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## Spatial variability in surficial Christchurch soils via 5 m shear wave velocity $V_{s5}$

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### ABSTRACT

This paper provides a summary of the development of a shear wave velocity ( $V_s$ ) model for the greater urban area of Christchurch, New Zealand. The model is based on the application of the recently developed Christchurch-specific empirical correlation between  $V_s$  and cone penetration test (CPT) data (McGann et al. 2015a,b) to the large existing high-spatial-density database of CPT logs in the Christchurch region (CGD 2014). Applications of this  $V_s$  model are demonstrated through the development of a map of time-averaged  $V_s$  in the first 5 m below the surface and typical  $V_s$  profiles for different regions within Christchurch.

### Introduction

The 2010-2011 Canterbury earthquake sequence (Bradley and Cubrinovski 2011; Bradley 2012a,b; Cubrinovski et al. 2010; Cubrinovski et al. 2011a,b) resulted in widespread damage and continuing disruption to the infrastructure of Christchurch at a level unprecedented in New Zealand history. The 4 September 2010  $M_w$  7.1 Darfield earthquake, occurring 15 km west of central Christchurch city, was the first event in the sequence and resulted in moderate damage to local infrastructure and widespread liquefaction (GEER 2010). The 22 February 2011  $M_w$  6.2 Christchurch earthquake occurred approximately 4 km southwest of the city center, and the high-frequency amplitudes of the resulting ground motions experienced across most of the city were much larger than in the Darfield event (Bradley 2012a,b). The significant spatial variability of the surficial ground motions recorded from these two strong earthquakes not only illustrates the importance of local site effects (seismic response of surficial soils) on surface ground motions and the importance of site-specific response analysis (Bradley 2012b), but identifies the importance of a detailed characterization of the near-surface variability of the soils in the Christchurch region, especially in the immediately near-surface zone where liquefaction-related phenomena most often occur.

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 (GEER 2010, 2011; van Ballegooy et al. 2014). 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 boreholes and standard penetration tests (SPT), cone

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penetration tests (CPT), surface wave analysis methods, and other testing approaches have been made available for use through the Canterbury Geotechnical Database (CGD 2014) project sponsored by the New Zealand Earthquake Commission (EQC) and the Canterbury Earthquake Recovery Authority (CERA). In this study, a CPT dataset of 10550 records was selected from sites located throughout Christchurch and the surrounding towns and suburbs as elaborated upon by McGann et al. (2015c,d). This CPT data was used in conjunction with the Christchurch-specific CPT- $V_s$  correlation of McGann et al. (2015a,b) to develop a model of time-averaged shear wave velocity in the first 5 m below the surface ( $V_{s5}$ ) that is used to assess the spatial variability of the soils in this immediately near-surface zone. Comparisons to surficial observations of the severity of liquefaction-induced damage, and to typical  $V_s$  profiles developed for various regions within Christchurch, are used to identify and discuss the implications of observations made from the Christchurch  $V_{s5}$  model.

### **Regional $V_{s5}$ Model for Greater Christchurch Urban Area**

The adopted CPT dataset is used to develop a surface describing the distribution of  $V_{s5}$  across the greater Christchurch urban area by estimating  $V_s$  profiles, and subsequently computing  $V_{s5}$  values, for each CPT site. The shear wave velocity profiles are estimated for each CPT record using the Christchurch-specific CPT- $V_s$  correlation of McGann et al. (2015a,b)

$$V_s(z) = A q_c(z)^b f_s(z)^c z^d \quad (1)$$

where  $A = 18.4$ ,  $b = 0.144$ ,  $c = 0.083$ ,  $d = 0.278$ , and  $q_c(z)$  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 SCPTu sites located in the surficial Springston and Christchurch Formations, therefore, CPT sites outside of these geologic units, e.g. in the loess soils found near the base of the Port Hills, were not considered.  $V_{s5}$  values are computed as

$$V_{s5} = (\sum d_i) / (\sum (d_i / V_{si})) \quad (2)$$

where  $d_i$  are CPT depth measurement increments up to the target depth of 5 m, and  $V_{si}$  are mean shear wave velocities over each measurement increment.

