

# LISTENING TO THE EARTH: AN UNCONVENTIONAL SCIENTIFIC APPROACH TO UNDERSTANDING SUB-SURFACE GROUND CONDITIONS

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## ABSTRACT

Digitally recorded background ambient noise can be used to extract details regarding subsurface soil conditions. This unique methodology has been implemented to provide comprehensive assessments of geotechnical site conditions. Ambient noise is the persistent vibration of the ground in response to anthropogenic and natural causes. In many contexts, these background vibrations are classified as noise, and efforts are made to remove these signals from recorded data. However, these background vibrations also contain valuable information regarding the materials they travel through. The refraction microtremor (ReMi) technique separates these waves from noise recordings to determine soil shear-wave velocities. Interpolation of the closely spaced one-dimensional velocity-depth profiles along linear arrays allow two or three-dimensional velocity-versus-depth representations to be produced, thereby mapping lateral variations and extending subsurface characterisations between more expensive spot borehole measurements. ReMi technique provides a non-invasive and cost-effective way of estimating vertical soil/rock shear-wave versus depth profiles. This paper examines the contribution ReMi shear-wave velocity assessments can make towards enhancing subsurface geological and geotechnical models to mitigate risk from unforeseen ground conditions.

## 1 INTRODUCTION

We present a unique methodology that has been implemented to provide a more comprehensive assessment of geotechnical site investigations. Digitally recorded background ambient noise is used to extract details regarding subsurface soil conditions. Ambient noise is the persistent vibration of the ground due to anthropogenic and natural environmental causes. For activities sensitive to vibrations, these background vibrations are classified as noise, and efforts are made to remove these signals from recorded data. However, these noise sources emit energy, exciting surface waves that contain information regarding the materials they travel through. The refraction microtremor (ReMi) technique separates these surface waves from ambient noise recordings to determine soil shear-wave velocities. Developed by Louie (2001), the method has widely been used to determine shear wave velocity profiles (Vs). Velocity profiles obtained using ReMi have been used extensively to characterise sites for both engineering investigations and site response evaluations (e.g. Rucker, 2003; Pullammanappallil, 2006; Coccia et al, 2010).

The technology was initially developed by Louie (2001) to rapidly and cost-effectively measure the average shear-wave velocity to 30m depth to meet U.S.A. building code requirements, but has since been further developed towards comprehensive engineering applications. The technology is owned by the State of Nevada, exclusively licensed to Optim, and only available commercially as SeisOpt ReMi (Optim 2001–2019). The methodology is being standardised by the Consortium of Organizations for Strong-Motion Observation Systems (COSMOS) “International Guidelines on Applying Non-invasive Geophysical Methods for Characterizing Seismic Site Conditions” with the United States Geological Survey.

ReMi is a non-intrusive method that involves the deployment of a linear array of instruments to record ambient noise. Recorded data are analysed to extract information from the waveforms that reveal details regarding the subsurface shear-wave velocity profile with depth. Because determination of a reliable velocity model requires a regular and dense distribution of seismic noise sources, the ReMi method thrives in noisy environments, meaning data acquisition does not require construction activities to be halted. This differs from many other geophysical seismic methods that utilise active hammer seismic sources, such as seismic refraction techniques, and multichannel analysis of surface waves (MASW), which require background noise to be at a minimum.

Geotechnical field investigation tests such as Cone Penetrometer Testing (CPT) can often be limited due to the rig encountering practical refusal in very stiff cohesive soils, dense non-cohesive soils or buried construction debris, thereby providing an incomplete vertical profile. Boreholes and downhole shear-wave methods techniques are more reliable, but are costly, and only provide point measurements at a specific location. In contrast, ReMi can detect velocity inversions, and as such, is commonly used to measure shear-wave velocity profiles for engineering applications. Traditional seismic refraction methods are unable to detect softer soils which lie underneath harder material, or material layers that are very thin, often resulting in an incorrect interpretation of shear velocities and associated depths.

Here we describe the ReMi methodology in more detail, outlining the field data acquisition, the analysis procedure, and the parameters controlling the depth of investigation and resolution. Three case studies presented in this paper demonstrate the benefits of incorporating the shear-wave velocity estimates from ReMi into the geotechnical investigations. These include identifying the location of buried stream channels, characterising palaeo-topographical features, identifying areas of low velocity which may be prone to liquefaction, and assessing the thickness and velocity variations within geological units between geotechnical point investigation tests locations. We demonstrate how use of ReMi enhances the ability to obtain a thorough geological understanding of sites, allow better characterisation of subsurface material properties, and hence minimising geotechnical risks. Use of multiple methods supports thorough understanding of subsurface conditions enabling adoption of appropriate geotechnical design parameters to support the fundamentals of “good design”.

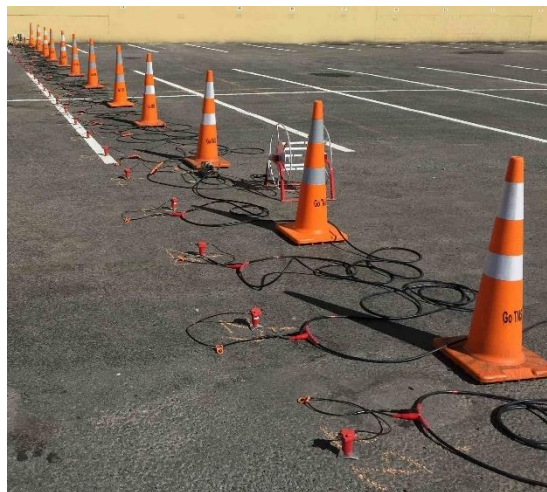
## 2 THE REFRACTION MICROTREMOR TECHNIQUE

The ReMi technology was initially developed by Louie (2001) as a non-invasive surface-performed geophysical survey technique, to rapidly and cost-effectively measure the average shear-wave velocity to 30m depth to meet U.S.A. building code requirements but has since been further developed towards comprehensive engineering applications. The essence of the refraction microtremor technique is that ambient vibrations contain usable signal that can be used to predict velocity structure underneath the measurement array. ReMi exploits the fact that random ambient ground vibrations generate surface Rayleigh waves that transfer significant information about the velocity structure of the subsurface materials. Rayleigh waves are a seismic surface wave that travels along the surface of the earth, causing the ground to shake in an elliptical motion. These recorded Rayleigh waves include high-frequency (short wavelengths, with frequencies  $>2$  Hz) ground motions that have physical characteristics governed by the elastic properties of the very shallow near-surface materials through which they propagate. Meanwhile, lower frequency motion (longer wavelengths, with frequencies  $\leq 2$  Hz) are influenced by material properties at greater depth. More importantly, Rayleigh waves are dispersive, meaning that wave velocity is dependent on frequency, with low frequencies normally propagating at higher velocity. This unique property of Rayleigh waves allows information regarding the shear-wave velocities of the subsurface materials to be determined. Results from ReMi analysis have been validated through comparison to borehole profiles (Asten et al., 2005; Stephenson et al., 2005; Thelen et al., 2006), synthetic data (Heath et al., 2006), as well as MASW, and spectral analysis of surface waves (Liu et al., 2005; Stephenson et al., 2005).

