Earthquake Commission Report

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Dynamic Site Characterisation of Canterbury Strong Motion Stations using Active and Passive Surface Wave Testing

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Abstract

An extensive database of ground motion records was captured by the SMS network in the Canterbury region during the Canterbury earthquake sequence. However in order to comprehensively understand the ground motions recorded at these sites and to be able to relate these motions to other locations, a detailed understanding of the geotechnical profile at each SMS is required. This report presents an overview of the development of dynamic site characterisation metrics at a number of strong motion station (SMSs) sites across the Canterbury Plains, and wider regional site period characterisation.

This report summarises the characterisation of the shallow shear wave velocity profile (to 30 m) and site period (T_0) at seven SMS locations across the Canterbury Plains, and uses site period to characterise an additional 14 SMS. According to NZS1170.5 (SNZ 2004), all SMS outside of the urban Christchurch region and greater than a few hundred metres from the Canterbury foothills and the Banks Peninsula outcrops should be classified as site subsoil class D. Moving inland from the coast, the time averaged shear wave velocity to a depth of 30 m (V_s30) increases as stiff surface gravels increasingly dominate the near surface profile.

Wider regional site characterisation using site period measurements was able to provide an indication of the variation in depth across the Canterbury Basin, and the effects of multiple impedance contrasts close to the coast. H/V spectral ratio peaks indicate site periods in the range of 5-7 seconds across much of the Canterbury Plains. Site periods decrease rapidly in the vicinity of the Canterbury foothills and the Banks Peninsula outcrops. In Christchurch, the Riccarton Gravel and the Miocene Volcanics result in a significant mode of vibration that has a much shorter period than the site period of the entire soil column down to basement rock. Further study is required to determine the impacts of these shallower impedance contrast on ground motion amplification and how to best account for it within the NZ1170.5 site classification framework.

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1 Introduction

This report presents the methodology and results from recent geophysical field investigations that were carried out to estimate the shear wave velocity (V_S) profile and site periods across the Canterbury Plains region north of the Rakaia River.

The Canterbury Plains is an area approximately 50 km wide and 160 km long that was formed by deposition of eroded material from the coalesced floodplains of rivers flowing east from the Southern Alps. Christchurch is located on eastern edge of the Plains, in an area where episodic glacial and interglacial periods have resulted in the deposition hundreds of metres of interbedded terrestrial gravel and fine grained marine sediments (Brown & Weeber 1992, Forsyth et al. 2008).

An overview the methodology used to define the V_S profiles using surface wave methods at seven strong motion stations (SMSs), and the estimation of the site period (T_0) at over 80 locations across the Canterbury Plains and Christchurch using the horizontal-to-vertical (H/V) spectral ratio method (Nakamura 1989) is presented.

Updated soil profile classifications for a selection of strong motion stations (SMSs) are presented, with surface wave testing and H/V calculations performed at seven SMS locations, and H/V spectral ratio calculations performed at 14 additional SMS locations. The other H/V spectral ratio measurements were spread across the Canterbury Plains and in Christchurch to provide coverage across the region and better constrain the Canterbury Basin characteristics.

1.1 Canterbury Strong Motions Station Network

Outside of Christchurch on the Canterbury Plains (from Rakaia north to Amberley) there are five SMSs as part of the National Strong Motion Network and sixteen as part of Canterbury regional strong motion network (Avery 2004). This network of SMSs recorded a vast database of strong ground motions during the Canterbury earthquake sequence. At this time the National Strong Motion Network (NSMN) uses Kinemetrics Etna strong motion accelerographs, and the Canterbury regional strong motion network (CanNet) uses CSI CUSP3B strong motion accelerographs. The SMS sites, their network, and their coordinates are summarised in Table 1. An overview of location of the SMS sites across the Plains is presented in Figure 1.

Prior to 2011, little information regarding the subsurface geotechnical characteristics of the strong motion station locations in and around Christchurch was available. As noted in Cousins & McVerry (2010), the soil profiles and site classes at each SMS were assumed from well logs and regional geological knowledge.

Table 1 Strong Motion Station details and coordinates (WGS 84). Shaded SMS's were the focus of more detailed study.

Station Name	Code	Network	Latitude	Longitude
Amberley HDC	AMBC	CanNet	-43.154666	172.730877
Ashley School	ASHS	NSMN	-43.274399	172.595942
Cust School	CSTC	CanNet	-43.312279	172.381335
Darfield High School	DFHS	NSMN	-43.489324	172.101112
Dunsandel School	DSLC	CanNet	-43.667406	172.198036
Greendale	GDLC	CanNet	-43.58684	172.089292
Hororata School	HORC	CanNet	-43.538339	171.959848
Kowai	KOWC	CanNet	-43.322214	171.855218
Kaiapoi North School	KPOC	CanNet	-43.376460	172.663760
Lincoln Crop and Food Research	LINC	CanNet	-43.622602	172.468765
Methven North	MTHS	NSMN	-43.557908	171.670242
Rakaia School	RKAC	CanNet	-43.750892	172.022959
Rolleston School	ROLC	CanNet	-43.592773	172.382406
Southbridge School	SBRC	CanNet	-43.808680	172.252618
Sheffield School	SHFC	CanNet	-43.391123	172.025912
Selwyn Lake Road	SLRC	CanNet	-43.675208	172.318451
Summerhill	SMHS	NSMN	-43.263734	172.332277
Springfield Volunteer Fire Station	SPRS	NSMN	-43.337866	171.929263
Swannanoa School	SWNC	CanNet	-43.370714	172.495167
Templeton School	TPLC	CanNet	-43.550297	172.472808
Whitecliffs	WCSS	NSMN	-43.45775	171.86346