A smooth surface of  $V_{s5}$  that approximates the CPT-based  $V_{s5}$  data points was fit to a  $200 \times 200$  m grid using a modified ridge estimator (Khalaf et al. 2013) that is biased towards smoothness. The resulting surface is representative of the trends in the CPT results without necessarily representing  $V_{s5}$  at any particular site. To ensure that the surface focuses only on well-constrained estimates, the  $200 \times 200$  m grid was defined such that only grid points within 300 m of a CPT record are retained. This 300 m distance was selected based on an examination of the spatial variability in the soil profiles, and the enforcement of this constraint avoids estimates in areas without data. The grid is subdivided according to the surficial geologic units (QMAP units) indicated on the 1:250,000 scale geologic map of Christchurch (Forsyth et al. 2008). The full  $V_{s5}$  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.

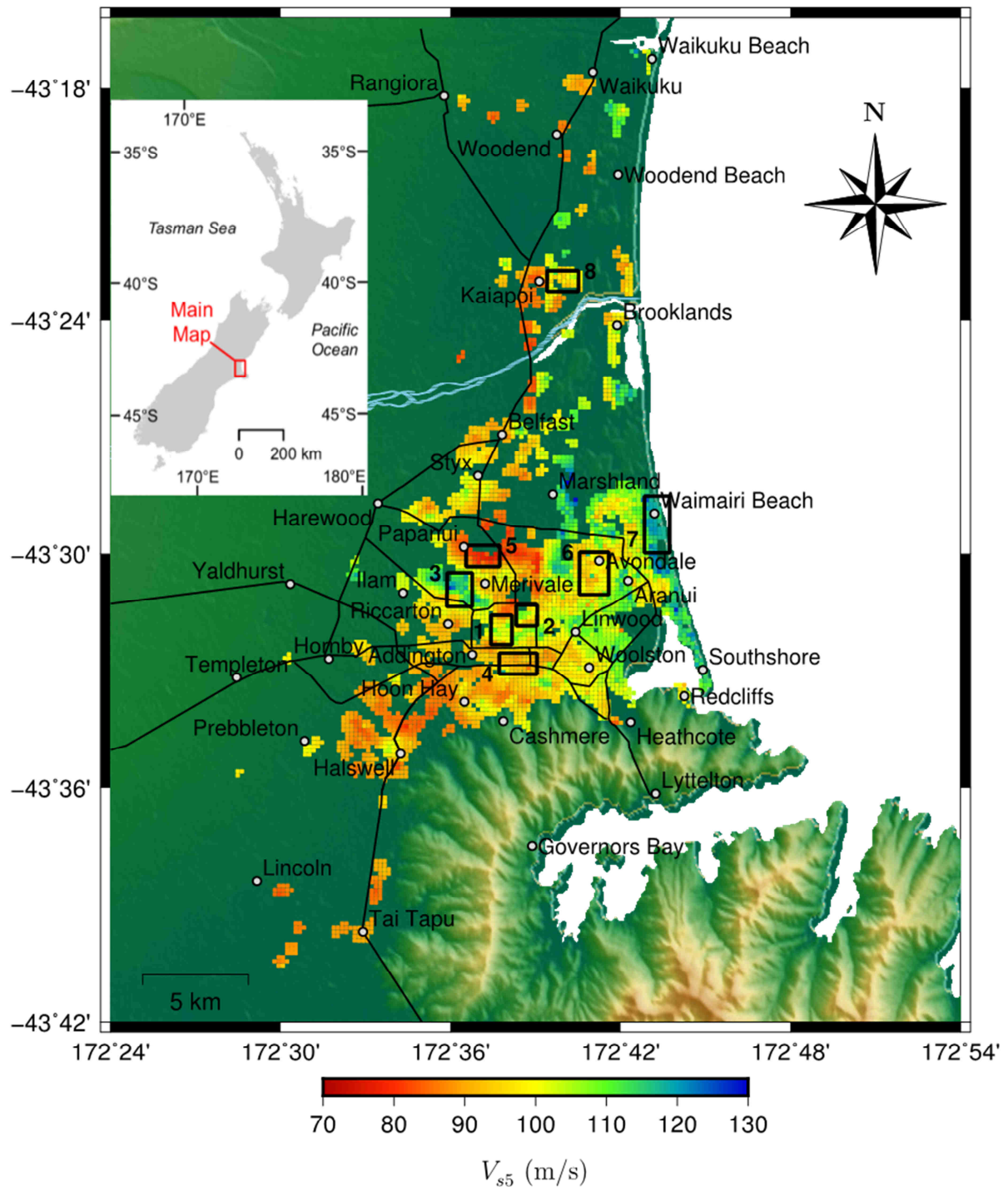


Figure 1.  $V_{s5}$  surface on uniform  $200 \times 200$  m grid for Christchurch region. Predictions are only provided in each grid cell if there is at least one CPT record within 300 m.

Figure 1 shows the  $V_{s5}$  surface developed using this procedure. As shown, there is a large degree of spatial variability in  $V_{s5}$ , with about a 60-80 m/s range between the minimum and maximum values (scale is slightly clipped to improve visibility). The  $V_{s5}$  values near the coast in the east (marine/dune QMAP unit) 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 to 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 very soft locations indicated in Figure 1 (red and red-orange with  $V_{s5} \leq 85$  m/s) are

highly correlated with locations of in-filled swamps/lagoons, and other current and formerly wet regions as inferred from the 1856 black maps of Christchurch (Wilson 1989). The inland areas of higher  $V_{s5}$  (e.g. directly north of Ilam and Riccarton), along with the inland areas without predictions (i.e. CPT penetration not possible), tend to correlate well with overbank gravel deposits (gravel  $\leq 1$  m below the surface) of the Springston Formation as inferred from the dominant surficial geologic deposits in Brown and Weeber (1992). The other areas in which there is a distinct lack of CPT data (i.e. no estimate made in surface) likely correspond to soils that are similarly dominated by gravels at shallow depths, or rural areas where no critical damage was observed following 2010-2011 earthquakes due to lack of infrastructure.

