ReMi array Vs30 result of 570 m/s. The MDVS NS array exhibits the site's lateral heterogeneity, returning a ReMi Vs30 of 633 m/s, 8% above the RF#19 downhole Vs30. RF#19 and the MDVS NS array center point are separated by more than 200 m. Both of the MDVS arrays agree that the shallowest interface has a depth of 14 m (Figure 6). Nearby borehole RF#19 shows a top interface depth of 12 m, ignoring the slow, 5-m-thick surface layer, not seen in any ReMi results (Figure 5). The depth is different by 2 m or only 8%.

The ReMi results from EXHS show a top interface with a depth of 32 m (Figure 5), which is almost twice the depth of the comparable interface in the nearby borehole RF#28 (Figure 4). However, RF#28 is only 32 m deep. Both EXHS ReMi arrays match the RF#28 downhole Vs30 of 764 m/s very well, with 666 m/s from EXHS EW (13% lower) and 708 m/s from EXHS NS (7% lower).

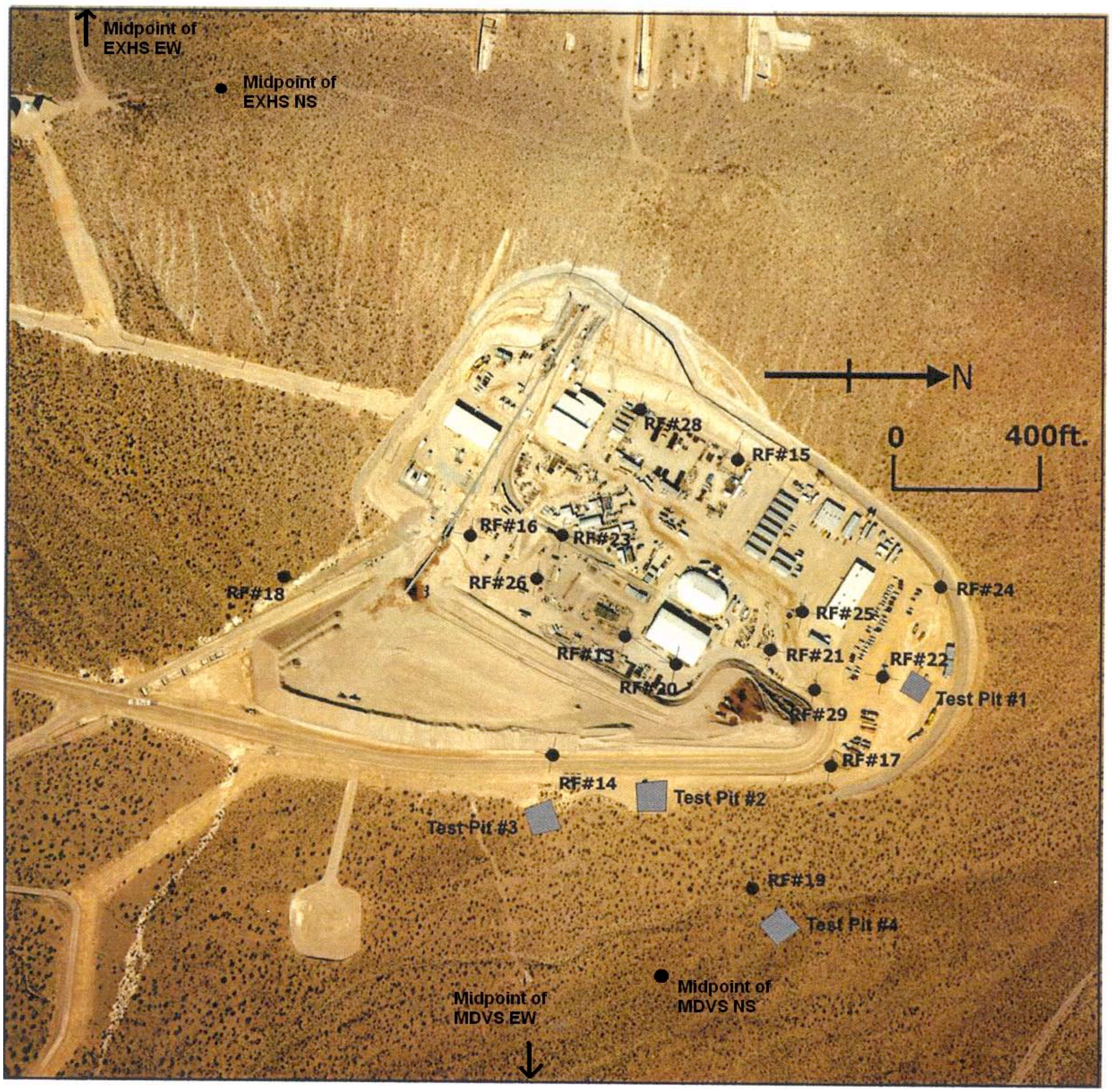

Figure 4. Map of the Yucca Mountain Tunnel Entrance pad from Luebbers et al. (2002), modified to show ReMi measurement sites MDVS and EXHS. The midpoint of the MDVS EW array is ~200 ft (60 m) east of eastern map edge (bottom). The midpoint of the EXHS EW array is ~200 ft west of the western map edge (top), following the road.

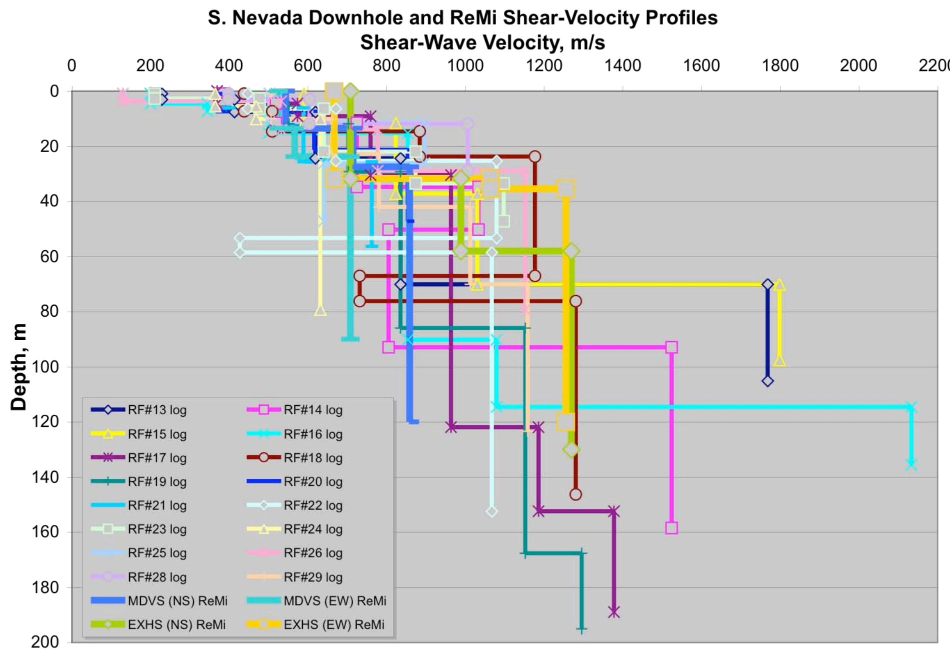

Figure 5. Shear-wave velocity profiles from the downhole and ReMi measurements examined at the Yucca Mountain Tunnel Entrance pad in southern Nevada (Figure 4).