### 2.1 DATA ACQUISITION

Testing is performed at the surface using the same conventional seismograph and vertical P-wave geophones used for refraction studies. Data acquisition is non-intrusive method involving the linear deployment of geophones, placed an even distance apart. This distance, as discussed below, is dependent on the target depth of investigation. Typically, standard vertical 4.5-Hz seismic refraction geophones are used. Where the ground is paved, the spikes will be removed and replaced by plates, as shown in Figure 1. Ambient ground motions, dominated by Rayleigh waves, are recorded by the arrays at a time-sample interval of two milliseconds for multiple records of 30 seconds each. Each seismic array placement collects

twelve to twenty 30-second recordings. Hammer hits using an 8-pound or 10-pound (3.5-4.5 kg) sledge and strike plate placed approximately 5 m and 10 m off both ends of each array augmented normal passive data collection, to increase high-frequency energy. Hammer hits may also be acquired at evenly spaced locations along the line, depending on the array length to assist with 2D analysis.



**Figure 1: An example of a 4.5-Hz seismic refraction geophone used to record ambient noise.**

## 2.2 DEPTH AND RESOLUTION OF INVESTIGATION

Although initially developed for determination of average shear-wave velocities to 30 m depth (VS30), the surface-wave theory behind ReMi technique can be applied to a multitude of applications at various scales, with the array configuration and data acquisition adjusted accordingly. The ability of any surface-wave seismic array to image velocity structure at any depth depends on the capability of the array to capture ground motion at wavelengths that sample the target depths. The wavelength content of the recorded data depends on several factors. These include the array length, geophone spacing, geophone frequency (the lower-frequency limit of motion detection), the time duration of the data records, the frequency content of the noise sources producing the recorded ground motions, and the material properties.

ReMi has been widely used for engineering applications to image very shallow subsurface material structure in the upper 10 m, using short geophone spacings between 0.5m and 3m combined with high-frequency geophones to successfully image near-surface shallow structure. For imaging of deeper structure, longer array lengths, along with larger geophone spacing and lower frequency geophones, can be utilized. The longer arrays and lower frequency geophones ensure that the longer-wavelength Rayleigh waves that sample deeper into the Earth's structure are captured by the recorded seismic data. Many studies have used the ReMi methodology with extended array lengths to successfully image subsurface velocity structure down to 200 m depth. In addition, 3km and 6km long arrays have been deployed to characterise basin geometry to 1km depth (Pancha et al., 2017). 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.

## 2.3 PROCEDURE TO ESTIMATE SHEAR WAVE VELOCITY FROM RECORDED NOISE

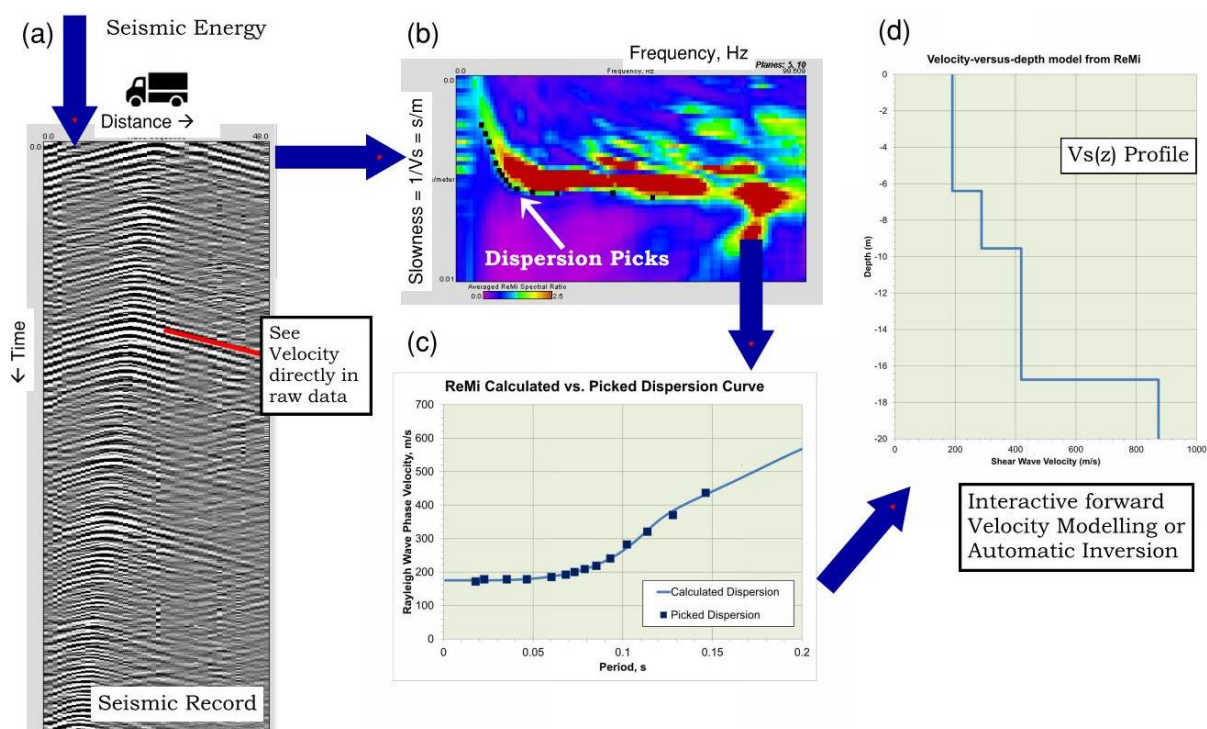
The vertical component of ambient noise, dominated by Rayleigh waves, is recorded by seismograph arrays, as illustrated in Figure 2(a). Once collected, the field data is reduced and processed by trace-equalisation and direct current offset removal. The Rayleigh waves are separated from other wave arrivals using a two-dimensional slowness–frequency ( $p$ - $f$ ) transform of the noise records. This 2D transformation creates a velocity spectrum imaging the Rayleigh-wave dispersion curve, as displayed in Figure 2(b). The spectrum is normalised as the ratio of the power spectrum at a particular frequency and slowness (inverse velocity) divided by the average value for all slowness values at that frequency. Imaging of the dispersion curve on a linear slowness scale, allows recognition of true phase velocity against apparent velocities compared to plots of the wavefield transformation on a linear scale of velocity. Use of a linear slowness scale identifies the Rayleigh-wave energy traveling parallel to the array more clearly. Energy propagating in both directions are analysed. The fundamental-mode phase-velocity Rayleigh wave dispersion curve is then picked along the minimum-velocity of the

