A high-resolution shear wave velocity model for near surface soils in Christchurch using CPT data

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ABSTRACT: This paper summarizes the development of a high-resolution surficial shear wave velocity model based on the combination of the large high-spatial-density database of cone penetration test (CPT) logs in and around Christchurch, New Zealand and a recently-developed Christchurch-specific empirical correlation between soil shear wave velocity and CPT. This near-surface shear wave velocity model has applications for site characterization efforts via the development of maps of time-averaged shear wave velocities over specific depths, as well as use in site response analysis and ground motion simulation.

1 INTRODUCTION

The 2010-2011 Canterbury earthquake sequence resulted in widespread damage to the infrastructure in the greater Christchurch urban area (Bradley 2012a, Bradley 2012b, Bradley and Cubrinovski 2011, Cubrinovski, et al. 2011a, Cubrinovski, et al. 2011b, Cubrinovski, et al. 2010). Much of the incurred damage was geotechnical in nature, and as a result, a significant portion of the post-earthquake recovery efforts in Christchurch have involved the characterisation of the near-surface (depth < 30 m) soil conditions in the region. Thousands of subsurface exploration logs obtained through these ongoing recovery efforts have been made available for research purposes through the Canterbury Geotechnical Database project, providing an unparalleled resource in terms of the scope and spatial density of available subsurface data. In this study, the available cone penetration test (CPT) data (> 15000 individual records as of 1 February 2014) is used together with the Christchurch-specific CPT-V_S model of McGann et al. (2015b, 2015c) to develop a set of regional near-surface shear wave velocity (V_s) models that describe the spatial and depth-wise variation of V_s in terms of travel time-averaged shear wave velocities (V_{sz}). This paper represents a summary of work in this area, interested readers are referred to McGann et al. (2015a) for further details.

2 DEVELOPMENT OF REGIONAL SHEAR WAVE VELOCITY MODELS

2.1 Data and assumptions

The CPT data referenced in this paper includes 13670 individual CPT records extracted from the Canterbury Geotechnical Database as at 1 February 2014 for sites located throughout Christchurch and the surrounding towns and suburbs. The CPT records in this dataset generally cover the range of depths extending from the ground surface to the upper surface of the Riccarton Gravel that exists beneath Christchurch (Brown and Weeber 1992) though a large portion of the CPT tests were terminated at a pre-defined target depth (typically 20 m) or upon effective refusal above the Riccarton Gravel. The raw CPT measurement data from the adopted dataset was evaluated for suitability using a series of filters and exclusion criteria to ensure that only sites with consistent and useful data are used in the subsequent analysis and development steps. After the application of this criteria, a total of 10550 CPT sites were retained (i.e. 3120 CPT records were excluded) (McGann, et al. 2015a).

Shear wave velocity profiles are estimated for each CPT record using the Christchurch-specific CPT-V_S correlation of McGann et al. (2015b, 2015c). These V_S profiles can be illustrated as: (1) a function of depth at a specific location; or (2) used to develop surfaces describing the distribution of time-averaged shear wave velocity (V_{sz}) across the Christchurch area for specific depth intervals. A target profile depth of z = 30 m is presented here to allow for an overall assessment of the near-surface zone (V_{s30}) that is commonly used for building-code based site characterisation (e.g. ASCE/SEI 7-05 2006, Building Seismic Safety Council 2003). V_{sz} values are computed for each profile depth as:

$$V_{sz} = \sum d_i / \sum (d_i/V_{si}) \quad (1)$$

where d_i are CPT depth measurement increments up to the target depth, V_{si} are the mean shear wave velocities over each increment, and Σ indicates the sum over all increments.

