Development of deep V_S profiles and site periods for the Canterbury region

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ABSTRACT: Recent field investigations were carried out to define the shear wave velocity (V_S) profile and site periods across the Canterbury region, supplementing earlier efforts in urban Christchurch. Active source surface wave testing, ambient wave field (passive) and H/V spectral ratio methods were used to characterise the soil profile in the region. H/V spectral ratio peaks indicate site periods in the range of 5-7 seconds across much of the Canterbury Plains, broadly consistent with those based on a 1D velocity model for the region. Site periods decrease rapidly in the vicinity of the Canterbury foothills and the Banks Peninsula outcrops. 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.

1 INTRODUCTION

This paper presents the methodology and preliminary 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 region north of the Rakaia River. An overview the methodology used to define the V_S profiles using surface wave methods at 10 strong motion stations (SMSs) across Canterbury is initially presented. The main focus of the paper is the estimation of the site period (T) at over 80 locations across the Canterbury Plains and Christchurch using the horizontal-to-vertical (H/V) spectral ratio method (Nakamura 1989). A detailed study of the site period in the Heathcote Valley is also presented, with 26 measurements within an approximately 2 km^2 region in the valley.

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 and Weeber 1992, Forsyth et al. 2008).

The research presented here ties into ongoing work presented in Cox et al. (2014) and Wotherspoon 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 summarized in Figure 1. Toshinawa et al. (1997) also used the H/V spectral ratio method to investigate the site period characteristics across Christchurch. In this paper we present the cumulative insights from both the urban and rural Canterbury areas. Ultimately, the detailed characterization of soil conditions in the region will allow for back-analysis of ground motions recorded during the Canterbury earthquake sequence, and forward estimates of the characteristics of future events.