envelope of the energy within the slowness–frequency spectral image where the gradient of the power spectral ratio is greatest (Louie, 2001; Panca et al., 2008).

The fundamental-mode Rayleigh dispersion is then picked along the minimum-phase-velocity envelope, as shown in Figure 2(b) for which the gradient of the power spectral ratio is greatest. These points “picked” along the Rayleigh wave dispersion curve are then interactively modelled, using trial-and-error adjustments of the velocity–depth model, to obtain a shear-wave velocity that produces a calculated dispersion curve that matches the data (Figure 2(c) and 2(d)). These shear-wave velocity profiles provide both geotechnical and engineering parameters.

However, like the MASW surface wave method, ReMi suffers from non-unique interpretations, meaning that a given data set can be represented by multiple subsurface geological models. Trade-off between layer thickness and the material property generates the issue of non-unique modelling results, and as such, neither the thickness nor the material property of the layer can be independently determined. To obtain a valid model, independent physical evidence and constraints from geotechnical investigation tests are incorporated into the interpretation of the data to further constrain the possible velocity models.

ReMi is a volume-averaging surface-wave measurement, which averages the velocities where geology is laterally variable. This differs from the single-point measurements obtained by downhole logs, as concluded by Raptakis (2012). Interpolation of closely spaced one-dimensional velocity–depth profiles along linear arrays (or transects) allow two-dimensional velocity-versus-depth representations to be produced. These two-dimensional representations can thereby map lateral heterogeneity of the soil profile and geological structure and extending subsurface characterisations between more expensive spot geotechnical investigation tests. ReMi therefore provides a non-invasive and cost-effective way of characterising ground conditions across entire sites, with data acquisition able to take place in areas where drill-rig access is restricted or drill location quantities can potentially be reduced.



**Figure 2: Schematic of the ReMi technique. (a) Refraction Microtremor involved the deployment of a linear array of vertical geophones to record Rayleigh waves generated by ambient noise. The velocity of the Rayleigh waves can often be observed directly from the raw data. (b) The recorded data are transformed into the frequency-slowness (p-f) domain (see Louie, 2001). The fundamental-mode phase-velocity of the Rayleigh wave is “picked” along the lowest-velocity envelope (black squares). (c) Dispersion curves and associated picks from p-f plots and matching fits. Modelling of the dispersion curve produces a velocity–depth model that matches the data. (d) Modelled shear-wave velocity–depth profiles.**

### 3 KEY BENEFITS

A primary benefit of utilising ReMi measurements for geotechnical ground characterisation is the ability to increase spatial sampling density so that background and anomalous conditions can be identified early in the investigation. Because conventional seismic equipment is used to record data, and ambient noise is used as a seismic source, the ReMi method is less costly, faster and more convenient than boreholes methods and other surface seismic methods to determine shear-wave profiles. The method works best in a seismically noisy urban setting, so can be used on busy construction sites. The method thus affords itself as an effective tool for both reconnaissance for and extrapolation of more expensive geotechnical spot measurements.

ReMi surveys are not intended to replace traditional subsurface sampling and field investigation tests. However, they aid in quickly and economically extending subsurface characterisation over larger areas, correlating between the boreholes, test pits, and other investigation data points to characterise lateral changes in geology and/or material properties. More importantly, the method often allows assessment to deeper depths than the shallow geotechnical investigations. By providing details regarding different material properties of the sub-surface ground conditions, ReMi velocity models contribute towards the development of a more integrated site model.

#### 4 APPLICATIONS OF THE REFRACTION MICROTREMOR TECHNIQUE

Refraction Microtremor has become a standard tool for assessing shear-wave velocities for many geotechnical applications and site response evaluations. ReMi is routinely used to determine velocity-vs-depth information across a range of depths from very shallow right down to a few hundred metres. It is also adept at resolving relatively thin soil layers. Shear-wave velocity data enhances the overall geotechnical investigation by providing a means of assessing soil cyclic resistance, liquefaction potential, and estimates of soil engineering properties such as low strain elastic and shear moduli.

The ReMi ambient noise data can be used to create 1D and 2D shear-wave velocity models for:

- Characterise lateral changes in the ground properties across the site.
- Estimating the strength of subsurface materials.
- Calculate engineering properties of soils and rock such as low strain elastic and shear moduli.
- Estimating Site period and site subsoil classification for NZS1170.5:2004 “Earthquake Design Actions” (Standards New Zealand, 2004).
- Mapping subsurface bedrock depth extents and topography.
- Building foundation assessment and design.
- Assessing bedrock quality.
- Assess liquefaction potential
- Mapping soil discontinuities.
- Identifying fault locations.
- Mapping basalt flows.
- Mapping subsurface voids and cavities.
- Mapping the extent of reclamation fill.
- Identifying soft spots and low shear strength layers.
- Determination of buried morphology – e.g. buried streams.
- Locating and mapping features related to historical site development.
- Finding buried cultural features, as well as landfills and piers.
- Identifying geohazards such as landslide slip planes.
- Image to deeper depths than the shallow geotechnical boreholes and test pits.
- Correlate soil profiles between the boreholes, test pits, and other investigation data points

#### 5 CASE STUDIES

Aurecon New Zealand Ltd (Aurecon) have utilised ReMi towards supplementing data between sparsely distributed and more expensive geotechnical spot measurements (e.g. boreholes, CPT’s and test pits). We present three case studies demonstrate the benefits of incorporating the shear-wave velocity estimates from ReMi into the geotechnical investigations. Results allow the correlation and extrapolation of geotechnical knowledge between geotechnical investigation locations, and the further assessment of subsurface material properties. More importantly, the method allows assessment of soil conditions to deeper depths than the shallow geotechnical boreholes, test pits.

