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Applications of Refraction Microtremor Done Right, and Pitfalls of Microtremor Arrays Done Wrong

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Abstract

The geotechnical industry has widely adopted the refraction microtremor shear-wave velocity measurement technique since Louie's original paper on the method in 2001, and is accepted by building authorities around the world. After successful initial commercialization, the developers have further adapted the method to new applications. Clark County and the City of Henderson, Nevada populated their Earthquake Parcel Map with over 10,000 site measurements for building code enforcement, made over a three-year period. A new 2D refraction microtremor analysis now allows engineers to image lateral shear-wave velocity variations and do passive subsurface imaging. The developers have extended the range of 2D refraction microtremor analysis to several kilometers depth, completing several deep-basin shear-wave velocity measurement programs for the USGS.

We present an uncertainty analysis that incorporates variance in picking of the dispersion curves together with trade-offs in the modeled shear-wave velocities. The uncertainty analysis extends to 2D refraction microtremor sections. The goal is to provide users with confidence limits on the results when using them for site classification, geological interpretation, or community velocity models for scenario shaking computations.

Unfortunately, any useful and popular measurement technique can be abused. Practitioners must carefully follow correct data collection, analysis, interpretation, and modeling procedures, or the outcomes cannot be labeled "refraction microtremor" or "ReMi™" results. Inexperienced or ill-informed practitioners have at times failed to produce correct shear-wave velocities, due to either improper data acquisition or faulty analysis techniques. We present some of the common mistakes, and provide solutions with the objective of establishing a "best practices" template for getting consistent, reliable models from refraction microtremor measurements.

Keywords: Geotechnical shear velocity, Seismic microzonation, Surface-wave dispersion, Uncertainties, Modeling.

1. Recent Developments in Refraction Microtremor

The original journal paper on the "refraction microtremor" shear-wave velocity measurement technique emerged in 2001 [1]. The U.S. Geological Survey conducted blind tests of refraction microtremor against other surface-wave techniques and downhole surveys (e.g., [2]). Since then, building authorities around the world accept refraction microtremor measurements of shear-wave velocity, time-averaged from the surface to 30 m depth, known as "Vs30", for evaluation of seismic site class [3] in enforcing building design and performance standards. With successful commercialization as the SeisOpt® ReMi™ technology by Optim of Reno, Nevada, USA, the method has been widely adopted by the geotechnical industry. Optim and the University of Nevada continue their research and development of refraction microtremor, and have further adapted the method to new applications.

In particular, the refraction microtremor method is capable of efficiently measuring shear-wave velocity at large numbers of sites in heavily urban areas. The University of Nevada has completed transects of closely spaced (300 meters) shear-wave velocity versus depth profiles, to depths exceeding 300 meters, across three urban basins. The initial transect across Reno, Nevada measured 52 velocity-depth profiles along a distance of 15 km [4]. A transect in Los Angeles, California crossed both the San Gabriel and Los Angeles basins with 200 profiles over 60 km [5]. As well, a transect through Las Vegas, Nevada measured 47 profiles over a distance of 13 km [6]. Examining the large amount of closely spaced shear-velocity data showed they have fractal spatial statistics, similar to downhole measurements [5]. Across all three transects, existing soil and geologic maps failed to predict the measurements [4, 5, 6].

The spatially fractal variance of the closely spaced velocity measurements includes both the epistemic uncertainty of the measurement method and the aleatory uncertainty due to spatial variations of ground conditions. Since these data are characterized as fractal over all spatial frequencies, horizontal as well as vertical, they conform to a self-similar process, meaning variance increases as lag distance increases. These results indicate that the velocity measurements contain aleatory variance at all distances, reflecting the natural heterogeneity of ground velocity properties [5]. The first half of this paper examines recent developments in high-density shear-velocity measurement programs, going far beyond the 300 sites measured in the urban transects to explore spatial variations in velocity; the extension of one-dimensional refraction microtremor profiles into two-dimensional cross sections; an uncertainty analysis examining the epistemic and aleatory uncertainties of the surface-wave dispersion modeling process; and the extension of refraction microtremor results to depths of one kilometer or more.

Unfortunately, any useful and popular measurement technique can be abused. Practitioners must carefully follow correct data collection, analysis, interpretation, and measurement procedures, or the outcomes cannot be labeled "refraction microtremor" or "ReMi™" results. Inexperienced or ill-informed practitioners have at times failed to produce correct shear-wave velocities, due to either improper data acquisition or faulty analysis techniques. The second half of this paper presents some of the common mistakes, and provides solutions with the objective of establishing a "best practices" template for getting consistent, reliable shear-wave velocity models from refraction microtremor measurements.

1.1 The Clark County Earthquake Parcel Map

The building departments of Clark County and the City of Henderson, Nevada contracted in 2007 with the Nevada System of Higher Education and Optim to make standardized Vs30 measurements using the SeisOpt® ReMi™ method across 1500 km^2 of the Las Vegas urban area within 3 years, at over 10,000 sites (Figure 1). With a spacing between measurement sites of 300 m or less, the Parcel Map classifies every parcel on the NEHRP scale [7]. While Vs30 average values are unable to capture all the aleatory variability in the shallow surface that affect site conditions, the parcel mapping exposed details of localized harder and softer locations [7, 8]. Identification of such anomalies is only possible through densely spaced measurements of shallow shear-wave velocities at the parcel scale. The detailed Vs30 mapping also delineated the location and boundaries of a previously unknown buried alluvial fan surface [9]. The detailed Parcel Map shows that current parametric approaches applied to create site-condition maps cannot account for distinctions between closely related units, and fail where relationships between the parameters and velocity vary spatially [5, 8, 9].

