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The Effects of Multiple Impedance Contrasts on Microtremor Horizontal-to-Vertical Spectral Ratio Site Period Estimates in Aotearoa New Zealand

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ABSTRACT

The microtremor horizontal-to-vertical spectral ratio (mHVSR) is often used to estimate the fundamental period of vibration of soil above bedrock and has enabled rapid characterization of city and region-scale sedimentary basins. Recent ground motion modeling efforts have considered the inclusion of site period estimates and/or the full mHVSR spectra as a proxies soil site effects. Often, multiple peaks are observed in mHVSR spectra which may be attributed to the fundamental period of vibration soils and weathered rock above stiffer strata. These peaks may indicate that several impedance contrasts may contribute to the site, but often deeper impedance contrasts are not identified or considered in site response analyses.

In light of these observations, recent experimental studies in Aotearoa New Zealand have used hundreds of microtremors measurements from the temporary deployment of broadband seismometers to characterize deep sedimentary basins. When present, multiple peaks and the associated period estimates are tied known impedance contrasts, based on geological, geophysical, and geotechnical data. Of particular interest is the Canterbury Plains on the South Island of New Zealand, a deep sedimentary basin subjected to severe ground shaking following the 2010-2011 Canterbury Earthquake Sequence. Three impedance contrasts associated with the soil/rock above the deep greywacke basement bedrock, the Banks Peninsula volcanic rock, and the Riccarton Gravel Formation contribute to multiple mHVSR peaks observed across the region. The presence and thickness of the stiff Banks Peninsula volcanic rock strata under a site influences or obscures the observation of the long period mHVSR peaks associated with the bedrock.

Keywords: microtremor horizontal-to-vertical spectral ratio, ambient vibrations, site period, site effects, site classification, impedance contrasts

INTRODUCTION

The effects of soil stratigraphy, particularly impedance contrasts between soft and stiff soil/rock strata, on earthquake ground shaking have been observed world-wide and are well known in seismology and geotechnical earthquake engineering. Observed ground shaking in sedimentary basins exhibits amplified and prolonged ground motions due to the entrapment of seismic waves within the basin and the generation of localized surface waves [1]. The characterization of the geometry and stiffness of strata within sedimentary basins is necessary to understand and model soil and sedimentary basin site effects and is an ongoing area of research.

In engineering practice, often soil site effects are modeled using simplified metrics. The most common site metric is time-averaged shear wave velocity over the top 30 meters (V_{S30}). V_{S30} alone may be suitable in cases where bedrock is shallower 30 meters, but it is not sufficient to capture the response of deep soil profiles. Recent ground motion models , such as the NGA-West2 models [2] supplement V_{S30} with metrics such as the depth to a layer with a shear wave velocity (V_S) of 1.0 or 2.5 km/s, $Z_{1.0}$ and $Z_{2.5}$, respectively. However, in practice $Z_{1.0}$ and $Z_{2.5}$ are challenging to measure and quantify in regions where stiff bedrock is deep. Another site metric is the fundamental site period (T_0) or its inverse, the fundamental site frequency (f_0). The ability of T_0 to capture site effects is well-known [3]. Recent studies have shown that using V_{S30} and T_0 together improves linear site effect terms in ground motion models. [4].

The horizontal-to-vertical spectral ratio (HVSR) of ambient vibration records (also called microtremors) (mHVSR) from a single three-channel sensor is commonly used to estimate T_0. In the past few decades, mHVSR has seen increased usage due to its simplicity in both data acquisition and analysis. Nakamura [5, 6] proposed the use of mHVSR to characterize site effects and popularized the method. With the increasing use of mHVSR testing for site characterization, the SESAME European Research Project developed guidelines for the implementation of the method [7] and more recently Molnar et al. [8] provided an overview of the method including the most recent understanding of the microtremor wavefield and best-practice recommendations for data acquisition and analysis.

This paper presents the results of mHVSR analysis of ambient vibration data collected as a part of several studies [9-13] following the 2010-2011 Canterbury Earthquake Sequence (CES) aimed at the characterization of the sediments beneath the Canterbury Plains on the South Island of New Zealand. Ambient vibration data was collated at 152 locations, shown in Figure 1, and processed using the mHVSR method. Observed resonance peaks in the experimental mHVSR spectra and the associated period have been shown to correlate well with existing geological models in the region [12, 13], In particular, the response of the soil and/or soft rock above three key geologic layers in the basin are considered: (1) the deep greywacke basement bedrock, (2) the Banks Peninsula Volcanics (BPV), and the shallow Riccarton Gravel Formation. This paper expands upon previous work by the authors [13] to explore the effects of the BPV layer on site period observations and link mHVSR resonances to ground shaking observed in the CES at three strong motion stations (SMS).