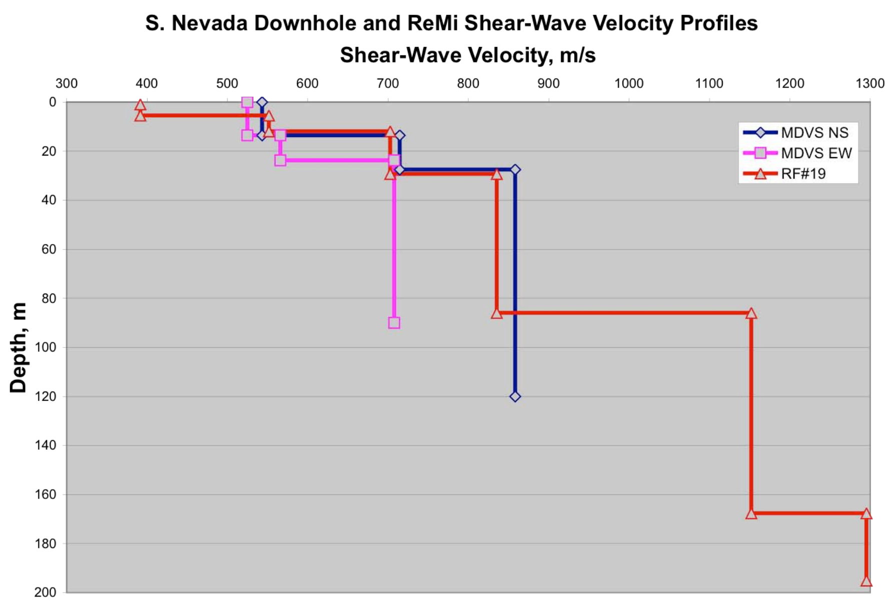

Figure 6. Profiles of shear-wave velocity versus depth of ReMi site Midway Valley and borehole site RF#19 in southern Nevada. RF#19 was the borehole measurement taken nearest, within 300 m, to both Midway Valley array center points.

Discussion and Conclusions

Analyzing the synthetic data using the ReMi process succeeded in creating profiles that correspond well to the model profiles. Both of the parameters that were examined in this test, Vs30 and Z0, resulted in error margins well below 20% in blind tests. More than half of the resulting parameters had error margins within 10% of the original parameters. ReMi analysis was able as well to match H-type and K-type velocity profiles, which involve velocity inversions with depth (Models 10 and 12 in Figure 1). ReMi quickly produces a very detailed dispersion curve (Louie, 2001), showing the slope changes in the dispersion trend needed to model velocity inversions. In our synthetic tests, ReMi proved to be an accurate method for making Vs30 measurements over the three types of canonical profiles we tested- A, H, and K. Vs30 determinations are an important parameter in seismic hazard analysis.

ReMi is a measurement of waves on the surface only, and uses only the phase information in the dispersion curve. No information from wave amplitudes enters ReMi analysis. These limitations allow measurement only of depth-averaged properties, and interface depths have to be a product of an inversion process. ReMi-derived depths of the top interface (Z0) are surprisingly accurate. But the depth-averaging property degrades the accuracies of depths to deeper interfaces, and of the half-space velocity. These characteristics are shared by other wave-measurement techniques at the surface such as SASW, MASW, and refraction, where they have been compared directly with ReMi (Stephenson et al., 2005).

Comparing the ReMi results to downhole logs from a complex site in southern Nevada showed that the ReMi shear-velocity profiles were largely similar. There was an excellent correspondence in Vs30 between ReMi results and adjacent downhole profiles, again with less than 20% mismatch. For the most part there were only small differences between the shallowest-interface depths from the ReMi results and from the downhole data, once surface layers seen only in the boreholes are ignored. These low-velocity surface layers may be laterally limited "soft spots" that are not prevalent over the 1x1-km area, but happened to be sampled by a few boreholes. The four ReMi array results represent reasonably well the large range of velocities and interface depths seen in the 16 downhole logs.

Since ReMi analysis measures the average behavior of Rayleigh waves along 300-m-long arrays, the technique is averaging over the highly heterogeneous properties of this site. This averaging effect does not appear noticeably biased toward the high or the low velocity extremes found in the downhole logs. This stable behavior can be expected from the long wavelengths of the Rayleigh microtremor being measured. The wavelengths used in the southern Nevada measurements here vary from 30 m to 700 m.

It should be pointed out that the borehole logs used were downhole surveys, which are single point measurements. On the other hand, ReMi is a measure of a volume average, incorporating velocities found within those long 30-700-m wavelengths. The value acquired using ReMi analysis is usually assigned to the midpoint location of the array; in our southern Nevada measurements the array midpoint has located 100-200 m away from the boreholes. These differences alone could cause more disparity between the borehole logs and ReMi profiles, as seen in Stephenson et al. (2005). But a few ReMi arrays provided a remarkably good characterization of the southern Nevada site, smoothing over large but not extensive heterogeneities yet providing a measure of the site's overall velocity variation.

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