The Clark County Parcel Map achieved a nearly complete geotechnical characterization of the majority of Las Vegas Valley (Figure 1; [7, 8]). Such detailed 3D characterization is unprecedented. Together with earlier results on the thickness of Quaternary and Tertiary basin sediments underlying Las Vegas [10, 11], the city may well be the best-characterized in the world for 3D physics-based prediction of earthquake shaking. Incorporation of the full Parcel Map was required to effectively simulate the 1992 M_L 5.6-5.8 Little Skull Mountain earthquake 120 km northwest of Las Vegas, and the ground shaking it caused within the city [12]. Peak ground velocities predicted by the 3D model matched what was recorded, to closer than a factor of two. Replacing default geotechnical velocities with the Parcel Map velocities in a sensitivity test produced PGV amplifications of 5% to 11% in places, even at low frequencies of 0.1 Hz. In local-scenario sensitivity tests at 0.5 Hz, the aleatory variations measured by the Clark County Parcel Map produced PGV amplifications and de-amplifications of factors of two [13].

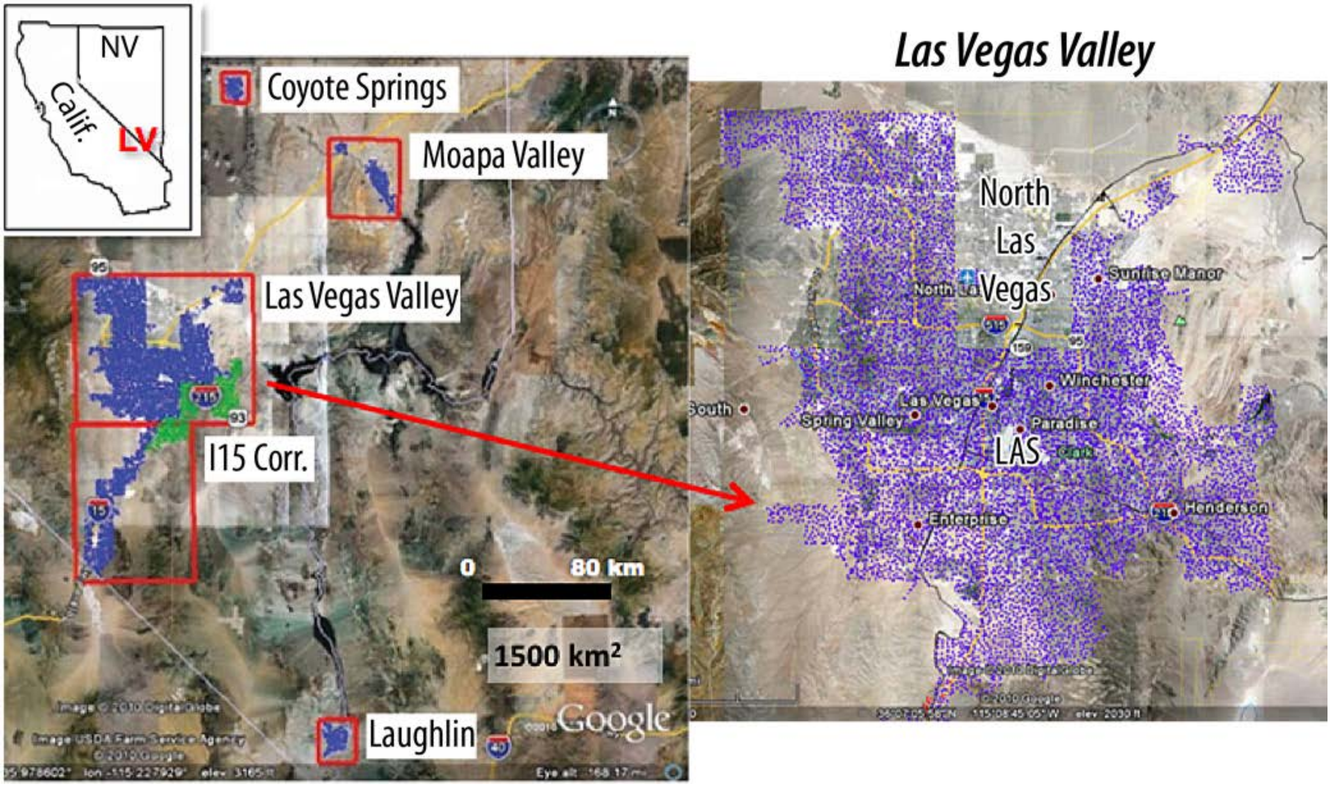

Fig. 1 – (left) Map showing the locations of >10,700 ReMi™ array deployments measuring shallow shear-wave velocities for the Earthquake Parcel Mapping projects undertaken by Clark County (blue dots) and the City of Henderson (green dots), in southern Nevada (LV in index map). The projects assessed a total of 1500 km^2 of currently urbanized areas of Las Vegas Valley and central Laughlin, as well as exurban areas of future development such as outer Laughlin, the Interstate-15 (I15) highway corridor, Moapa Valley, and Coyote Springs. (right) Larger-scale map showing the locations of about 9,000 Parcel Mapping ReMi™ arrays in Las Vegas Valley. No arrays could be placed on the active runways or ramps of the LAS McCarran International Airport; and funding was not available to cover the City of North Las Vegas. Within the 1500 km^2 area covered, the maximum distance between arrays was 300 m. The Parcel Map is freely available from the OpenWeb GIS interface at http://www.clarkcountynv.gov .

