Soil Profile Characterisation of Christchurch Strong Motion Stations

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ABSTRACT: This paper presents an overview of the soil profile characteristics at a number of strong motion station (SMS) sites in Christchurch and its surrounds. An extensive database of ground motion records has been captured by the SMS network in the Canterbury region. 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. The original NZS1170.5 (SNZ 2004) site subsoil classifications for each SMS site based on regional geological information and well logs located at varying distances from the site. Given the variability of Christchurch soils, more detailed investigations are required in close vicinity to each SMS. In this regard, CPT, SPT and borehole data, and shear wave velocity (V_s) profiles in close vicinity to the SMS are currently being used to develop representative soil profiles at each site. Site subsoil classifications based on V_s measurements performed by the authors do not always agree with the original classifications, often indicating that a softer site class is appropriate. However, SPT N values often indicate a stiffer site class than the V_s data, in some cases also disagreeing with prior assumed classifications. Hence, the recent site investigation data presented herein highlights the importance of having detailed site-specific information at SMS locations in order to properly classify them. Furthermore, additional studies are required to harmonize site classification based on SPT N and V_s.

1 INTRODUCTION

This paper presents updated soil profile classifications of a selection of strong motion stations (SMS) in the vicinity of Christchurch based on recently completed geotechnical site investigations. The aim of this on-going research is to develop representative soil profiles at each of these sites and to define the NZS1170.5 site classes with more confidence than the previously assumed classifications. Cone penetrometer testing (CPT), boreholes and standard penetration testing (SPT), and surface shear wave velocity (V_s) profiling was performed at the majority of SMS in the focus area within the city of Christchurch and the towns of Kaiapoi and Lyttelton.

1.1 Christchurch strong motion station network

Prior to the 2010 Darfield earthquake, the city of Christchurch was instrumented with a large network of strong motion stations. Within Christchurch there were seven SMS as part of the National Strong Motion Network and nine as part of CanNet (Avery et al. 2004). Additionally, there are SMS located in both Lyttelton (LPCC) and Kaiapoi (KPOC), all combined as part of the GeoNet project. This network of SMS recorded a vast database of strong ground motions during the 2010-2011 Canterbury earthquake sequence.

Since the 2010 Darfield earthquake, nine additional SMS have been added to the National Strong Motion Network within Christchurch (as of February 2012), and of these, four are located on rock sites. This research focuses on the definition of the site classes at the SMS installed prior to the Darfield earthquake, however future investigations are essential in order to classify the newer sites and to be able to relate the site geotechnical conditions to the recorded ground motions. An overview of the SMS network in Christchurch and Lyttelton is presented in Figure 1, while the SMS at Kaiapoi is outside the boundaries of this figure.

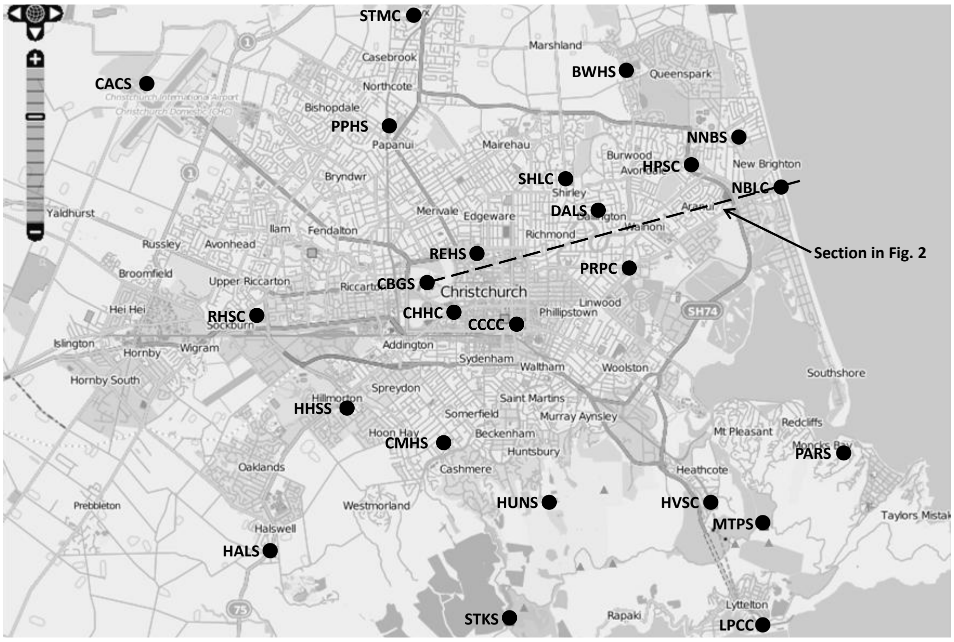

Figure 1. Christchurch and Lyttelton Strong Motion Station Network (adapted from GeoNet 2013).