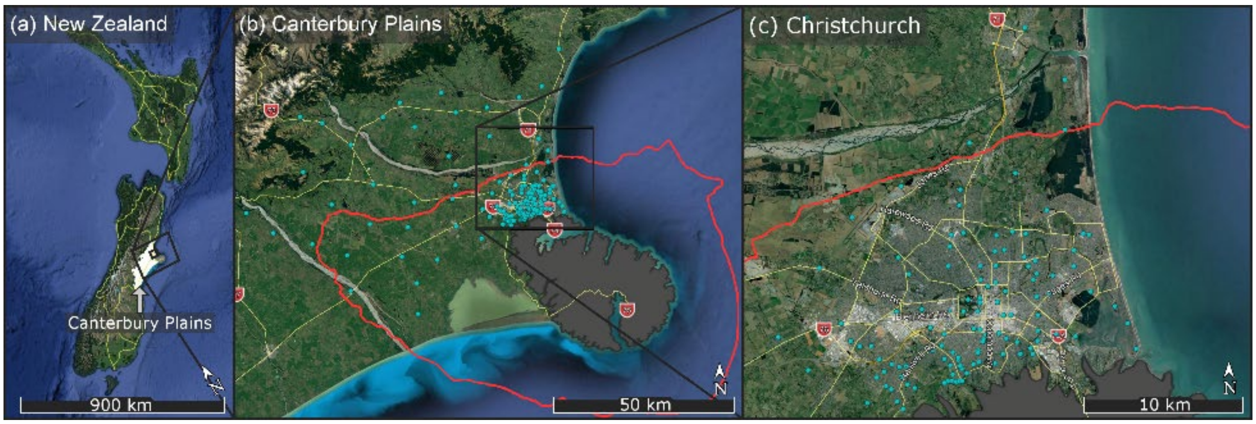

Figure 1. Map of (a) New Zealand, (b) the Canterbury Plains, and (c) the city of Christchurch. mHVSR testing locations are indicated by cyan circular markers. The grey shaded area and the red line indicate the ground surface outcropping and the estimated sub-surface extent of the BPV, respectively.

BACKGROUND AND METHODS

Geology of the Canterbury Plains

The Canterbury Plains are located on the east coast of South Island of New Zealand (refer to Figure 1a) and are approximately 160 km long and 50 km wide, between the Southern Alps and the coast. Broadly the sediments of the Canterbury Plains are of two types: (1) fluvial, coarse grained (gravels and silts) soils were carried by rivers from the Southern Alps and (2) the predominantly fine grained (silts and silty sands) marine deposits. The interaction of two depositional processes has resulted in series of interlayered gravels and marine sediments [14, 15]. In Christchurch, particularly in the eastern suburbs, the near-surface soils are the marine Christchurch Formation and fluvial Springston Formation. These Quaternary sediment overlie the fluvial Riccarton Gravel Formation, which outcrops at the ground surface to the northwest of the city. In the Miocene, volcanic activity deposited a series of igneous rock layers, known together as the Banks Peninsula Volcanics (BPV). The extinct volcanic complex outcrops at the Banks Peninsula, as indicated by the grey shaded area in Figure 1b, and steeply plunges beneath the Canterbury Plains. The top of the BPV is generally well-constrained by deep boreholes and seismic geophysical testing. The stiff volcanic rock is underlain by less stiff sedimentary rock. The deeps basement bedrock is the greywacke of the Torlesse Composite Terrane, which is up to 2.5 km deep beneath the Canterbury Plains and outcrops to the northwest at the foothills of the Southern Alps.

The Canterbury Velocity Model (CVM) is a 3D model of the structure and stiffness of the geologic strata underlying the Canterbury Plains for use in ground motion simulations. The CVM was developed in two parts: (1) a relatively shallow model of the near-surface interlayered sediments, based on invasive geotechnical data (e.g., boreholes and cone penetration test soundings) and near-surface geophysics [16] and (2) a deeper model of the underlying BPV, sedimentary rocks, and the basement bedrock, based on deep petroleum exploration boreholes and seismic geophysical surveys [17]. Digital elevation models for each key layer were extracted from the CVM for comparison with mHVSR results in the discussion section below and were used to develop the illustrative simplified cross section shown in Figure 2a. Previous studies [12, 13] have identified three strong impedance contrasts that may be attributed to observed resonance peaks in mHVSR spectra: (1) marine sediments overlying the Riccarton Gravel Formation, (2) the sediments overlying the BPV, and (3) the sediments and sedimentary rock overlying the greywacke basement bedrock