1.2 Two-dimensional refraction microtremor sections

A new 2D refraction microtremor analysis now allows engineers to image lateral shear-wave velocity variations and perform passive subsurface imaging. Recording refraction microtremor records on an array of 24 or more sensors allows an experienced analyst to carry out effective ReMi™ analyses on overlapping sub-arrays (Figure 2). Starting with a dispersion curve and modeled velocity profile determined from the entire array, the *p-f* images from the sub-arrays can yield variations in the phase velocity of the dispersion curve, along the array. The interpretation and modeling of the fundamental-mode Rayleigh dispersion still uses the 1D theory originally set out for refraction microtremor [1]. Because the sub-arrays are shorter than the entire array, *p-f* images derived from them are often more difficult to interpret. However, the differential analysis can reveal surprisingly sharp lateral contrasts in velocity, showing in some cases factor-of-two lateral changes over distances as small as 10% of the array length. Since the survey is still entirely passive, the additional information does not come at the expense of additional field effort, only analysis effort. 2D ReMi™ surveys have found frequent application in civil engineering, for foundation design, pre-trenching surveys, and karst and landslide hazards assessment [14].

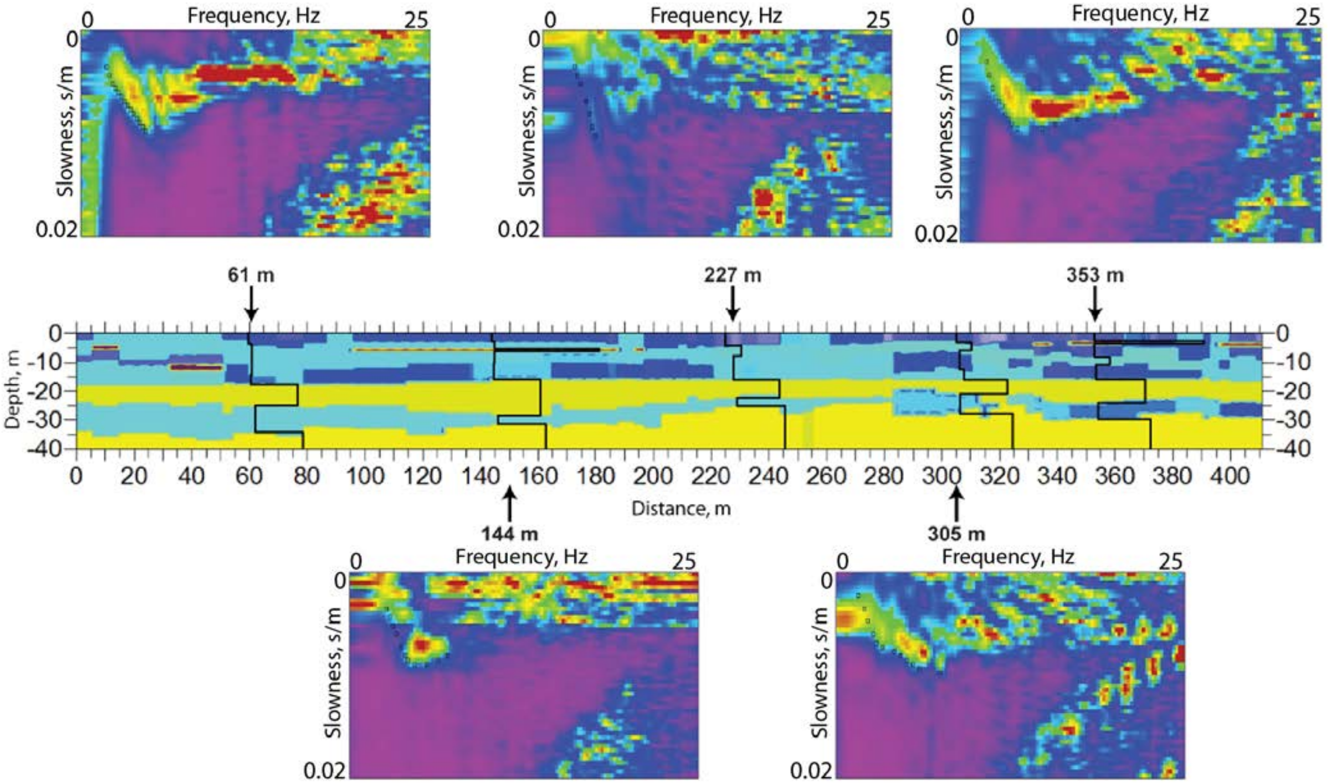

Fig. 2 – Example of a two-dimensional ReMi™ analysis performed for an engineering evaluation at shallow depths. ReMi™ slowness-frequency *p-f* spectral images, upper and lower row, are computed on dozens of overlapping sub-arrays at intervals through a 410-m-long multichannel ReMi™ array. Picking the lowest-velocity envelope on each *p-f* image and modeling the picks for a velocity vs. depth profile centered on each sub-array allows assembly of a 2D section, center row, showing lateral as well as vertical distribution of low velocities (cool colors) and high velocities (warm colors).

1.3 Velocity uncertainty analysis

We present an uncertainty analysis that incorporates uncertainties in picking of the dispersion curves together with trade-offs in the modeled shear-wave velocities. Louie [1] originally presented a method of picking a range of phase velocities at each frequency, to assess dispersion-curve uncertainty. Uncertainty in the dispersion can vary widely with frequency, with <2% uncertainty at some frequencies and >50% uncertainty at others. Pancha et al. [15] defined high-accuracy dispersion picking at the slowness having the sharpest gradient of the ReMi™ spectral ratio versus slowness, and the increasing uncertainty of shallower gradients. Modeling procedures can use the interpreted ranges of possible phase velocities at each frequency, or period, to create high- and low-velocity "bounding" models for the 1D shear-velocity vs. depth profile. Such procedures effectively evaluate the epistemic uncertainty in the 1D velocity profile due to the measurement and modeling procedures.