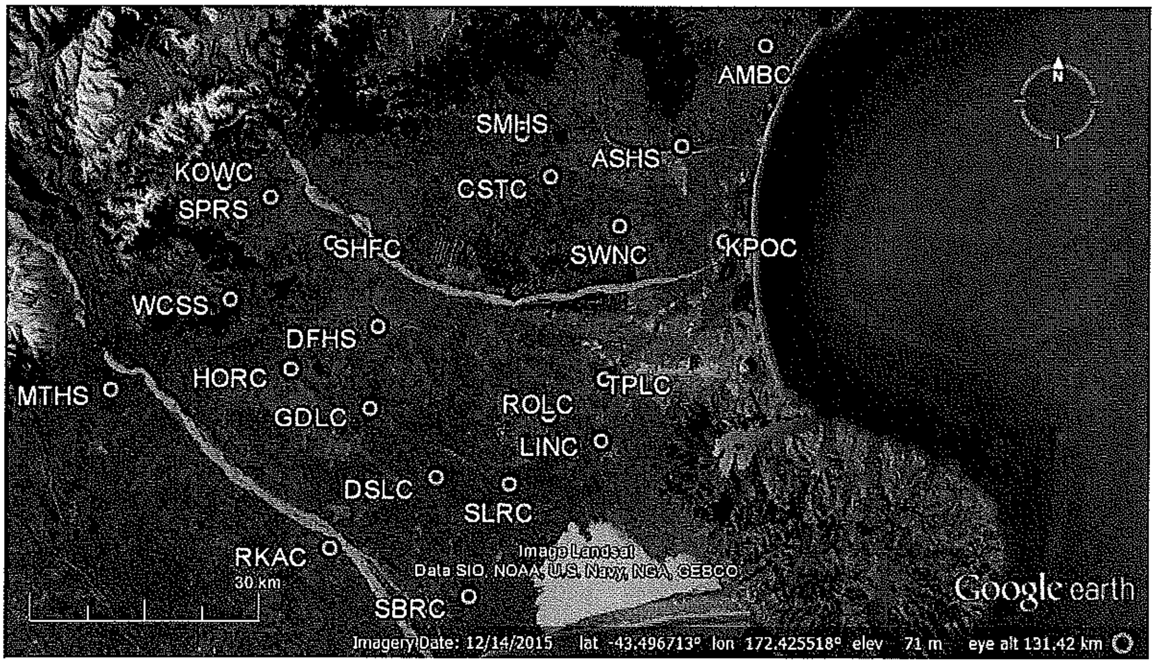

Figure 1 Canterbury Strong Motion Station locations included in this research

2 Site Characterisation

The focus of this study is the Canterbury Plains north of the Rakaia River and south of Amberley, and the location of investigations for this and related studies summarised in Figure 2. V_S profiles were developed using surface wave methods at seven strong motion stations locations outside of Christchurch, indicated by circle symbols in Figure 1. The site period (T_0) was estimated at over 80 locations additional across the Canterbury Plains and within Christchurch, indicated by the cross symbols in the same figure. A detailed study of the site period in the Heathcote Valley is also presented, with 26 measurements within an approximately 2 km2 region in the valley.

The research presented here ties into ongoing work presented in Cox et al. (2014) which characterised deep V_S profiles at 14 locations within Christchurch City limits and shallow V_S profiles and site periods at 16 Christchurch SMSs, respectively, which is also summarized in Figure 2. Toshinawa et al. (1997) also used the H/V spectral ratio method to investigate the site period characteristics across Christchurch.