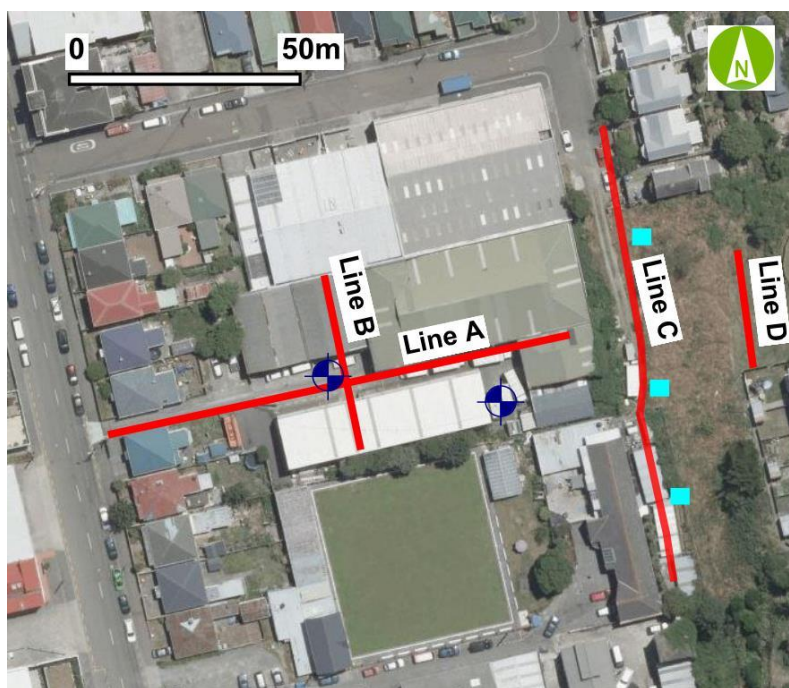
##### 5.1 TERRACE TOWNHOUSES – WELLINGTON, NEW ZEALAND

Towards supplementing data between geotechnical borehole and test pit investigations, ReMi investigations were undertaken to determine the sub-surface velocity structure beneath the site of the proposed Terrace Townhouses (Figure 3). 2D velocity-versus-depth representations mapping the lateral velocity heterogeneity beneath Line A and Line C are presented in Figure 4.

Borehole data from two locations along Line A were used to constrain the velocity profile. Both boreholes terminate at the bedrock interface. These constraints were then used to produce 2D velocity-depth representations beneath each seismic array and extrapolate site condition knowledge across the entire investigation site. As seen from Figure 4(a), there were notable lateral changes that were important for the liquefaction assessment of the site, with interbedded zones of low velocity sediments defined. The non-intrusive technique was also able to define the location of a historical buried stream channel along Line A, documented to have run through the site during the mid-1800's that would otherwise not have been discovered.

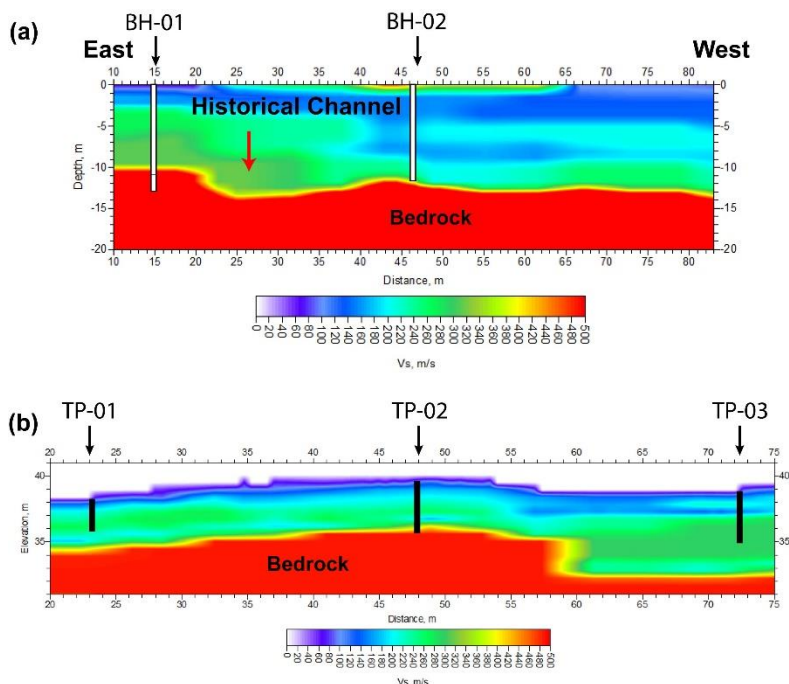
Interpretations along Line C, shown in Figure 4(b), were controlled by stratigraphy from three test pits. Bedrock was only encountered in TP-02. An abrupt change in bedrock depth and soil thickness was revealed through the investigation. The development site was the location of a historic brick factory (circa 1895), which extracted clay material in the immediate vicinity. The increase in bedrock depth observed along Line C is interpreted to be anthropogenic in nature and was undetected and unforeseen from the geotechnical investigation.

The ReMi investigations allowed the correlation and extrapolation of geotechnical data between investigation locations, and the further assessment of material properties. More importantly, the technique permitted the assessment of material properties to deeper depths than the shallow test pits.



**Figure 3: Locations of the ReMi seismic arrays (red lines) undertaken for the geotechnical investigation for a Terrace Townhouse development. Borehole (blue symbols) and test pit (cyan squares) locations are displayed. Aerial photograph sourced from LINZ Data Service (<https://data.linz.govt.nz/data/category/aerial>) and licenced under the Creative Commons Attribution 4.0 New Zealand**

Use of ReMi in conjunction with boreholes and test pits for the Terrace Townhouse project enabled the ability to acquire a more comprehensive assessment of site conditions than traditional methods allowed. The geophysical ReMi data also aided in assessing the liquefaction potential of the site by identifying areas of low velocity between borehole locations, as well as assessing the thickness and velocity variability of geological units between borehole and test pit locations. Most importantly for this case study, ReMi characterised an otherwise unknown dramatic increase in bedrock depth.