Due to the nature of the stratigraphy beneath the Christchurch region, the computation of V_{s30} (time averaged shear wave velocity to 30 m) requires the estimation of the depth to the upper surface of the Riccarton Gravel and volcanic rock surfaces that underlie the surficial sediments (Brown and Weeber 1992), along with the estimation of the V_s values within these materials. A pair of interpolated surfaces describing the upper boundaries of the Riccarton Gravel and volcanic rock layers have been developed using well log data from about 530 sites in the Canterbury region (Lee, et al. 2014) and, for the Riccarton Gravel, the western outcrop of this surface per the GNS QMAP data for the Christchurch area (Forsyth, et al. 2008). These surfaces are used to estimate the depth to the top of the Riccarton Gravel or volcanic rock layers at each CPT site. For sites where the CPT termination depth is deeper than the estimated depth to these surfaces, the termination depth is used. Shear wave velocities for the Riccarton Gravel are estimated using the dense gravel reference V_s profile suggested by Lin et al. (2014) and Vs for the volcanic rock is assumed to be a constant 750 m/s. For CPT sites where the depth to one of these surfaces is < 30 m, these assumed gravel and rock velocities are appended to the CPT-V_s profile to get the 30 m deep V_s profiles necessary for the V_{s30} model.

2.2 Spatial interpolation for V_{sz} surfaces

Smooth surfaces of V_{sz} that approximate the CPT-based V_{sz} data points determined using equation (1) were fit to 200 m x 200 m grids. If no CPT record was within 300 metres of a single grid point, then no estimate of V_{sz} was computed at that point. This 300 m boundary distance was selected based on an examination of the spatial variability in the soil profiles, and was enforced to ensure the resulting surfaces focus only on well-constrained estimates as opposed to estimates over the full urban region. Each grid is subdivided according to the surficial geologic units (QMAP units) indicated on the 1:250,000 scale geologic map (QMAP) of Christchurch (Forsyth, et al. 2008), and for each target depth, z, the full V_{sz} surface is compiled from separate surfaces fit to the CPT results located in the alluvium, marine/dune, estuarine, and peat/swamp QMAP units to avoid interpolation or extrapolation across surficial geologic boundaries. The surface-fitting procedure uses a modified ridge estimator that is biased towards smoothness to achieve surfaces that are representative of the trends in the CPT results without necessarily representing V_{sz} at any particular site. V_{sz} values on the edges of the interpolated surfaces are naturally less constrained by existing CPT data, and are often based on extrapolation (up to the predefined 300 m boundary distance), thus, such values should be interpreted with a greater degree of uncertainty than values in the middle of the surfaces that are better constrained.

3 REGIONAL V_{S30} MODEL

Figure 1 shows the V_{s30} surface model developed from the aforementioned methodology. Major roads are indicated as black lines and the locations of a number of Christchurch suburbs and surrounding towns are indicated and labelled. The horizontal and vertical axes indicate the distance in kilometres from the lower-left datum noted in the figure caption. As shown in Figure 1, there is a large degree of spatial variability in V_{s30}, with values varying by about 100-120 m/s across the area. With the exception of some western sites with shallow gravels, there is a general trend of increasing V_{s30} from west to east in CPT-penetrable soils, as the values within the marine/dune QMAP unit located in the east tend to be higher than those in the alluvial, peat/swamp, and estuarine units located further west. The increased velocities in the marine/dune deposits may be due a combination of densification due to wave-action during deposition and the relative lack of fines and plastic soils in these deposits in comparison to the other surficial units. The general band of softer (i.e. low V_{s30}) alluvial sites located between Belfast in the north and the Port Hills in the south in particular have an increased amount of silty and clayey soil relative to the rest of the region. The eastern edge of this soft band, extending south from Belfast to Woolston, roughly corresponds with the coastline that existed approximately 3000 years ago (see Fig. 7, Brown and Weeber, 1992).