The uncertainty analysis extends to 2D refraction microtremor sections. The goal is to provide users with confidence limits on the results when using them for site classification, geological interpretation, or community velocity models for scenario shaking computations. Given that the 2D sections are composed of multiple adjacent 1D profiles, assessing the procedural epistemic uncertainty of each profile allows some degree of separation of the epistemic from the intrinsic aleatory uncertainty, partly expressed as the lateral variation of shear-wave velocity between adjacent profiles.

The analysis takes advantage of the simulated-annealing optimization of velocity profiles from phase-velocity dispersion curves developed by Pei et al. [16], which produces a suite of alternative profiles that all fit the dispersion picks equally well. A simplified R/T coefficient matrix [17, 18] speeds the forward modeling of dispersion curves that occurs thousands of times in the annealing optimization. But interactive dispersion modeling by an experienced interpreter almost always precedes optimization. Including the dispersion-pick uncertainties in the objective function of the optimization, and thus in the posteriori probability densities of the models, allows the variance of the resolved profiles to vary with depth in concordance with how the variance of the dispersion picks varies with period. The procedure produces many trial 2D sections as it scans the dispersion picks from sub-array to sub-array, fitting the lateral variations in dispersion. Varying the number of layers between tight constraints, and whether velocity inversions with depth are allowed, further explore the model space. Figure 3 shows some of the dozens of best-fit 2D model sections produced by this optimization. Summing the average velocity, and its standard deviation throughout the section (Figure 3, lower) effectively assesses the shear-wave-velocity uncertainty within the section. The warm colors in the standard-deviation cross section follow the bedrock interface, an expression of the uncertainty of the depth of the interface.

1.4 Deep refraction microtremor surveys

We have extended the range of 2D refraction microtremor analysis to several kilometers depth, completing several deep-basin shear-wave velocity measurement programs for the U.S. Geological Survey. Figure 4 shows the location and results of the 2012 deep ReMi™ surveys in Reno, Nevada, USA [19], over the deepest point of the city's sedimentary basin. That initial survey recorded three arrays of thirty, 4.5 Hz vertical geophone sensors 3 or 6 km long, for more than four hours per array. The *p-f* images (shown in [19]) allowed reliable picking of fundamental-mode Rayleigh dispersion to frequencies as low as 0.30 Hz. Two-dimensional modeling recovered shear velocities at depths greater than 1000 m, providing thorough characterization of the basin. Extending a velocity isosurface through the sections at a value of 1.5 km/s provides an assessment of the depth of basement (Miocene volcanics here), often called "Z1.5". This ReMi™-derived basement depth falls between alternative geophysical gravity and geologic analyses of basement depth [20, 21], in the lower part of Figure 4.

In 2014 the U.S. Geological Survey funded a second survey, in the northeastern part of the Reno-area basin, under the City of Sparks, Nevada. Changing the survey parameters to arrays of sixty, 4.5-Hz sensors 3 km long allowed good definition of the 0.6-km-deep basin floor, along with the edges of the basin [22]. Gravity constraints in that sub-basin were not as complete as in the deeper western sub-basin [20, 21], giving additional value to the deep ReMi™ results. A 2015 survey of two 3-km-long arrays crossed the center of the Reno-area basin, between the 2012 and 2014 survey areas [23]. The shear-wave-velocity cross sections suggest that a previously known west-dipping normal fault [21] offsets the floor of the sedimentary basin by more than 100 m [23]. The Miocene volcanic basin floor throughout the Reno-area basin shows a shear-wave velocity of 2000-2300 m/s.

The 2012 surveys in Reno were accompanied by a 6-km-long deep ReMi™ array in South Lake Tahoe, Calif., funded by Optim and the University of Nevada. This survey imaged shear velocity to the basin floor, as deep as 700 m. But the Mesozoic granitic and metamorphic Tahoe basin floor has a shear velocity of 3200 m/s, substantially above the 2300 m/s shear velocity of the Miocene volcanic floor of the Reno-area basin. In March 2016, The Univ. of Nevada recorded two deep ReMi™ arrays of 90, 4.5 Hz vertical sensors, 15 and 22 km long, crossing the Reno-area basin west to east and north to south. Early data analyses suggest that the arrays have detected the 2300 m/s to 3200 m/s shear-velocity interface at 1-2 km depth, representing the floor of the Miocene basin's volcanic fill, with Mesozoic bedrock below. This interface is visible in the mountains around the margins of the Reno-area basin [21].