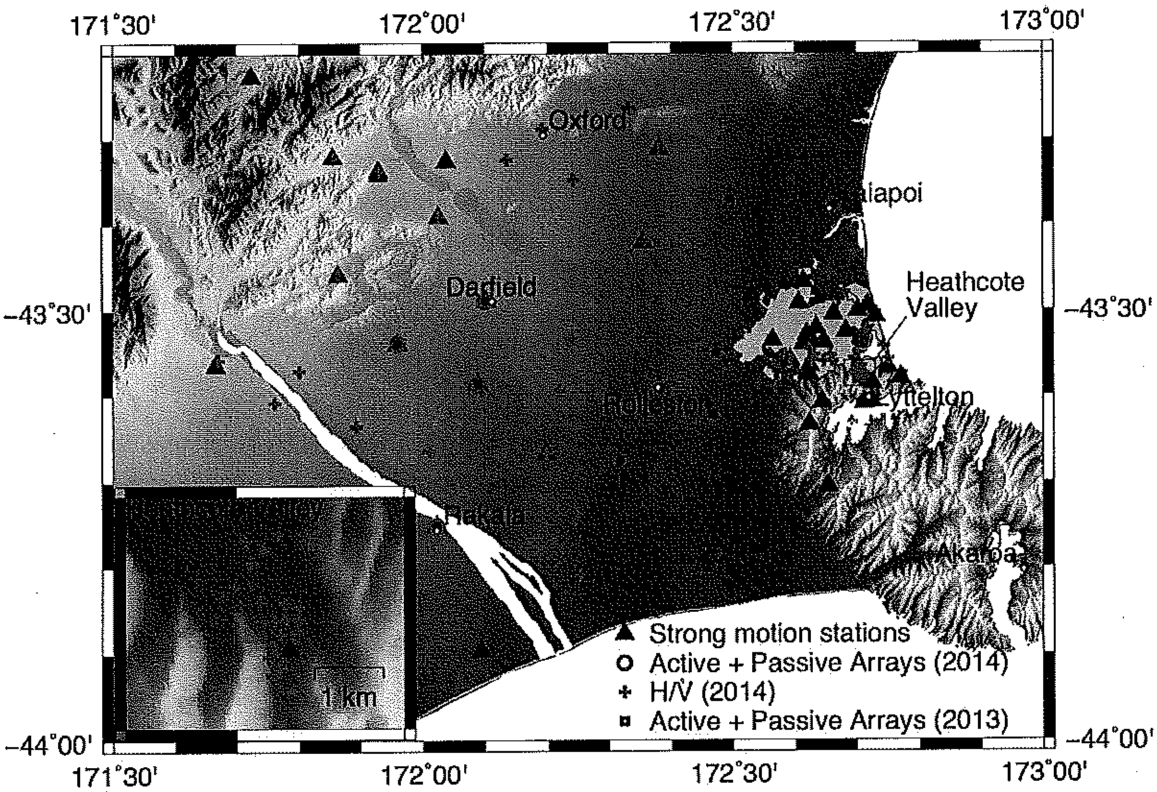

Figure 2 Illustration of the location of experimental testing performed in this study and those from previous studies (Cox et al. 2014, Wotherspoon et al. 2014)

2.1 Subsurface Investigation Data

To provide constraints on the subsurface layering across the study region the 3D Canterbury Seismic Velocity Model (Lee et al. 2015) was utilised. This model collated data from a number of sources to constrain the geological and geotechnical units across the Canterbury Plains and define surfaces to represent the boundary between each unit. The data of interest to this study was:

- Seismic reflection lines and petroleum industry boreholes that constrained the significant geologic horizons between approximately 500 m and 2.5 km depth (including basement depth).
- Water wells that constrained the Quaternary horizons
- Borehole and CPT data that constrained the near surface profile.

All available data across the Canterbury Plains was collated in the development of this model and is therefore the best reference for the definition of the subsurface layering at each investigation location presented herein.

2.2 Shear Wave Velocity Profiles

A combination of active-source and passive-source surface wave techniques were used to resolve the shear wave velocity and layering beneath each SMS. Active-source methods included a combination of the Spectral Analysis of Surface Waves (SASW) (Nazarian & Stokoe 1984, Stokoe et al. 1994) and the Multi-channel Analysis of Surface Waves (MASW) (Park et al. 1999). The investigation methodology was similar to that used by Cox et al. (2014) at 14 locations within the city of Christchurch, and intended to spatially complement those earlier investigations.

2.2.1 Active Source Methods

Active source data was acquired using a sledgehammer source with a steel strike plate with a rubber damping pad to collect Rayleigh wave data, and a shear beam with vertical load applied by a vehicle to collect Love wave data. 24 or 48 4.5 Hz vertical geophones with 2 m spacing were used to collect Rayleigh wave dispersion data, and 24 4.5 Hz horizontal geophones with 2 m spacing were used to collect Love wave dispersion data. Four source offsets of 5, 10, 20 and 40 m were used for both sets of testing, and at each source offset 10 sledgehammer impacts were recorded and stacked.

At this same source location, SASW data was also collected using select pairs of geophones within the linear array. Typical receiver spacing's included 1dx, 2dx, 3dx, 4dx, 6dx, 8dx, 10dx and 12dx. These pairs of receivers were always chosen to maintain the source-to-first receiver distance equal to the first-to-second receiver distance, as is typical in SASW testing (Stokoe et al. 1994).

At sites with surface soil conditions, a P-wave refraction survey was performed using the linear array (P-wave refraction could not be conducted at sites with asphalt or concrete at the surface). These measurements were used to determine the depth to saturation (ground water table) at each station for input into the surface wave inversion. For refraction testing, five hammer blows (shots) located one receiver spacing in front of the first receiver were stacked to increase the signal-to-noise ratio.

The SASW data was analysed using the phase unwrapping method to determine the individual Rayleigh wave dispersion curves from each receiver spacing. The individual dispersion curves were then combined to form a composite dispersion curve over the frequencies/wavelengths of interest. The MASW data was analysed using the frequency domain beamformer (FDBF) method (Zywicki 1999). For each source offset, a dispersion curve was generated by picking the maximum spectral peak in the frequency/wavenumber domain. This was used to develop both Rayleigh wave and Love wave dispersion curves.

2.2.2 Ambient Wavefield (Passive) Methods

Ambient wavefield records were collected using 10 broadband 3-component seismometers (Nanometrics Trillium Compacts, 20 second period) arranged in circular arrays with diameters of 50, 200 and 500 m at each SMS location (an example layout is shown in Figure 2b). At two locations, 1000 m diameter arrays were also deployed. The ideal layout at each array consisted of a central location and nine spaced evenly around the circumference, however constraints at some locations required slight modifications to this layout. Each seismometer was placed in a hole approximately 10-15 cm in depth (greater than the height of the seismometer) and oriented towards north. Soil was then tightly compacted around the seismometer to provide a good connection with the surrounding ground.

The ambient-wavefield surface wave data was processed using both the 2D high-resolution frequency-wavenumber (HFK) method (Capon 1969) and the modified spatial autocorrelation (MSPAC) method (Bettig et al. 2001). HFK dispersion processing using MATLAB and developed both Rayleigh wave and Love wave dispersion data, while the MSPAC processing produced only Rayleigh wave dispersion data. A detailed overview of the data processing methodology for both the active and passive methods is summarised in Wood et al. (2014).