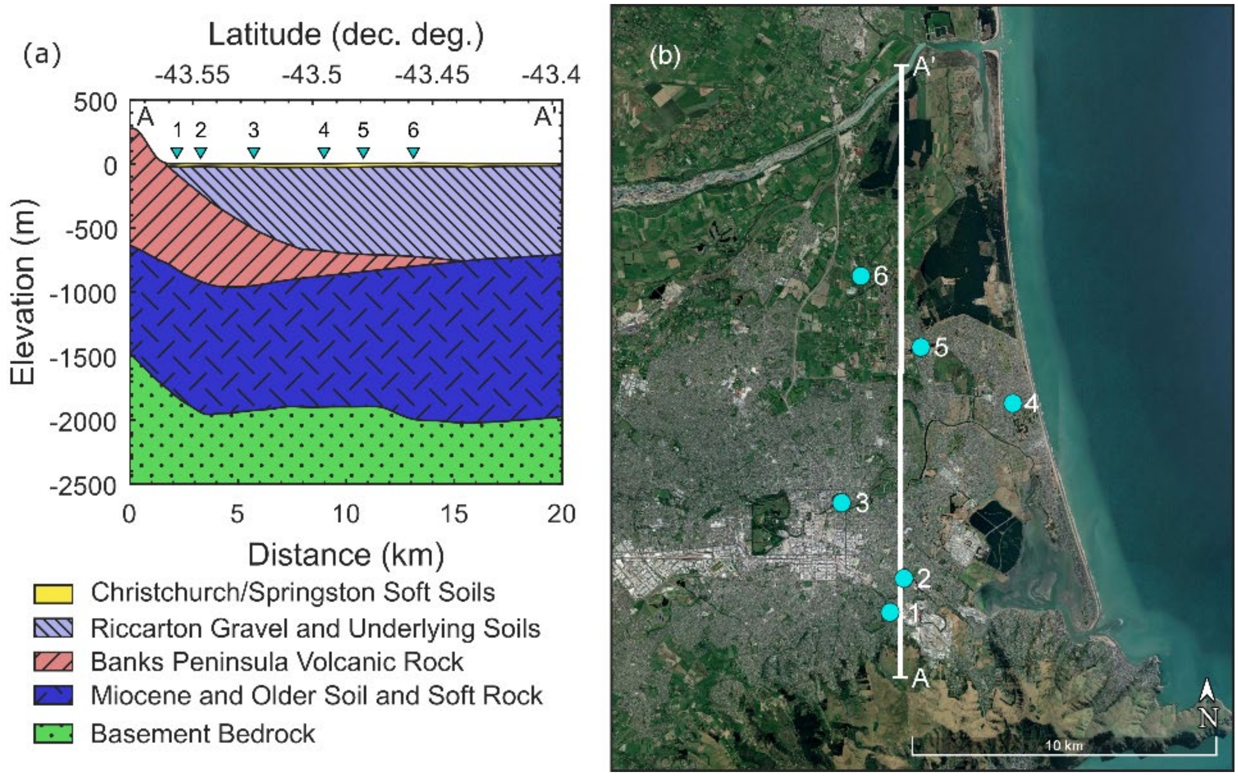

Figure 2. (a) Simplified cross section A-A' of the geology underlying the Canterbury Plains and (b) map of eastern Christchurch with the location of six example mHVSR testing sites indicated by cyan circular markers.

Dataset Specifics

Following the 2010-2011 CES, several studies used non-invasive seismic geophysical methods to characterize the soils of the Canterbury Plains and improve understanding of observed ground shaking [9-11]. Teague et al. [10] and Deschenes et al. [11] combined active and passive surface wave testing methods to infer the deep V_S structure of the soils underneath Christchurch and the wider Canterbury plains. The passive surface wave testing methods used arrays of Nanometrics Trillium Compact 20s or 120s three-component broadband seismometers with either Nanometrics Taurus or Centaur data acquisition systems to measure and record ambient vibrations. These ambient vibration recordings are also well-suited for mHVSR analysis. The field testing programs were supplemented with single-station ambient vibration recordings at additional sites across the region [9, 12, 13]. This paper and previous work by the authors [13] collate the ambient vibration data collected in the region in 2013-2018 at 152 locations via the temporary deployment of broadband seismometers. The testing locations are shown in Figures 1b and 1c.

At each location, the broadband seismometers were either buried in 15-cm-deep hole with soil compacted around the sensor or placed on a leveling tripod on the ground surface. The sensors were oriented towards magnetic north and covered for protection from the wind and rain. The ambient vibration record lengths varied from 30 to 180 minutes, depending on anticipated ground conditions (e.g., shallow or deep soil sites) and the original purpose of the data acquisition. In all cases the sampling frequency was 100 Hz.

mHVSR analysis

The collated ambient vibration records were processed by the authors as detailed in Stolte et al. [13] and the present study refines some of the analysis developed therein. The HVSR method [5] was applied to the ambient vibration waveforms. The 30+ minute-long records were windowed to capture at least 10 cycles of the fundamental site period, as recommended by the SESAME guidelines [7]. Shorter record window lengths (30 – 60s) were used at shallow soil testing locations near the Southern Alps or locations where the long period peak associated with the basement bedrock impedance contrast could not be identified. The ambient vibration records were broken in to longer windows (60 – 120 s) at locations in the middle of the Canterbury Plains where the long period peak was discernable. Time windows with transient noise (such as people walking near the instrument) were removed from the analysis. There was no overlap between the time windows and a cosine taper of 5% the record length was applied to the start and end of each time window to limit spectral leakage in the frequency domain. For each time window, the vertical and two horizontal time records were transformed in to the frequency domain. The geometric mean of the two horizontal components was divided by the vertical component on a frequency-by-frequency basis to evaluate the HVSR. A Konno and Ohmachi [18] smoothing function with a smoothing constant of b = 40 was applied to the resulting mHVSR curves. All HVSR analysis, including signal conditioning, was competed using version 2.9.1 of the open source software Geopsy [19].

A each testing location, the mHVSR spectra was evaluated for each time window. The mean and standard deviation mHVSR curves were evaluated between 0.1 and 10 Hz. Any resonance peaks identified in the mHVSR data were assessed for clarity and reliability following the SESAME guidelines [7]. Peaks that passed at least 4 of the 6 SEASME clarity criteria and had a mean spectral ratio greater than 2 (criterion 3) were retained for subsequent interpretation. The mean and standard deviation of the frequency associated with each retained mHVSR resonance peak was evaluated from the suite of accepted time windows. The retained mHVSR resonance peak associated frequency (or period) values were related back to geologic knowledge of the region and attributed the key impedance contrasts: (1) the Riccarton Gravel Formation, (2) the BPV, or (3) the basement bedrock. For the remainder of paper, the mHVSR spectra are plotted and discussed in terms of period, which is commonly used in engineering practice.

