Ongoing development of a 3D seismic velocity model of Canterbury, New Zealand for broadband ground motion simulation

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ABSTRACT: This paper presents the ongoing development of a new 3D seismic velocity model of Canterbury, New Zealand. The model explicitly represents the Canterbury sedimentary basin, and other significant geologic horizons, which are expected to have important implications on observed ground motions. The model utilizes numerous sources of data, including 3D regional tomography with a variable-depth inferred Moho, seismic reflection survey lines, geotechnical boreholes and well logs, spectral analysis of surface waves, and CPT logs which provide velocity constraints over their respective ranges of application. The model provides P- and S-wave velocity and density (i.e. V_p, V_s and ρ) over a grid of input points, and is presently being utilized in broadband ground motion simulations of the 2010-2011 Canterbury earthquakes. Comparison of simulated ground motions with those observed in the 2010-2011 Canterbury earthquakes will help provide a better understanding of the salient physical processes which characterized the unique set of strong ground motions recorded in this sequence of earthquake events.

1 INTRODUCTION

The 2010-2011 Canterbury earthquake sequence produced severe ground motions which caused significant ground failure and structural damage in Christchurch city and its surrounding suburbs. A large number of ground motions from these earthquakes were recorded due to a dense array of strong motion instruments over the Canterbury plains, producing a dataset which reveals numerous ground motion phenomena of likely importance, such as rupture directivity, basin-generated waves, basin edge effects, and nonlinear surficial soil response (Bradley, 2012; Bradley & Cubrinovski, 2011). Such observations provide an unparalleled opportunity for new ground motion understanding. However, although empirical ground motion prediction equations (GMPEs) allow for a comparison of these ground motions, they provide little insight into the underlying physics of these observations. In order to fundamentally understand the salient features of the ground motion phenomena, a physics-based approach is required. Hybrid broadband ground motion simulation (e.g. Graves & Pitarka, 2010) is one such physics-based approach which can produce synthetic ground motions that can properly represent the complex geology and topography within a region. Such simulations require a realistic 3D seismic velocity model as a domain for the numerical solution of the seismic wave propagation equations.

In this paper, ongoing work on the development of a 3D seismic velocity model for hybrid broadband ground motion simulation of the 2010-2011 Canterbury earthquakes is presented. The velocity model represents the 3D variation of P- and S-wave velocity and density of the Canterbury region and hence must sufficiently represent the critical aspects of the crustal structure over multiple length scales. As a result, numerous sources of data are utilized in the model formulation to provide adequate resolution where necessary. The available data sources include: 3D regional tomography, seismic reflection survey lines, geotechnical boreholes and well logs, spectral analysis of surface waves, and cone penetration test (CPT) results, each of which provide velocity constraints over their respective ranges of application. The use of this velocity model in hybrid broadband ground motion simulation will ultimately result in synthetic ground motions which can be studied to quantify the significance of, and interaction between, earthquake source, wave path and site effects during the Canterbury earthquakes as well as predictions of future events in the Canterbury region. Due to space constraints, this paper is principally focused on the model formulation and an overview of the data sources utilized.

2 MODEL FORMULATION

Seismic velocity models are most commonly represented as a grid of points which are assigned P-wave and S-wave velocities, and density values (i.e. V_p, V_s and ρ). These velocity models are generally created by "stitching" together data from numerous sources such as regional tomography at large depths, seismic reflection surveying at moderate depths and geotechnical investigations at shallow depths. The Canterbury velocity model discussed here is formed via multiple 3D surfaces and a rule-based approach. The 3D surfaces are utilized to define the boundaries of different geological units (which subsequently have different geophysical and geotechnical characteristics). For example, such surfaces include the Riccarton Formation, base of the Quaternary sediments, and geologic basement horizons. Following the definition of these surfaces, rule-based models are utilized to provide the variation of P- and S-wave velocity, and density between neighbouring surfaces. Such rule-based models could involve simple linear interpolation of velocities and density in space, or any form of 3D interpolation (as guided by the relevant experimental data). Thus, for each (Lat,Lon,Depth) point at which the model properties are required, the relevant bounding 3D surfaces are first determined, and then the appropriate rule-based model utilized to compute V_p, V_s and ρ. Currently, the model domain has been set as a rectangular area between Lat = [-43.2°,-44.0°], and Lon = [171.5°,173.0°], and extends to a depth of 50km below sea level. This essentially spans the area between the foot of the Southern Alps in the North West to Banks Peninsula in the East as shown in subsequent figures.