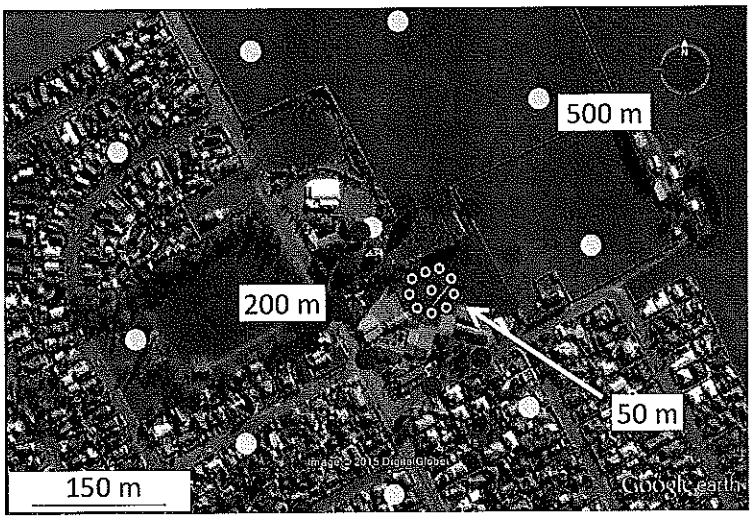

Figure 3 Aerial view of surface wave testing setup used at each SMS indicating location of circular arrays for ambient wavefield testing

2.2.3 Inversion Methodology

Once the surface wave dispersion trends from each method were obtained, a mixed-method composite dispersion curve was generated by combining the dispersion data from each active and passive surface wave method. The dispersion data was then divided into bins using a log distribution. The mean phase velocity and associated standard deviation was then calculated for each bin, resulting in an experimental dispersion curve with associated uncertainty.

The dispersion estimates from the active-source and ambient-wavefield data at each site were combined to produce an inter-method composite dispersion curve with associated data uncertainty bounds. The open-source software package Geopsy (Wathelet 2008) was then used to perform a multi-mode, joint inversion of the dispersion data and the peak frequency of the mean horizontal-to-vertical (H/V) spectral ratio curve for the site. The forward model calculations were originally developed by Thomson (1950) and Haskell (1953) and later modified by Dunkin (1965) and Knopoff (1964).

Rather than providing a single, deterministic V_s profile for each site, these inversions provide a suite of profiles that fit the experimental data equally well. Estimates of the uncertainty in the shear wave velocity profile are obtained, as such uncertainty is critical for site-response analyses and other applications of the site characterisation information. In order to develop the most realistic profiles at each location a-priori geotechnical and geologic data and empirical reference shear wave velocity profiles for different materials were used constrain layering and material property ranges. A detailed summary of this methodology is provided in Teague et al. (2015).

2.3 Horizontal to Vertical Spectral Ratio

To estimate the site period (T_0) of each SMS, the ratios of the horizontal-to-vertical Fourier amplitude spectra (FAS) of the recorded ambient noise was used (i.e., H/V spectral ratios). The premise of the H/V spectral ratio approach is that the vertical component of surface ground motion reflects only source and path effects and is not significantly influenced by site effects (due to a large P- to S wave velocity ratio). In contrast, the horizontal component of ground surface motions reflects source, path, and site effects. As a result, the H/V spectral ratios primarily reflect site effects, similar to the transfer function, and the source and path effects largely normalize out (Nakamura 1989, Field et al. 1990, Lermo & Chavez-Garcia 1993, 1994, Field & Jacob 1993, Field et al. 1995, Konno & Ohmachi 1998).

A field testing protocol similar to that used during the ambient wavefield testing explained in the previous section was used to collect H/V spectral ratio data for sites across the Canterbury Plains shown in Figure 1, and sites in urban Christchurch shown in Figure 2a. For sites in close vicinity (less than a few hundred metres) to the surrounding hills (such as the Port Hills and those surrounding the Canterbury Plains), 30 minute records were taken at each location. For sites further out from this, recording periods of at least 60 minutes were used. A sampling frequency of 100 Hz was used in all cases. Data from the ambient wavefield testing at the SMSs was also used to analyse the H/V spectral ratio at these locations.

H/V data were processed using the software Geopsy (Wathelet 2008). Time windows that were overly noisy were removed, with the remaining windows used to develop the spectral average at each location. The geometric mean of the horizontal-component Fourier spectra were used to develop the H/V spectral ratios, and a Konno & Ohmachi (1998) smoothing function with a smoothing constant of b=40 was applied. The H/V spectral ratios from a range of time window lengths were compared during processing to determine the influence of window lengths on the estimated spectral peak(s) and to estimate the uncertainty associated with the spectral peak(s). The data presented in this paper used a window length of 100 seconds with no overlap and a 5% cosine taper.

2.4 Site Classification Metrics

Three site classification metrics are summarised in this report:

- Site period
- Time averaged shear wave velocity to 30 m depth (V_S30)
- NZS1170.5 site subsoil class

The site period is the fundamental period of vibration of the overall soil profile above bedrock at a particular location. The site period (T_0) can be calculated as:

$$T_0 = \frac{4H}{V_{Savg}} \quad (1)$$

where H is the thickness of the soil profile above bedrock and V_{Savg} is the time averaged shear wave velocity of the profile. V_{Savg} is calculated using:

$$V_{Savg} = \frac{\sum_i h_i}{\sum_i \frac{h_i}{V_{si}}} \quad (2)$$

where h_i is the thickness of layer i, and V_{si} is the shear wave velocity of layer i. The time averaged shear wave velocity to 30 m calculated using the above equation with a total thickness of 30 m.

2.4.1 NZS1170.5 site subsoil class

NZ1170.5 (SNZ 2004) uses a combination of undrained shear strength (s_u), SPT N, V_S, and site period (T_0) to define site classes. In this report, all SMSs have greater than 3 m of soil above bedrock at their location, which is the cutoff between site class B – rock, and site class C – shallow soil. Therefore, the remaining SMS are classified as either site class C – shallow soil, site class D – deep or soft soil, or site class E – very soft soil. A summary of the site classes are provided in Table 2.