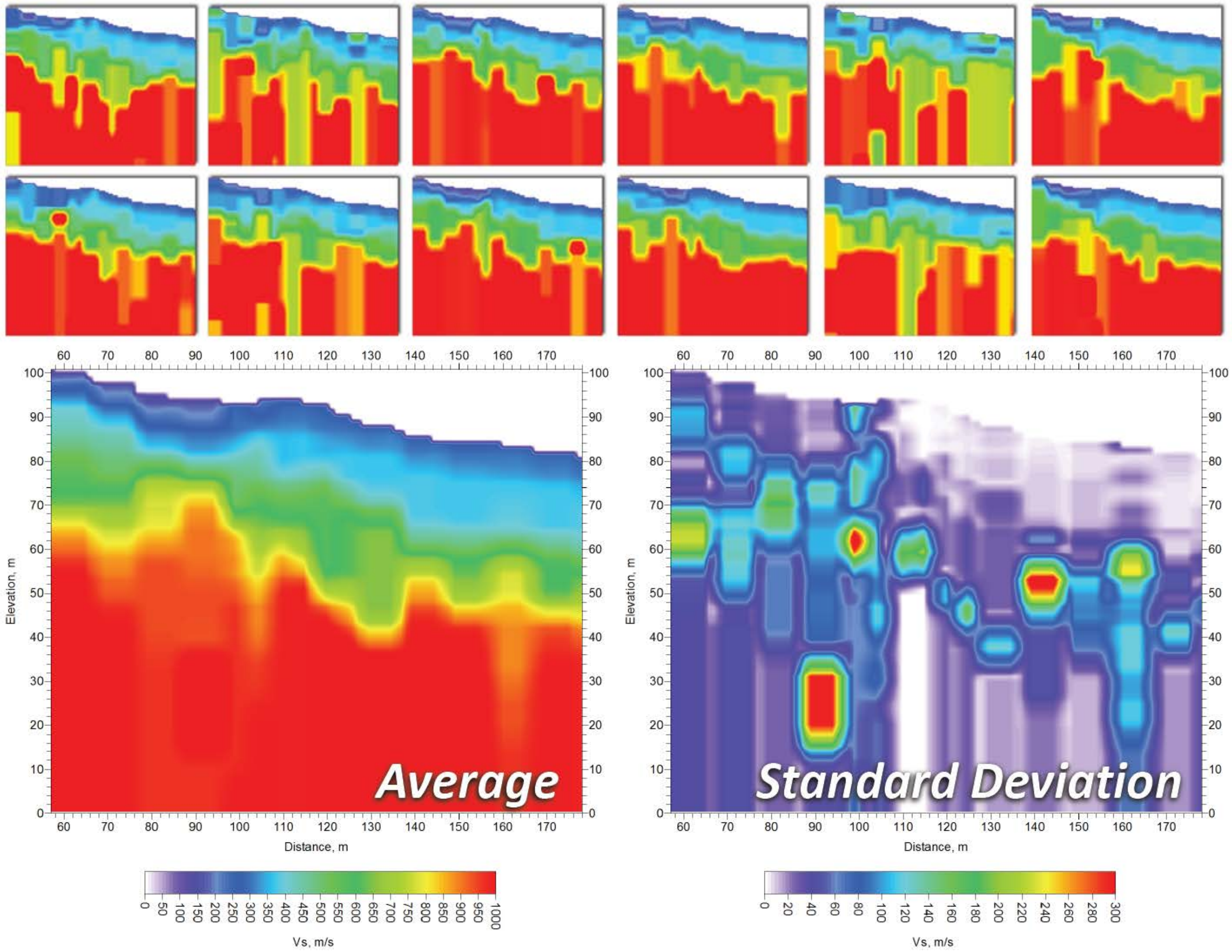

Fig. 3 – Example of dispersion-modeling error analysis on a two-dimensional ReMi™ survey performed in an area of high topographic and rock-depth variation. Top two rows show example velocity sections from a suite of several dozen trial models optimized under varying constraints of number of layers and dispersion-curve uncertainties (same axes and color bar as lower left). Low shear-wave velocities within the sections are shown as cool colors; high velocities are warm colors. The time-averaged-velocity section at lower left is computed from the velocities of all trial models at each depth point in the section, with the standard deviation of the average at each point given by the section at the lower right. On the standard-deviation section, purple and white indicate velocity uncertainty of <5%; red an uncertainty over 30%.

2. Pitfalls, and Best Practices in Refraction Microtremor

The developments listed above have taken place against a background of continuous commercial and academic activity employing refraction microtremor. There are hundreds of users of the refraction microtremor technique around the world. This section is for users who have not been able to obtain all the experience and training from which long-term license holders have benefitted. Here we address four phases of ReMi™ analysis: data collection; processing; dispersion picking; and modeling. Common pitfalls are denoted in *Italics*:

2.1 ReMi™ array data collection

Lines too short– Practitioners sometimes use a linear refraction microtremor array that is too short, given their target depth. Total array length should generally be greater than twice the maximum target depth. Rayleigh waves are most sensitive to velocities and structures that are within a half-wavelength of the surface. To properly time the velocity of such a wave, the sensor array needs to be at least as long as the wavelength.

Geophone spacing too wide– Conversely, geophone spacing should not be greater than the minimum desired target depth. To resolve a one-meter-thick layer at the surface, use a spacing of less than one meter.

Recording time too short– Practitioners who have experience with active-source Multichannel Analysis of Surface Waves (MASW) surveys sometimes assume that the 4- or 5-second-long hammer-source records recorded for that technique are adequate for ReMi™ analysis. This may be true only if the maximum target depth is less than 20 m. Standard practice for commercial ReMi™, reliably getting the time-averaged shear-wave velocity property to a depth of 30 meters, is to record ten records at least 30 seconds long each. Longer records improve the frequency resolution of the *p-f* image and thus of the dispersion curve.

Site too quiet– Urban areas with some noise coming from all directions are where the ReMi™ technology works most easily. Remote, quiet locations can be tricky to survey. Even sites with completely omnidirectional noise can yield good ReMi™ analyses if the survey party adds noise by hammering off the end of the array, or by driving their largest truck along it. Sledgehammer blows help define the dispersion curve above 10 Hz, while a heavy truck can yield broad-band microtremor down to 2 Hz. Records with added noise may need to be processed and picked differently.

Bad geophone sensors– Seismic quality control is critical to a successful ReMi™ survey. Test your array after installation with some hammer blows to check for bad or unconnected geophone sensors. Any geophone with a natural frequency of less than 8 Hz needs careful leveling. While it is often easy to achieve a good geophone plant for ReMi™ with a 4-in spike into turf, with no need to remove the turf; brushy or sandy sites may require shovel work to properly bury each leveled geophone. Rocky or cobbled sites require particular care to get good geophone connection with the ground, and keep them from rocking on their spikes. ReMi™ surveys across pavements are easy, with tripod geophone bases.