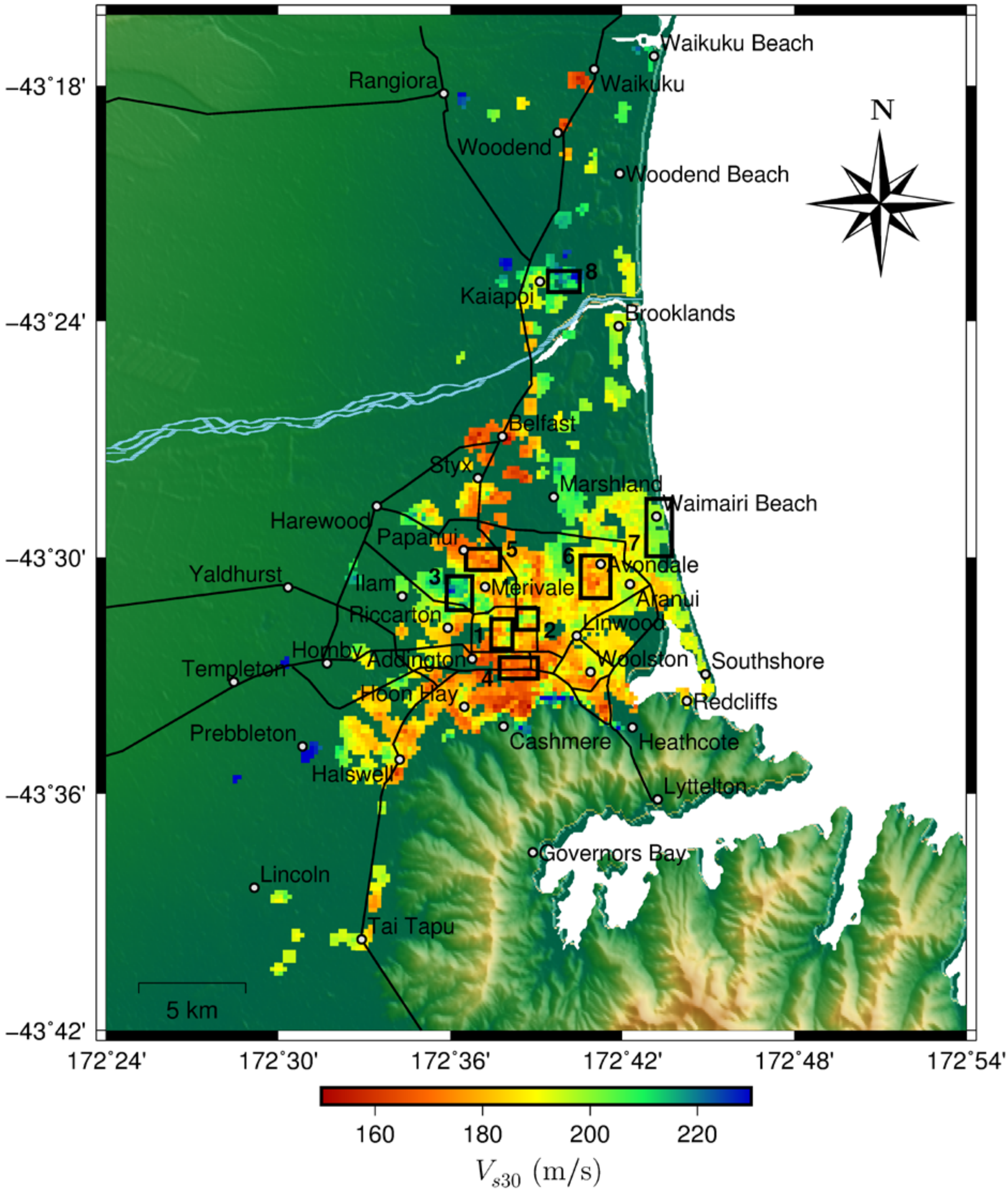

Figure 1. V_{s30} surface on uniform 200 x 200 m grid. Predictions are only provided in each grid cell if there is one or more CPT record within 300 m. Boxed regions of specific interest are subsequently discussed.

The sites located at the toe of the Port Hills to the south of Christchurch city display some of the highest V_{s30} values for the region, as these sites are generally underlain by volcanic rock at shallow depths ($z < 30$ m), as opposed to the Riccarton Gravels below the remainder of the sites. Other areas that have notably increased values of V_{s30} include the surficial dune sands in the east, which are clearly visible on the coast and the immediate western side of the estuary near Aranui, and some of the

Springston Formation over-bank deposit `lobes' in the western part of the city (Brown and Weeber, 1992). One such lobe is visible as the blue path between Ilam, Merivale, and Bryndwr, while others are notable for their absence from the surfaces (i.e. no CPT data for sites with surficial gravels).