Locations are defined as site class E if they have greater than 10 m of low strength material with s_u<12.5 kPa, SPT N < 6 blws/0.3 m, or V_S < 150 m/s. Sites outside these limits will be either site class C or D, and can be differentiated using two approaches. Firstly, if the low amplitude natural period, T_0, (or site period) is less than or equal to 0.6 seconds, the site is classified as site class C. Otherwise, the site is site class D. The natural period of a site can be estimated from (a) a V_S profile that extends down to bedrock (or another significant impedance contrast) or (b) direct horizontal-to-vertical spectral ratio (H/V) measurements at the site. For method (a), the natural period of a site is approximated as four times the thickness of the soil deposit over bedrock divided by the average V_S of the soil deposit (equivalently stated as four times the shear wave travel time from bedrock to the surface). Secondly, maximum depth limits are defined for a range of representative s_u and SPT N soil profiles to delineate the site class C and D boundary in Table 3.2 of NZS1170.5. The maximum depth for very dense cohesionless soils is 60 m, and the maximum depth of gravels is 100 m. Utilizing natural period to define site class is the preferred of the two approaches.

Table 2 Summary of the NZS1170.5 site class guidelines (SNZ 2004)

3.1.3.3 *Class B – Rock*
Class B is defined as rock with:
(a) A compressive strength between 1 and 50 MPa; and
(b) An average shear-wave velocity over the top 30 m greater than 360 m/s; and
(c) Not underlain by materials having a compressive strength less than 0.8 MPa or a shear-wave velocity less than 300 m/s.
A surface layer of no more than 3 m depth of highly-weathered or completely-weathered rock or soil (a material with a compressive strength less than 1 MPa) may be present.

3.1.3.4 *Class C – Shallow soil sites*
Class C is defined as sites where:
(a) They are not class A , class B or class E sites; and
(b) The low amplitude natural period is less than or equal to 0.6 s; or
(c) Depths of soil do not exceed those listed in Table 3.2.
The low amplitude natural period may be estimated from four times the shear-wave travel time from the surface to rock, be estimated from Nakamura ratios or from recorded earthquake motions, or be evaluated in accordance with Clause 3.1.3.7 for sites with layered subsoil, according to the hierarchy of methods given in Clause 3.1.3.1.

3.1.3.5 *Class D – Deep or soft soil sites*
Class D is defined as sites:
(a) That are not class A , class B or class E sites; and
(b) Where low-amplitude natural period is greater than 0.6 s; or
(c) With depths of soils exceeding those listed in Table 3.2; or
(d) Underlain by less than 10 m of soils with an undrained shear-strength less than 12.5 kPa or soils with SPT N-values less than 6.
The low amplitude natural period may be determined in accordance with Clause 3.1.3.4.

3.1.3.6 *Class E – Very soft soil sites*
Class E is defined as sites with:
(a) More than 10 m of very soft soils with undrained shear strength less than 12.5 kPa; or
(b) More than 10 m of soils with SPT N-values less than 6; or
(c) More than 10 m depth of soils with shear-wave velocities of 150 m/s or less; or
(d) More than 10 m combined depth of soils with properties as described in (a), (b) and (c) above.

3 Canterbury Basin Site Period Characteristics

H/V spectral ratio measurements were made at over 80 sites across the Canterbury Plains, with a number of these within the Christchurch city limits. More than 30 additional H/V spectral ratio measurements have been previously made in Christchurch in the studies of Wotherspoon et al. (2014) and Cox et al. (2014) using similar methodologies and equipment.

The H/V spectral peak(/s) from ambient noise recordings likely correspond to: (1) the site period for the entire soil profile down to basement rock (a significant impedance contrast); (2) the site period of shallow sandy soils above Miocene Volcanics Quaternary gravels; or (3) the site period of shallow sandy soils above Quaternary gravels. The final two are the strong shallow impedance contrasts present in the Canterbury region. This and other studies (Toshinawa et al. 1997, Wotherspoon et al. 2014) have shown that the dominant peak in the H/V spectral ratio measurements can result from a shallower impedance contrast. In Christchurch, the Riccarton Gravels create a significant impedance contrast with the overlying looser sediments (Christchurch and Springston Formations) across much of the city and result in a significant mode of vibration that has a much shorter period than the site period of the entire soil column down to basement rock. Examples of the three common H/V cases outlined above are presented in Figure 4. This data clearly indicates that independent knowledge of the general geologic characteristics at a location are required in order to appropriately interpret the data from H/V measurements.

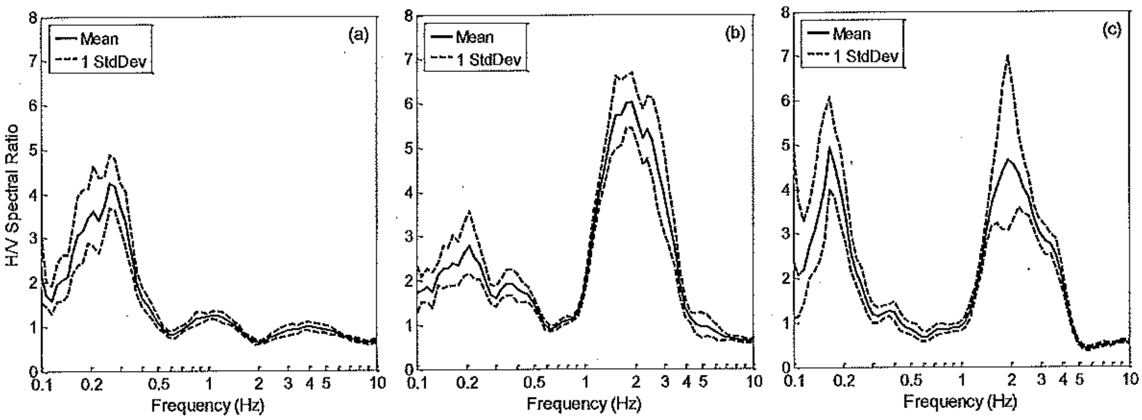

Figure 4 Example H/V spectral ratio data from ambient noise records across Canterbury (a) Single predominant peak corresponding to deep site period above basement rock, (b) single predominant peak corresponding to shallow site period above gravels, (c) Double peak corresponding to both shallow and deep site periods