RESULTS AND DISCUSSION

Each of the 152 testing locations targeted soil sites, thus one to three resonance peaks were identified in the mHVSR spectra. Six example mHVSR spectra and the identified resonance peaks are shown in Figure 3. The locations of each example site are indicated on the map in Figure 2b and are located roughly along cross section A-A’ (refer to Figure 2a). Sites 1 and 2 were located near the Banks Peninsula; at these sites the a resonance peak associated with the BPV is sharp and clear. A slightly shorter period peak associated with the Riccarton Gravel Formation is identifiable at Site 2. Site 3 is near the central business district of Christchurch and three resonance peaks were identified and associated with each of the key impedance contrast. Moving further Porth along cross section A-A’ and away from the Banks Peninsula volcanics, peaks associated with the BPV were not evident in the mHVSR spectra (e.g., Sites 4, 5 and 6). At Site 4, a peak near 0.3 seconds was attributed the Riccarton Gravel Formation impedance contrast, but the peak does not pass the SESAME clarity criteria. Conversely, at Site 5 the long period peak associated with the basement bedrock was lost due to poor coupling of the sensor with the ground, causing the apparent asymptotic HVSR spectra.

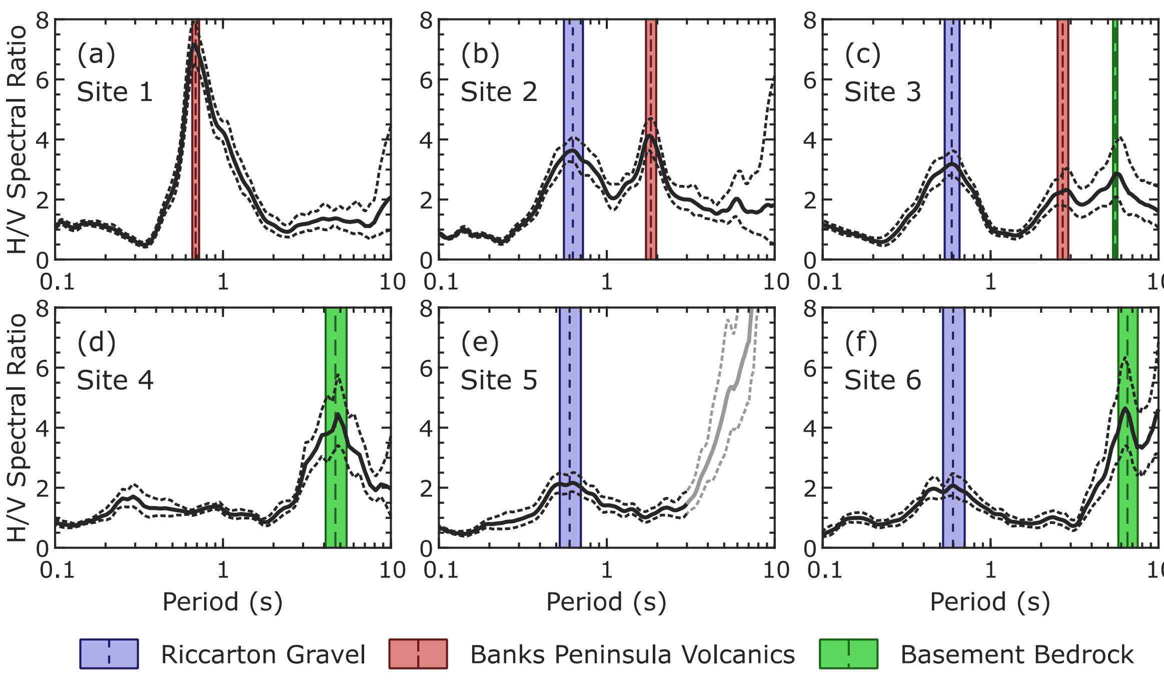

Figure 3. Example mHVSR spectra from six testing locations indicated in Fig. 2. The mean mHVSR curve is indicated by a solid black line and the ±1 standard deviation spectra are indicated by dashed lines. The mean and ±1 standard deviation period values associated with identified resonance peaks are indicated by colored vertical dashed lines and shaded box, respectively.

A 69 of the 152 testing locations a resonance peak was attributed to greywacke basement bedrock impedance contrast. The associated periods are inferred to represent the fundamental period of vibration the strata above the basement bedrock. These period estimates are shown in Figure 4a, with lighter colors indicating relatively short periods and dark colors indicating large site periods. Near the Southern Alps (i.e., the outcropping of the basement bedrock) the mHVSR resonance peak periods are less than 3.0 s. The shortest resonance peak period (0.3 s) was identified at a site nearest the foothills. The basement bedrock resonance peak period increases towards the middle of the Canterbury Plains and exceeds 5.0 s at locations 10+ km way from the Southern Alps. Near the Banks Peninsula the basement bedrock resonance period slightly decreases due the presumed uplift of the bedrock associated with the volcanic activity that formed the peninsula. The depth to the basement bedrock was extracted from the CVM and is shown as a contour map across the Canterbury Plains in Figure 4b. Notably, a relative shallower saddle shaped feature is evident from Christchurch running northwest to the Southern Alps with two deep pockets, one North and one West of Christchurch [17]. These deep pockets (2.5+ km) correspond to the longest period observed mHVSR resonance peaks with periods exceeding 6.5 s.