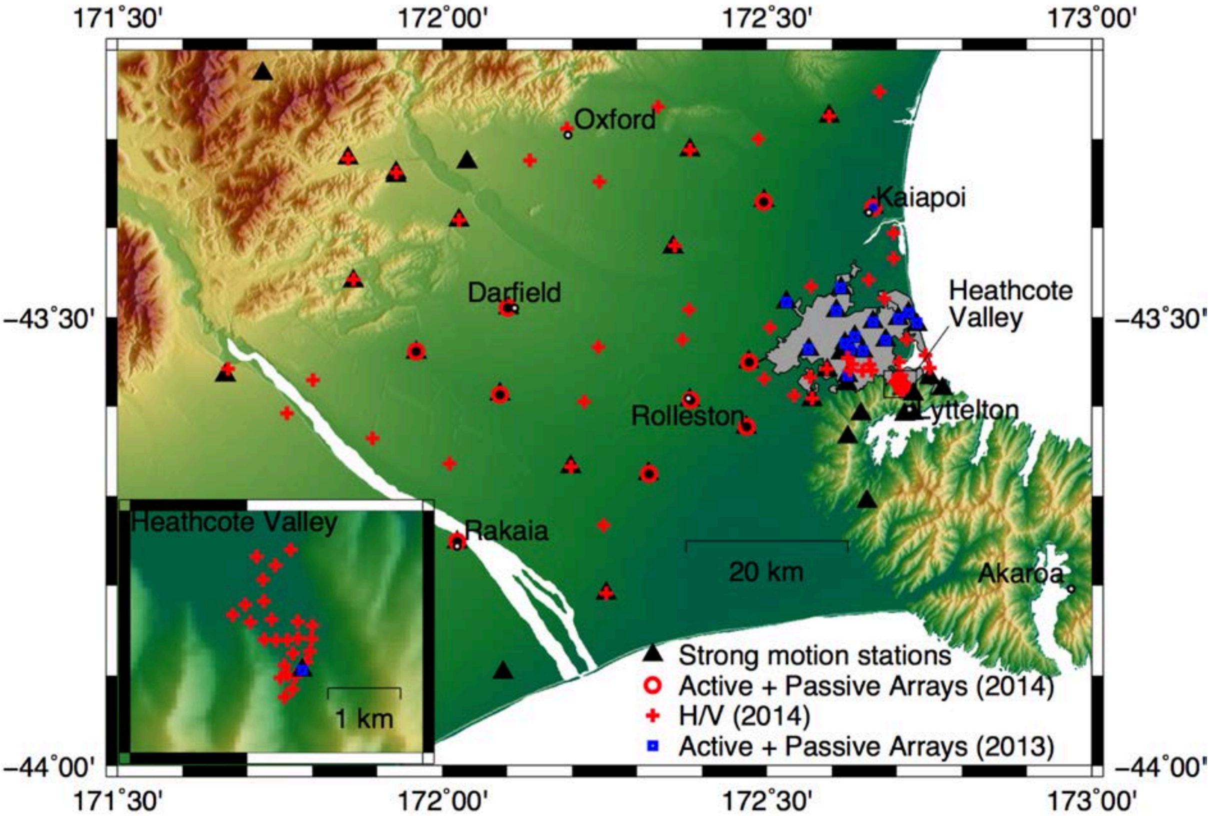

Figure 1. Illustration of the location of experimental testing performed in this study and those from previous studies (Cox et al. 2014, Wotherspoon et al. 2014).

2 METHODOLOGY

2.1 Surface wave testing

Active source surface wave testing and ambient wavefield (passive) methods were used to characterise the V_S profile at 10 SMSs across the Canterbury Plains in December 2014 (Figure 1). 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.

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.

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. A detailed overview of the data processing methodology is presented in Wood et al. (2014).

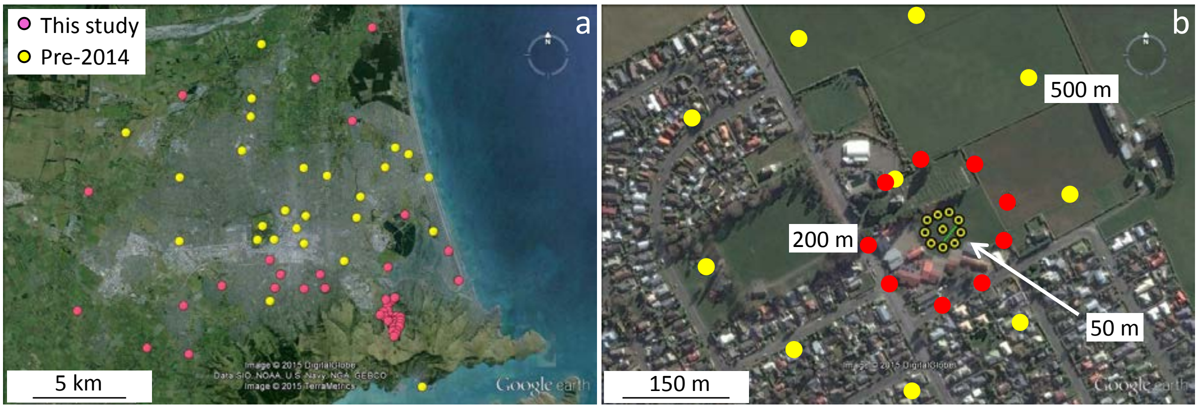

Figure 2. Aerial view of: a) H/V testing locations in Christchurch from this study and from previous studies using similar methodologies; b) surface wave testing layout at TPLC SMS.

2.2 H/V spectral ratio

To estimate the site period (*T*) at each location, the ratios of the horizontal-to-vertical Fourier amplitude spectra (FAS) of recorded ambient noise were used (i.e., H/V spectral ratios) (Nakamura 1989, Field et al. 1990, Field and Jacob 1993, Sánchez-Sesma et al. 2011). 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 (www.geopsy.org). 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 and 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.

3 CANTERBURY-WIDE SITE PERIODS

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); or (2) the site period of shallow sandy soils above either Quaternary gravels or Miocene volcanics (which are the strong shallow impedance contrasts in the Canterbury region). This paper focuses on the estimates of the site period for the entire soil profile to basement rock or the Miocene volcanics close to the Port Hills. However, as indicated in this and other studies (Toshinawa et al. 1997, Wotherspoon et al. 2014), the dominant peak in the H/V spectral ratio measurements can also result from a shallower impedance contrast. In Christchurch, 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 3. Hence, it should be clear that independent knowledge of the general geologic characteristics at a location are required in order to appropriately interpret the data from H/V measurements.

