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Development of a regional V_{s30} model and typical V_s profiles for Christchurch, New Zealand from CPT data and region-specific CPT-V_s correlation

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ABSTRACT

A high-resolution near-surface shear wave velocity (V_s) model is developed for the Christchurch, New Zealand region through the application of a recently developed Christchurch-specific empirical correlation between soil V_s and cone penetration test (CPT) data [1,2] to the large, high-spatial-density CPT database [3] available for the Christchurch region. A regional model of time-averaged 30 m soil shear wave velocity (V_{s30}) is developed from this surficial V_s model with consideration for the variable surficial geology and underlying non-CPT-penetrable shallow stratigraphy of the region. Typical V_s and soil behaviour type index profiles are also developed from the CPT-V_s data found within a series of subregions located throughout Christchurch to supplement the general regional characterization provided by the V_{s30} model with more detailed and locally relevant descriptions of the soil and velocity profiles typical to the chosen subregions. The high spatial density and extent of the V_s model enable it to be used for both general site classification and site-specific understanding of surficial site effects, the applications of which are examined further in the companion work of McGann et al. [4].

1. Introduction

The 2010–2011 Canterbury earthquake sequence [5–10] resulted in widespread damage and continuing disruption to the infrastructure of Christchurch at a level unprecedented in New Zealand history. The ground motions associated with the earthquakes of the 2010–2011 Canterbury earthquake sequence were recorded on a dense array of strong motion instruments located throughout the Christchurch region, and the numerous ground motion records obtained from these instruments were found to exhibit phenomena such as basin edge effects, basin-generated waves, rupture directivity, and nonlinear soil response [5,6]. The confluence of money, research, and data collection devoted to the ongoing earthquake recovery efforts, and the quality ground motion observations at a variety of locations for a number of events presents a unique opportunity to identify and understand the physical processes resulting in the observed ground motion phenomena through such techniques as hybrid broadband ground motion simulation (e.g., [11]). A detailed characterization of the subsurface velocities associated with the complex regional geology is an essential tool to enable such studies.

Much of the damage incurred to residential and commercial structures in Christchurch due to the 2010–2011 Canterbury earthquakes was geotechnical in nature (e.g. the widespread and severe liquefaction and lateral spreading that occurred throughout the area [12–14]). As a result, the post-earthquake recovery efforts in Christchurch have involved a significant focus on the characterization of the near-surface soil conditions in the region through subsurface explorations. Thousands of individual site exploration records obtained through borehole/standard penetration tests (SPT), cone penetration tests (CPT), surface wave analysis methods, and other testing approaches have been made available for use in research efforts through the Canterbury Geotechnical Database [3] project sponsored by the New Zealand Earthquake Commission (EQC) and the Canterbury Earthquake Recovery Authority (Note: following the completion of this research, the Canterbury Geotechnical Database has been generalized to the New Zealand Geotechnical Database, NZGD). Seismic cone penetration test (SCPT) data obtained as a part of this effort were used to develop a Christchurch-specific CPT-V_s correlation by McGann et al. [1,2]. This empirical CPT-V_s relationship was based on SCPT data from 86 general soil sites located throughout the greater Christchurch area, and used multiple linear regression with non-constant variance to account for the greater uncertainties observed at shallow depths. The

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Christchurch-specific CPT-V_s model is generally applicable to the near-surface soils of the Canterbury plains, and was shown to compare favorably with V_s profiles independently-obtained using surface-wave analysis techniques at several Christchurch strong motion stations in McGann et al. [15].

In this paper, the methodology for the development of a high-resolution near-surface Christchurch V_s model is presented, including descriptions of the processing steps applied to the adopted CPT dataset, the consideration made for the regional geology, and the selected spatial interpolation/extrapolation schemes. This regional surficial V_s model is used to create a model of time-averaged shear wave velocity to 30 m depth (V_{s30}) for the greater Christchurch urban area. This V_{s30} model provides a characterization of the near-surface shear wave velocity of the Christchurch region that has useful connotations for site classification. Detailed analysis of specific subregions of Christchurch is also undertaken through the development of typical V_s and soil behaviour type index [16] profiles from the CPT-V_s data contained within the subregions. It is shown that the distribution of soil V_s in the Christchurch region is highly variable both spatially and with depth due to the varied geological histories for different parts of the area and the highly stratified nature of the near-surface deposits. This inherent variability is explored further using the surficial V_s model of Christchurch in the companion work of McGann et al. [4], which provides a more detailed discussion of the depth variability in the region and its implications in expected seismic response, an assessment of the applicability of conventional site classification metrics to the Christchurch region, and investigates connections between features of the V_s model and regional observations of surficial liquefaction-induced damage.

2. Adopted CPT dataset

The CPT data used in this study includes 13,670 individual CPT records extracted from the Canterbury Geotechnical Database [3] on 1 February 2014 from sites located throughout Christchurch and the surrounding towns and suburbs. This CPT dataset was primarily obtained to aid in the assessment of insurance claims made after the events of the 2010–2011 Canterbury earthquake sequence and to help establish the residential land zoning categories used by the Canterbury Earthquake Recovery Authority (CERA) [17] to assess the viability of rebuilding in liquefaction-affected areas. Though these CPTs were not originally performed with the intention of a subsequent region-wide near-surface soil characterization, they represent an unparalleled resource in terms of scope and spatial density of subsurface data. This dataset presents a unique opportunity for understanding the nature of the soils in the greater Christchurch area, and, through the subsequent development of associated subsurface models, the implications of these soil on the strong ground motions associated with the 2010–2011 Canterbury earthquake sequence.

The CPT data obtained for the Canterbury Geotechnical Database sites represent a variety of soil types and site conditions typical in region. These records generally cover the range of depths extending from the ground surface to the upper surface of the Riccarton Gravel, a dense gravel deposit that exists beneath Christchurch, though a large portion of the CPT tests were terminated at a pre-defined target depth (typically 20 m) or upon effective refusal due to a cobble, boulder, or dense gravel layer (e.g., Springston Formation overbank gravel lobes) encountered 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 were used in the subsequent analysis and development. The overall data processing procedure developed for this purpose is summarised in Fig. 1. This chart shows the order in which the various steps were carried out and indicates in red the number of CPT records (if any) removed from the dataset in each step.

The initial criteria were established for the zone of soil immediately below the ground surface (pre-drill zone), as this region is often poorly characterized by the CPT due to lack of confinement, and many of the CPT sites made use of an approximately 0.5–1.5 m deep pre-drilled or hand-dug-and-backfilled hole as a starting point for the test to ensure infrastructure clearance. In order to consider this pre-drill zone consistently for the entire database, the end of the pre-drill zone, $z_p \geq 1.0$ m, was defined as the first depth where $q_{c1N} > 50$ (corrected dimensionless tip resistance [16,18]) and $V_s > 65$ m/s. At any site where this depth was <1 m, z_p was set equal to 1 m. The values of cone tip resistance, q_c, and cone frictional resistance, f_s, for $z \leq z_p$ were taken as constants, and set equal to the respective values at z_p. Any sites where z_p was more than 30% of the total profile length, or where the q_{c1N} and V_s criteria were not met at any depth, were excluded from the processed CPT dataset.

All readings with $q_c \leq 0$ MPa, $f_s \leq 0$ MPa, or $V_s < 60$ m/s were removed from the CPT profiles, and records with excessively large friction readings ($f_s > 1.5$ MPa anywhere in profile) were excluded from the processed dataset due to the questionable validity of these readings. A number of CPT sites were listed with identical locations to one or more other CPT sites. As it is not clear where these sites were actually located, any sites with duplicated coordinates were excluded from the processed CPT dataset. Additional criteria were based on the locations of the CPT sites. The surficial geologic unit (QMAP unit) corresponding to each site was identified using the Forsyth et al. [19] geologic maps. Any sites located in non-applicable QMAP units (e.g., man-made soil deposits, or locations identified by the map as active river beds or ocean) were removed from the processed dataset. Additionally, all CPT sites with a maximum depth <2 m located east of Fitzgerald Avenue (where it is highly likely that a termination depth <2 m represents a cobble or boulder rather than a true geologic feature), and all extreme spatial outliers (sites in Lyttelton, Akaroa, north of the Ashley River, and far to the west of Christchurch) were also excluded from the processed dataset.

Another spatial consideration made when establishing the processed CPT dataset involved the models developed by Lee et al. [20,21] for the depth to the upper boundaries of the Riccarton Gravel deposit and the Banks Peninsula Volcanic complex that lay beneath Christchurch. These models are poorly constrained due to lack of information in certain areas (e.g. near the Port Hills south of Christchurch city), and any CPT sites located in these poorly constrained regions were omitted from the processed dataset to avoid any problems introduced by these geologic models. Section 3.1 provides a more comprehensive discussion on these models and their use in the development of the V_{s30} model.