**Figure 4: 2D shear-wave velocity representations beneath (a) Line A and (b) Line C. Borehole BH-01 and BH-02 terminated at the weathered bedrock interface. Relative locations of the seismic arrays are displayed in Figure 4. The shear-wave velocity scale displayed below each figure range from 0m/s to +500 m/s, with bedrock velocities > 500m/s. Warm colours indicate high velocities, while cooler colours indicate low velocities. Test pit locations and depth extent are displayed as back lines in figure (b).**

## 5.2 WELLINGTON CHILDREN'S HOSPITAL – WELLINGTON, NEW ZEALAND

Wellington Children's Hospital Charity Limited (WCH) have begun construction of the new children's hospital on an existing carpark site, immediately to the north of the Wellington Hospital complex. The proposed building comprises a ground floor for car parking and three stories of wards built above the ground floor. WCH engaged Aurecon Ltd. to provide an initial geotechnical assessment of the site. Experience from sites within the general area, indicated variable layers of fill, (including potential infilled gully/streams and ponds), underlain by undifferentiated alluvium and greywacke rock with an extensive weathering profile were likely to make up the geological profile at the site. As part of the geotechnical investigations, a ReMi seismic investigation was carried out to determine the subsoil structure and estimate the subsoil shear wave velocity profiles to:

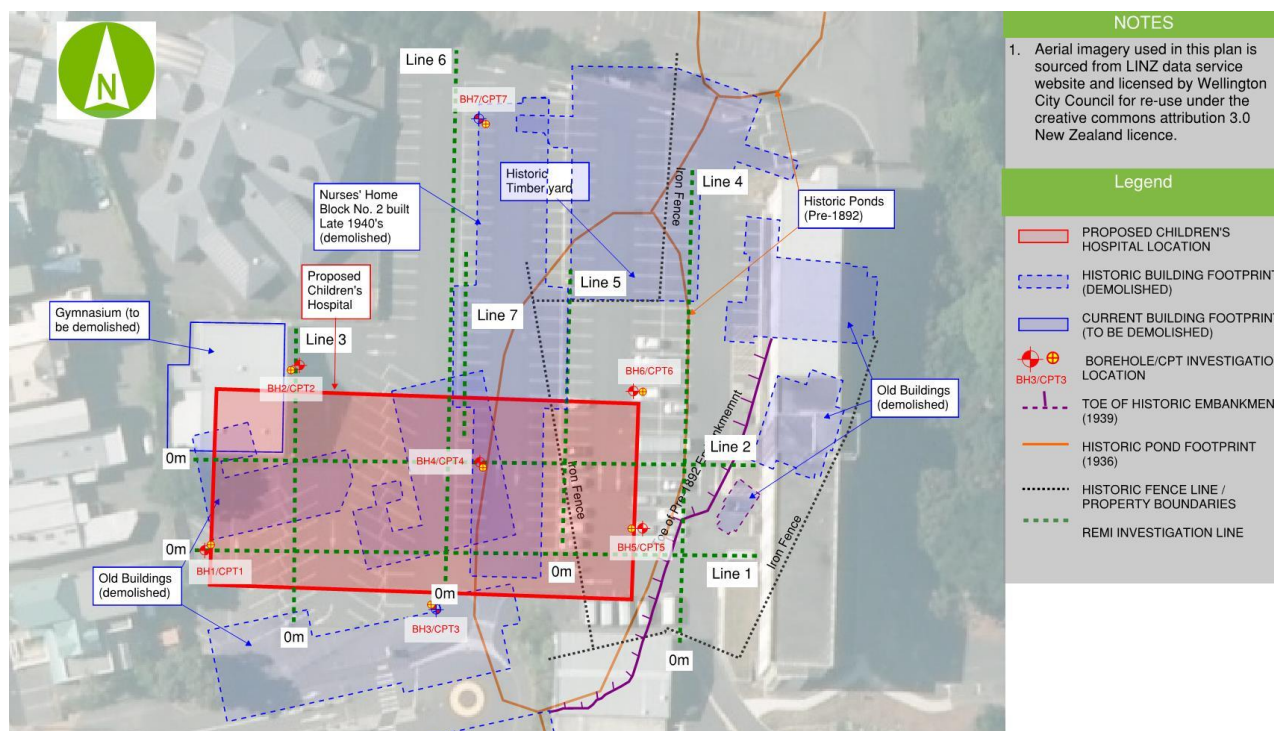
- Characterise the variation of soil properties across the site.
- Determine changes in the soil lithology across the site.
- Determine variations in the bedrock depths across the site.
- Calculate engineering properties of soils and rock such as low strain elastic and shear moduli.
- Determination of liquefaction potential across the site.

The site has a long and complex history of building development. Early maps indicate that site was originally a natural drainage pathway that included a swamp area and several ponds. Over the course of human occupation and subsequent building developments successive infilling has occurred up to present day. Aerial photographs dating back to 1923 through to the present day of Wellington Hospital shows numerous historical buildings have occupied the investigation area. In addition, a plan from 1939 indicate an embankment existed along western side of the investigation site. The site is known to have been underlain by 2.6m to 6m of non-engineered fill underlain by alluvial soils. The non-engineered fill was considered to be very loose and to include rubbish comprising concrete pieces, bricks, wood, nails, metal sheets, metal pieces, old pipes and isolated layers of decomposed vegetation. Figure 5 illustrates the locations of the proposed building site, the historical building, and the old drainage features.

The ReMi investigation for the site included seven seismic arrays, Line 1 to Line 7 (dashed green lines), between 47m and 92m long, the locations of which are shown in Figure 5. Results of the ReMi survey demonstrate that in general, the reclamation fill deposits consist of materials with a relatively low shear-wave velocity as compared to the underlying alluvial soils. Shear wave velocities of the non-engineered fill has shear wave velocities ranging between ~125m/s and

250m/s, while the alluvium/ colluvium overlying the bedrock range between ~175m/s and 400m/s. In comparison, the highly weathered greywacke bedrock had velocities of 300m/s to 600m/s, with >700m/s for the more competent rock.

Based on the historic evidence, both Line 1 and Line 2 traverse the historical pond, which has undergone progressive reclamation during the development of the land. The 2D velocity representations for these two investigation lines, shown in Figure 6(a) and 6(b) respectively. As seen in the cross-sections, the bedrock depth varies, delineating a depression within the bedrock terrain. Along Line 1, the greywacke bedrock beneath is deepest towards the eastern end of the array, with a maximum depth of 13.6m. Towards the western end, the bedrock is at 6m depth below the ground surface, consistent with BH-01. Where the bedrock deepens, a 300m/s layer overlies the bedrock surface. Based on correlations with the geotechnical boreholes the 300m/s layer likely represents gravels associated with the undifferentiated alluvium. In comparison, for Line 2 bedrock depths are deepest nearer the centre of the array, with a maximum depth of 12.3m becoming shallower towards both the west and the east. For both Line1 and line 2, bedrock is shallowest towards the eastern side of site, near the location of the historical embankment, shown in Figure 5.