3.1 Canterbury

Figure 5 illustrates the long period H/V peaks over the entire Canterbury region (locations at which the H/V peak at long periods could not be resolved are not shown). There are three clear visual trends that can be derived from the figure and relate to known geologic features. Within the broad plains area away from the hills, the deep site period remains largely constant with all measurements falling within the range of T_0=5-7 seconds. Across this region, the local site geology is relatively consistent (Brown & Weeber 1992, Lee et al. 2015). A sharp change in site period is observed within the vicinity of the Canterbury foothills in the west, where the period varies between 0 and 5 seconds across a distance of approximately 10 – 20 km, as a result of the basement rock shallowing toward the ground surface.

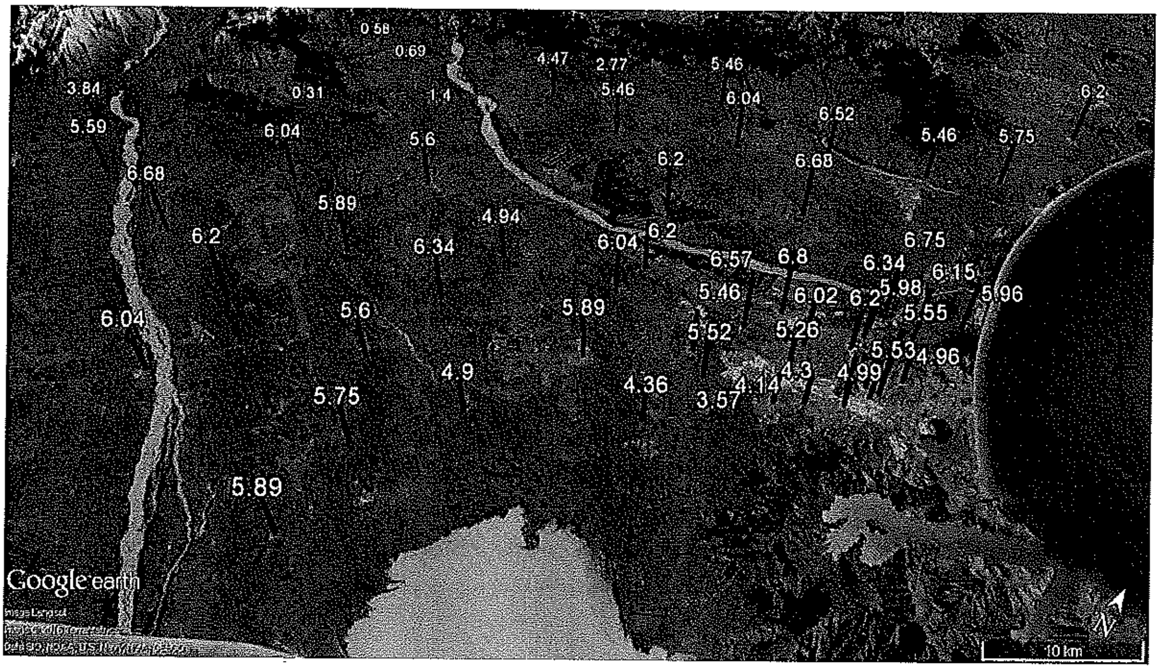

Figure 5 Summary of period of soil profile above bedrock (fundamental period) obtained from H/V spectral peaks across the Canterbury Plains.

3.2 Christchurch

The period above basement rock formed the dominant site response in the northern and western regions of the city where the volcanic deposits from the Banks Peninsula did not exist in the profile. Figure 6 summarises the period above basement across Christchurch, increasing from 3.5 to 7 seconds moving away from the Port Hills. The shorter site periods in the urban Christchurch region are inferred as the result of a shallowing basement rock depth in this region associated with uplift during Miocene volcanism. Period above basement rock could not be identified close to the Port Hills where the significant impedance contrast above the Banks Peninsula Volcanics dominates, and a significant thickness of Volcanic deposits likely exists.

The period above volcanics in Figure 7 were readily classified near the Port Hills in the south of the city where the volcanic rock was close to the surface. This strong impedance contrast is reflected in the clarity and amplitude of the peaks, which indicated that the response was that above the volcanic rock, a more significant impedance contrast than the Riccarton Gravel. These peaks moved to longer periods and gradually became less clear with increasing distance from the Port Hills.

Near the Christchurch CBD the periods became harder to constrain, with the basement period and/or Riccarton Gravel response also present in the HVSR spectral peaks. At some sites a potential combined basement and volcanic rock response was observed. This occurred when the volcanic rock was at a greater depth and means that the volcanic periods further from the Port Hills had less surety in their constraint.

Figure 6 Summary of period of soil profile above bedrock (fundamental period) obtained from H/V spectral peaks across Christchurch

Figure 7 Summary of period of soil profile above volcanics obtained from H/V spectral peaks across Christchurch.

The Riccarton Gravels create a significant impedance contrast with the overlying looser sediments (Christchurch and Springston Formations) across much of the city and result in a significant mode of vibration that has a much shorter period than the site period of the entire soil column down to basement rock. Clear short period peaks corresponded to the response above gravels, except close to the Port Hills where the volcanic rock is very near to the surface. These gravel peaks were relatively clear across the city and often simple to constrain due to their shorter period than the volcanic and basement response. Gravel periods show no clear trend in relation to period and depth, with these variations across the study region attributed to the complex surficial geology that overlies the Riccarton Gravels.