3.1 Site classification from V_{s30}

One application of V_{s30} that is widely used for site characterisation purposes is the definition of V_{s30}-based site classes, e.g. the United States National Earthquake Hazards Reduction Program (NEHRP) site classes (ASCE/SEI 7-05 2006, Building Seismic Safety Council 2003), that dictate various seismic design requirements in building codes. Figure 2 shows the NEHRP site classes inferred from the V_{s30} surface of Figure 1 (without regard for the special conditions for site class F). As shown, the Christchurch sites are characterised as either NEHRP site class D (blue markers) or class E (red markers). The class E sites primarily correspond to known areas of silty, clayey, or swampy soils such as Papanui and Sydenham. There are also a few sporadic zones of class E soils along the path of the Avon river through the eastern suburbs of the city. Because only those CPT sites that penetrated to a useful depth were utilized, and because sites in the loess deposits were omitted, the results of Figure 2 do not depict stiff sites in the Port Hills or western suburbs which may be characterised as NEHRP site classes B or C.

It is noted that NZS1170.5 defines site classes on the basis of V_{s30} as well as other site conditions (site period, compressive strength) and therefore an "NZS1170.5-based map" is not trivial to derive directly from the V_{s30} map developed here.

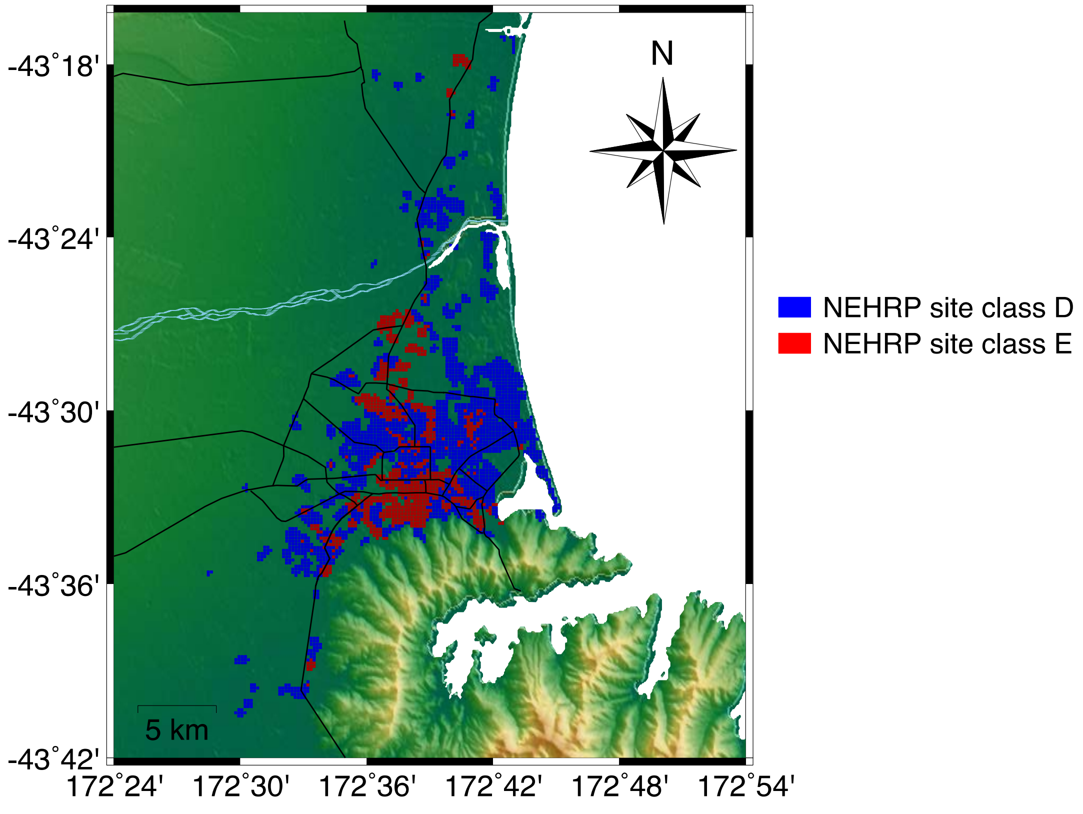

Figure 2. NEHRP site classes for Christchurch V_{s30} surface model. Red markers indicate site class E (V_{s30} < 180 m/s) and blue markers indicate site class D (180 < V_{s30} < 360 m/s).