Based on the aforementioned exclusion criteria, 10550 CPT sites were retained in the processed dataset (i.e., 3120 CPT records were removed). Fig. 2 summarizes the characteristics of the processed CPT dataset, showing the distributions of z, q_c, f_s and soil behaviour type index, I_c [16]. As shown, the majority of the data is for $z \leq 20$ m, $q_c \leq 20$ MPa, and $f_s \leq 0.15$ MPa, and the overwhelming majority of the CPT readings possess a soil behaviour type index in the clean to silty sand range ($1.31 \leq I_c \leq 2.05$), though there is a fair amount of coverage for I_c values up to about 3.0.

3. Regional V_s model methodology

The CPT dataset is used to develop surfaces describing the distribution of time-averaged shear wave velocity, V_{sz}, across the greater Christchurch urban area. Target profile depths of $z = 5,\ 10,\ 20,\ 30$ m were considered to allow for an assessment of the distributions of soil stiffness with depth across the region. V_{sz} values are computed for each target depth, z, as

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

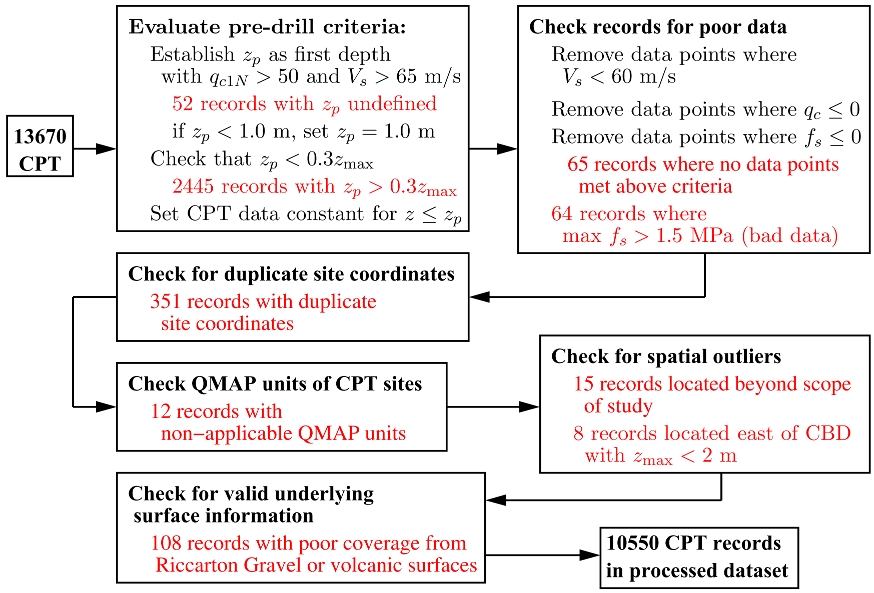

Fig. 1. Summary of data processing steps indicating order of operations and number of records removed in each step.

where d_i are CPT depth measurement increments up to the target depth, and V_{si} are mean shear wave velocities over each measurement increment estimated for each CPT record using the Christchurch-specific CPT-V_s correlation of McGann et al. [1,2].

$$V_s(z) = Aq_c(z)^b f_s(z)^c z^d \tag{2}$$

where A =18.4, b =0.144, c =0.083, d =0.278, $q_c(z)$ and $f_s(z)$ are the cone tip and frictional resistances (units of kPa) at the depths, z, below the ground surface in meters. This empirical model was developed from sites located in the surficial Springston and Christchurch Formations, and is therefore not applicable to soil types not represented in these geologic units such as the loess and colluvium deposits found in the ridges and valleys of the Port Hills to the south of Christchurch city. The CPT-V_s model can be used to characterize the uncertainty in the estimated V_s profiles; however, the focus here is given to the use of the mean correlation as this uncertainty is relatively small and the emphasis in the current work is on region-wide estimation instead of site-specific characterization. A target profile depth z=30 m is presented in the current work (i.e., V_{s30}) to allow for an overall assessment of the near-surface zone that is commonly used for building-code based site characterizations [22,23]. The corresponding surfaces for the other target depths are presented and compared further in McGann et al. [4,24].

3.1. Consideration of regional geology

The development of the regional V_{sz} models is performed with consideration for the varying surficial geology of the region as well as for the stratigraphy underlying the surficial deposits. The 1:250,000 scale geologic map (QMAP) data for Christchurch [19] presented in

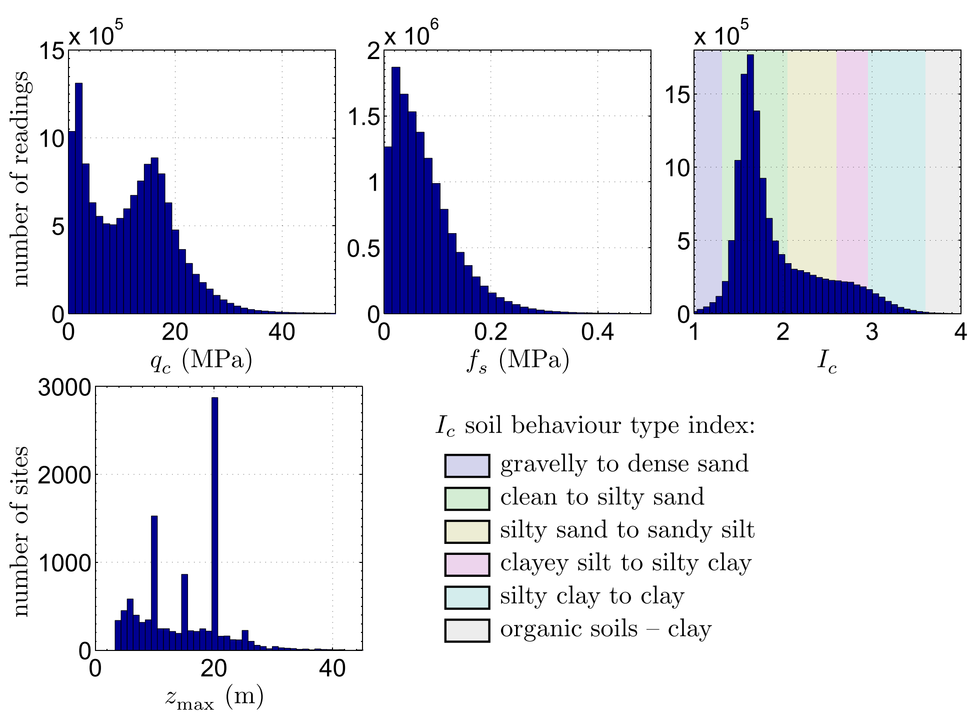

Fig. 2. Summary of CPT dataset showing distributions of cone tip resistance, q_c, cone frictional resistance, f_s, soil behaviour type index, I_c, and termination depth, $z_{\max}$.