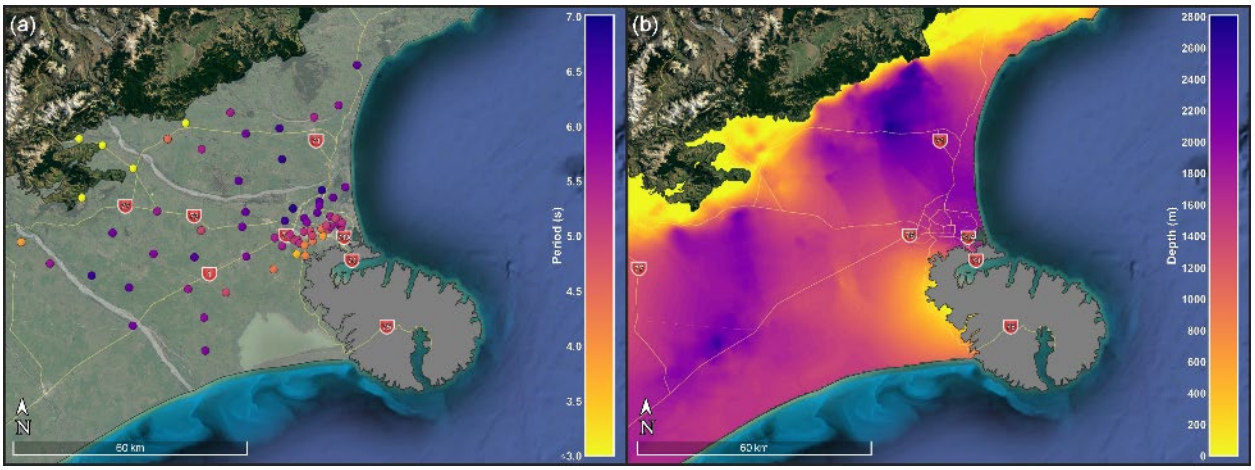

Figure 4. Map of the Canterbury Plains with (a) mHVSR periods associated with the fundamental period of vibration of the geologic strata above the greywacke basement bedrock and (b) depth contours of the greywacke basement bedrock extracted from the CVM.

While the long period resonance peak associated with the basement bedrock often is evident in the mHVSR spectra across the Canterbury Plains, in many cases the resonance peak is relatively low amplitude or difficult to identify in “ramp up” of the mHVSR spectra associated with poor coupling of the sensors (refer to Figure 3e). Often stronger resonance peaks may be identified in the mHVSR spectra at locations near the city of Christchurch. These resonances are attributed to the impedance contrast between the near-surface sediments and Riccarton Gravel Formation and the BPV rock. An example of these relatively short period peaks are shown in Figure 3, indicated by blue and red shaded boxes for the Riccarton Gravel Formation and BPV, respectively. The testing locations with resonance peaks periods attributed the Riccarton Gravel Formation and the BPV are shown in Figure 5a and 5b, with the circular marker color indicating the associated period.

The shallowest impedance contrast is associated with the Riccarton Gravel Formation. These gravels are deepest beneath the eastern suburbs of Christchurch, near the coast. Moving north and west, the marine sediments thin out and the gravels approach the ground surface. The mHVSR resonance peak associated with the Riccarton Gravel Formation were identified at 77 of the 152 locations and the periods range from 0.2 to 0.8 s. However, there is no clear geospatial trend with the periods. This is likely due to the highly variable nature of the shallow sediments overlying the formation, which have been deposited by range of processes. In particular, the stiffnesses of these soils is quite variable with V_S ranging from 90 to 350 m/s [10, 11].

The period of the mHVSR resonance peaks associated with the BPV range from 0.3 to 3.6 s. The BPV resonance peaks were identified at 55 of the 152 testing locations. The volcanic rock outcrops at the ground surface in the Port Hills on the Banks Peninsula, just south of Christchurch. Northwest of the Port Hills, the BPV formation steeply plunges beneath the overlying sediments. As the depth to the top of the BPV increases, the corresponding mHVSR period estimates increase. The shortest observed periods are near the Port Hills and the period steadily increases to 3.8 s as measured near the Christchurch city center. At locations where resonances associated with the Riccarton Gravel and the BPV Formations are identifiable in the mHVSR spectra, the peak associated with the BPV is generally sharp, narrow, and clear due the strong impedance contrast between the stiff BPV (V_S = 1,900 – 2,600 m/s [10]) as compared the Riccarton Gravel Formation (V_S = 400 – 600 m/s [10, 11]) and other sediments.