4 TYPICAL VELOCITY PROFILES FOR SUBREGIONS OF CHRISTCHURCH

The V_{s30} maps discussed in the previous sections reveal the spatial variation in average shear wave velocity (and implied variation in average shear modulus) inherent to the Christchurch region, which are useful for generalised evaluations of the relative stiffness of different areas. However, it should be clear that soil profiles will vary with depth across the city and thus metrics such as V_{s30} provide only a highly simplified representation of site characterisation and site response. To investigate this further, typical V_s profiles are defined for a series of subregions of the Christchurch area and discussed in this section.

Figure 1 illustrates the locations of the eight subregions selected, while Figure 3 illustrates the velocity profiles with depth for these sites obtained based on the statistics of all the CPT measurements performed within these subregions. The mean V_s profiles are noted as solid blue lines in each plot, and the dashed lines represent ± one standard deviation from the mean profiles. The smoothly-varying velocities reached near the base of the profiles are the simplified representation of the Riccarton Gravels.

To provide a general characterisation of each typical velocity profile that is useful for comparisons between the subregions, the V_s plots for each case also note the time-averaged shear wave velocities, V_{sz}, computed for the mean profiles using Eq. (3.1) on 5 m intervals for the maximum target profile depths. As shown in Figure 3, the uncertainty in the mean V_s profiles is relatively small, with a maximum standard deviation of approximately 50-60 m/s, indicating that they provide reasonable representations of the soil profiles in the considered subregions that can be used to evaluate characteristic seismic responses and develop simplified profiles.

In an overall sense, and in the context of the NEHRP site classification system (all of the typical profiles correspond to site class D or E), the V_{s30} values for all of the subregions are nominally the same. However, as shown in Figure 3, there is a fair amount of variability in the typical V_s profiles for the considered subregions both in terms of the shear wave velocities represented, and in terms of the depth to the top of the Riccarton Gravel.

4.1 **Comparison of transfer functions for typical profiles**

Figure 4 illustrates the site response transfer functions that were computed from the mean V_s profiles shown in Figure 3 to investigate the similarities and differences in low-amplitude seismic response for 30 m deep profiles within the considered Christchurch subregions. Regions with similar V_{s30} values are grouped together in Figure 4 to emphasize the relative differences in seismic response indicated for regions that are classified as similar according to V_{s30}-based criteria such as the NEHRP site classes. Figure 4a shows the soft subregions, Sydenham (region 4) and Papanui (region 5) where V_{s30} < 180 m/s; Figure 4b includes the intermediate V_{s30} subregions, Avondale (region 6), North New Brighton (region 7), and the two CBD regions (regions 1 and 2); and Figure 4c shows the two stiff subregions, Fendalton (region 3) and Kaiapoi (region 8) where V_{s30}> 210 m/s due primarily to the presence of the previously discussed shallow gravels. As shown in Figure 4, there is quite a bit of difference between the transfer functions computed from the typical 30 m V_s profiles for subregions 1-8. The differences are most apparent in the upper and lower plots of Figure 4, which compare the transfer functions for the softest and stiffest regions, respectively.

The typical profiles for regions 4 and 5 have essentially identical V_{s30} values (176.6 and 179.6 m/s, respectively). However, based on the results of Figure 4, given identical input motions at 30 m depth, the resulting surficial motions, and the associated effects on structural response, would likely be quite different. The peak amplifications occur for different frequencies (max amplification for region 4 at 4.7 Hz and at 2.5 Hz for region 5), and have different amplitudes (max amplification factor is 2.4 in region 4 and 2.8 in region 5). In addition, the peak amplification factor for region 4 occurs in the second mode rather than in the first mode as for region 5, and the amplification for higher modes in region 4 is generally greater than or equal to that in region 5. The typical profiles for regions 3 and 8 are also nominally identical in terms of V_{s30} and show a similar difference in peak amplification magnitude (2.2 in region 3, 2.5 in region 8). The transfer functions for these subregions also show a difference in frequency for the first mode (2.8 Hz in region 3, 3.7 Hz in region 8). The higher modes in Fendalton have amplification factors greater than or equal to those in Kaiapoi and occur at lower frequencies.