### **Liquefaction Severity Identification from Regional $V_{s5}$ Model**

The strong shaking associated with the events of the 2010-2011 Canterbury earthquake sequence triggered extensive liquefaction in the Christchurch area. As shown in the residential liquefaction-induced land damage map in Figure 2(a), the surface manifestations and damage associated with this liquefaction were particularly severe in the suburbs to the east and immediate north of the central business district (CBD) near the present-day route of the Avon river. The  $V_{s5}$  model shown in Figure 1 corresponds reasonably well with the liquefaction damage map, with areas where liquefaction occurred typically displaying lower  $V_{s5}$  values than surrounding areas where liquefaction was not observed (the implication being that lower  $V_s$  corresponds to lower relative density). For example, the boundary between the yellow markers ( $V_{s5} \leq 105$  m/s) and the green markers ( $V_{s5} \geq 115$  m/s) in the eastern suburbs near region 6 roughly approximate the damage/no damage boundaries reported by van Ballegooy et al. (2014), and delineates the liquefaction-susceptible alluvial soils near the Avon river from the marine/dune deposits where severe liquefaction was less prevalent.

The very soft locations indicated in Figure 1 ( $V_{s5} \leq 85$  m/s) are primarily areas where liquefaction did not occur. This is likely due to the nature of the soils in these areas, which can be evaluated in terms of their typical soil profiles. Figure 3 shows soil behaviour type index,  $I_c$  (Robertson and Wride 1998), and  $V_s$  profiles for all of the CPT records contained within boxed regions 5 and 6 (gray lines) along with the mean profiles (solid blue lines) computed from the CPT data. The profiles for these regions highlight how spatial variation in soil composition dramatically affects liquefaction response. In region 5 (and similarly in the profiles for region 4 not shown here), the soils in the upper 10 m are comprised primarily of silts, clays, and/or silty sands. While the predominance of these soils at shallow depths results in low  $V_{s5}$ , these areas generally do not correspond with severe liquefaction observations as these soil types are either less susceptible to liquefaction or not liquefiable. In contrast, potentially liquefaction-susceptible soils are much more prevalent in region 6 where severe manifestations of liquefaction were common.