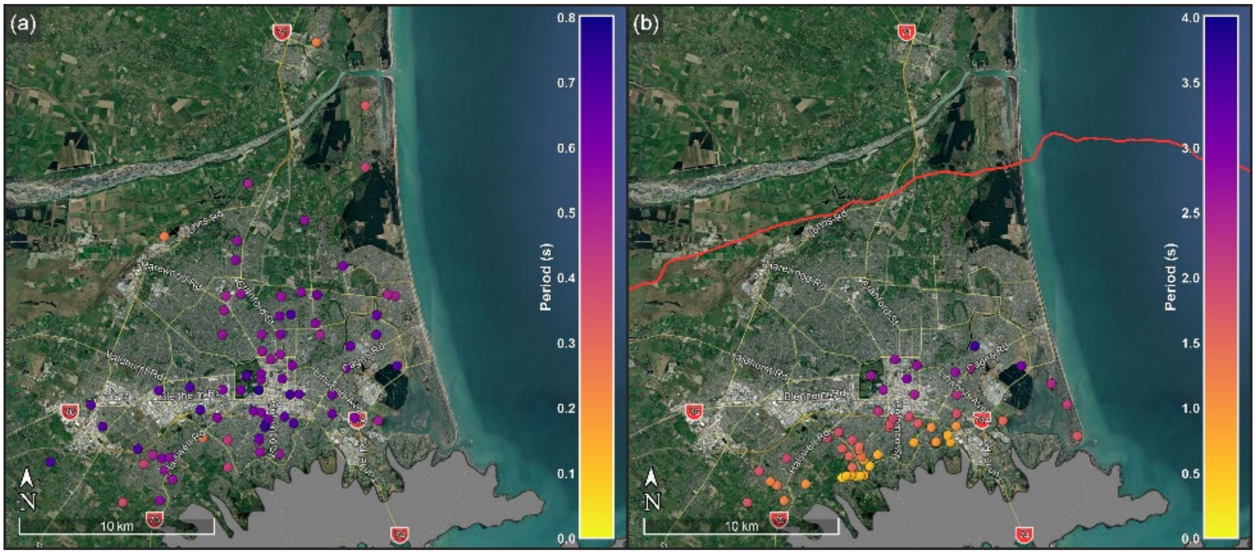

Figure 5.Map of Christchurch with (a) mHVSR periods associated with the fundamental period of vibration of the sediments above the (a) Riccarton Gravel and (b) BPV Formations. The grey shaded area and the red line indicate the ground surface outcropping and the estimated sub-surface extent of the BPV, respectively.

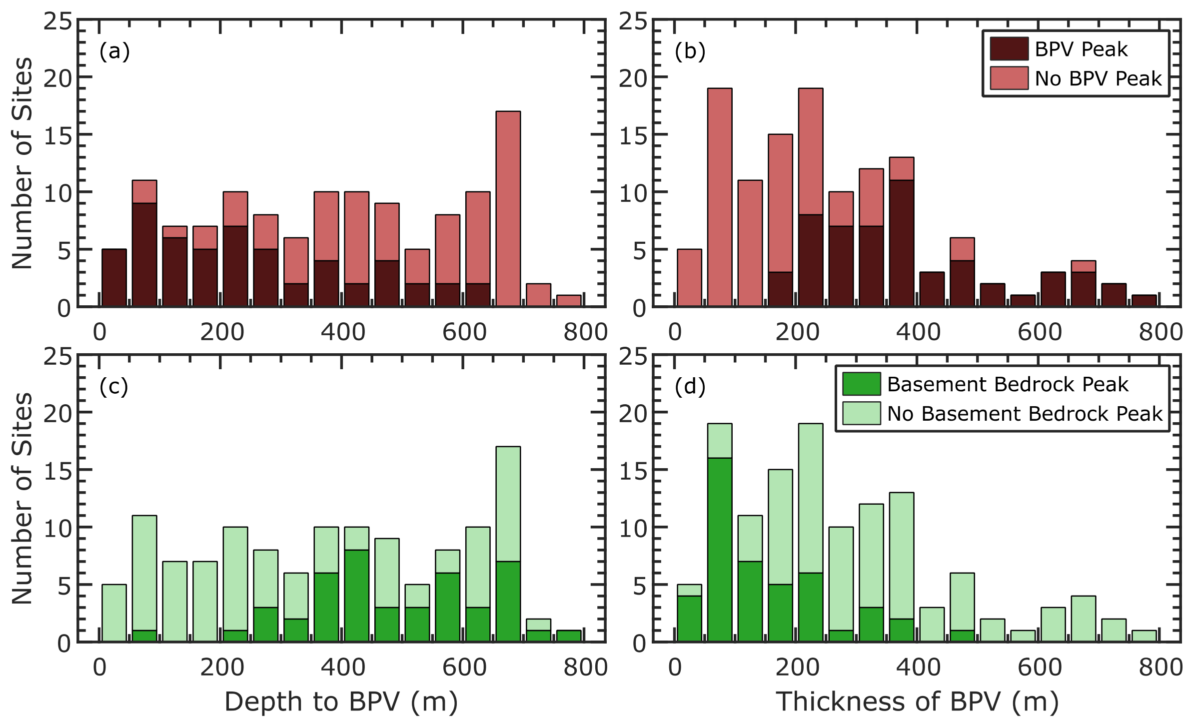

Figure 6. Histograms of mHVSR data from 126 testing locations with the estimated horizontal subsurface extent of the BPV. Sites with or without mHVSR periods associated with the BPV impedance contrast are binned by estimates of (a) depth to and (b) thickness of the underlying BPV layer extracted from the CVM. Sites with or without mHVSR periods associated with the greywacke basement bedrock impedance contrast are binned by estimates of (c) depth to and (d) thickness of the overlying BPV layer. Reproduced from Stolte et al. (2023) [13]

Effect of BPV depth and thickness on observed mHVSR resonances.