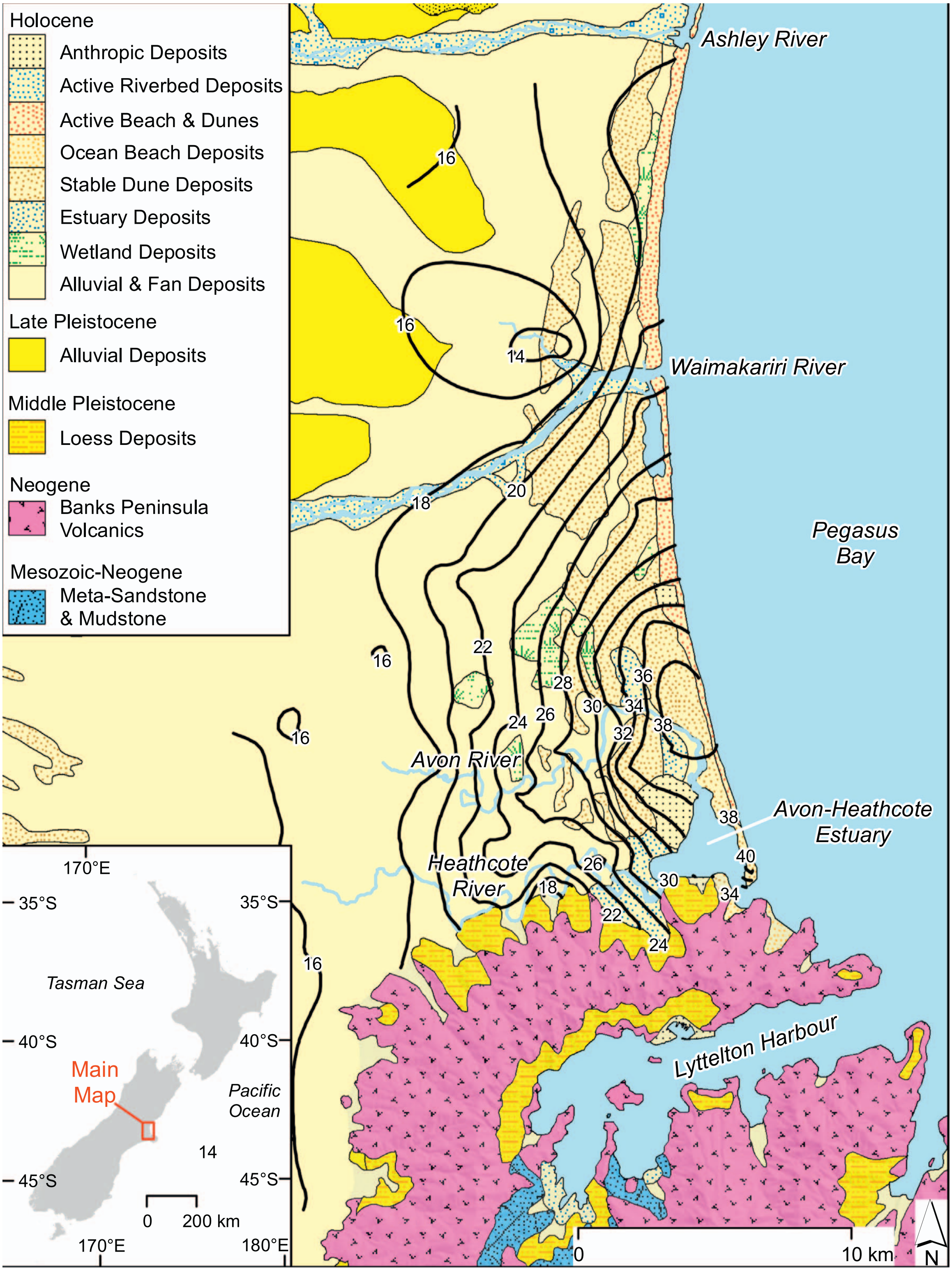

Fig. 3. Surficial geology of Christchurch region with contours showing depth (in meters) to the top of the Riccarton Gravel and/or volcanic rock surfaces underlying the Holocene sediments. Contour lines are spaced on 2 m intervals.

Fig. 3 shows the various surficial geologic deposits in the area. The Holocene deposits shown in Fig. 3 can be roughly grouped into four main groups (QMAP units): alluvium, estuarine, marine, and peat/swamp. The spatial interpolation grids for the regional V_{sz} models are subdivided according to these QMAP units, and for each target depth, z, the full V_{sz} surface is compiled from separate surfaces fit to the CPT results located in these four QMAP units to avoid interpolation or extrapolation across surficial geologic boundaries. As previously mentioned, CPT sites located in the remaining deposits, e.g. anthropic, active river bed, and loess/colluvium are omitted from subsequent development due to the inapplicability of the Christchurch CPT-V_s model to these deposit types, or the inapplicability these locations to the current study.

The Holocene deposits beneath Christchurch are directly underlain by dense gravel or volcanic rock layers with upper boundaries typically located at depths ≤30 m. The computation of V_{s30} from the CPT data therefore requires knowledge of the depth to this stratigraphic interface at each site and the V_s of the underlying material. The Riccarton Gravel is the uppermost gravel layer in a series of interbedded gravels deposited during alternating periods of glaciation and elevated sea level [25], and the upper boundary of this layer represents the most significant near-surface velocity contrast for sites located in the Canterbury plains. Near the Port Hills south of Christchurch city, instead of gravels, the surficial sediments are often directly underlain by the volcanic rock of the Lyttelton Volcanic Group and Mount Pleasant Formation.

A pair of interpolated surfaces describing the elevations of the upper boundaries of the Riccarton Gravel and volcanic rock layers have been developed using several forms of constraints, including well log data from about 530 sites in the Canterbury region by Lee et al. [20,21]. These surfaces were 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 was deeper than the estimated depth to these surfaces, the termination depth was used. The Riccarton Gravel and volcanic rock surfaces (modified based on CPT termination) are shown using contour lines in Fig. 3. As shown, the upper boundary of the Riccarton Gravel is shallower (≈15 m depth) to the west and increases in depth moving east (up to about 40 m deep near the coast). The areas where the volcanics are more shallow than the Riccarton Gravel are indicated in Fig. 3 as the shallower contours near the Port Hills.

Shear wave velocities for the Riccarton Gravel are estimated using the dense gravel reference V_s profile suggested by Lin et al. [26]

$$V_s = A_s\left(\frac{\sigma_v{}'}{p_a}\right)^n \tag{3}$$

where $A_s = 312$ m/s, n=0.331, σ'_v is the vertical effective stress, and p_a is the atmospheric pressure. Effective stress profiles at each site are estimated using a soil density $\rho = 1.8$ Mg/m^3 and the estimated groundwater table depth at that location. For the volcanic rock, V_s is assumed to be constant with depth at 750 m/s. These gravel and rock velocity profiles are appended to the end of the CPT-V_s profile at each CPT site, up to a depth of 30 m. Fig. 4 shows two example 30 m V_s profiles for sites underlain by each surface type. The Riccarton Gravel site of Fig. 4(a) includes an indication of the full V_s profile obtained from Eq. (3) (dashed line) to illustrate the difference between the CPT-based V_s and adopted gravel V_s across the full 30 m profile, though only the portion of the gravel velocity profile below the estimated Riccarton Gravel surface depth (about 23 m at this site, depicted as solid line) is used in subsequent computations.

The depth of the groundwater table at each CPT site was obtained from information reported in the CPT logs. The median estimated groundwater elevation surface of Ballegooy et al. [27], developed from long term (≥12 months) observations at 657 monitoring wells, was used to supplement the data available in the CPT records for sites where no measured groundwater table depth was reported or where the reported water table depth did not correspond with surrounding readings. The groundwater data does not directly influence the shear wave velocities estimated from the CPT logs, as the adopted Christchurch-specific CPT-V_s correlation [1,2] is based on depth instead of vertical effective stress, but groundwater data is used to compute vertical effective stress profiles used for the computation of the Riccarton Gravel shear wave velocity as well as CPT-based parameters such as q_{c1N} and I_c.

Only a small portion of the processed CPT records (about 550 out of 10550) were terminated at the upper boundaries of the Riccarton Gravel and/or volcanic rock surfaces. At the approximately 10000 sites remaining, the portion of the V_s profile between the CPT termination depth and the top of the underlying gravel/rock surface is not directly obtainable. A 'fill-in' technique based on spatial interpolation was used to increase the utility of these incomplete V_s profiles. Interpolated surfaces of V_s were generated on 0.5 m depth intervals up to a depth of 30 m from all of the CPT-based V_s profiles with data at each depth interval. An allowable fill-in length was selected based on an examination of the resulting error, and for sites meeting this criteria, the portion of the V_s profile between the termination depth and the top of the underlying gravel/rock surface was filled-in with values queried from these interpolated surfaces. This fill-in technique is discussed further in Section 4.2.

3.2. Spatial interpolation for V_{sz} models

Smooth surfaces of V_{sz} that approximate the CPT-based V_{sz} data points determined using the aforementioned approach were fit to 200×200 m grids. If no CPT record was within 300 m of a single grid point, then no estimate of V_{sz} was computed. This 300 m boundary 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. A modified ridge estimator [28] biased towards smoothness was used to achieve surfaces that are representative of the trends in the CPT results without necessarily representing the V_{sz} values at any particular site. As previously mentioned, the four main QMAP units were considered separately during this development to avoid interpolation or extrapolation across surficial geologic boundaries. The level of smoothness chosen for the spatial interpolation within each QMAP unit and for each target depth was selected to provide the best representation of the corresponding CPT results without becoming overly bumpy, and the surfaces are regularized such that extrapolation is minimized.

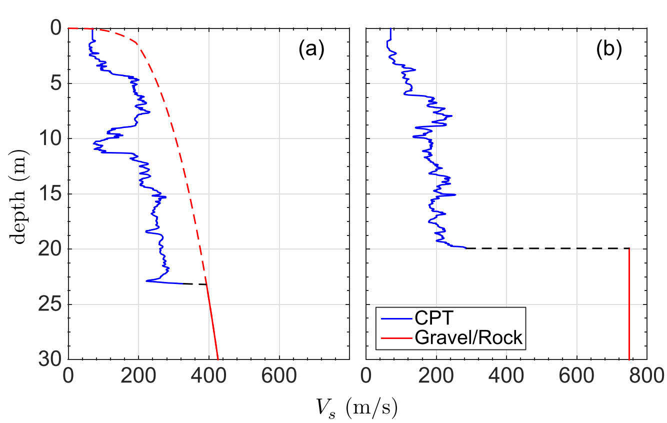

Fig. 4. Example 30 m V_s profiles including CPT-based V_s values and assumed V_s values for depths within underlying surfaces. (a) Site underlain by Riccarton Gravel. (b) Site underlain by volcanic rock.