As demonstrated with the typical profiles in Figure 3,  $V_{s5}$  cannot be directly used as a tool for liquefaction hazard identification in a regional sense. In addition to information about the groundwater table, the soil composition must also be considered. To isolate the  $V_{s5}$  values corresponding to liquefaction-susceptible deposits, the average soil behaviour type index from 1.2-5 m depth is computed as

$$I_{c5} = (\sum d_i I_{ci}) / (\sum (d_i)) \quad (3)$$

where  $d_i$  are CPT measurement increments over which each  $I_{ci}$  value applies. The uppermost 1.2 m is ignored in  $I_{c5}$  as it is assumed that this crustal soil is not necessarily indicative of the

soil types in the zone of interest. An  $I_{c5}$  surface is developed in a manner similar to that described for the  $V_{s5}$  surface and shown in Figure 2(b), which indicates that there is a general correspondence between areas of  $I_{c5} > 2.3$ -2.4 and areas with less severe observations of liquefaction effects. Four values of  $I_{c5}$  are used to filter out locations where shallow soils can be considered less susceptible to liquefaction or not liquefiable;  $I_{c5} = 2.3, 2.4, 2.5$ , and  $2.6$ . Filtered  $V_{s5}$  surfaces (called  $V_{s5f}$  for distinction purposes) are determined by removing all grid points with  $I_{c5}$  greater than each bounding value and shown successively in Figure 3.