3 DATA SETS EMPLOYED

3.1 Overview of Velocity Model

The development of a Canterbury seismic velocity model requires collection and utilization of numerous sources of data to adequately constrain the desired domain at length scales required to propagate low as well as reasonably high frequency ground motions. Although there have been some simplified studies on the geologic and velocity structure of the Canterbury region in the past, there is also now an abundance of high quality data from both recent and ongoing studies as a result of the 2010-2011 Canterbury earthquake sequence. This section will detail the different data sets employed in the development of the Canterbury velocity model. Figure 1 schematically shows the different data sets and their approximate depths of application. Gravity data is also available for interpreting basement depths (Hicks, 1989), but has yet to be considered in the model development.

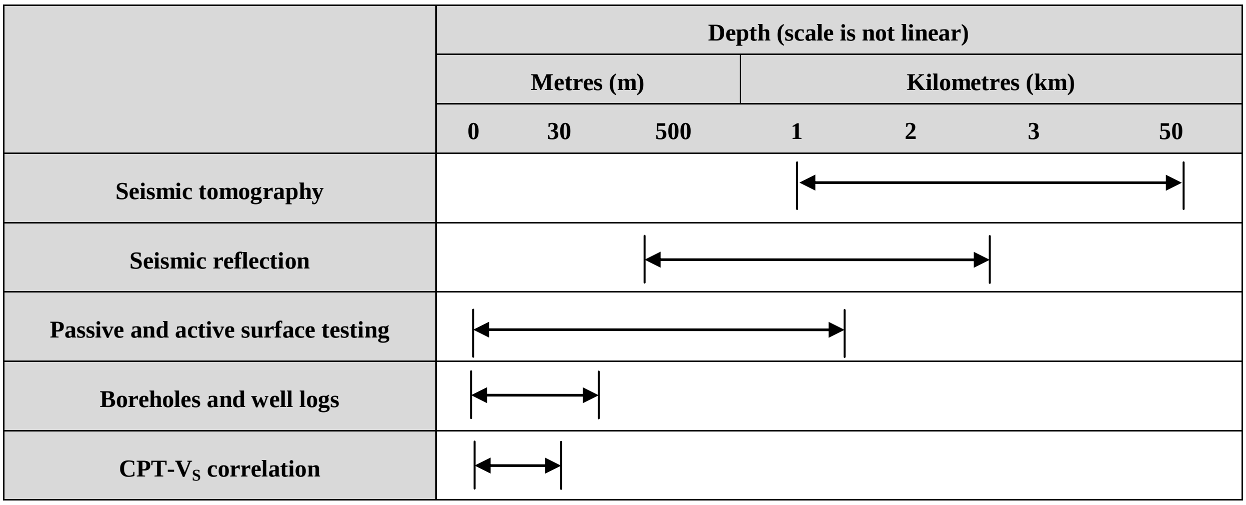

Figure 1. Applicable depth ranges for each current data source in the Canterbury velocity model.

3.2 Seismic Tomography

3D seismic tomography data with a variable-depth Moho (Eberhart-Phillips et al., 2010) is utilized for the deeper parts of the velocity model, roughly between 1km to 50km (although the accuracy for depths shallower than 3km notably reduces). The data is provided as a 3D grid of P-wave and S-wave velocities, and density values. This 3D grid is separated into horizontal reference surfaces at constant depths. The rule-based model for this data is that the velocity at a given point is obtained via inverse distance weighting interpolation within horizontal surfaces (i.e. Lat,Lon), followed by linear interpolation with depth between two reference surfaces. Figure 2 illustrates the model domain along with the 3km and 8km depth P-wave velocity contours.