Figure 8 Summary of period of soil profile above gravels obtained from H/V spectral peaks across Christchurch. Legend indicates period in seconds.

3.2.1 Heathcote Valley Study Area

A detailed investigation of site periods was carried out within the Heathcote Valley, situated on the south-eastern edge of the city. 26 H/V spectral ratio measurements were made in an area of approximately 2 km^2 in the valley in order to better characterise the valley sediments above Miocene Volcanics. Given the relatively shallow depth expected in this region, 30 minute records were used at each location. The Heathcote Valley Primary School (HVSC) SMS is also located near the head of this valley, and accelerograms recorded at this location during the Canterbury Earthquake Sequence were some of the most severe of all SMSs across the city (Bradley and Cubrinovski 2011). Seismic recordings at the Heathcote School SMS suggest basin/edge amplification effects played a significant role in amplification of ground motion produced during the February 2011 earthquake in Christchurch (Bradley, 2012, Cubrinovski et al., 2011, Wotherspoon et al., 2014) and as such has been a focus of recent research efforts (e.g. Jeong et al. 2014).

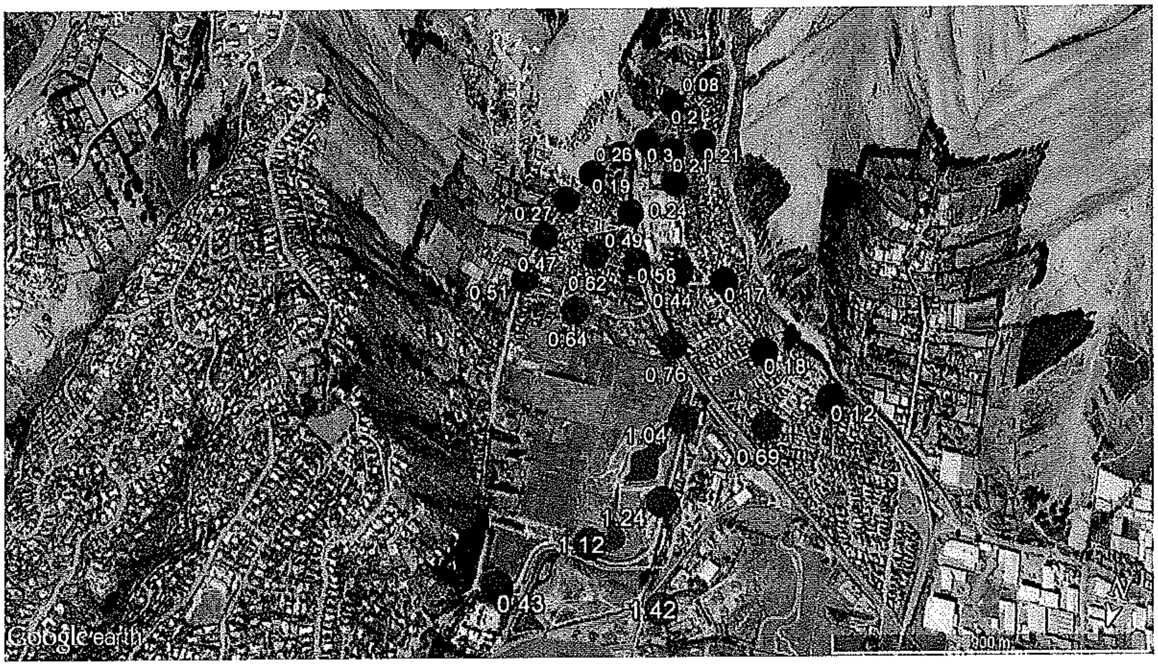

Figure 9 Summary of estimated period of profile above volcanics from H/V spectral peaks in the Heathcote Valley.

The predominant site periods at the 26 locations where measurements were made in the Heathcote Valley (shown inset in Figure 2) are displayed in Figure 9. Two clear trends can be observed from the figure; firstly, the period increases moving longitudinally down the valley from the head; secondly, there is evidence of increasing predominant site period moving from the valley edges into the centre. Both results are expected intuitively based on the simple geology in the region. In both cases the trend can be attributed to an expectation that the depth of sediment is larger within the valley centre and lesser at the head and valley edges where the bedrock approaches the ground surface. Perhaps the only other notable locations where this is not observed is at the middle-right of Figure 9, where a mid-range period of ~0.5 seconds can be seen. In this region, the adjacent Morgan's Valley meets the Heathcote Valley and as such the depth to basement rock in this area is expected to be deeper than the same point on the west side.

4 Summary of Strong Motion Station Characteristics

This section provides a summary of the SMS characteristics developed using the methodologies outlined in the previous sections. Regional geologic characteristics are outlined first, followed by a discussion of the estimated site period developed using the procedures outlined in Section 2. This data is combined with the other surface and subsurface investigation details to define the NZS1170.5 site class at each SMS location based on V_S and T_0. Finally, the time-average shear wave velocity to a depth of 30 m (V_{S30}) is discussed, as it is a common site classification measure used in ground motion prediction equations and other site classification methodologies.

4.1 Regional Geology

General geologic characteristics at each SMS location is summarised in Table 3, based on Brown & Weeber (1992). This delineates between postglacial fluvial deposits, glacial outwash, and pre-quaternary sediments and rocks. The maximum inland extents of paleo-coastlines were used to define locations were interbedded marine and terrestrial Quaternary deposits would be expected (Lee et al.2015), with Table 3 providing a summary of this interbedded characteristics at each SMS site.