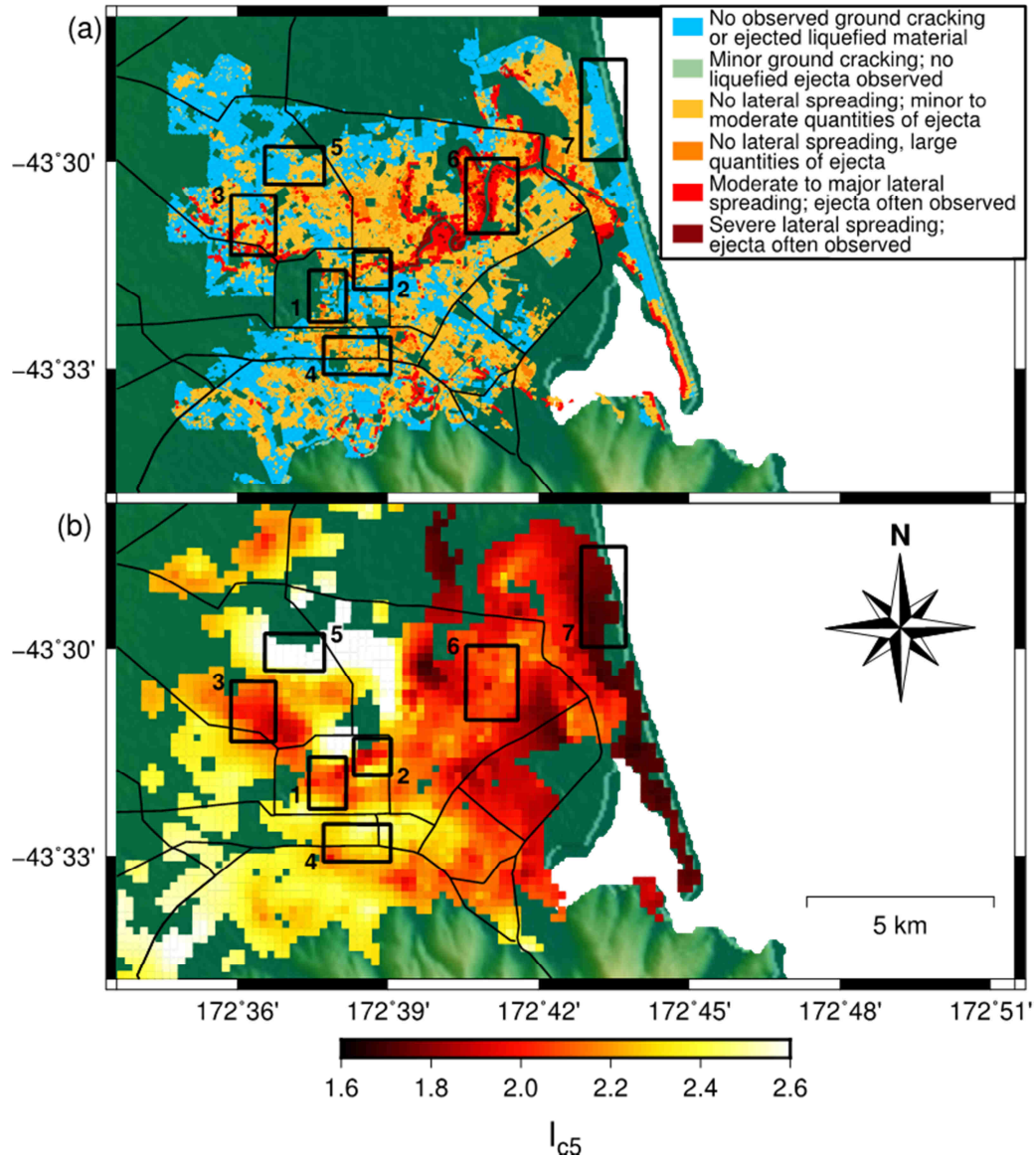


Figure 2. Comparison of  $I_{c5}$  surface with observations of liquefaction severity (after van Ballegooy et al. 2014) following 22 February 2011 earthquake.

It is generally observed in Figure 3 that the areas of lower  $V_{s5}$  ( $< 95$ -100 m/s) correspond with areas of more severe liquefaction-related phenomena, especially for areas of lower  $I_{c5}$  such as those sites along the Avon and Heathcote rivers (northeast and southeast of CBD, respectively), and the  $V_{s5f}$  surfaces for  $I_{c5} < 2.3$  and  $2.4$  appear to perform better in this regard than those for the higher values. In the  $V_{s5f}$  surfaces for  $I_{c5} < 2.5$  and  $2.6$ , there are large areas of low  $V_{s5}$  in regions where no damage was observed, while for the most part, such areas



have been removed from the  $V_{s5f}$  surfaces for  $I_{c5} < 2.3$  and  $2.4$ . This tendency for better correlation for the lower  $I_{c5}$  bounding values makes sense in terms of what  $I_{c5}$  represents. While it is conventionally assumed that  $I_c > 2.6$  is the delimiting value between potentially liquefiable and non-liquefiable deposits, this is likely conservative in that  $I_c = 2.6$  represents a high probability that the soil is not liquefiable rather than a definitive boundary. Additionally, because  $I_{c5}$  is an average value across a range of depths, it becomes even more important to consider smaller bounding values, as sites with  $I_{c5} < 2.6$  may still contain non-liquefiable soils (in terms of  $I_c > 2.6$  criterion) over significant portions of this depth interval.