No QC– Accessing a field site is often the most expensive part of ReMi™ surveying. Do not leave the site until you are assured that your data are adequate for your objectives. Take the extra 15 minutes and try test processing before pulling the array. Examine the *p-f* images of at least a few records. If you cannot recognize the minimum-velocity envelope, across the range of frequencies you need, consider adjusting your array parameters and additional recording.

2.2 Transformation to ReMi™ *p-f* images

The objective of deriving the *p-f* image is to recognize the minimum-velocity envelope. The minimum-velocity envelope is not subjective and can always be identified on the ReMi™ *p-f* image, so long as two conditions are met: 1) the microtremor energy is not entirely unidirectional, with at least a few percent of the wave energy traveling in the direction of the linear array; and 2) at low apparent velocities across some range of frequencies, a region of near-zero energy appears on the *p-f* image, often with a purple color as in Figures 5 and 6. Since the apparent velocity of the Rayleigh wave on the microtremor array records can be higher than, but can never be lower than the Rayleigh phase velocity at a given frequency, the low-energy and low-spectral-ratio area must be bounded at the top by the minimum-velocity envelope.

High Vmin– The blue or purple low-spectral-ratio region may not appear on the ReMi™ *p-f* image if the minimum velocity of the analysis is set too high. Start with a low value for Vmin such as 100 m/s to check, then repeat and refine. The most interpretable *p-f* image will show a clear low-spectral-ratio region, but occupying no more than a third of the *p-f* image.

Low fmax– Start high to check, perhaps at 50 or 100 Hz. Though most projects will not be interested in dispersion measurements above 30 Hz, you may find a clear minimum-velocity envelope at higher frequencies. That can guide your interpretation of the dispersion at your frequencies of interest.

Summing in bad records– When summing the individual *p-f* images together for final picking of the dispersion curve, some records may not produce *p-f* images with clear low-spectral-ratio regions. You should try summing with and without these records, to see which strategy yields the clearest minimum-velocity envelope.

No tests– Try forward-only direction of analysis, reverse-only, and both on all records. See which strategy yields the broadest-band low-spectral-ratio region, and thus the clearest minimum-velocity envelope. You can pick dispersion just on the records where the envelope is clear, and only at the clear frequencies on each *p-f* image, and combine the picks later for modeling.