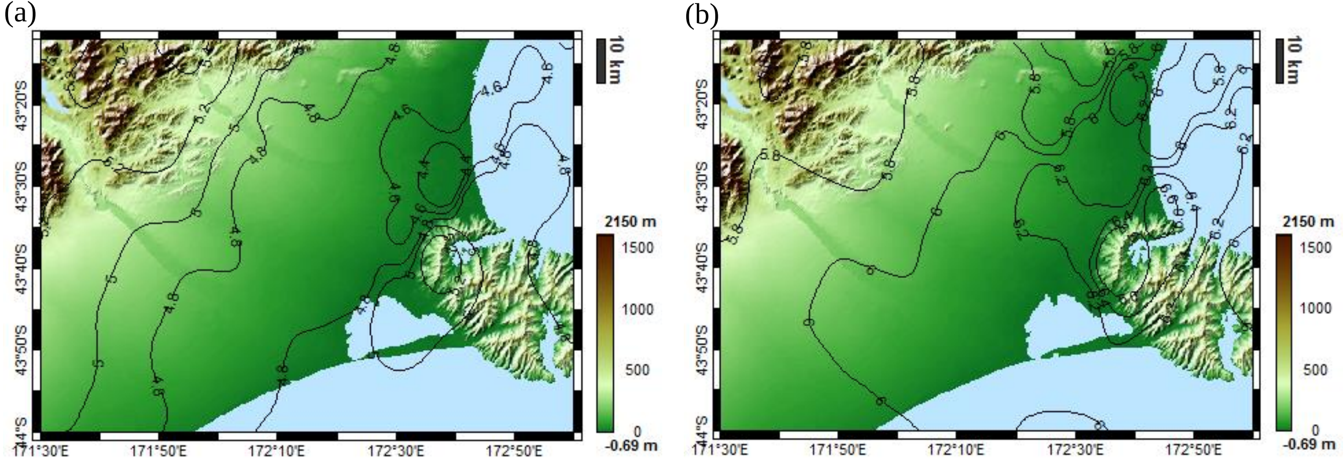

Figure 2. Contours of the tomography P-wave velocities (km/sec) at a depth of (a) 3km, and (b) 8km.

3.3 Onshore and Offshore Seismic Reflection Lines

Onshore and offshore seismic reflection lines (Barnes et al., 2011; Pettinga, pers comm; Kirkaldy et al., 1963; Schlumberger Geco-Prakla, 1998, 1999, 2000) are used to constrain the velocity model in the intermediate depths, roughly between 500m and 2.5km. Figure 3 illustrates the numerous reflection lines collected and the relatively good coverage provided across the Canterbury region which provides good spatial constraint at the intermediate depths. The Barnes et al. (2011) and Pettinga (pers comm) lines were collected for post-earthquake reconnaissance, while the British Petroleum (BP) (Kirkaldy et al., 1963) and IndoPacific (IP) (Schlumberger Geco-Prakla, 1998, 1999, 2000) lines were collected for petroleum exploration. It should be noted that there are additional offshore reflection lines which are outside the model domain that are used for constraint, but not shown in Figure 3.

An example interpreted seismic reflection line from Barnes et al. (2011) is shown in Figure 4 which illustrates ‘interval’ P-wave velocities and also various significant geologic horizons. The P-wave velocity variation between geologic horizons of this and other reflection lines form the basis of a rule-based approach for 3D interpolation. However, as the reflection data only provide P-wave velocity, empirical correlations are required to generate S-wave velocities and densities in their absence. For this purpose, the Brocher (2005a, 2005b) empirical correlations between $V_p - V_s$ and $V_p - \rho$ were examined for the 3D tomography dataset. Figure 5 provides an example of the comparison between the Brocher correlation and the tomography data, from which it can be seen that the comparison is favourable. Hence, its use with V_p values from seismic reflection at slightly shallower depths appears to be satisfactory.