4. Examination of developed V_{s30} model

Fig. 5 shows the values of V_{s30} computed from the CPT dataset and plotted at the CPT locations and Fig. 6 shows the corresponding V_{s30} model. V_{s30} is the primary site classification metric used internationally [23,22,29] and may also be used in New Zealand [30]. Ground motion prediction equations (GMPEs) also use V_{s30} as an explanatory metric for site effects, both in New Zealand [31,32] and internationally (e.g., [33]). Due to the ubiquity of V_{s30} as a distinguishing variable for site classification purposes, and due to the general utility of shear wave velocity (V_s) as a descriptor of soil conditions, this V_{s30} model for the Christchurch region is a valuable tool for use in learning from the processes resulting in the strong ground motions observed in the 2010–2011 earthquakes.

As shown in Figs. 5 and 6, the regional V_{s30} model is representative of the significant trends present in the CPT-based data, and serves to expand the scope of the more discrete CPT data in data-rich areas while

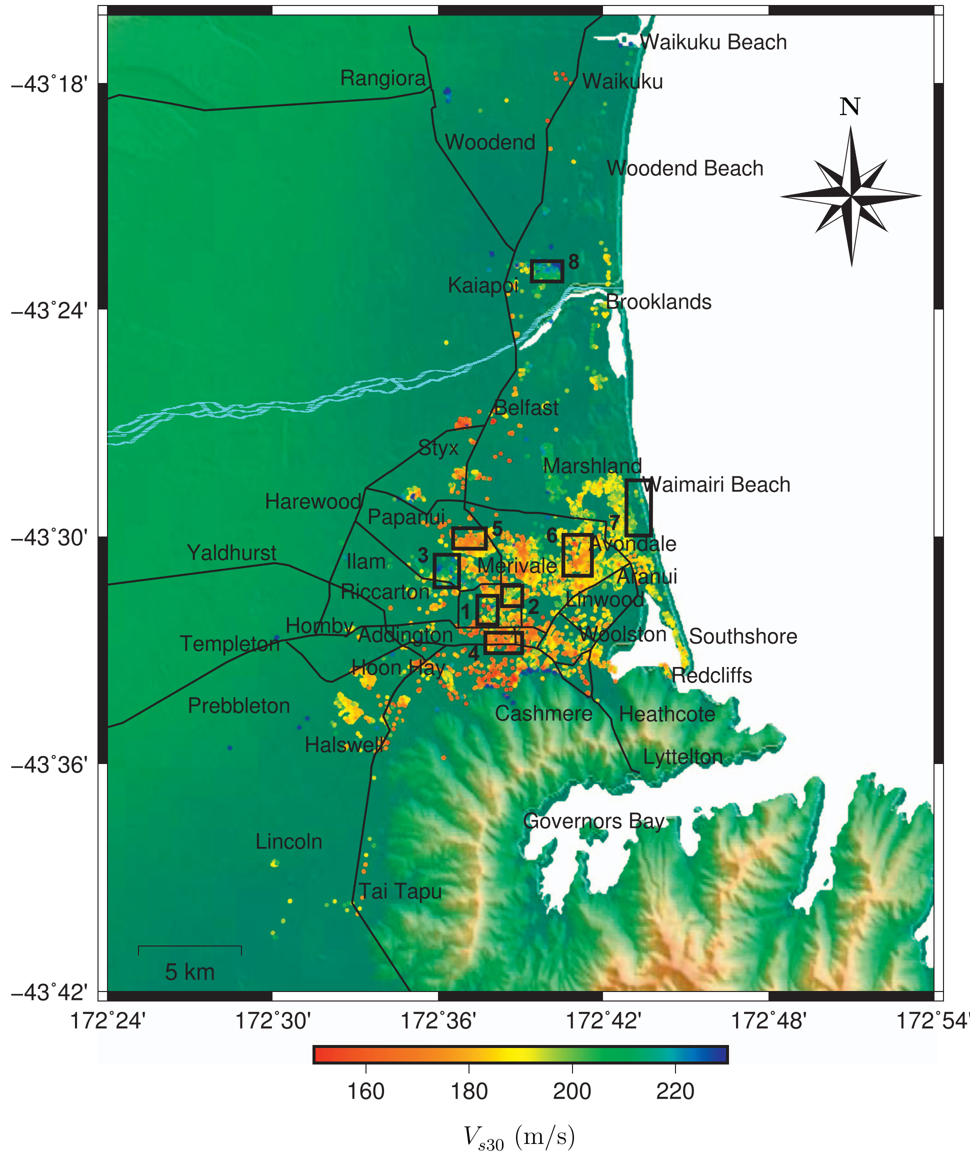

Fig. 5. V_{s30} at CPT sites. Numbered boxes refer to subsequently discussed subregions of specific interest.

avoiding significant extrapolation into areas of little or no CPT data. Edge extrapolation was restricted to 300 m, however, extrapolation may still occur over this allowable distance, and the outer edges of the V_{s30} surface (and any edge bordering an area without data) are inherently less constrained than the interior portions of the surfaces. Edge values should therefore be treated with less confidence than interior areas, and it is beneficial to consult the corresponding CPT-based V_{s30} map in Fig. 5 to qualitatively assess such locations. The primary benefit of the imposed extrapolation restriction is to keep the focus of the model on areas with well-constrained predictions and avoid making predictions in areas with insufficient information, and in this sense the model performance is exactly as intended.

There is a large degree of spatial variability evident in the V_{s30} model, with values varying between 145–265 m/s. Extreme values are clipped in the colour scale of Figs. 5 and 6 to increase visibility as 90% of the sites have V_{s30} = [165, 212] m/s, where 165 and 212 m/s are the 5th and 95th percentiles, respectively. With the exception of some western sites with shallow gravels (e.g. vicinity of boxed region 3), there is a general trend of increasing V_{s30} from west to east for the 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 plastic soils in these deposits in comparison to the other surficial units. The general band of softer 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, and the eastern edge of this soft band, extending south from Belfast to Woolston in Fig. 6, roughly corresponds with the coastline that existed approximately 3000 years ago [25].

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. The fill-in criteria specified to account for sites that did not terminate directly at the interface with the volcanics surface creates a slight bias towards increased V_{s30} in these areas, as typically only the sites with relatively shallow rock surfaces meet the fill-in criteria. While this is generally true for the entire dataset, the relative scarcity of sites that are underlain by the volcanics increases the visibility of this bias. The 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