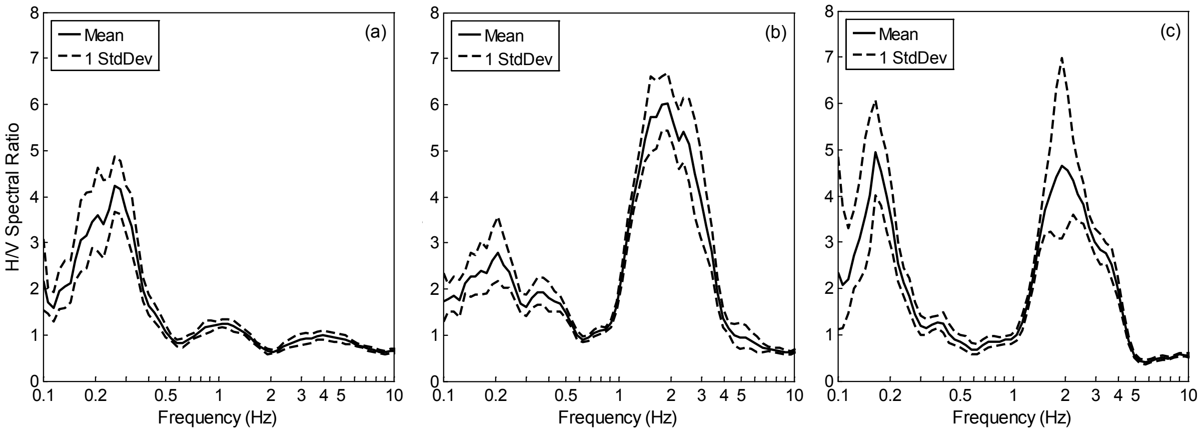

Figure 3. Example H/V spectral ratio data from ambient noise records across Canterbury (a) Single predominant peak corresponding to deep site period above basement rock, (b) single predominant peak corresponding to shallow site period above gravels, (c) Double peak corresponding to both shallow and deep site periods.