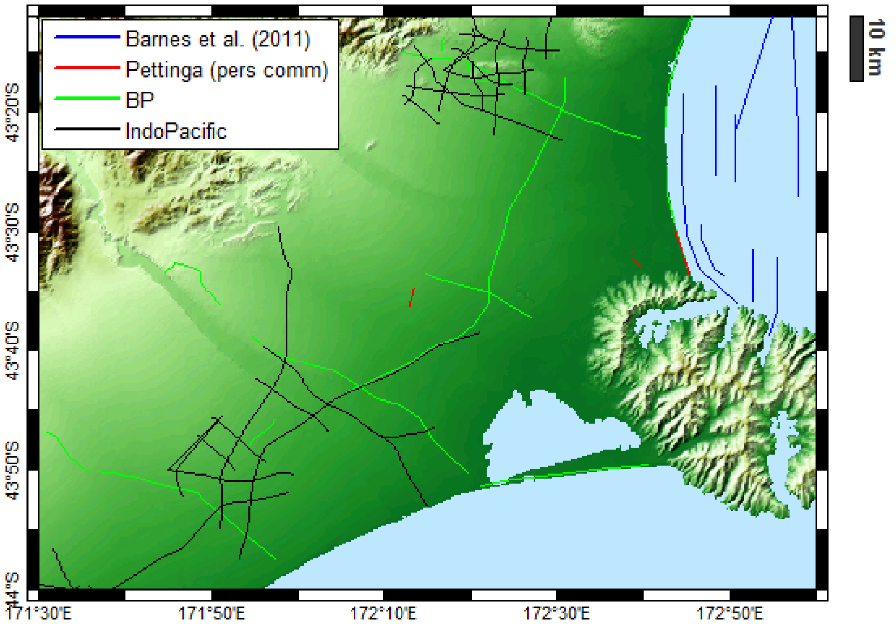

Figure 3. Seismic reflection lines across the Canterbury region. There are both Pettinga (pers comm.) and BP lines overlapping along the eastern shoreline.

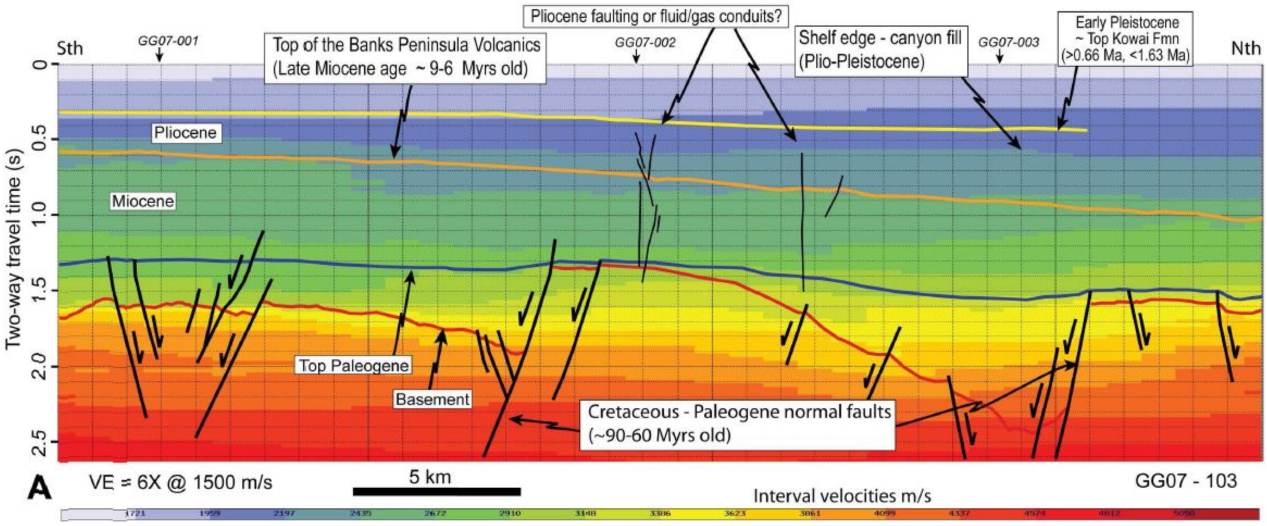

Figure 4. An offshore seismic reflection line showing P-wave velocities and geologic horizons (Barnes et al., 2011). (Located outside the model domain and therefore is not shown in Figure 3. Seismic reflection lines across the Canterbury region.)