1.2 NZS1170.5 Site Subsoil Classes

NZ1170.5 uses a combination of undrained shear strength (s_u), SPT *N*, V_s, and site period (*T*) to define site subsoil classes (referred to as site classes in the remainder of this paper). In this paper, all SMS 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 SMS are classified as either site class C – shallow soil, site class D – deep or soft soil, or site class E – very soft soil.

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 (or site period) is less than or equal to *T*=0.6 seconds, the site can be classified as site class C. The natural period of a uniform soil deposit over bedrock is theoretically calculated as four times the thickness of the soil divided by the V_s of the soil (equivalently stated as four times the shear wave travel time from bedrock to the surface). Natural period can be estimated from a V_s profile that extends down to bedrock (or another significant impedance contrast) or from direct horizontal-to-vertical spectral ratio (H/V) measurements. Secondly, maximum depth limits are defined for a range of representative s_u and SPT *N* soil profiles. The maximum depth for very dense cohesionless soils is 60 m, and the maximum depth of gravels is 100 m. Natural period is the preferred of the two approaches.

2 GEOTECHNICAL SITE INVESTIGATION

Prior to 2011, little information regarding the subsurface geotechnical characteristics of the strong motion station locations was available. The soil profiles and site classes were assumed from well logs and regional geological knowledge (Cousins & McVerry 2010). An overview of the site class classifications based on this prior knowledge is presented and a more detailed summary of site investigations at select SMS are presented on a site-by-site basis in the following sections.

Initially, existing borehole and CPT test data in the vicinity of each SMS was collated. At locations with a paucity of data, an additional program of subsurface site investigations is in process. Surface wave testing to infer V_s layering at 13 SMS in Christchurch and Kaiapoi is summarised in Wood et al. (2011), with all V_s profiles presented here taken from this paper. These profiles were all developed without any a priori knowledge of the subsurface stratigraphy.

Because the interpretation of sites classes in NZS1170.5 is based on SPT data for cohesionless soils, CPT data was converted to an equivalent SPT N_{60} value using the approach from Lunne et al. (1997):

$$\frac{\left(q_t / p_a\right)}{N_{60}} = 8.5\left(1 - \frac{I_c}{4.6}\right) \qquad (1)$$

where q_t is the corrected cone resistance, p_a is atmospheric pressure, and I_c is the soil behaviour type index (Robertson & Wride 1998). Additionally, because the energy efficiency of the SPT hammers used in investigations were variable, and significantly higher than the 60% benchmark, SPT N_{60} values rather than raw SPT N values have been used for the site classifications in this paper.

2.1 Regional Overview

Of all the sites investigated, only Cashmere High School (CMHS), Heathcote Valley Primary School (HVSC) and LPCC encountered bedrock at depths less than 25 m, consistent with these sites' proximity to the Port Hills. Using the NZS1170.5 preferred approach, Wood et al. (2011) showed that these locations had estimated site periods less than the T=0.6 second threshold for site class D. Of these three sites, only the HVSC site is discussed in detail in this paper. Away from the Port Hills, the shear wave velocity profiles presented in Wood et al. (2011) did not encounter bedrock, as these SMS sites are likely underlain by deep (i.e. many hundreds of metres) sedimentary deposits of interbedded gravels and fine to very fine grain sediments (Brown & Weeber 1992). Using four times the average shear wave velocity between the base of the V_s profile and the ground surface, the site period at the remainder of sites was determined to be greater than 0.57 seconds, which is the estimated value at RHSC using the shallow V_s profile. Given that the total soil profile to bedrock was deeper than the shallow V_s profiles available at these sites, and in many cases likely to be significantly deeper, it is reasonable to conclude that the site periods of the remainder of these SMS locations are dominated by these deep deposits and are well in excess of the T=0.6 second threshold for site class D.