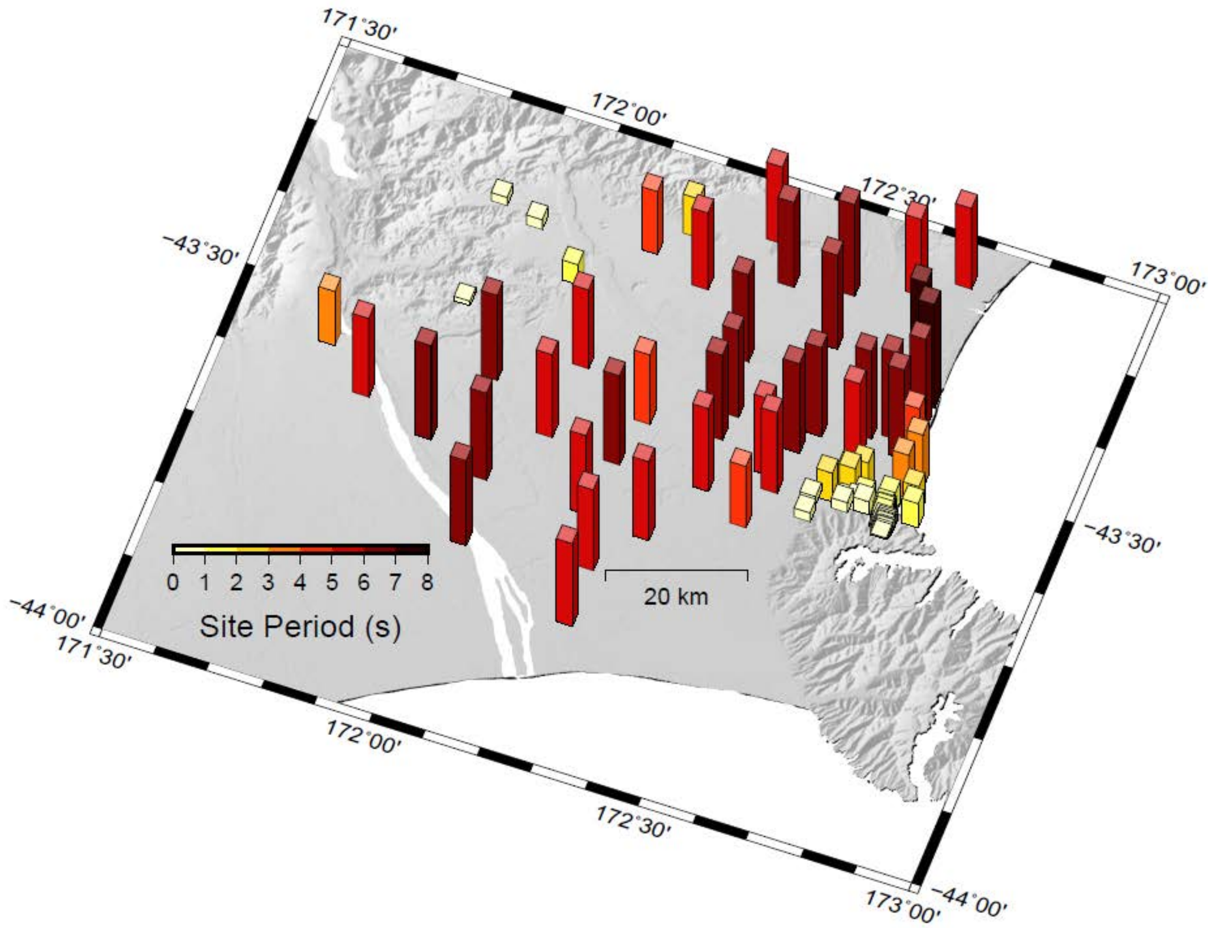

Figure 4. Site periods obtained from long period H/V spectral peaks across the Canterbury Plains and Christchurch.

Figure 4 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=5-7 seconds. Across this region, the local site geology is relatively consistent (Brown and 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. A similar trend is observed within close proximity to the urban Christchurch area. In the central and southern urban city limits the predominant site period shown in Figure 4 ranges from T=0 – 3 seconds, whereas in the west and north of the city, site periods increase to approximately T=5 seconds. 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. In this area site periods greater than 0.6 seconds were evident less than 300 m from the base of the Port Hills.

3.1 Site period correlation with basement depth

Based on the assumption that the long period H/V spectral peak corresponds (approximately) to the site period of a soil profile down to basement rock, there should be some correlation between the experimentally measured site period and the depth to basement rock (a non-perfect correlation however because of spatial variability in sediment velocities above the basement). Figure 5 illustrates the deep site periods (from Fig. 4) plotted against the depth to basement rock derived from Lee et al. (2015). Each of the estimated site periods includes a standard deviation, as a result of the uncertainty arising from the use of multiple time windows. This dataset excludes the short period data associated with an impedance contrast over shallow rock associated with the extinct Lyttleton volcanic complex discussed previously. The plot shows somewhat of a plateau in site period at approximately 6 s indicating any increase in bedrock depth past ~1000 m does not lead to any significant increase in the site period. This behaviour is somewhat intuitive based on the assumption that the stiffness of the sedimentary soil layers increases with depth below the ground surface.

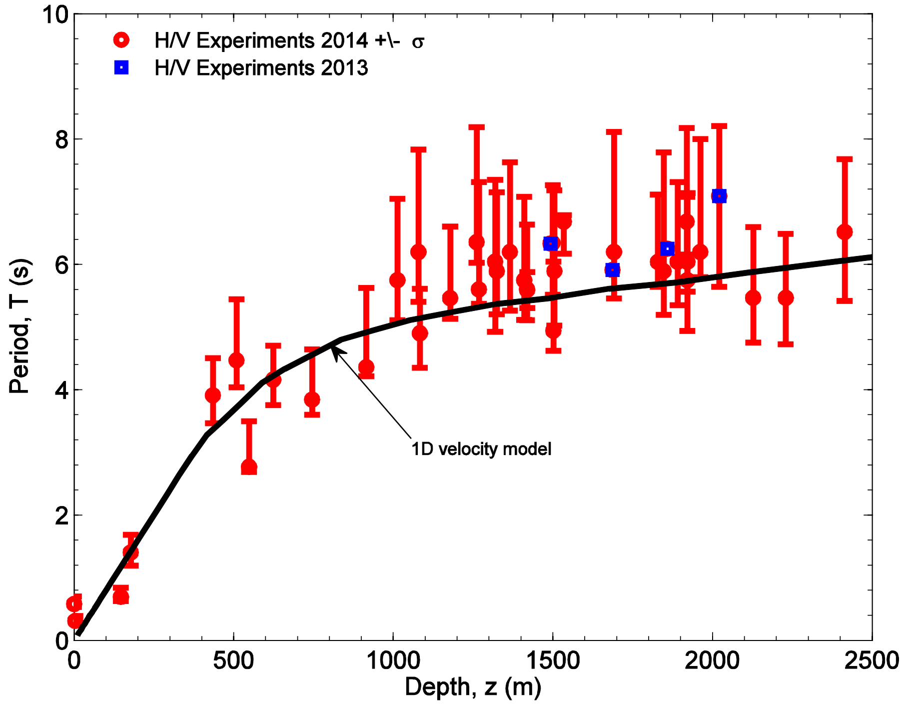

Figure 5. Comparison of estimated site period from H/V measurements and depth to basement rock from Lee et al. (2014)

Figure 5 also displays a simple 1D velocity model (in black) for the Canterbury region constructed based on the investigations of Cox et al. (2014) and Bradley and Graves (2014) (for shallow and deep layering, respectively). The site period of this 1D model for each specified depth, z, is calculated based on the fundamental period of the transfer function for the modelled soil layers above a half-space at depth z. The figure indicates that despite its simplicity, the 1D model is a good fit to the experimental results.