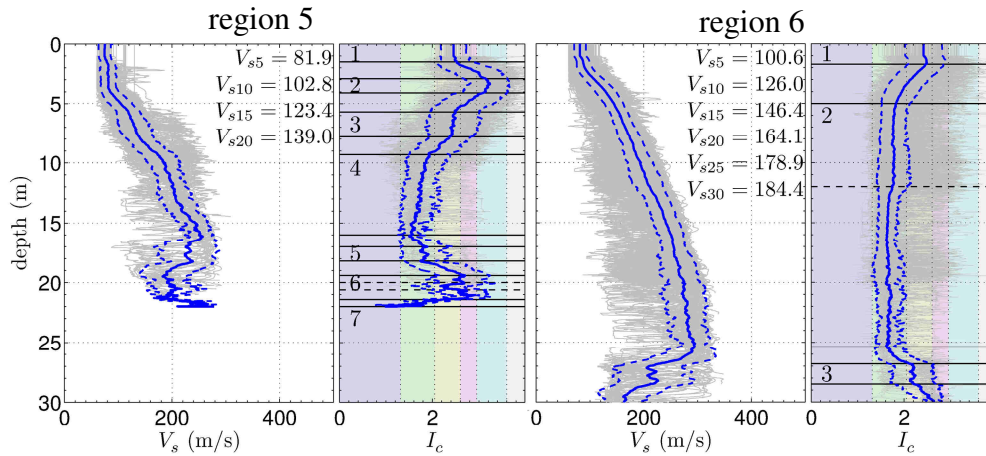


Figure 3. Typical  $V_s$  and  $I_c$  profiles from CPT sites in regions 5 and 6 (see Figures 2 and 3).

While it is clear that the  $V_{s5f}$  surfaces filtered for  $I_{c5} < 2.3$  and  $2.4$  are not perfect indicators of liquefaction severity, they appear to work well in an overall sense, especially when considered in tandem with the corresponding  $I_{c5}$  surface. Certain areas correspond very well; for example, there is a reasonably high degree of correspondence between  $V_{s5}$  magnitude and observations of liquefaction severity along the path of the Avon river (near region 6). In this part of the city, the areas where liquefaction was most severe correspond well with  $V_{s5} < 95$ - $100$  m/s, while areas of minor to moderate liquefaction indicate higher  $V_{s5}$  values. The regions where these general observations tend to fail, such as the large area of low  $V_{s5}$  in the vicinity of region 4 where there is generally poor correspondence between  $V_{s5}$  magnitude and liquefaction severity (though it tends to improve for the lower  $I_{c5}$  bounding values), also tend to correspond to areas where  $I_{c5} > 2.2$ - $2.3$ . Such locations may be places where non- $I_c$ -based factors that contribute to the uncertainty in liquefaction potential (e.g., soil age, plasticity, grain size distribution, fabric) reduce the liquefaction potential despite an  $I_{c5}$  value that may be classified as potentially liquefiable if considered alone.