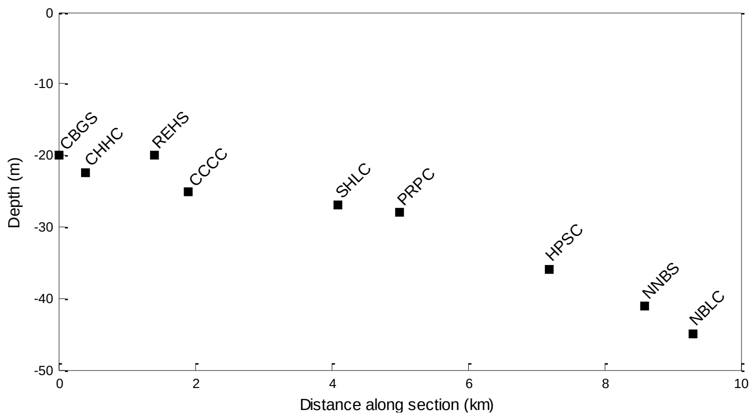

Figure 2. Cross section showing depth to Riccarton Gravels beneath Christchurch (location indicated by dashed line in Figure 1)

Another depth measure in the city of Christchurch is the depth to the Riccarton Gravel Formation, important because it is the most suitable founding depth of deep foundation systems and is an aquifer that forms a major part of the Christchurch water supply. Taking a cross section of the city from CBGS to NBLC (shown by the dashed line in Figure 1), and projecting the depths to the Riccarton Gravels from the subsurface site investigations at surrounding SMS onto this section, an overview of the depth variation beneath the city was developed as shown in Figure 2. The Riccarton Gravels create a significant shear wave velocity contrast with the overlying looser sediments (Christchurch and Springston Formation) across much of Christchurch and is likely to result in a significant higher mode of vibration that has a much shorter period than the site period of the entire soil column down to bedrock. This requires further study to determine the impacts on site classification.

2.2 **Christchurch Botanical Gardens (CBGS)**

The CBGS SMS is located approximately 600 m west of the western edge of the Christchurch CBD, housed in a wooden building with a shallow concrete pad foundation (approx. 5 x 10 m). There was no clear manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following any of the major earthquakes in the Canterbury earthquake sequence. However, acceleration records from the 2011 Christchurch earthquake showed a clear indication of liquefaction of the underlying soils, with characteristic acceleration spikes and reduced high frequency content in the latter part of the record (Bradley & Cubrinovski 2011). A few hundred metres to the north of the SMS significant volumes of ejecta were evident at the ground surface in North Hagley Park.