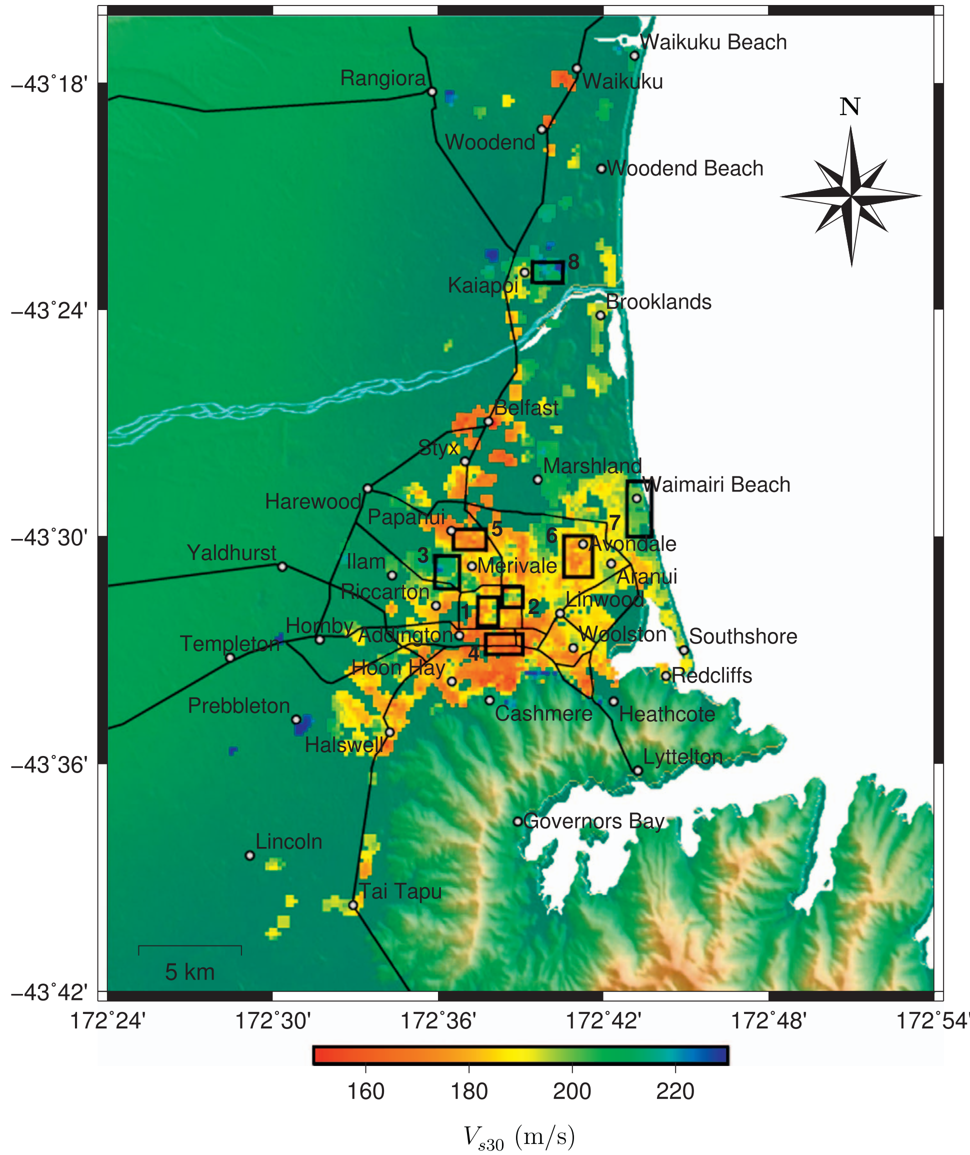

Fig. 6. V_{s30} surface on uniform 200×200 m grid. Predictions are only provided in each grid cell if there is one or more CPT record within 300 m. Numbered boxes refer to subsequently discussed subregions of specific interest.

of the Springston Formation over-bank gravel lobes in the western part of the city [25]. One such lobe is visible as the blue/green path between Ilam and Merivale while others are notable for their absence from the surfaces (i.e., no CPT penetration possible for surficial gravels) [34]. The very soft locations indicated in Fig. 6 (red-orange and red with V_{s30} < 170 m/s) are generally areas where much of the soil profile is composed of silts, clays, and silty sands, particularly in the upper 5–10 m below the surface. Such regions are highly correlated with locations of in-filled swamps and other current or former wet areas as inferred from the 1856 black maps of Christchurch [34,35].

4.1. Assessment of V_{s30} model quality

Fig. 7 shows the distributions of V_{s30} at the CPT sites and the grid points of the fitted surface model. The distributions of V_{s30} for the two cases are well represented by normal distributions and, as shown in Fig. 7 and the final row of Table 1, the two cases are similar in terms of mean values (μ_{CPT} and μ_{surface}) and variance (standard deviation, σ, and coefficient of variation, COV), demonstrating that the fitted surface captures the CPT-based data well in an overall sense. Table 1 also separately lists the normal distribution parameters for the CPT sites located within the four considered QMAP units and the corresponding

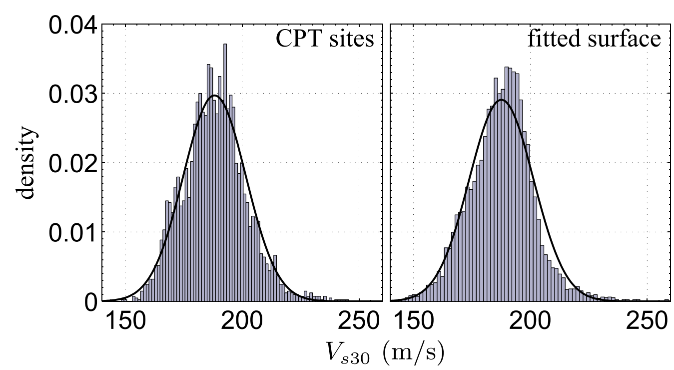

Fig. 7. Distributions of V_{s30} at CPT sites and grid points of 200×200 m surface. The parameters of the approximate normal distributions are provided in Table 1.

subsurfaces for these units that were compiled into the overall V_{s30} model. As shown, the subsurfaces associated with each QMAP unit are also representative of the corresponding subsets of the CPT dataset in an overall sense.

It is interesting to note the differences in the nature of the soils

Table 1
Mean, standard deviation, and coefficient of variation for V_{s30} at CPT sites and surface grid points for QMAP units and overall dataset.

QMAP Unit	μ_{CPT}	$\mu_{surface}$	σ_{CPT}	$\sigma_{surface}$	COV_{CPT}	$COV_{surface}$
Alluvium	184.3	186.0	15.5	17.5	8.4%	9.4%
Marine/dune	192.6	196.3	8.6	9.7	4.4%	4.9%
Estuarine	187.9	185.2	10.1	10.2	5.4%	5.5%
Peat/swamp	190.3	193.0	15.4	14.4	8.1%	7.5%
All data	187.6	188.2	13.7	13.4	7.3%	7.1%

contained within the considered QMAP units revealed by the normal distribution parameters of Table 1. The marine/dune deposits have higher V_{s30} values on average than the other deposits (though the differences are relatively small), perhaps due to wave-action-based densification, and also display less variance, indicating a greater level of homogeneity in comparison to the other units. The alluvial deposits show the largest amount of variance, which is consistent with expectations as this is the largest and most varied of the four considered units. These differences in character between the QMAP units (subtle for mean V_{s30}, less so for variance) support the decision to generate the overall V_{sz} surfaces as a set of subsurfaces that consider only the CPT sites within each QMAP unit. The generation of a single surface without regard to the surficial geology of the considered sites may have obscured some of the natural spatial variability of the region.

Fig. 8 compares the North-South and East-West spatial variability in V_{s30} at the CPT locations and the surface grid points (red and blue markers, respectively) by plotting the moving averages (solid lines) for the two cases with their associated 95% confidence intervals (dashed lines). The North-South and East-West variability are shown at the left and right, respectively, and the distance scales for the northing and easting correspond to those in the V_{sz} maps of Figs. 5 and 6. As shown in Fig. 8, the V_{s30} model generally captures the average spatial trends evident in the CPT results, and the confidence intervals for the two cases are nearly coincident, especially in the data-rich areas away from the extents of the CPT dataset. The CPT sites and the surface grid points do not represent the same geographic locations, additionally the surface grid points have a more uniform spatial density across the region, while the CPT sites display a degree of spatial clustering. These differences in location and spatial distribution for the two data sets likely influence the results shown in Fig. 8 in different ways, potentially obscuring any effects of pure spatial interpolation on the running average and 95% confidence interval lines. However, the fitted surface appears to be representative of the CPT dataset in an overall sense despite these inherent differences.

The results shown in Figs. 7 and 8 and Table 1 provide strong support for the adequacy of the smoothened surfaces in representing the spatial variation in V_{sz} suggested by the CPT dataset. The V_{s30} surface captures well the mean and variance of the CPT results for the entire dataset and within each QMAP unit, and also captures the spatial variation inherent in the CPT results. This spatial variability is explored further in subsequent sections through the development of typical shear wave velocity and soil behaviour type index profiles for different subregions within the greater Christchurch urban area.

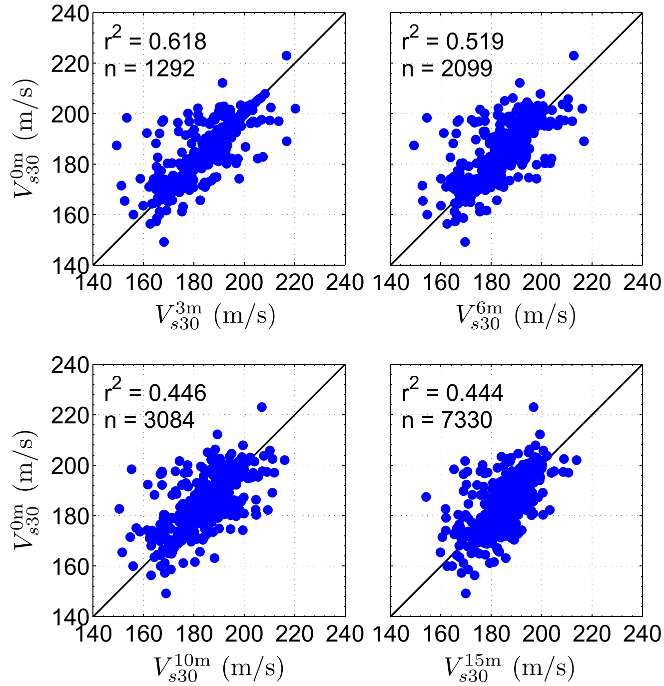

Fig. 9. Comparison of V_{s30} values for four allowable V_s profile fill-in lengths (3, 6, 10, 15 m) to zero fill-in length results. Number of sites, n, indicates the number of CPT sites that meet the allowable fill-in length criteria for each case (e.g., 1292 sites meet the 3 m fill-in criteria).