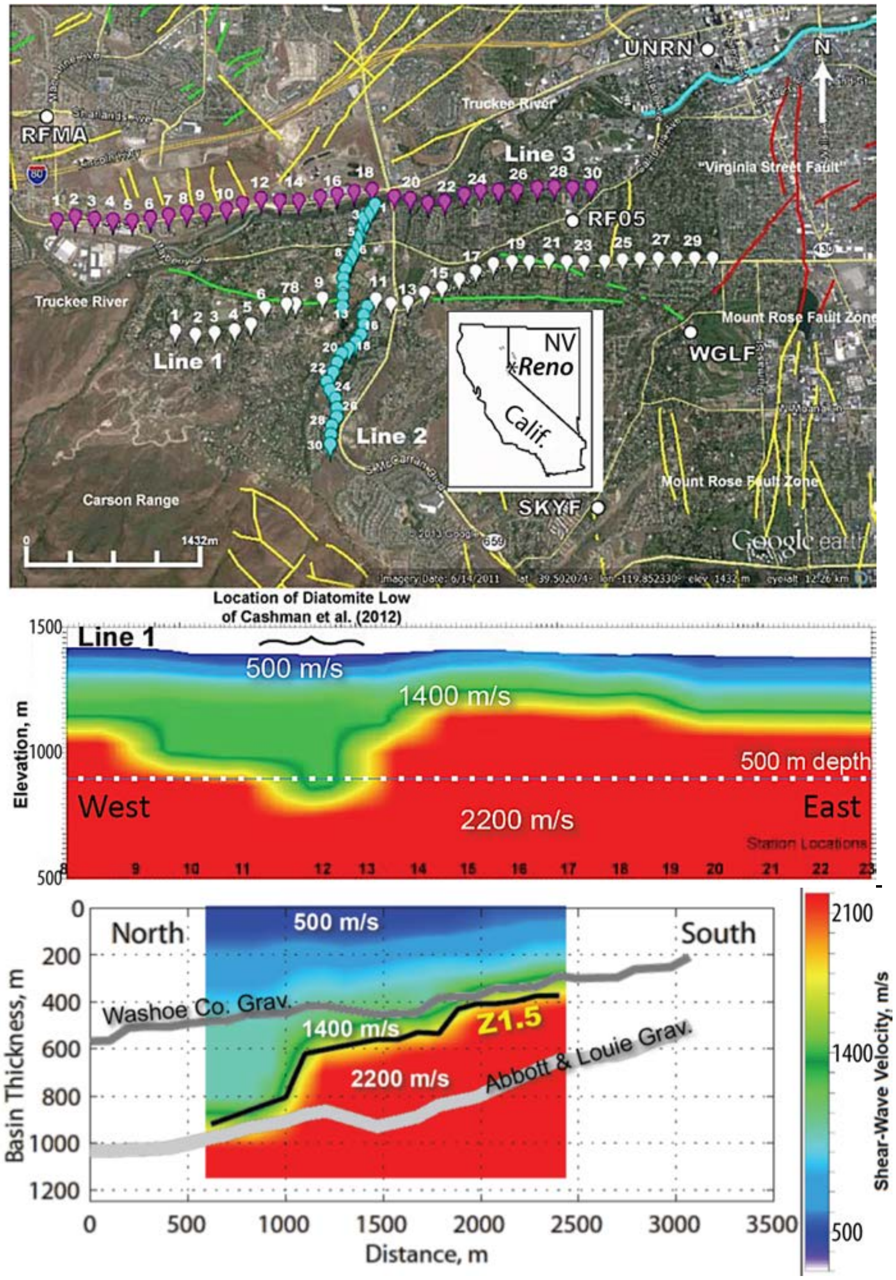

Fig. 4 – Example of two-dimensional deep ReMi™ results obtained in 2012 from the Reno-area, Nevada basin [19]. Arrays of 30 sensors 3 and 6 km long determined shear-wave velocities to depths of 1000 meters, to the Miocene volcanic basement. Cool colors show low velocities and warm colors high velocities. The lower panel compares Line 2 velocities against the results of the geophysical gravity analyses of Plio-Pleistocene sedimentary basin thickness by Washoe County [21] and by Abbott and Louie [20]. Z1.5 is the minimum depth in the section at which shear-wave velocity exceeds 1.5 km/s.

Linear velocity transformations– Practitioners sometimes attempt to make ReMi™ analyses with MASW software, which plots the wavefield transformation on a linear scale of velocity, rather than the linear slowness scale that ReMi™ *p-f* images use. The linear velocity scale is appropriate for MASW surveys, with their active sources in-line with the recording array. In a microtremor survey, most of the Rayleigh wave energy is not traveling in the direction of the linear array. ReMi™ *p-f* images use a linear slowness scale to identify the energy arriving broadside to the array, with zero slowness and infinite apparent velocity, such as within the red oval on Figure 5. A plot with a linear velocity scale cannot show the energy at infinite apparent velocity, while a ReMi™ *p-f* image will show it clearly. Although you will not be making any dispersion picks on such energy, it is helpful to identify the frequency range of such effects, as they can add uncertainty to the minimum-velocity envelope.

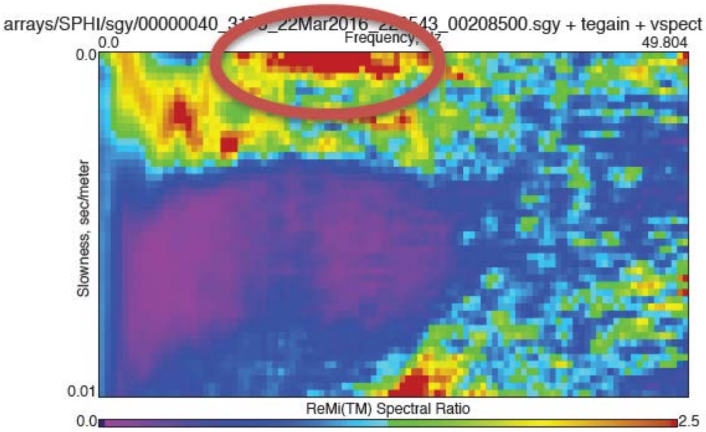

Fig. 5 – Example of a ReMi™ *p-f* slowness-frequency image derived from wavefield transformation of a microtremor record. Frequency increases to the right, from 0.0 to 50 Hz; slowness increases linearly down, from 0.0 at the top to 0.01 s/m at the bottom. Cool colors indicate a low ratio of energy at a combination of slowness and frequency, compared to the total energy across all slownesses at that frequency. Purple is near-zero spectral ratio; warm colors mark high spectral ratios and the predominant energy in the record. Since the slowness is the inverse of the apparent wave velocity along the array, velocity increases non-linearly upwards, from 100 m/s at the bottom to infinity at the top. An infinite apparent velocity simply means a wave front is hitting the array broadside, arriving simultaneously at all sensors. The red oval marks a strong such simultaneous wave, between 15 and 30 Hz. The minimum-velocity envelope is still clear there, between the green and purple colors.

2.3 Interpretation of ReMi™ *p-f* images for dispersion

Picking maxima– Always make dispersion picks along minimum-velocity envelope. In Figure 6, the red, high-spectral-ratio features, or their lower bounds, often do not help identify the minimum-velocity envelope. Once the interpreter has identified that low-ratio region, and picked dispersion across the top of it, they are often able to extend dispersion picks into lower and higher-frequency areas of the *p-f* image, that do not show near-zero ratio below. The interpreter's experience with modeling dispersion picks, and identifying the slowness at which the steepest gradient of ratio appears at each frequency as suggested by Pancha et al. [15], can aid this process. Only pick at ratio maxima where you know you have a record and a frequency range dominated by an in-line source. Even so, you will notice that the picked dispersion velocity at the peaks is only a 3-5% higher than on the minimum-velocity envelope; that observation will assist you with describing dispersion uncertainties.

Picking into gaps– Skip over frequency bands with too little energy along the minimum-velocity envelope, as the white line in Figure 6 illustrates. Picking up into the "scallops" above the envelope and above the low-spectral-ratio area will produce a dispersion curve that no model will fit. Dispersion curves are smooth.

Picking few records– Make sure you are picking at the minimum-velocity envelope across all records and tests. Different records have different microtremor conditions; each one that shows a clear blue or purple low-spectral-ratio region will have an interpretable minimum-velocity envelope, and thus will contain some information on the dispersion curve. You can make dispersion picks wherever the envelope is clear, and later combine the picks for modeling.