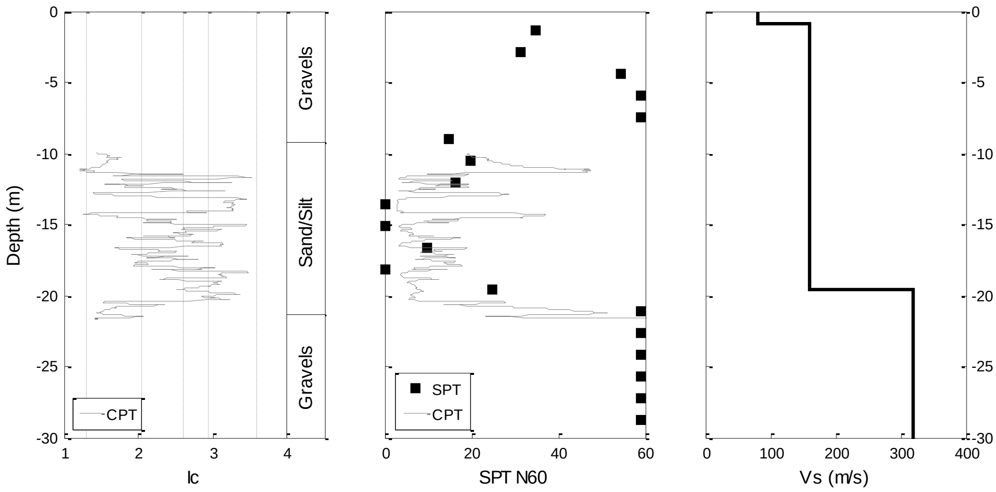

Figure 3. Christchurch Botanical Gardens (CBGS) soil profile data to 30 m

Borehole, SPT and CPT data within a few metres of the SMS is summarised in Figure 3, with the soil type from the borehole logs and I_c values from a CPT sounding represented in the left hand plot (I_c<1.31: Gravelly sand to sand; 1.31< I_c <2.05: Clean sand to silty sand; 2.05< I_c <2.6: Silty sand to sandy silt; 2.6< I_c <2.95: Clayey silt to silty clay; 2.95< I_c <3.6: Silty clay to clay; I_c >3.6: Organic material). Borehole logs indicate approximately 9 m of gravels at the surface overlying interbedded layers of sand, sandy silt and silt down to 21 m. I_c values also indicate the variability of deposits within the 9-21 m depth range, with the lowest SPT N_{60} values measured in the silt layers. The Riccarton Gravels were encountered at a depth of 21 m, coinciding with a sharp increase in SPT N_{60} values.

Shear wave profile data from surface wave measurements performed 20 m from the SMS are also summarised in Figure 3. The V_s profile illustrates that there are some very soft surface deposits, underlain by 18 m of soft deposits with a V_s of 160 m/s. At a depth of approximately 20 m there is an increase in the shear wave velocity to 320 m/s, correlating to the depth to Riccarton Gravels at this location. Using this depth and the V_s profile information, the estimated natural period of the deposits above the Riccarton Gravels is equal to 0.51 seconds, which shows good agreement with the H/V spectral ratio derived period of 0.45 seconds from Wood et al. (2011). Note that a much longer fundamental site period is expected for the entire soil profile down to bedrock.

As shown in Figure 3, bedrock was not encountered in any of the in-situ tests at this location, with the site period using the top 36.6 m of the soil profile from V_s measurements determined to be greater than 0.72 seconds, putting it outside the site class C limits (Wood et al. 2011). Using the NZS1170.5 site class definitions, the location aligns to site class D using SPT *N* values, with less than 10 m of material with N<6 blws/0.3 m. V_s data shows that there is almost 20 m of material with V_s<165 m/s. V_s estimates from surface wave methods are considered accurate to within 10% (Wood et al. 2011), with the application of this 10% offset shifting this profile below the site class E limit. Based on this possibility, and that the depth of soft deposits is almost double the site class E thickness criteria, the site has been given a dual classification of site class D/E (denoted as E* in Wood et al. 2011).

2.3 **North New Brighton School (NNBS)**

The NNBS SMS is located in the north east region of Christchurch, housed in a small wooden shed with a shallow concrete pad foundation (approx. 5 x 7.5 m). There was no liquefaction manifestation at the ground surface in the direct vicinity of the SMS, however just 60 m to the north there was ejected sands in the school grounds. These regions with and without ejected material were separated by a slight elevation change (less than 0.5 m), with ejecta evident in the lower areas.

Site investigation data is summarised in Figure 4, with two CPT soundings and a V_s profile within 50 m of the SMS location. I_c values from CPT data are summarised in the left hand plot in Figure 4. Data from a borehole 100 m to the west of the SMS was included here, with soil type again summarised in the left hand plot. Borehole records show the transition from a medium dense sand with trace silt to a dense sand with minor silt at approximately 10 m depth, with I_c values indicating similar soil types.