The clarity and amplitude of resonance peaks in the mHVSR spectra associated with the BPV diminish moving away from the Banks Peninsula. Near the Port Hills, the observed mHVSR resonance peaks are sharp, clear, and distinguishable from the resonance peaks associated with the Riccarton Gravel Formation (e.g., Figure 3a and 3b). To the North, near the center of

Christchurch, the mHVSR BPV resonance peaks broaden and decrease in amplitude (e.g., Figure 3c). There is a ~10 km-wide band between the cluster of sites with mHVSR BPV resonance peaks and the edge of the estimated sub-surface horizontal extent of the BPV formation, as shown in Figure 5b. In a previous study [13], these geospatial trends were attributed to the decreasing thickness and the rapidly increasing depth to the top of the BPV formation. Another effect of the BPV layer is difficulty in identifying mHVSR resonance peaks associated with the long period response of the underlying greywacke basement bedrock at testing locations near the Port Hills and the Banks Peninsula.

To quantitatively explore the effects of the BPV formation of mHVSR spectra, the thickness and depth to the BPV formation were extracted from the CVM for each of the 126 testing within the estimated sub-surface horizontal extent of the BPV and organized into the four histograms shown in Figure 6. A resonance peak associated with the BPV was identified at 55 testing locations and not identified at the remaining 71 locations. These positive or negative peak observations at each site were binned by the estimated depth and thickness of the BPV formation, as shown in Figures 6a and 6b, respectively. Few BPV resonance peaks were identified at sites where the depth of the BPV formation was greater than 300 m and no peaks were identified at sites where the depth to the BPV exceeded 650 m. Furthermore, no BPV resonance peaks were identified at sites where the thickness of the BPV was less than 150. Resonance peaks were identified at only 3 of the 15 sites where underlying BPV was 150 to 200 m thick. At these relatively thin BPV formation sites, the formation itself is generally deep and would correspond to a resonance period greater than 3 s. The lack of an mHVSR BPV resonance peak may be attributed to long-period and long-wavelength waves not "seeing" the relatively thin BPV layer.

A mHVSR resonance peak associated with the greywacke basement was identified at 46 of the testing locations within the horizontal sub-surface extent of the BPV and not identified at the remaining 88 locations. In general, the basement bedrock resonance peaks were not identified at sites near the Port Hills and the Peninsula, as shown at sites where the depth to the top of the BPV formation is less than 350 m and/or the thickness of the BPV is greater than 250 m.

Comparison with EQ ground motions

Following the Sept. 2010 M_W 7.1 Darfield earthquake, over 15,000 aftershocks have been recording including the Feb. 2011 M_W 6.2 Christchurch earthquake which resulted in widespread liquefaction damage across the city. The ground shaking from 2010-2011 CES events was recorded by strong motion stations installed across the Christchurch, nearby suburbs, and the wider Canterbury Plains. For a qualitative comparison, three SMS with co-located temporary deployment of broadband seismometers were selected: (1) CMHS in Cashmere, (2) KPOC in Kaiapoi, and (3) LINC in Lincoln. The pseudospectral acceleration (pSA) response spectra at 5% damping for the 2010 Darfield and 2011 Christchurch EQs are indicated by solid and dashed black lines, respectively, in the top panels of Figure 7. The corresponding mean and ±1 standard deviation mHVSR spectra are indicated by solid and dot-dashed teal lines, respectively, in the bottom panels of Figure 7. The vertical dashed line and the colored boxes shown on both the pSA and mHVSR spectra indicate the mean and ±1 standard deviation of the period of the resonance peaks identified in the mHVSR spectra and attributed to the three key impedance contrasts discussed in the previous sections.

The CMHS SMS site is located close to the Port Hills. At this site, a single, strong mHVSR resonance peak was attributed to BPV impedance contrast. The mHVSR peak period roughly corresponds to the peak period range in the pSA spectra from the Darfield event. During the 2011 Christchurch event, the CMHS site liquefied resulting in a softening of the site response and the shift in the pSA peak to longer periods. At KPOC, the mHVSR resonance peak period associated with the Riccarton Gravel Formation is evident in the pSA for both earthquakes. The peak in the pSA for the Darfield event is broader due in part to the long period energy being excited by the larger earthquake. This broadened peak matches the mHVSR peak period associated with the BPV formation. A long period peak is identifiable (if not passing all of the SESAME criteria) in the mHVSR spectra and was attributed to the deep greywacke basement bedrock. A small long-period peak was observed in the pSA for the Darfield event. At the LINC SMS site, the mHVSR resonance peak period associated with the Riccarton Gravel Formation strongly matches the peak pSA response for the Darfield earthquake. Further research is needed, to robustly explore the qualitative insights from these three sites. However, it is evident that depending on location and the intensity of ground shaking deep impedance contrasts, not often included in 1D site response analysis, may contribute to the overall site response and affect the observed ground motions.

CONCLUSIONS

Ambient vibrations recordings were collected at 152 testing locations across the Canterbury Plains on the South Island of New Zealand as a part of several field testing programs aimed at characterizing the properties of the underlying soil and rock [9-13]. These ambient vibration records were analyzed using the mHVSR method to identify resonance peaks associated with three key impedance contrasts in the region: (1) the shallow soils over the Riccarton Gravel Formation, (2) the soils over the Banks Peninsula Volcanics, and (3) the strata above the greywacke basement bedrock. Geospatial trends in the associated fundamental period of vibration of the strata above these impedance contrasts were tied to the depths of various layers in a 3D structural model of the Canterbury Plains (i.e., the Canterbury Velocity Model).