Auto-picking in MASW software– Automatic picking of dispersion curves is appropriate for MASW surveys, having strong active sources located in-line with the arrays. Such sources produce strong energy peaks along the dispersion curve. No reliable automatic picking method has yet been developed for the minimum-velocity envelopes in refraction microtremor *p-f* images. Compare the white minimum-velocity envelope with the dashed red line along the peaks, on the left side of Figure 6. Using MASW software to make automatic dispersion picks at peaks in the ReMi™ *p-f* image is unlikely to produce valid dispersion data, especially at the lower frequencies. Pick dispersion by hand.

Picking a higher mode– Higher-mode surface waves will appear above the minimum-velocity envelope, though they may intersect it as in Figure 6. Picking the dispersion phase velocity by hand allows the best interpretation of the curve.

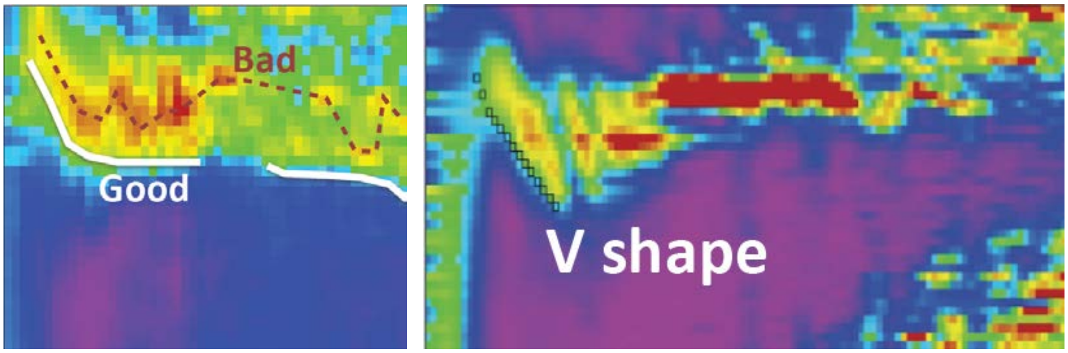

Fig. 6 – (left) Close-up of a ReMi™ *p-f* slowness-frequency image illustrating good and bad fundamental-mode Rayleigh-wave dispersion picks. The good picks are made by hand, by an experienced interpreter along the minimum-velocity envelope; the bad picks could be made automatically, at spectral-ratio peaks that likely are following higher modes. (right) Close-up of another *p-f* image illustrating the "V" shape that often clearly demonstrates an inversion in shear-wave velocity with depth.

2.4 Modeling dispersion for velocity profiles

Recent results from the InterPACIFIC project suggest that surface-wave surveying methods, whether they use an active source or a microtremor source, can often obtain very similar dispersion data over a wide band of frequencies [24]. It is in modeling the shear-wave-velocity versus depth profile from the dispersion curve that it is difficult to get different methods to agree, even when the modeling is done by very experienced practitioners. Refraction microtremor shares these characteristics. ReMi™ practitioners should expect to obtain stable, reliably accurate dispersion data without extreme levels of effort, following the best practices outlined above. Observing the quality and the uncertainties in the dispersion data at different frequencies is a fairly cut-and-dried procedure.

In contrast, modeling velocity profiles from dispersion data is fraught with uncertainty. Experienced ReMi™ modelers, just as with the InterPACIFIC project [24], can and do produce different profiles from identical dispersion data. It can be very difficult to determine what features of the modeled profiles are most reliable. Additional prior constraints on the geology and bedrock velocities, or interface depths or thicknesses of prominent layers from borehole data, assist in defining the most plausible range of possible models for a site.

In closing, the following best practices for ReMi™ modeling will assist practitioners in creating velocity profiles with state-of-the-art reliability. Since the original 2001 paper [1], the ReMi™ technique has been applied on a wide variety of site conditions ranging from hard-rock sites to deep, soft basin fill; on planar topography and on steep hill slopes; and has imaged a range of buried cultural features (e.g., tunnels, culverts, building foundations). The application of ReMi™ over such varying conditions has improved ReMi™ interpretation practices, and allowed the development of 2D ReMi and Deep ReMi. But, the current state of the art of dispersion modeling needs many improvements. The ongoing analysis of ReMi™ from a variety of applications and subsurface conditions facilitates modeling developments.

Ignoring corroborating data– Leave blind tests to the researchers; proper engineering practice and due diligence require practitioners always use all the information on a site that they have. Interactive ReMi™ forward-modeling tools and procedures are built to easily accommodate corroborating and constraining data.

Overfitting– Do not fit all the dispersion picks exactly; they all have a finite uncertainty. Occam's Razor applies, so create the simplest velocity profile that fits each dispersion pick in accord with its uncertainty.

Overfitting is often a weakness of the use of automated inversion packages, which may ignore the finite uncertainty of the dispersion data, and do not allow manual testing of the data sensitivity to velocity-depth trade-offs, or the incorporation of prior data such as bedrock velocities or approximate interface depths and thicknesses.

Spurious inversions– Learn to recognize the V shape in the *p-f* slowness-frequency image that demands a velocity inversion with depth, as shown on the right side of Figure 6. Without that direct evidence in the *p-f* image, you may be able to include a velocity inversion in your profile, but the ReMi™ dispersion curve does not verify the inversion. In the absence of the V shape in the *p-f* image, only include a velocity inversion if corroborating data demand it.

3. Conclusions

New applications of refraction microtremor measurements at large scale include the Clark County and Henderson, Nevada Earthquake Parcel Map for building code enforcement; and deep refraction microtremor analyses to several kilometers depth. At all scales, 2D refraction microtremor analysis allows passive subsurface imaging; and an uncertainty analysis gives confidence limits on shear-velocity results. Practitioners who carefully follow the correct data collection, analysis, interpretation, and modeling procedures given here will obtain consistent and reliable results from refraction microtremor measurements.

4. Acknowledgements

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