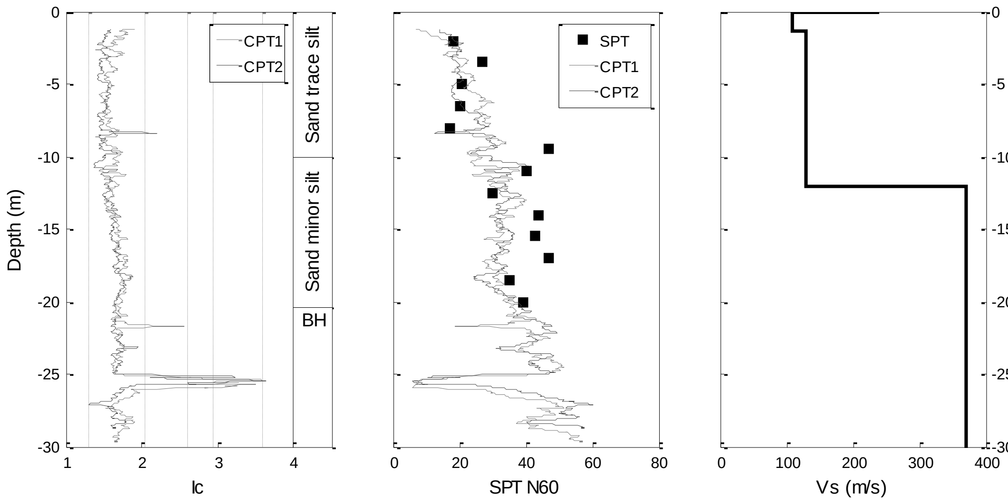

Figure 4. North New Brighton School (NNBS) soil profile data to 30 m

SPT N_{60} values from SPT and CPT correlation (Eqn. 1) agree fairly well, showing an increase in the penetration resistance of the profile at a depth between 10 and 12 m. Approximately 80 m from the SMS, a CPT was carried out to refusal at a depth of 40 m, where the cone likely encountered the Riccarton Gravels. This depth to the Riccarton Gravels has been deemed appropriate to classify the soil profile at the SMS.

The shear wave velocity profile in Figure 4 shows 12 m of soft surface deposits, with a V_s increasing from 110 to 130 m/s. Below this, a much stiffer deposit with a V_s of 370 m/s is shown. This depth correlates well with the change in SPT N_{60} and stratigraphy shown in the subsurface investigations.

Similar to CBGS, bedrock was not encountered in any of the in-situ tests, and the NNBS site period estimate using the top 37 m of the soil profile from V_s measurements was greater than 0.64 seconds, putting it outside the range of a class C soil. If the V_s profile is extended to the top of the Riccarton Gravels at 40 m depth and V_s=370 m/s is assumed between 37 and 40 m, the estimated natural period of the deposits above the Riccarton Gravels is equal to 0.68 seconds, which again shows good agreement with the H/V spectral ratio derived period of 0.73 seconds from Wood et al. (2011). Using the NZS1170.5 site class definitions for SPT N this location aligns to site class D, with values consistently above 20 blws/0.3 m, well above the site class E cutoff of 6 blws/0.3 m. However, the V_s measurements show more than 10 m of material with V_s<150 m/s, aligning to site class E. As a result, Wood et al. (2011) classified NNBS as site class E, in agreement with the assumption made prior to site-specific testing.

2.4 Heathcote Valley Primary School (HVSC)

The HVSC SMS is located in the south east region of Christchurch on a colluvium wedge at the head of the Heathcote Valley in the Port Hills. The sensor and equipment at this site are housed in a steel clad shed with a shallow slab foundation (approx. 8 x 9 m) which is attached to a larger building also on a shallow foundation. This SMS is located at 25 m RL, a much higher elevation than the other SMS presented in this paper that are at or below 7 m RL. There was no surface evidence of liquefaction in the surrounding area following any of the major earthquakes, with ground motions at the site also showing none of the characteristics of liquefaction triggering.

In-situ test data from five CPTs and a V_s profile within 60 m of the SMS are summarised in Figure 5. Three CPTs reached refusal at a depth of approximately 17 m, and two at a depth of approximately 20 m. I_c values indicate that the majority of the profile consists of a mix of silty sands, sandy silts, clayey silts and silty clays. The variability of the SPT N_{60} values in this figure is not unexpected given the nature of the deposition and the variable particle sizing of the colluvium.