**Figure 5: Map showing locations of the seven seismic array lines used to determine bedrock and soils structure beneath the site of the proposed Wellington Children's Hospital. Previous site developments and historical natural features are also displayed**

Line 3 is located in a north-south orientation along the western side of the site. A notable 1.5m step down in the bedrock profile occurs at approximately 21.5m along the array. A 2D plot of the velocity-depth representation determined below this array is presented in Figure 7. Between 21m and 27m distance along the array, an area of slightly higher velocity is noted in the upper 1.3m below the surface. Historical records were used to determine the locations of old structures that previously occupied the site, as shown in Figure 5. The location of the edge of the Nurses' Home Block 2 demolished pre-1943 coincides with the approximate location of these high velocities.. It is likely that the origin of the step is associated with the foundation footprint of this demolished building.

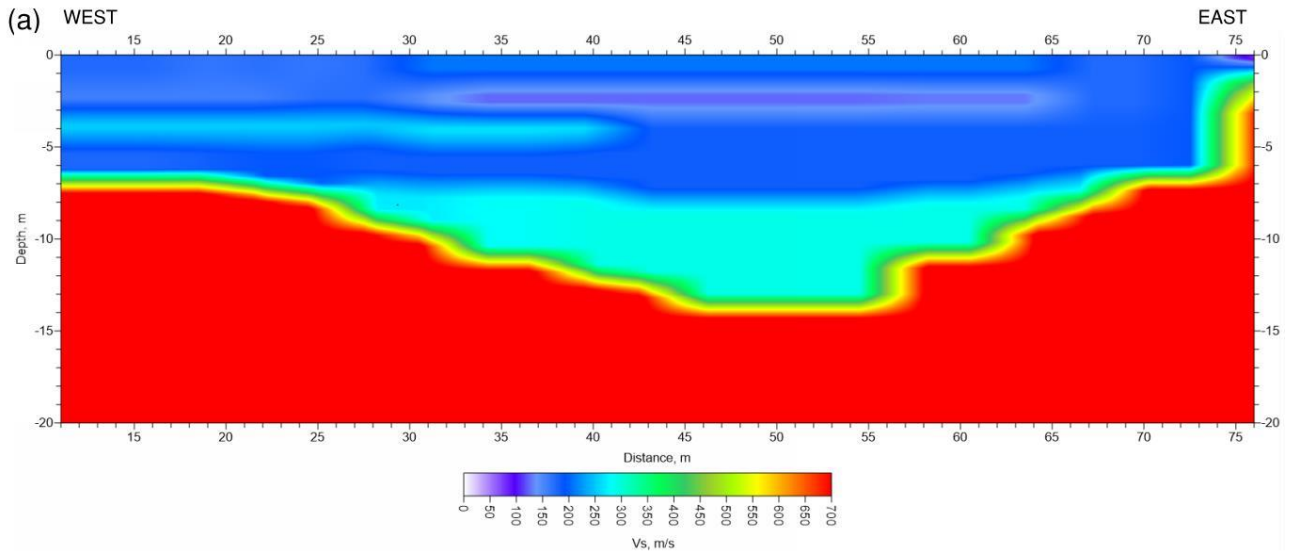


Figure 6(a): 2-D S-wave velocity ( $V_s$ ) model along Line 1. Distances are from the beginning of the array as shown in Figure 5

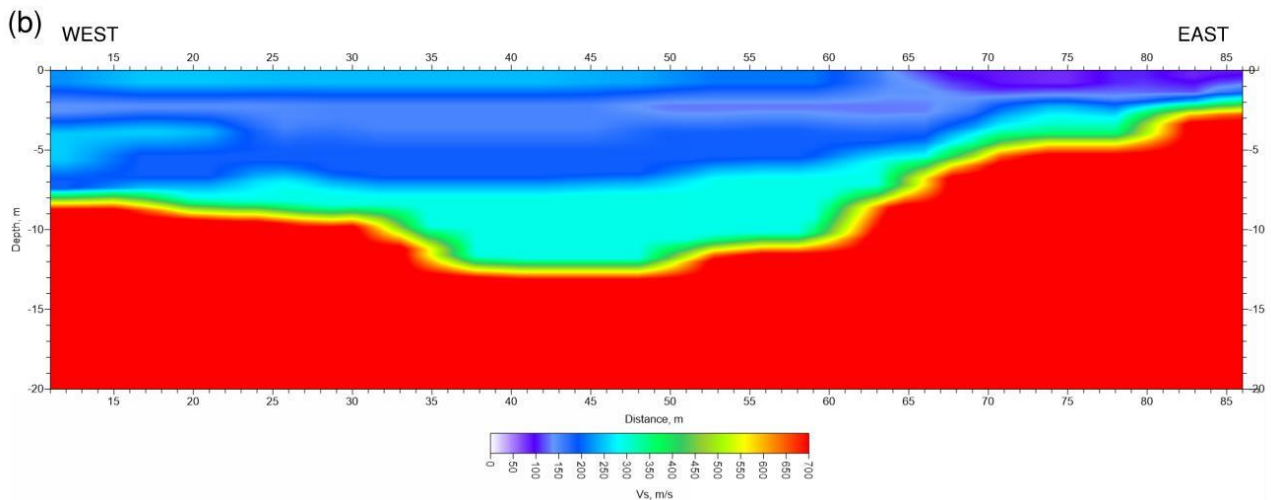


Figure 6(b): 2-D S-wave velocity ( $V_s$ ) model along Line 2. Distances are from the beginning of the array as shown in Figure 5