4.2. Evaluation of fill-in interpolation technique for V_{s30} model

This section examines in detail the profile 'fill-in' technique used to estimate V_s values for unknown depths due to CPT termination above the Riccarton Gravel and volcanic rock surfaces. It is important to assess this technique to ensure that no significant error or bias was introduced to the final model. The profile fill-in technique is evaluated by comparing the V_{s30} values at the 554 sites that did not require fill-in

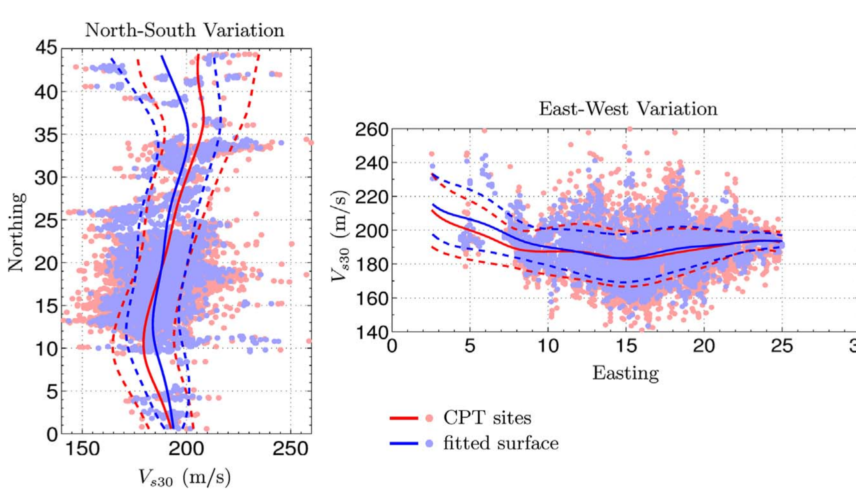

Fig. 8. North-South and East-West spatial variability in V_{s30} for CPT sites (red lines and markers) and grid points in the V_{s30} model (blue lines and markers). Solid and dashed lines indicate running average with 95% confidence intervals.

(fill-in length =0 m) to the corresponding V_{s30} values returned by four allowable fill-in lengths: 3, 6, 10, and 15 m. This comparison is made at the grid points of an interpolated surface fit to the V_{s30} values for each case. The interpolation grid uses 200×200 m spacing, and all grid points are within 300 m of the 554 zero fill-in CPT sites. Fig. 9 shows the results of these comparisons with the zero fill-in values ($V_{s30}^{0\text{m}}$) on the vertical axes and the corresponding V_{s30} values for each allowable fill-in length on the horizontal axes. The coefficients of determination, r^2, and number of sites corresponding to each fill-in length, n, are indicated for each case.

As the allowable fill-in length increases from 3 to 15 m, the degree of correlation to the zero length cases decreases from 0.618 to 0.444, while the number of CPT sites that can be used in the computation of V_{s30} increases from n =1292 to n=7330. Though the degree of correlation with the zero fill-in cases is lowest for the 15 m allowable length, the overall error for this case evidenced in Fig. 9 is not substantially greater than the shorter allowable lengths. Based on these results, the fill-in length at each CPT site is restricted to be ≤50% of the depth to the top of the underlying layer or the target depth of the time averaged profile. For V_{s30}, this restricts the maximum acceptable fill-in length to 15 m, though for most sites a lesser length was used. For example, approximately 15% of the 7330 sites included in this criterion have a profile fill-in length <1 m, about 25% of the sites have a fill-in length <5 m, and nearly 70% have a fill-in length <10 m.

5. Typical velocity profiles for subregions of Christchurch

The V_{s30} model illustrated in Fig. 6 reveals the spatial variation in average shear wave velocity (and implied variation in average shear modulus) inherent to the Christchurch region. This model is useful for generalized evaluations of the relative stiffness of different areas and coarse site classification for expected site effects. Comparisons between the V_{sz} values computed for different target depths and shown in McGann et al. [4,24], reveal that there is also a large degree of depth variation in the considered soils. The lack of correlation between V_{s5} and/or V_{s10} with V_{s30} in many areas of Christchurch suggests that expected seismic site response cannot be well represented by a single metric such as V_{s30}. To investigate this further, typical V_s and I_c profiles are computed and presented in this section for a series of subregions of the Christchurch area. These typical profiles are used to assess the inherent variability of the regional near-surface soils at a finer level than is possible using the associated regional V_{s30} model, to compare the different stratigraphy that exists in the overall region, and, in the companion study of McGann et al. [4], to assess the typical small strain seismic response of the considered subregions through a comparison of their transfer functions.

5.1. Considered subregions

The eight subregions selected from across the greater Christchurch area are indicated by numbered black boxes in Figs. 5 and 6, and are assigned the following names and numbers:

1.	Central CBD	2.	Northeast CBD
3.	Fendalton	4.	Sydenham
5.	Papanui	6.	Avondale
7.	North New Brighton	8.	Kaiapoi

These subregions encompass areas of nearly constant V_{s30} (or areas of particular interest) and were selected to be representative of a variety of site conditions (e.g., soft, stiff, and intermediate soils), surficial geologic units (e.g., alluvium, marine/dune), and/or seismic response types (e.g., liquefaction, no liquefaction). Regions 4, 5, and 6 were defined to encompass three areas of relatively low V_{s30} in the fitted surface of Fig. 6 where differing soil types are encountered: silty soils in region 4, reclaimed swamp in region 5, and primarily sandy soils in region 6. Regions 3, 7, and 8 consider areas of relatively higher V_{s30}, and

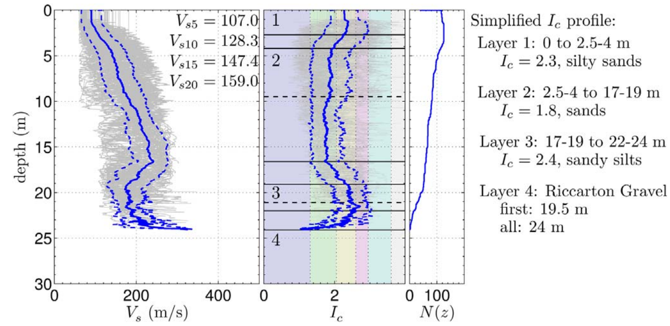

Fig. 10. V_s and I_c profiles for CPT sites in region 1 (central CBD) for depths above estimated Riccarton gravel surface at each CPT site. $N(z)$ indicates number of CPT records with depth.

represent two general conditions: the relatively shallow gravels of regions 3 and 8, and the dune sands of region 7. Regions 1 and 2 are located in the Christchurch central business district (CBD) and encompass areas of intermediate V_{s30}.

5.2. Typical profiles for subregions

Figs. 10 through 17 show the V_s and I_c profiles for all of the CPT records in each subregion (gray lines) along with characterizations of the mean profiles and the variance in the dataset. The mean V_s and I_c profiles are noted as solid blue lines in each plot, and the dashed lines represent ± one standard deviation from the mean profiles. For each subregion, the variation in V_s with depth was assumed to be normally distributed. The number of CPT records with data at each depth, $N(z)$, is indicated for each subregion for reference. To provide a general characterization 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. (1) on 5 m intervals for target profile depths, $z < z_{\text{term}}$ (i.e. the deepest CPT termination depth in the subregion).

As shown in Figs. 10–17, the uncertainty in the mean V_s profiles is relatively small, with a maximum standard deviation of approximately 50–60 m/s. The uncertainty in the I_c profiles is somewhat greater for most of the subregions, however, the zone of I_c values bounded by the ± standard deviation profiles appear to be reasonably representative of the CPT-based data, particularly for depths below 5 m. It is also evident that there is much less uncertainty for I_c values less than about 1.8–2.0 (see Figs. 11, 15, and 16) than there is for siltier soils (higher I_c) or near-surface locations. Overall, the relatively small levels of uncertainty observed for these typical V_s and I_c profiles indicates that they provide reasonable representations of the soil profiles in the considered subregions that can be used to evaluate characteristic seismic responses and develop or verify simplified profiles for use in numerical models.

Figs. 10–17 also provide simplified I_c profiles developed for the 8

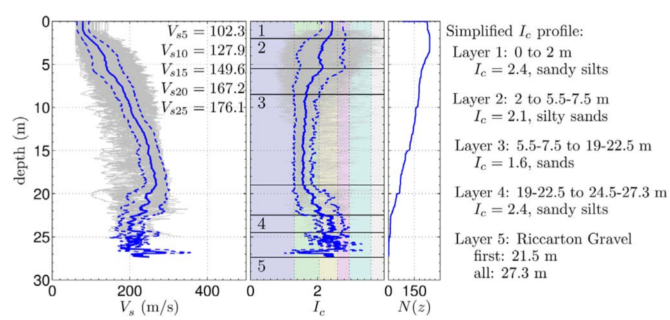

Fig. 11. V_s and I_c profiles for CPT sites in region 2 (northeast CBD) for depths above estimated Riccarton gravel surface at each CPT site. $N(z)$ indicates number of CPT records with depth.