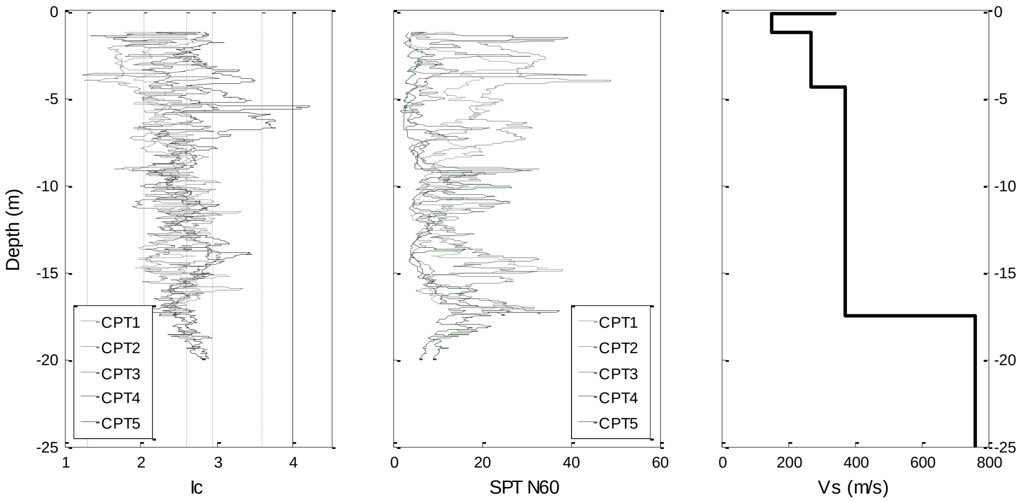

Figure 5. Heathcote Valley Primary School (HVSC) soil profile data to 25 m

The V_s profile in Figure 5 shows an increase in V_s to 760 m/s at a depth of 17.5 m, correlating well with the depths of CPT refusal and suggesting the existence of bedrock at this depth. Between this depth and 4.5 m, the V_s was equal to 370 m/s, indicating that the near surface loess deposits at this site were much stiffer than the alluvial deposits at the other two locations presented in this paper.

The estimated site period using the V_s profile was equal to 0.22 seconds, well below the maximum site period for site class C. A representative lower bound SPT N_{60} value of 10 is appropriate for this site over a depth of 20 m, well within the site class C maximum depth limit of 40 m for this SPT N value.

3 REVISED SITE CLASS SUMMARY

Collating the most up-to-date site investigation data from all SMS locations, a preliminary summary of the site classes defined using the V_s profiles and subsoil geotechnical in-situ test data is presented in Table 1. The site period details for the SMS locations have been outlined in Section 2.1. Based on V_s, the majority of the sites shown in Table 1 had sites classes that differed from what had previously been assumed based on the NZS1170.5 guidelines. The rationale behind these classifications is explained in more detail in Wood et al. (2011). In this paper dual classifications have been used for some sites instead of the single site classifications (e.g., E*, E**, etc) used in Wood et al. These dual classified sites align to site class D if the NZS1170.5 guidelines are strictly followed, however, engineering judgement suggests that site class E may be appropriate.

A summary of the SPT N_{60} data from the sites that have not been previously discussed is presented in Figure 6. Based on the measured and/or correlated N_{60} values, three sites (HPSC, NNBS, PRPC) in Table 1 had site classes that differed from the original assumptions, with each of these shifting to a stiffer site class (i.e. a shift from site class E to D), while one site with a dual classification (SHLC) was reclassified as the stiffer of these site classes. Each of the sites that were originally assumed site class D were again classified using the SPT N data (CBGS, CCCC, CHHC). If raw SPT N values were used to classify these sites rather than SPT N_{60}, there would still be no site class E classifications. Only two of the eight sites were classified as the same site class using V_s and SPT N (HVSC, SHLC), with HVSC agreeing with the originally assumed site class, and SHLC matching the stiffer of the original dual classifications. This disagreement between V_s and SPT N site classification has also been identified in other studies. Some potential issues may be: (1) correlating SPT N values from a generic (i.e., not regional specific) CPT relationships, and (2) using uncorrected/raw SPT N values without adjusting for overburden pressure and hammer efficiency as is typically done for liquefaction triggering analyses. Regarding potential differences in site classification obtained from SPT N, s_u and V_s, the American Association of State Highway and Transportation Officials (AASHTO) recommends "In all evaluations of site classification, the shear wave velocity should be viewed as the fundamental soil property, as this was used when conducting the original studies defining the site categories" (AASHTO 2011). This course of action obviously requires high-quality V_s measurements made by competent experts, as V_s profiles obtained from surface wave methods require a great deal of expertise and care. None of the sites classified as D via SPT N values were close to the site class E SPT N boundary of 6, yet many of them had significantly thick layers of low V_s material. Clearly the decision to classify a site based on SPT N versus V_s requires further study.

Table 1. Site class definitions – original assumptions and updated classifications

Station Code	Original Assumed Site Class	Site Class Based on V_s	Site Class Based on SPT N
CBGS	D	D/E*	D
CCCC	D	E	D
CHHC	D	D/E**	D
HPSC	E	D/E***	D
HVSC	C	C	C
NNBS	E	E	D
PRPC	E	D/E*	D
SHLC	D/E	D	D

* Profile with greater than 10 m of V_s<165 m/s

**Profile with greater than 20 m of V_s<180 m/s

*** Profile with 8 m of V_s≤150 m/s

4 CONCLUSIONS

This paper has presented updated soil profile classifications of a selection of strong motion stations (SMS) in the vicinity of Christchurch based on recently completed geotechnical site investigations. Site classifications based on V_s did not agree with all prior classifications, often indicating that a softer site class is appropriate. SPT N values often indicate a stiffer site class than the V_s data, in some cases also disagreeing with prior assumed classifications. Hence, the recent site investigation data presented herein highlights the importance of having detailed site-specific information at SMS locations in order to properly classify them. Furthermore, additional studies are required to harmonize site classification based on SPT N and V_s. Additional site investigations will be performed in the near future to further refine the soil profile details using both surface and subsurface methods, with subsurface details used to refine the previously defined V_s profiles and seismic CPT investigations used as a comparison to the shear wave profile data derived from surface wave tests.