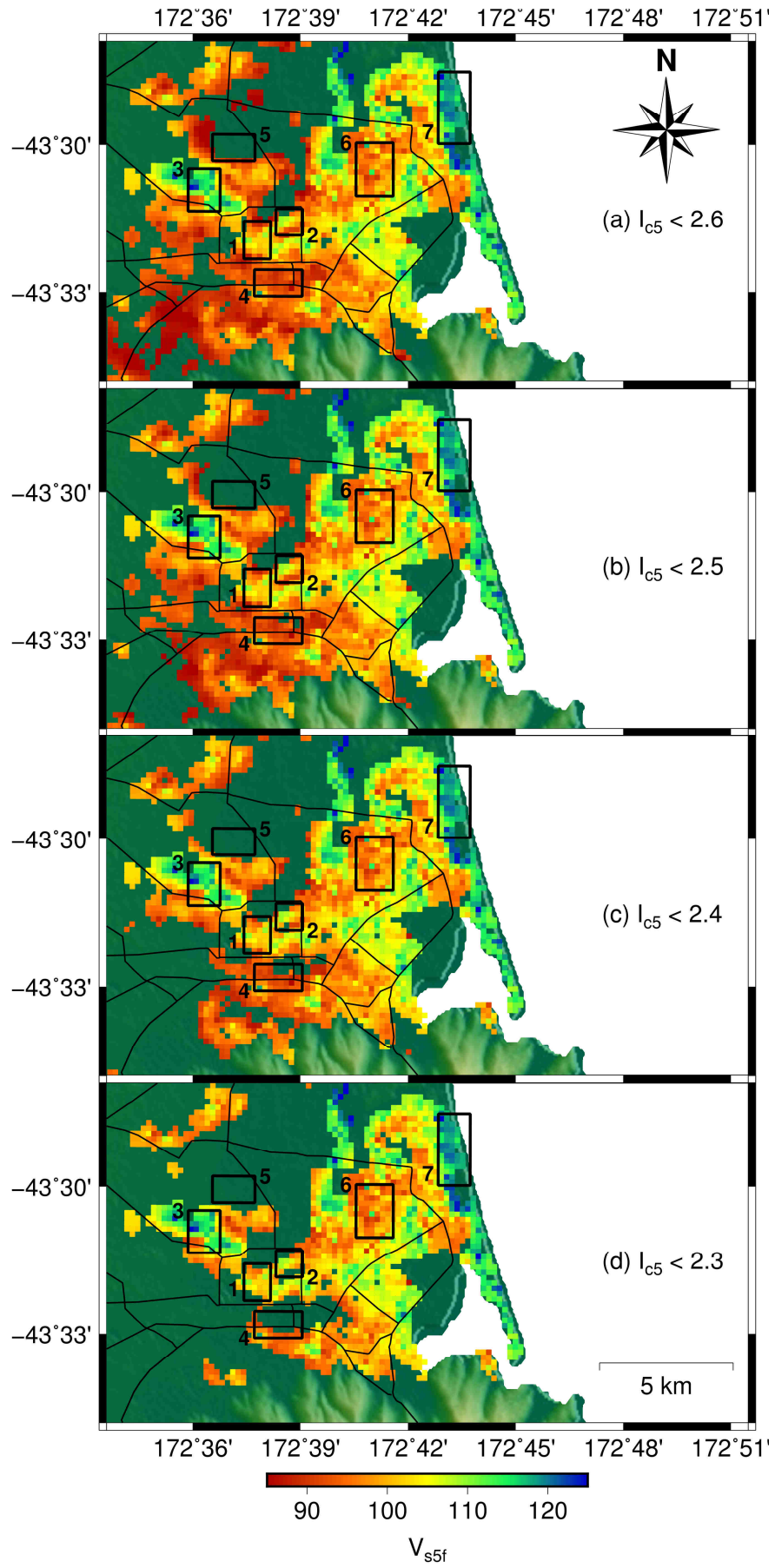


Figure 3.  $V_{s5f}$  surfaces filtered by  $I_{c5}$ . (a)  $I_{c5} < 2.6$ ; (b)  $I_{c5} < 2.5$ ; (c)  $I_{c5} < 2.4$ ; (d)  $I_{c5} < 2.3$ .



## Conclusions

The effects of spatial variability in the near-surface soils of the greater Christchurch urban area were keenly evident in the ground motion records and damage observations associated with the 2010-2011 Canterbury earthquake sequence. A model of 5 m shear wave velocity developed from 10550 CPT logs obtained throughout the region and a Christchurch-specific CPT- $V_s$  correlation (McGann 2015a,b) was used to characterize the spatial variability of the immediately near-surface soils of the region. This  $V_{s5}$  model captures the inherent variability of the soils typical to the region and was found to correspond well with known geological and historical features of the Christchurch area such as areas of in-filled swamps and significant surficial gravel deposits. Comparisons to observations of the severity of liquefaction-induced damage made following the 22 February 2011 event were made to assess the degree of correspondence between the regional  $V_{s5}$  model and the observed liquefaction. It was shown that when filtered based on the 5 m average soil behaviour type index ( $I_{c5}$ ), the  $V_{s5}$  model corresponds well in a general sense, with areas of severe liquefaction damage characterized by lower  $V_{s5}$  values, and areas of little or no damage characterized by higher  $V_{s5}$  values or higher  $I_{c5}$  values that indicate less likelihood for a prevalence of liquefaction-susceptible soil types in the upper 5 m zone.

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