The transfer functions for the subregions shown in Figure 4b (regions 1, 2, 6, and 7) are more similar to each other than in the previously discussed groupings, but differences are still apparent. The V_{s30} values for the profiles in all four of these subregions are within about 12 m/s of each other, however, there is a clear distinction between the transfer functions for the CBD (regions 1 and 2) and eastern Christchurch (regions 6 and 7) subregions that does not correspond to their relative V_{s30} values. The magnitude of the peak amplification in the first two modes of regions 1 and 2 are nominally identical at about 2.1, but the modal troughs in region 2 are less pronounced and the modal peaks are generally greater in amplitude beyond the second mode. For the eastern Christchurch subregions, the amplification and frequency for the first mode are similar (amplification of about 1.6-1.9 at 2.25 Hz) and the second mode response has a larger amplification factor in both cases. The higher modes in region 6 generally occur at lower frequencies than in region 7, and beyond the third mode, the amplification factors in the higher modes for region 7 are generally higher.

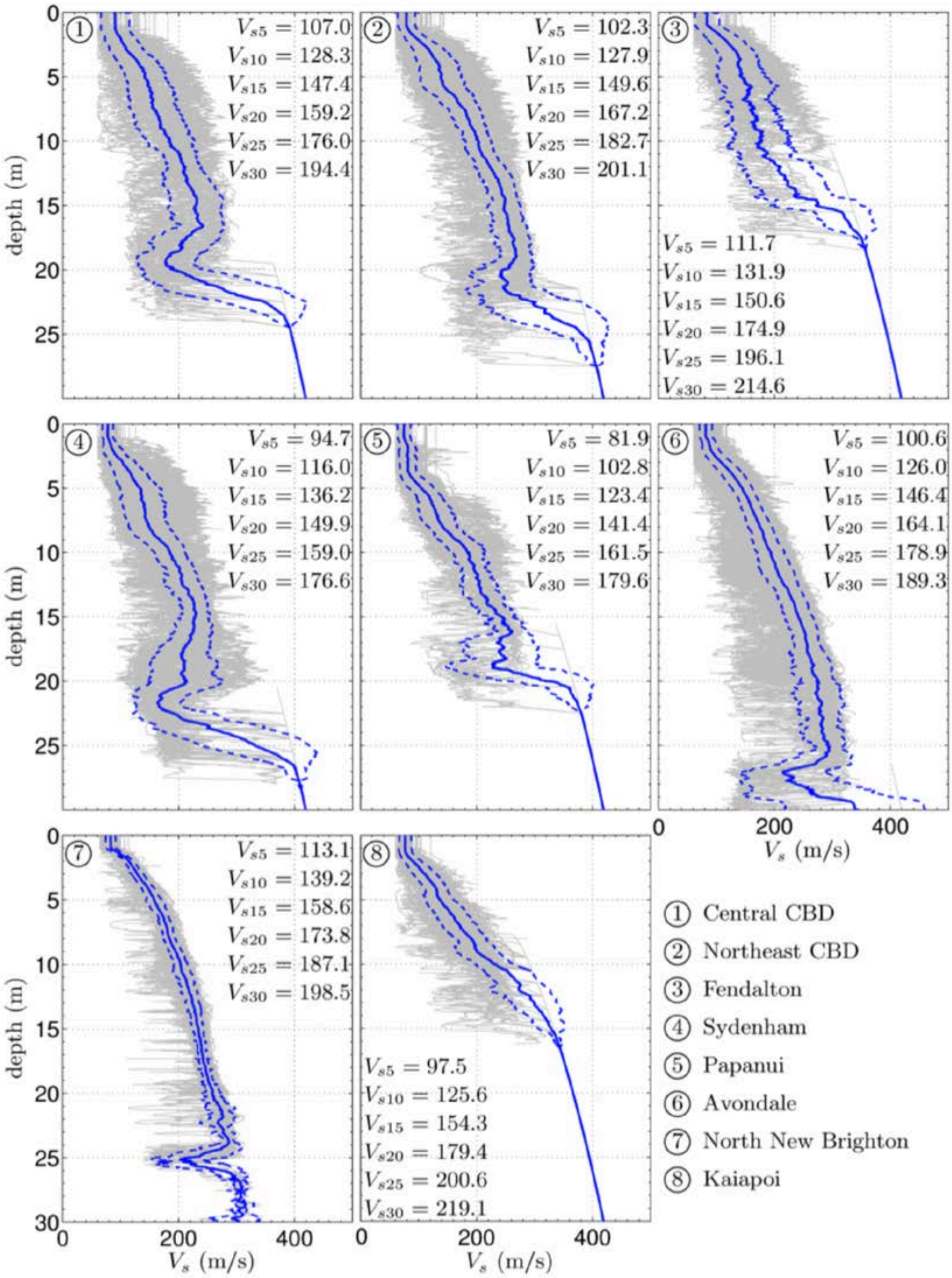

Figure 3. Typical V_S profiles for 8 Christchurch subregions including estimated gravel velocities for depths below top of Riccarton Gravel surface. Region number is noted in upper left of each plot corresponding to Figure 1.