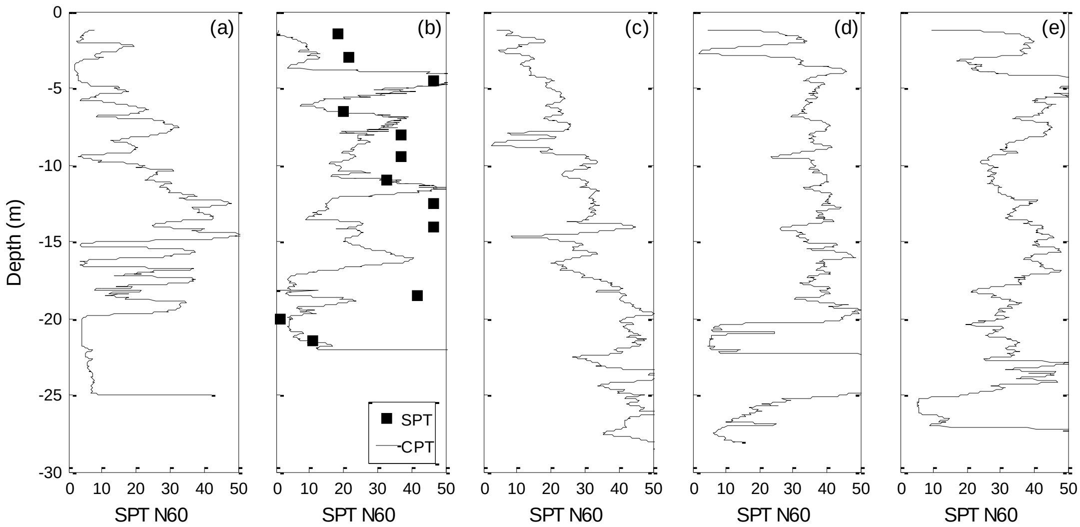

Figure 6. SPT N_{60} profiles at SMS locations: (a) CCCC; (b) CHHC; (c) HPSC; (d) PRPC; (e) SHLC

5 ACKNOWLEDGEMENTS

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REFERENCES

American Association of State Highway and Transportation Officials 2011. *Guide Specifications for LRFD Seismic Bridge Design.* 2nd Edition, Washington, DC.

Avery, H.R., Berrill, J.B., Coursey, P.F., Deam, B.L., Dewe, M.B., Francois, C.C., Pettinga, J.R., & Yetton, M.D. 2004. The Canterbury University strong-motion recording project. *Proc. 13th WCEE, Vancouver, August 1- 6, 2004.*

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

Brown, L.J. & Weeber, J.H. 1992. *Geology of the Christchurch urban area.* Institute of Geological and Nuclear Sciences, Lower Hutt.

Cousins, J. & McVerry, G. 2010. Overview of strong motion data from the Darfield Earthquake, *Bulletin of the NZSEE*, Vol 43(4): 222-227.

GNS Science 2013. *GeoNet* http://www.geonet.org.nz (accessed January 15, 2013)

Lunne, T., Robertson, P.K. & Powell, J.J.M. 1997. *Cone Penetration Testing in Geotechnical Engineering Practice*. Blackie Academic and Professional, New York.

Robertson, P.K. & Wride, C.E. 1998. Evaluating cyclic liquefaction potential using the cone penetration test, *Canadian Geotechnical Jnl.*, Vol 35: 442-459.

Standards New Zealand 2004. *NZS1170.5 Earthquake actions*. Wellington, NZ.

Wood, C.M., Cox, B.R., Wotherspoon, L.M. & Green, R.A. 2011. Dynamic site characterization of Christchurch strong motion stations, *Bulletin of the NZSEE*, Vol 44(4): 195-204.