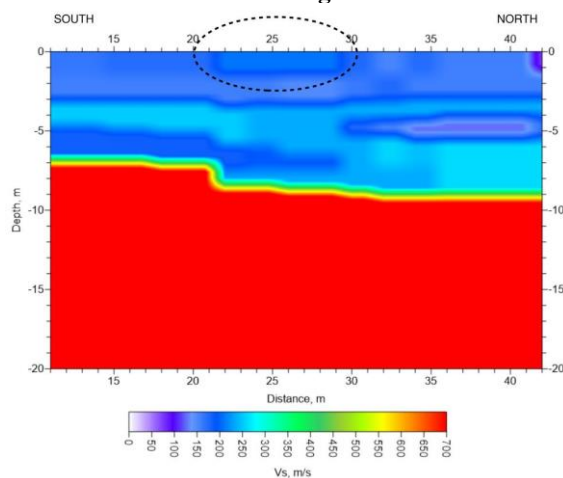
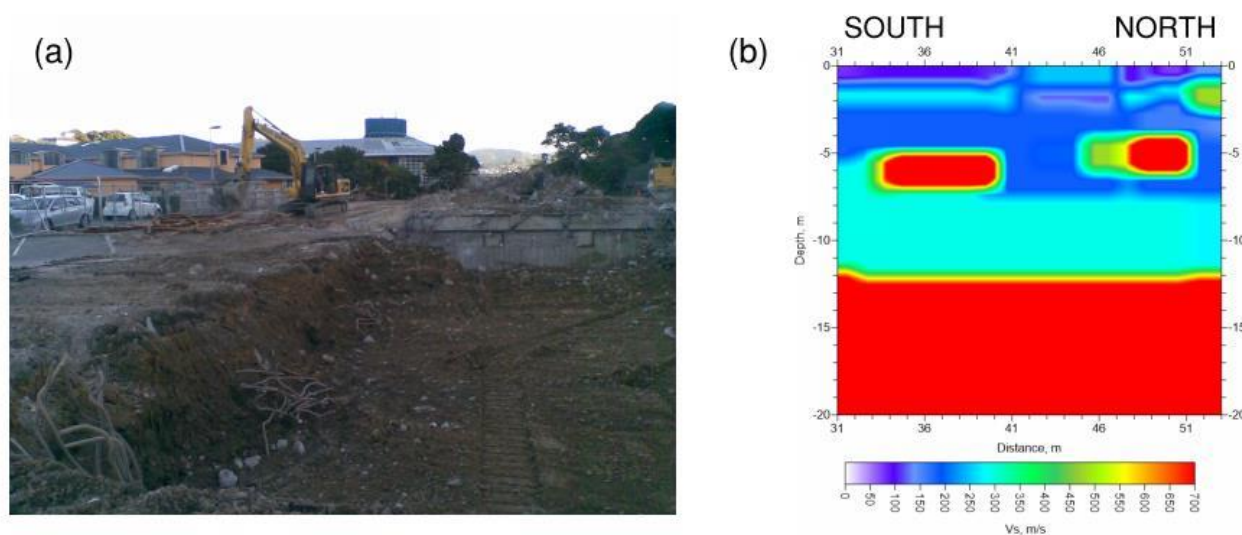


Figure 7: 2-D S-wave velocity ( $V_s$ ) model along Line 3. Distances are from the beginning of the array as shown in Figure 5. The circled area highlights a zone of low velocity likely associated with the location of an historical structure

The largest historical structure that encroached onto the site was the Nurse's Home Block No.2, built in the late 1940s and demolished in 2010. Historical photos together with allowed the approximate location of the foundation, to be determined, as illustrated in Figure 5. Building plans, together with photographs taken during the 2010 demolition (Figure 8a), documented that the building foundations were still present entrenched at approximately 5.5m apart. To resolve the detailed soil structure of the fill material in the upper 5m of the surface and detect buried building foundations associated with the demolished Nurses' home (shown in Figure 5), data acquisition along Line 7 was acquired using a shorter geophone spacing of 0.5m, compared to 1m for the remaining seismic arrays. Results of the analysis are presented in Figure 8(b). The shear-wave velocity of the fill material in the upper 2m of the soil profile is found to be highly variable. In addition, areas of with a very high shear-wave velocity were detected and may be related to historic foundations of the demolished Block No. 2 Nurses' Home or buried concrete rubble.



**Figure 8: (a) Photo showing reinforcement rebar from the foundations of the Nurse's Home Block No.2 during demolition in 2010. (b) 2-D S-wave velocity ( $V_s$ ) model beneath Line 7. Distances are relative to the beginning of Line 6 as shown in Figure 5**

### 5.3 BOWEN CAMPUS/PARLIAMENT PRECINCT – WELLINGTON, NEW ZEALAND

Parliamentary Service were proposing to construct a four-storey extension and a new six storey block to the west of the Beehive at their Parliament Precinct, located off Bowen Street, Wellington (Figure 9). This site is located directly adjacent to Bowen Campus, which is currently undergoing seismic strengthening and redevelopment of a 15-storey and 9-storey building. For this publication, we shall consider these as a single site. Geotechnical information was required to determine foundation design parameters, liquefaction potential and site subsoil classification. Initial geotechnical investigations comprised boreholes with Standard Penetration Tests (SPT), including down-hole shear-wave velocity testing. ReMi was then used to supplement the initial geotechnical investigation, correlating between the borehole data and determining lateral changes in bedrock depth across the site.

The Wellington region is a seismically active region with potential for a high level of ground shaking. In accordance with NZS1170.5:2004 "Earthquake Design Actions" (Standards New Zealand, 2004), a seismic site classification based on geological and geotechnical properties is used in the calculation of seismic loading of buildings and structures. The site subsoil classes are defined as Class A (strong rock), Class B (rock), Class C (shallow soil site), Class D (Deep or soft soil), and Class E (very soft soils). Each class quantifies the soil's propensity to amplify, or in some cases attenuate, surface ground motion from underlying rock, where rupture occurs during earthquakes. They are based on physical soil properties, including the site period. Site period is defined as four times the shear-wave travel time from the surface to bedrock (Larkin and Van Houtte, 2014), and is a measure of the period of vibration corresponding to the fundamental frequency of the column of soil.

Amendments to NZS1170.5 in 2016 now make interpolated design shape factors between Class C and Class D based on site period an acceptable solution. Assessment of the interpolated curves demands that accurate determination of bedrock depths together with robust measurement of shear-wave velocity to bedrock are required for site period calculation. Site

subsoil classifications for these development sites were assessed in accordance with NZS1170.5:2004 using Unconfined Compressive Strength (UCS) testing of the bedrock, down-hole shear wave velocity testing and ReMi investigation data.

Using the shear-wave velocity and depth information obtained from both methods, site period measurements were mapped across the site, as shown in Figure 3. Bedrock depths varied from 16m depth below ground surface to 80m depth, with prominent deepening of the bedrock surface towards the east. The detailed mapping of bedrock depth, coupled with the 2D shear-wave velocity information allowed comprehensive assessment of both the site subsoil conditions and the variability of the fundamental period of the soil column.