Because the transfer functions are based on the assumption of linear response, it is not expected that any observations made here will hold for large amplitude ground motions that induce nonlinear soil behaviour. Factors that are not captured here, such as soil composition, the relative distribution of soil density within the profile, and the location of the groundwater table become more important under large amplitude shaking and will arguably lead to further differences between the seismic response characteristics of the different deposits. However, the transfer functions for these velocity profiles provide a simple means with which to evaluate V_{s30} as a predictive metric for site response in the Christchurch area.

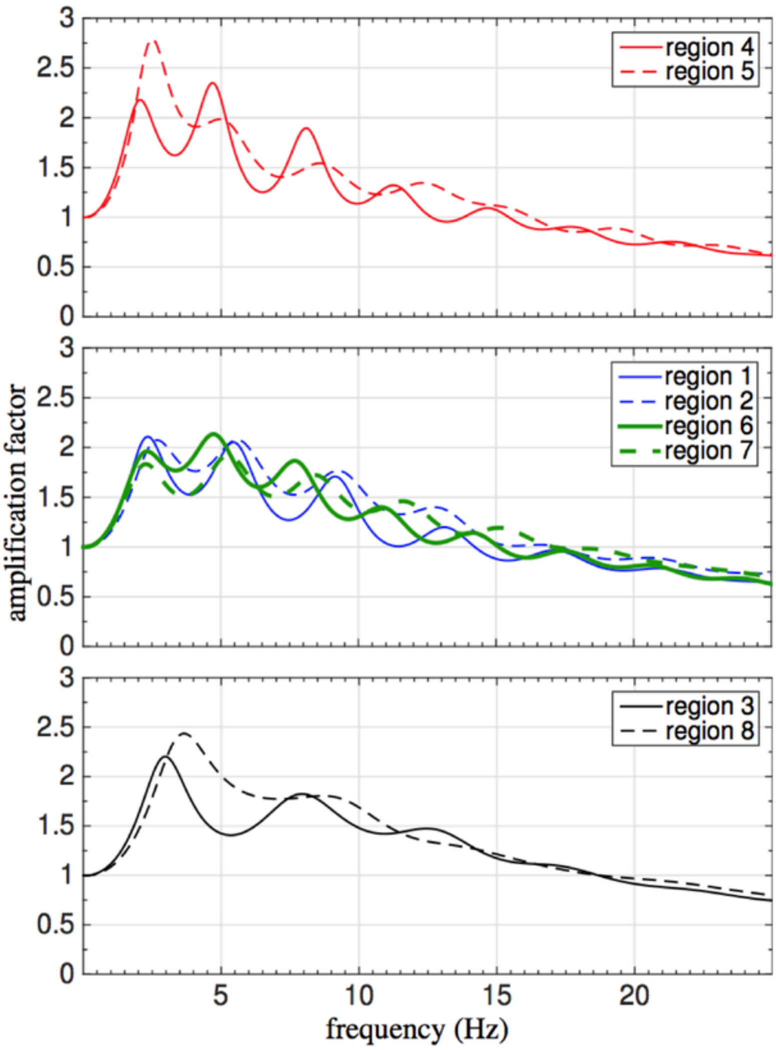

Figure 4. Transfer functions for 8 Christchurch subregions grouped by V_{s30}.