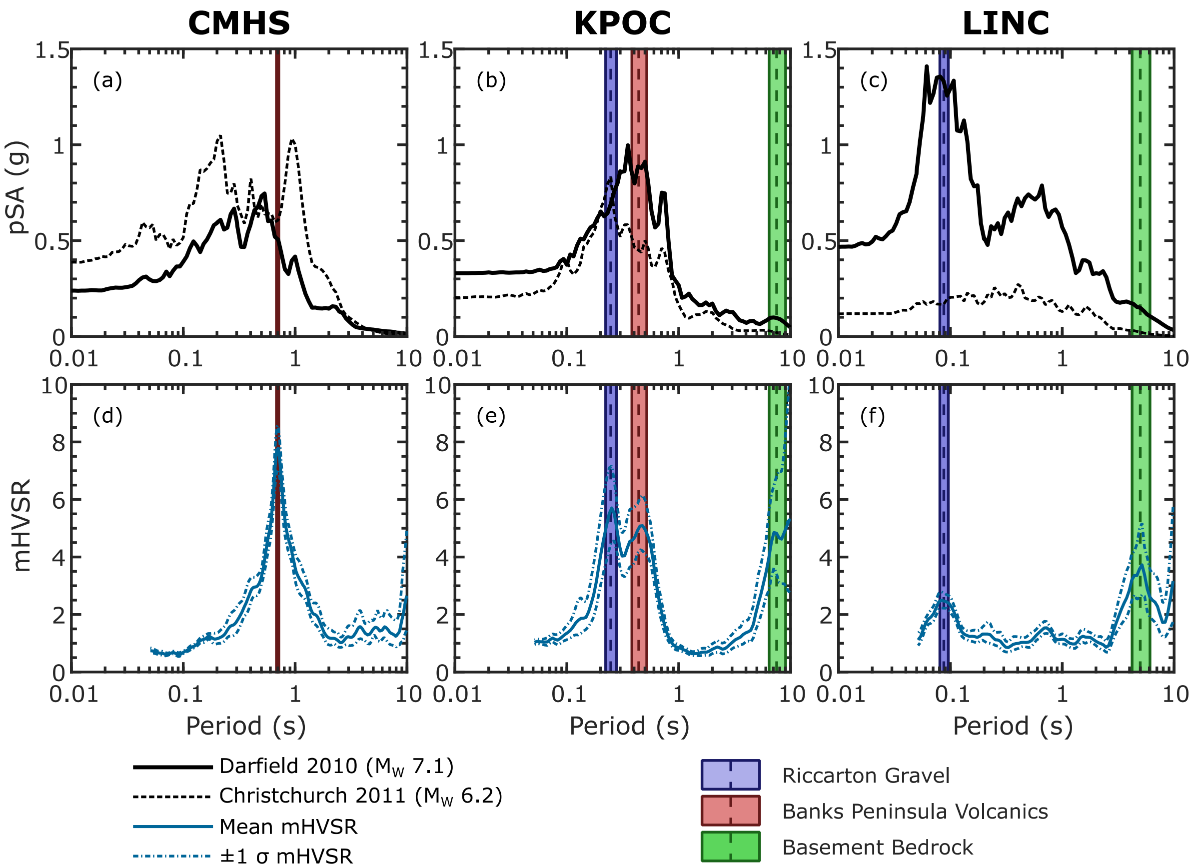

Figure 7. Observed geometric mean of the horizontal pseudospectral acceleration response spectra at 5% damping for the 2010 Darfield and 2011 Christchurch at three SMS in Canterbury: (a) CMHS, (b) KPOC, and (c) LINC. mHVSR spectra from temporary deployment of broad band seismometers at the SMS sites: (d) CMHS, (e) KPOC, and (f) LINC. The mean and ±1 standard deviation mHVSR resonance peak period associated with various impedance contrasts are indicated on both pSA and mHVSR curves.

In particular, the presence stiff volcanic rock of the BPV has been noted to strongly influence the resonance peaks observable in the mHVSR spectra. Near the Port Hills on the Banks Peninsula, the thick BPV deposit limits the identification of peaks associated with the deeper underlying basement bedrock. Away from the Banks Peninsula, the BPV layer tapers out and the depth to top of the layer increases, as reflected the decrease of mHVSR peak clarity and the increase in the corresponding period.

The resonance peak periods observed mHVSR spectra from ambient vibration data collected near SMS locations were compared to the pSA response spectra from strong motion records of the 2010 Darfield and 2011 Christchurch. While the comparisons drawn in the this study are qualitative, the multiple peaks identified in the mHVSR spectra associated with the different impedance contrasts correspond to peaks in the observed ground response. Notably, the short period peaks associated with the Riccarton Gravel or the BPV Formation correspond to peaks observed in both earthquake events, but longer period peaks associated with the BPV at greater depths and the deepest underlying basement bedrock were only observed in the ground shaking of the larger 2010 Darfield event. A key insight is that multiple impedance contrasts may contribute to ground shaking, and deep impedance contrasts (e.g., the basement bedrock in the Canterbury Plains) may be important for the long-period response of larger magnitude events.

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