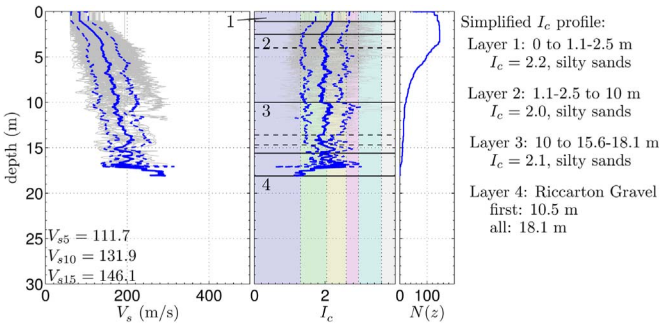

Fig. 12. V_s and I_c profiles for CPT sites in region 3 (Fendalton) for depths above estimated Riccarton gravel surface at each CPT site. *N*(*z*) indicates number of CPT records with depth.

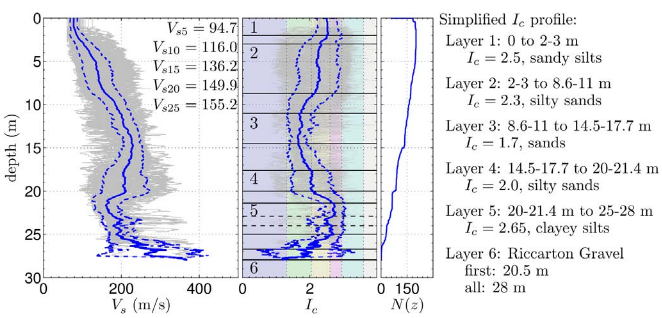

Fig. 13. V_s and I_c profiles for CPT sites in region 4 (Sydenham) for depths above estimated Riccarton gravel surface at each CPT site. *N*(*z*) indicates number of CPT records with depth.

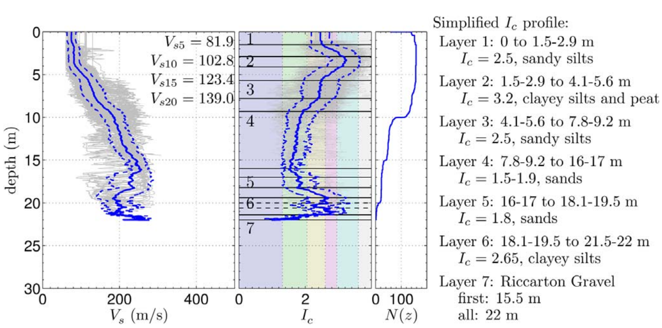

Fig. 14. V_s and I_c profiles for CPT sites in region 5 (Papanui) for depths above estimated Riccarton gravel surface at each CPT site. *N*(*z*) indicates number of CPT records with depth.

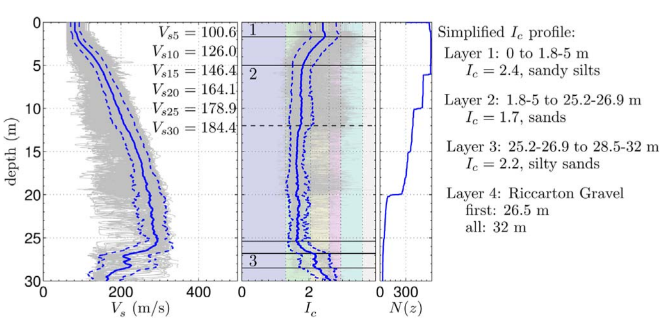

Fig. 15. V_s and I_c profiles for CPT sites in region 6 (Avondale) for depths above estimated Riccarton gravel surface at each CPT site. *N*(*z*) indicates number of CPT records with depth.

subregions from the mean I_c profiles. These simplified profiles are useful approximations for the typical soil profiles encountered the subregions that could be used to inform constitutive parameters or as rough guidelines for layering schemes for site-specific numerical

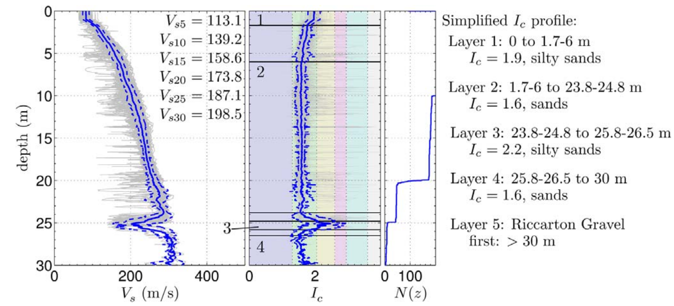

Fig. 16. V_s and I_c profiles for CPT sites in region 7 (North New Brighton) for depths above estimated Riccarton gravel surface at each CPT site. *N*(*z*) indicates number of CPT records with depth.

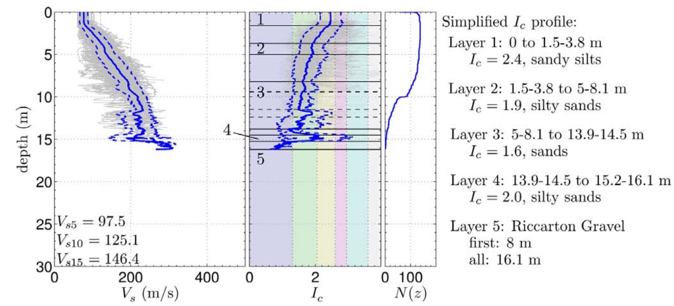

Fig. 17. V_s and I_c profiles for CPT sites in region 8 (Kaiapoi) for depths above estimated Riccarton gravel surface at each CPT site. *N*(*z*) indicates number of CPT records with depth.

analyses of the soils above the Riccarton Gravel. The depth to the top of the Riccarton Gravel is indicated in each simplified profile in terms the shallowest depth to this surface in each subregion (*first*) and the deepest (*all*). The layers of the simplified profiles are indicated on the I_c plots in Figs. 10–17 using solid black lines. An unlabeled transition zone exists between most of the layers, as the depths of the layer boundaries vary within the subregions. Dashed lines indicate transitions where there is a distinct change in variance (e.g., at 9.5 m depth in region 1) or small/minor change in the mean profile (e.g., at 23–24 m depth in region 4). Based on a survey of eight borelog records from random locations within each subregion, the I_c profiles obtained from the CPT records reasonably approximate the range of soil profiles and soil types within each subregion [24].

All of the eight subregions display an approximately 1–2 m deep zone of crustal soil with lower V_s values and the general behaviour type of a silty sand. As previously discussed, this immediately near-surface zone is not well characterized by the CPT dataset, however, the presence of this crust corresponds with borelog observations. Another characteristic that is shared by most of the typical profiles is the presence of an approximately 5 m thick layer of higher I_c soils directly above the Riccarton Gravel interface. This zone of siltier soil is present in subregions 1, 2, 4, 5, and 6, and also corresponds to the borehole records. The relative similarities and differences, and unique features, of the subregions are discussed in the following sections.

5.2.1. Fendalton subregion

The Fendalton subregion (region 3) is characterized by a relatively shallow depth to the Riccarton Gravel interface, especially in comparison to the other subregions. Additionally, the number of CPT sites in the Fendalton subregion decreases significantly from approximately 3.5 m depth, suggesting that gravels are dominant within the stratigraphy. The Riccarton Gravel surface is typically encountered between about 10.5–18 m depth, thus, the gravels implied by the steady termination of CPT records from 3.5 to 10.5 m are likely part of the Springston Formation. The Fendalton subregion is located primarily within an area dominated by an over-bank gravel lobe of the Springston Formation [25,34], and these observations, combined with the relative lack of CPT records compared to the other subregions, correspond well with the expected local geology. It is a limitation of the current approach that the typical V_s profiles are based only on CPT-penetrable soils. As a result, it is likely that the true in-situ V_s profile and V_{sz} values are underrepresented in this subregion, however, the typical profiles still hold for the non-gravel soils.

5.2.2. Kaiapoi subregion

The Kaiapoi subregion (region 8) is also characterized by a relatively shallow depth to the upper surface of the Riccarton Gravel, with sites encountering the Riccarton Gravel approximately 8–16 m below the ground surface. Significant evidence of liquefaction and lateral spreading was observed for the soils in Kaiapoi, especially after the September 2010 Darfield earthquake [8,10]. The sands in layers 2 and 3 of the simplified I_c profile have the lower V_s values (and lower I_c values) characteristic of liquefaction-susceptible deposits, especially given the depths at which these materials are located, and are likely representative of the types of materials in which liquefaction occurred. The variation in the number of CPT records with depth shown by the $N(z)$ plot in Fig. 17 suggests that Springston Formation gravels may be present above the Riccarton surface from about 5 m depth. The decrease in $N(z)$ is gradual from 5 to 8 m, so it is likely that such gravels are not dominant within the subregion. The distinct jump in $N(z)$ at exactly 10 m is almost certainly due to testing protocols (i.e. CPT target depth was reached) rather than a feature of the subsurface stratigraphy.