5 CONCLUSIONS

This paper summarized the development of a high-resolution surficial shear wave velocity model for Christchurch based on the combination of the large high-spatial-density database of CPT logs and a recently-developed Christchurch-specific empirical correlation between soil shear wave velocity and CPT. It was demonstrated that this near-surface shear wave velocity model can be utilized to develop maps of the time-averaged shear wave velocity for specific depths, V_{sz}, an example being V_{s30} commonly used in site characterisation. In addition, velocity profiles with depth were developed for eight different subregions to illustrate the variability in V_s with depth over Christchurch and also infer its implications for site response via a comparison of the site response transfer functions for each subregion. This high-resolution V_s model will therefore enable significant insights into the role of near-surface site response in the 2010-2011 Canterbury earthquakes as well as potential future events.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

ASCE/SEI 7-05. 2006. Minimum design loads for buildings and other structures, American Society of Civil Engineers. 388.

Bradley, B.A. 2012a. Ground motions observed in the Darfield and Christchurch earthquakes and the importance of local site response effects. *New Zealand Journal of Geology and Geophysics*; 55(3): 279-286.

Bradley, B.A. 2012b. Strong ground motion characteristics observed in the 4 September 2010 Darfield, New Zealand earthquake. *Soil Dynamics and Earthquake Engineering*; 42 32-46.

Bradley B.A. & Cubrinovski, M. 2011 Near-source Strong Ground Motions Observed in the 22 February 2011 Christchurch Earthquake. *Seismological Research Letters*; 82(6): 853-865.

Brown L.J. & Weeber, J.H. 1992. Geology of the Christchurch urban area, Geological and Nuclear Sciences. 110.

Building Seismic Safety Council. 2003. Recommended Provisions for Seismic Regulations for New Buildings and Other Structures. 356.

Cubrinovski, M., Bradley, B.A., Wotherspoon, L., Green, A.G., Bray, J., Wood, C., Pender, M., Allen, C.R., Bradshaw, A., Rix, G., Taylor, M., Robinson, K., Henderson, D., Giorgini, S., Ma, K., Winkley, A., Zupan, J., O'Rourke, T.D., DePascale, G. & Wells, D.L. 2011a. Geotechnical Aspects of the 22 February 2011 Christchurch Earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*; 44(4): 205-226.

Cubrinovski, M., Bray, J.D., Taylor, M., Giorgini, S., Bradley, B., Wotherspoon, L. & Zupan, J. 2011b. Soil Liquefaction Effects in the Central Business District during the February 2011 Christchurch Earthquake. *Seismological Research Letters*; 82(6): 893-904.

Cubrinovski, M., Green, R.A., Allen, J., Ashford, S.A., Bowman, E., Bradley, B.A., Cox, B., Hutchinson, T.C., Kavazanjian E., Orense, R.P., Pender, M., Quigley, M. & Wotherspoon, L. 2010. Geotechnical reconnaissance of the 2010 Darfield (Canterbury) earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*; 43(4): 243-320.

Forsyth, P.J., Barrell, D. & Jongens, R. 2008. Geology of the Christchurch area, GNS Science. 76.

Lee, R.L, Bradley, B.A., Ghisetti, F., Pettinga, J.R., Hughes, M.W. & Thomson, E.M. 2014. A 3D seismic velocity model for Canterbury, New Zealand for broadband ground motion simulation, in *Southern California Earthquake Centre (SCEC) Annual Meeting*: Palm Springs, California.

Lin, Y.-C., Joh, S.-H. & Stokoe, K. 2014. Analysis of the UTexas 1 surface wave dataset using the SASW methodology,, in *Geo-Congress 2014 Technical Papers*, *GSP 234*, 830–839.

McGann, C.R., Bradley, B.A. & Cubrinovski, M. 2015a. High-Density Shallow Shear Wave Velocity Characterization of the Urban Christchurch, New Zealand Region University of Canterbury Research Report No. 2015-02, University of Canterbury. 67.

McGann, C.R., Bradley, B.A., Taylor, M.L., Wotherspoon, L.M. & Cubrinovski, M. 2015b. Applicability of existing empirical shear wave velocity correlations to seismic cone penetration test data in Christchurch New Zealand. *Soil Dynamics and Earthquake Engineering*; (in press).

McGann, C.R., Bradley, B.A., Taylor, M.L., Wotherspoon, L.M. & Cubrinovski, M. 2015c. Development of an empirical correlation for predicting shear wave velocity of Christchurch soils from cone penetration test data. *Soil Dynamics and Earthquake Engineering*; (in press).