Table 3 Summary of near surface geology and interbedded characteristics at each SMS

Code	Surface Geology	Interbedded Profile
AMBC	Glacial outwash	No
ASHS	Glacial outwash	No
CSTC	Glacial outwash	No
DFHS	Glacial outwash	No
DSLC	Post-glacial fluvial	Yes
GDLC	Glacial outwash	No
HORC	Glacial outwash	No
KOWC	Glacial outwash	No
KPOC	Post-glacial fluvial	Yes
LINC	Post-glacial fluvial	Yes
MTHS	Glacial outwash	No
RKAC	Post-glacial fluvial	No
ROLC	Post-glacial fluvial	Yes
SBRC	Post-glacial fluvial	Yes
SHFC	Post-glacial fluvial	No
SLRC	Post-glacial fluvial	Yes
SMHS	Glacial outwash	No
SPRS	Post-glacial fluvial	No
SWNC	Glacial outwash	No
TPLC	Post-glacial fluvial	Yes
WCSS	Pre-Quaternary sediments	No

4.2 Site Periods

The site period estimates at each SMS are summarised in Table 4. The characteristics of these site periods are discussed in Section 3.

Table 4 Summary of site period estimates from H/V spectral ratio measurements at each SMS

Code	T_0 mean (secs)	T_0 mean-sigma (secs)	T_0 mean+sigma (secs)
AMBC	6.2	5.4	7.8
ASHS	5.5	4.7	6.5
CSTC	6.0	5.4	7.3
DFHS	5.6	5.4	7.3
DSLC	5.6	5.1	6.6
GDLC	5.9	5.2	7.8
HORC	6.0	5.6	7.1
KOWC	0.58	0.53	0.70
KPOC	7.1	5.7	8.2
LINC	4.4	4.2	5.6
MTHS	3.8	3.6	4.6
RKAC	6.0	5.7	7.1
ROLC	5.9	5.2	7.2
SBRC	5.9	5.0	7.2
SHFC	1.4	1.2	1.7
SLRC	4.9	4.4	5.6
SMHS	5.5	4.4	6.5
SPRS	0.69	0.63	0.84
SWNC	6.7	6.2	8.2
TPLC	5.5	5.1	6.6
WCSS	0.31	0.28	0.39

4.3 NZS1170.5 Site Class

A summary of the NZS1170.5 site classes at each SMS defined using the V_s profiles, site period, and subsoil geotechnical data and regional geology is presented in Table 5. Using the NZS1170.5 preferred approach, only WCSS had an estimated site period less than the T_0=0.6 second threshold for site class D. KOWC is on the border of site class C and D, with a site period of 0.58 seconds. The rest of the SMS investigated will be either site class D or E, with the site period of the profile above bedrock at all these locations greater than 0.6 seconds.

At the seven SMS locations where Vs profiles were developed, the combination of Vs and site period indicated that these sites should all be defined as site class D. Based on knowledge of regional geology combined with site period, all sites apart from WCSS and KOWC have been classified as site class D. All locations are dominated by gravels from near the ground surface, therefore it is unlikely that there will be greater than 10 m of material with V_s>150 m/s based on other regional V_s measurements.

Table 5 Summary of site classes based on original assumptions and T_0 and V_s *at each SMS*

Code	Original Assumed Site Class	T_0 and V_s Site Class	T_0 and Geology Site Class
AMBC	D	-	D
ASHS	D	-	D
CSTC	D	-	D
DFHS	D	D	D
DSLC	D	-	D
GDLC	D	D	D
HORC	D	D	D
KOWC	D	-	C/D Boundary
KPOC	E	-	D
LINC	D	D	D
MTHS	U	-	D
RKAC	D	-	D
ROLC	D	D	D
SBRC	D	-	D
SHFC	C	-	D
SLRC	U	D	D
SMHS	U	-	D
SPRS	U	-	D
SWNC	D	-	D
TPLC	D	D	D
WCSS	U	-	C

4.4 V_S30

A summary of the V_S30 estimates at the SMS where detailed characterisation was carried out are summarised in Table 6. No data is presented at the SMS locations where only H/V spectral ratio measurements were carried out. Moving inland from the coast, the V_S30 increases as stiff surface gravels increasingly dominate the near surface profile, and west of the region affected by episodic glacial and interglacial periods.

Table 6 Summary of V_S30 estimates at each SMS

Code	V_S30 mean (m/s)	V_S30 mean-sigma (m/s)	V_S30 mean+sigma (m/s)
DFHS	515	523	508
GDLC	455	464	447
HORC	535	566	517
LINC	293	297	288
ROLC	447	516	376
SLRC	323	338	307
TPLC	391	444	335

6 Conclusions

This report has presented updated soil profile classifications of a selection of strong motion stations (SMSs) in the Canterbury region based on recently completed site investigations.

Within the broad plains area away from the hills, the site period to basement rock remains largely constant, with all measurements falling within the range of T_0=5-7 seconds. Site periods decrease rapidly approaching the Canterbury foothills and the Banks Peninsula outcrops, due to the rapid shallowing of the basement rock towards the ground surface. This study has shown that in Christchurch, the Riccarton Gravels result in a significant mode of vibration that has a much shorter period than the site period of the entire soil column down to basement rock. The effect of this shallow impedance contrast and the Miocene Volcanics on ground motion amplification should be the target of future study. This dataset clearly indicates that independent knowledge of the general geologic characteristics at a location are required in order to appropriately interpret the data from H/V measurements.

According to NZS1170.5 (SNZ 2004), all SMS outside of the urban Christchurch region and greater than a few hundred metres from the Canterbury foothills and the Banks Peninsula outcrops should be classified as site subsoil class D. Moving inland from the coast, the $V_{S}30$ increases as stiff surface gravels increasingly dominate the near surface profile.

Ultimately, this detailed characterization of soil conditions in the region will allow for back-analysis of ground motions recorded at SMSs during the Canterbury earthquake sequence, and forward estimates of the characteristics of future events.

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