Constraints from the borehole descriptions, SPT, laboratory testing and downhole velocity measurements were used to constrain the velocity profiles determined from the ReMi data. The resultant 2D seismic profiles were able to provide vital information on bedrock depths, characterising the nature of the change. Most importantly, the ReMi investigation allowed the 1D point measurements from the vertical boreholes to be extrapolated across the entire development site.



**Figure 9: Locations of the ReMi seismic arrays and boreholes (red) at Bowen Campus/Parliament Precinct, Wellington, New Zealand. Site period measurement values across the site are presented, with estimates from the seismic ReMi data shown as cyan circles. Aerial photograph sourced from LINZ Data Service (<https://data.linz.govt.nz/data/category/aerial>) and licenced under the Creative Commons Attribution 4.0 New Zealand.**

In areas of complex geology, particularly where bedrock depth is variable in seismically active regions, there is often uncertainty in whether a borehole or downhole shear wave velocity investigation has been carried out where bedrock depths is the greatest. This was true for the Parliamentary Precinct site investigation. Establishing bedrock depths together with material shear-wave velocity profiles are now crucial for the determination of site period towards site subsoil classification in accordance with NZS1170.5. However, with depth to bedrock exceeding 60m beneath many urban areas, boreholes to bedrock are very costly to drill. This poses a major issue in correctly determining site period and thus site classifications for building code implementation. ReMi allowed the lateral extension of borehole information, adding a cost-effective assessment tool, providing information regarding the variability of both shear-wave velocity and bedrock depths across large sites.

## 6 CONCLUSIONS

Geotechnical engineering is one of the most challenging engineering disciplines. A geotechnical engineer has the job of investigating subsurface ground conditions and material properties to determine how the ground will interact with a piece of infrastructure or buildings. All too often unexpected ground conditions are encountered. There is always an inherent uncertainty associated with characterising the subsurface. A multidisciplinary ground investigation is the most preferred option to ensure a more comprehensive assessment of engineering site conditions is undertaken. Using refraction microtremor, we can remove some of the mystery surrounding the ground conditions between spot measurements. Here

we have demonstrated how a unique unconventional approach using ambient noise recordings to determine sub-surface material properties is an effective way of obtaining a more comprehensive assessment of engineering site conditions. Refraction microtremor seismic investigations supplement the overall geotechnical investigation, enabling better characterisation of the variation of soil properties across investigation sites. The objective is not to replace traditional geotechnical investigations, but complementing them to obtain a much more comprehensive understanding of the subsurface conditions.

The three case studies presented demonstrate the considerable contribution ReMi shear-wave velocity assessments can make towards a better understanding subsurface geological and geotechnical conditions beneath large development sites. Velocity measurements from ReMi were used to provide additional information for the geotechnical investigation tests. As the data can be obtained in very noisy urban environments, obtaining shear-wave velocity information using the ReMi method is less costly and allows for faster data acquisition than many other geophysical investigation methods. The results presented here demonstrate how ReMi investigations are an effective tool allowing us to strategically plan and optimally place more expensive intrusive investigations.

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## 8 REFERENCES

- Coccia, S., Del Gaudio, V., Venisti, N. and J. Wasowski, (2010). Application of Refraction Microtremor (ReMi) technique for determination of 1-D shear wave velocity in a landslide area. *Journal of Applied Geophysics*, 71(2-3), 71-89.
- Heath, K., J. Louie, G. Biasi, A. Pancha, and S. Pullammanappallil (2006). Blind tests of refraction microtremor analysis against synthetics and borehole data, *Proceedings of the Managing Risk in Earthquake Country Conference Commemorating the 100th Anniversary of the 1906 earthquake*.
- Larkin, T. and C. Van Houtte (2014). Determination of site period for NZS1170.5:2004, *Bulletin of the New Zealand Society for Earthquake Engineering*, 47(1), 28-40.
- Liu, Y., B. Luke, S. Pullammanappallil, J. Louie, and J. Bay (2005). Combining active- and passive-source measurements to profile shear wave velocities for seismic microzonation, in *Earthquake Engineering and Soil Dynamics*, R. W. Boulanger, M. Dewwolkar, N. Gucunski, C. Juang, M. Kalinski, S. Kramer, M. Manzari, and J. Pauschke (Editors), *Geotechnical Special Publication 133, American Society of Civil Engineers*, Reston, Virginia, 977-990.
- Louie, J.N. (2001). Faster, better: shear-wave velocity to 100 meters depth from refraction microtremor arrays. *Bulletin of the Seismological Society of America*, 91(2), 347-364.
- Raptakis, D. G. (2012). Pre-loading effect on dynamic soil properties: Seismic methods and their efficiency in geotechnical aspects, *Soil Dynamics and Earthquake Engineering*, 34: 69-377.
- Rucker, M.L. (2003). Applying the refraction microtremor (ReMi) shear wave technique to geotechnical characterization. *In Proc. In. Conf. of the third international conference on the application of geophysical methodologies and NDT to transportation and infrastructure*, Florida, 8-12.
- Pancha, A., Pullammanappallil, S., Louie, J.N., Cashman, P.H. and Trexler, J.H., 2017. Determination of 3D Basin Shear-Wave Velocity Structure Using Ambient Noise in an Urban Environment: A Case Study from Reno, Nevada. *Bulletin of the Seismological Society of America*, 107(6), 3004-3022.
- Pullammanappallil, S., 2006. Geotechnical and geophysical case studies involving the Refraction Microtremor (ReMi) method for shear wave profiling. *In Highway Geophysics Conference*, December, 5-7.
- Standards New Zealand (2004). *NZS 1170.5:2004 Structural design actions—Earthquake actions, Section 3—Site Hazard Spectra*, Standards New Zealand, 81 pp.
- Stephenson, W. J., J. N. Louie, S. Pullammanappallil, R. A. Williams, and J. K. Odum (2005). Blind shear-wave velocity comparison of ReMi and MASW results with boreholes to 200 m in Santa Clara Valley: Implications for earthquake ground motion assessment. *Bulletin of the Seismological Society of America*, 95(6), 2506-2516.
- Thelen, W. A., M. Clark, C. T. Lopez, C. Loughner, H. Park, J. B. Scott, S. B. Smith, B. Greschke, and J. N. Louie (2006). A transect of 200 shallow shear-velocity profiles across the Los Angeles basin, *Bulletin of the Seismological Society of America*, 96(3), 1055-1067.