5.2.3. Central Christchurch subregions

Subregions 1, 2, 4, and 5 are located in the area of Christchurch where the surficial Springston Formation soils are underlain by a wedge of the Christchurch Formation that extends inland to about the western edge of Hagley Park [36]. The likely transitions between these two geologic formations are apparent in the typical profiles for the central and northeast CBD subregions. All of these subregions display a reduction in V_s, and increase in I_c, immediately above the Riccarton Gravel that is characteristic of the silts, clays, and peats often found at the base of the Christchurch Formation [37].

The typical profiles for the two CBD subregions (regions 1 and 2) are similar in form overall. The Riccarton Gravel is deeper beneath region 2 (Riccarton Gravel becomes deeper from west to east, see Fig. 3) and the typical profiles in this region are correspondingly deeper than in region 1, but both share the same general features. Silty soils immediately below the surface transition into relatively clean sands, then silty soils return to the profile directly above the Riccarton Gravel interface. For region 1, located in the central CBD, the Springston-Christchurch Formation transition is likely located near 9.5 m depth, where the typical I_c profile moves further into the clean sand range and the variance in I_c becomes notably less. For region 2, in the northeast corner of the CBD, the transition from silty to clean sands that takes place between about 5.5–7.5 m depth (interface of layers 2 and 3 in the simplified I_c profile) likely corresponds with the transition between the Springston and Christchurch Formation soils. The sands from about 10–17 m in the typical I_c profile for region 1, and from 7 to 20 m depth for region 2, appear to be similar in nature to the sands found in the eastern subregions (Avondale and North New Brighton) where the Christchurch Formation is the dominant surficial geologic unit.

Sites in region 5, located in the reclaimed swampland near Papanui, are typically comprised of sandy silts, clayey silts, and peats in the upper 10 m. The typical V_s profile for this subregion correspondingly has the lowest average V_s in this zone (V_{s10} = 102.8 m/s). Based on the typical profiles, the transition between the Springston and Christchurch Formations for the Papanui subregion likely occurs around 8–10 m below the ground surface, where there is distinct change towards lower I_c values. The soils in region 4 near Sydenham are similarly silty immediately below the surface (up to about 8.6–11 m depth), but the typical V_s and I_c values in this zone are somewhat higher and lower, respectively, than in region 5. Sites in the Sydenham subregion typically have only a relatively thin layer of clean sand from approximately 11 to 15 m. The top of this sand layer likely indicates the transition point between the Springston and Christchurch Formation. Evidence of liquefaction-induced damage was observed in both regions 4 and 5 following the February 2011 earthquake, however, the severity of the liquefaction-related damage was much less than in some of the other subregions. As shown by Ballegooy et al. [14], there was about a 50/50 split between areas with no observed damage and areas of minor to moderate sand ejection in region 5, while region 4 contains a mix of areas without observed liquefaction evidence and areas of minor to severe sand ejection (as well as a small zone of moderate lateral spreading). It is likely that the predominantly silty soils (lower liquefaction susceptibility or non-liquefiable) in the upper 10 m are sufficiently thick as to prevent significant liquefaction-related effects from manifesting at the ground surface (or from occurring at all) in these areas, which is consistent with the findings of Maurer et al. [38].

5.2.4. Eastern Christchurch subregions

Regions 6 and 7 are characterized by the greatest depths to the Riccarton Gravel interface and profiles that are almost entirely composed of soils with the behaviour type of a relatively clean sand (typical mean $I_c \approx 1.6 - 1.7$). In the Avondale subregion (region 6), the top of the Riccarton Gravel is located around 30 m below the surface (slightly shallower for some sites) and there is a distinct zone of silty soils immediately above this interface represented by a decrease in V_s and increase in I_c. The typical profiles for the North New Brighton subregion (region 7) show the lowest uncertainty of all the considered subregions, consistent with the location of this subregion in the marine/dune sand QMAP unit. None of the CPT logs in this subregion encounter the Riccarton Gravel within the upper 30 m; the Riccarton Gravel surface shown in Fig. 3 indicates that this interface is located about 36–38 m below the surface beneath this subregion.

The Avondale subregion includes the present day path of the Avon river, and the area encompassed by this subregion corresponds to some of the most widespread observations of severe liquefaction and lateral spreading related damage following the February 2011 earthquake [12–14]. In contrast, post-earthquake observations in the North New Brighton subregion indicated less severe, and less overall, evidence of liquefaction-related phenomena; and these observations were constrained to the southwestern corner of the subregion. The typical profiles for these subregions provide some support for these noted differences in liquefaction response. The Avondale profiles in Fig. 15 reflect the potential for liquefaction-related phenomena, with generally lower V_s values in the upper 10 m and I_c values indicating behaviour types of predominantly sandy soils, especially below 4–5 m. The profiles for region 7 shown in Fig. 16 indicate similar soil types, however, the relative density of these deposits is likely greater (higher V_s and lower I_c) compared to corresponding depths in region 6. Furthermore, because the difference between V_{s5} and V_{s10} for regions 6 and 7 is greater than the differences for the other target depths (with the exception of V_{s30}, which is strongly affected in region 6 by the soft soils immediately above the Riccarton Gravel), it appears that the primary differences in the V_s profiles occur in the immediate near-surface zone. This difference in relative density at shallow depths, along with the differences in the groundwater table depth for the two subregions (typically at 0–3 m for region 6, and 1–6 m for region 7 per Ballegooy et al. [27]), provides a potential explanation for the significant differences in liquefaction response within the Avondale and North New Brighton subregions. The idea of using the Christchurch V_s model as an indicator of regional liquefaction vulnerability is explored further in the companion work of McGann et al. [4].

6. Conclusions

A high-resolution near-surface soil V_s model was developed for the greater Christchurch New Zealand urban area using the Christchurch-specific CPT-V_s correlation of McGann et al. [1,2] and a large CPT dataset (10,550 individual CPT logs) obtained from locations throughout the region via the Canterbury Geotechnical Database [3]. The near-surface V_s model makes consideration for the non-CPT-penetrable stratigraphy underlying the region using models [20,21] of the depth to upper boundaries of the Riccarton Gravel and the volcanic rock of the Lyttelton Volcanic Group and Mount Pleasant Formation, the two formations immediately beneath the surficial soils covered by the adopted CPT dataset, and the assumption of V_s profiles within these underlying layers. This surficial V_s model was used to create a regional model of V_{s30} through spatial interpolation/extrapolation from the CPT sites to a 200×200 m grid in which each grid space is within at least 300 m of a single CPT location. This V_{s30} model demonstrates the spatial variability of soil shear wave velocity inherent to the region in an overall sense. It is shown that there is a general trend of increasing V_{s30} from west to east across the region for *CPT-penetrable soils* (i.e. not gravels) and that the variability present in the model corresponds to known features of the surficial geology of the region.

Detailed characterizations of the soil profiles in 8 Christchurch subregions were used to supplement the regional V_s model. These subregions were characterized through the consideration of all of the CPT records contained within their bounds, from which typical V_s and I_c profiles were obtained to describe their soil profiles in an average sense. These typical profiles were used to show that the regional variability evident in the V_{s30} model is linked to the characteristic features of the stratigraphy in different areas. The relatively higher V_{s30} values in the west (as well as some western areas without CPT data) correspond to a shallow Riccarton Gravel interface and surficial gravel lobes of the Springston Formation. The areas of relatively lower V_{s30} near Sydenham and Papanui (regions 4 and 5, respectively), where evidence of liquefaction following the 22 February 2011 earthquake was generally less severe relative to other suburbs, were shown to typically have soil profiles with significant portions comprised of silty and clayey soils (i.e. low V_s but also less susceptible, or not susceptible, to liquefaction). The eastern subregion of Avondale, despite a relatively higher V_{s30}, was shown to consist primarily of clean to silty sands, supporting the basis for the extensive and severe liquefaction related damage observed in this area. It was also shown that certain regions may have different expected seismic responses despite their nominal similarity in V_{sz} for various profile depths due to difference in their V_s soil behaviour type profiles. These ideas of varying regional liquefaction vulnerability and expected seismic response are explored further in the companion work of McGann et al. [4] using the surficial V_s model and 30 m typical V_s profiles developed for the considered Christchurch subregions.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.soildyn.2017.01.032.

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