4 HEATHCOTE VALLEY SITE PERIODS

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).

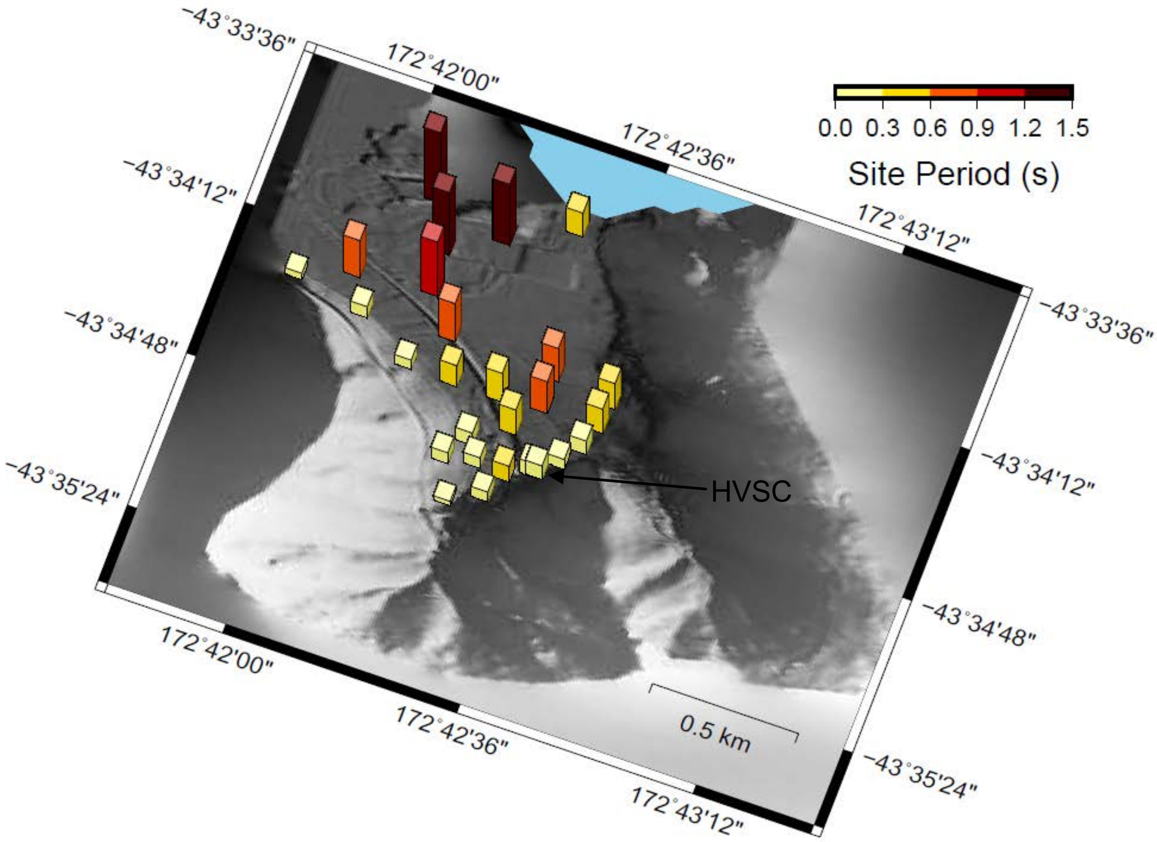

Figure 6. Summary of estimated site period from H/V spectral peaks in the Heathcote Valley and the location of the HVSC strong motion station.

The predominant site periods at the 26 locations where measurements were made in the Heathcote Valley (shown inset in Fig. 1) are displayed in Figure 6. 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 6, 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.

5 CONCLUSIONS

The main conclusions from this paper are focussed on the estimates of the site period at over 80 locations across the Canterbury Plains and Christchurch using the (H/V) spectral ratio method. 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=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. The 1D velocity model based on the studies of Cox et al. (2014) and Bradley and Graves (2014) is shown to provide a good fit to these experimental results. This study and previous studies have also 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.

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