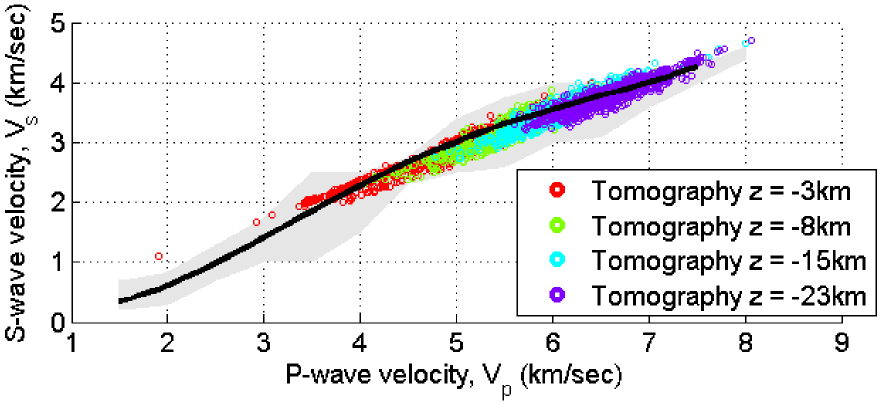

Figure 5. Comparison of Brocher (2005a, 2005b) V_P-V_S correlation with tomography data. The solid black line represents the published Brocher (2005a, 2005b) equation, while the shaded grey line represents the scatter in the empirical data utilized by Brocher.

As previously noted, the seismic reflection lines can be utilized to obtain the depths of significant geologic horizons, and from multiple reflection lines 3D surfaces of these horizons can be developed via interpolation. Surfaces which have been considered, as indicated in Figure 4, include the tops of the basement, Paleogene, Miocene, and Pliocene. Jongens (2011), in particular, examined seismic reflection lines from BP and IP to construct structural contours and develop a surface for the base of the Quaternary sediments (~Top Kowai Formation). Figure 6(a) shows the structural contours of the base of the Quaternary gravels based on Jongens (2011) ,but extended to the full model domain based on the additional reflection lines of Barnes et al. (2011), while Figure 6(b) shows the 3D surface produced. The surface clearly shows the Rakaia basin in the South West and Pegasus Basin in the East moving away from the Southern Alps (Hicks, 1989). Additionally, the Quaternary outcrop has been preserved with constraints at the foot of the Southern Alps and Port Hills. Above this outcrop, the values have been set to be equal to the ground surface and the model formulation has been set to enforce this when producing the velocity model.

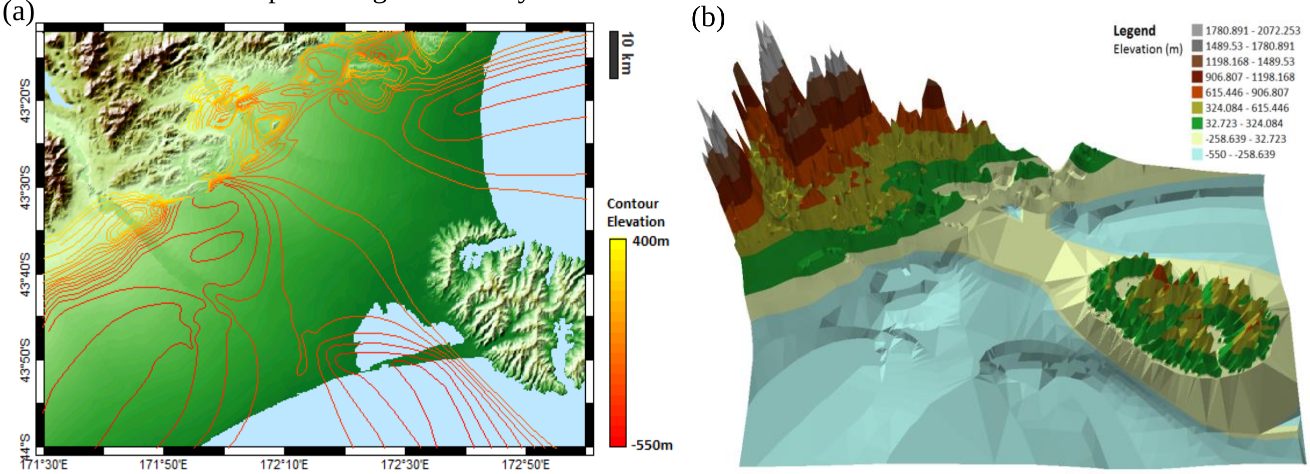

Figure 6. (a) Structural contours for the base of the Quaternary sediments (Jongens, 2011), and (b) Base of the Quaternary sediments surface.

3.4 Well Logs and Boreholes

Well logs (from Environment Canterbury, ECan) and boreholes (from the Canterbury Geotechnical Database, CGD) across the Canterbury region were also used as geologic surface constraints for the near surface region. The well logs and boreholes were inspected and filtered to obtain depths to significant geologic horizons at numerous locations. The depths of each geologic horizon are then used to produce a surface, such as the top and bottom of the Riccarton Formation, a shallow significant geologic formation underlying Christchurch. Figure 7(a) shows the distribution of well logs across the Canterbury region that have been identified as encountering the top of the Riccarton Formation. It can be seen that the top of the Riccarton Formation is shallower on the western side of Canterbury and increases in depth to the east. Figure 7(a) also shows a histogram detailing the distribution of depths where the top of the Riccarton Formation was encountered. It can be seen that the majority of well logs encounter the top of the Riccarton Formation between 10m and 30m depth. Additionally, Figure 7(b) shows one well log for the Bexley borehole which has been used in the surface wave inversions discussed in the subsequent section. The geologic horizons in this well log are particularly evident showing the top of the Riccarton Formation at roughly 40m depth.

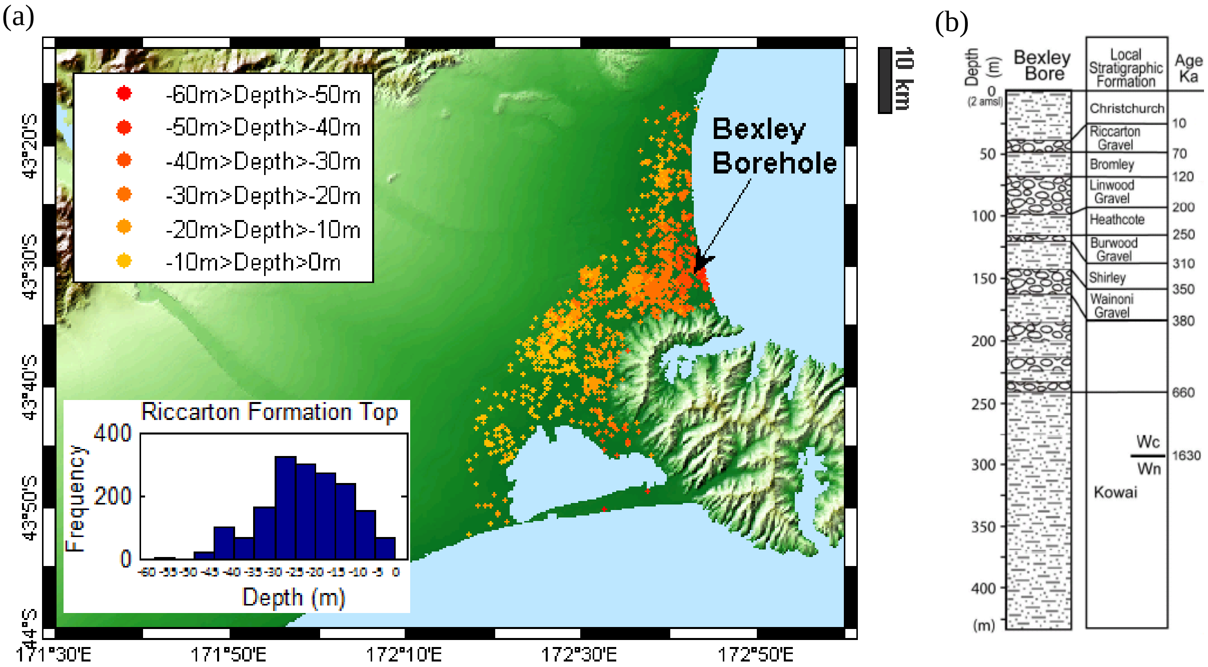

Figure 7. (a) Distribution of well logs used for the top of the Riccarton Formation, and (b) The Bexley borehole well log (Jongens, 2011).

3.5 Shear Wave Profiles from Surface Wave Analysis

Shear wave velocity profiles produced from forward modelling of passive and active surface wave testing (Wood et al., 2013) are the primary constraint for the near surface velocities from the ground surface to depths of up to 1.5km. Figure 8 shows the distribution of sites where surface wave analysis was carried out, largely spread around the urban Christchurch area where the response of shallow soils is of most interest.

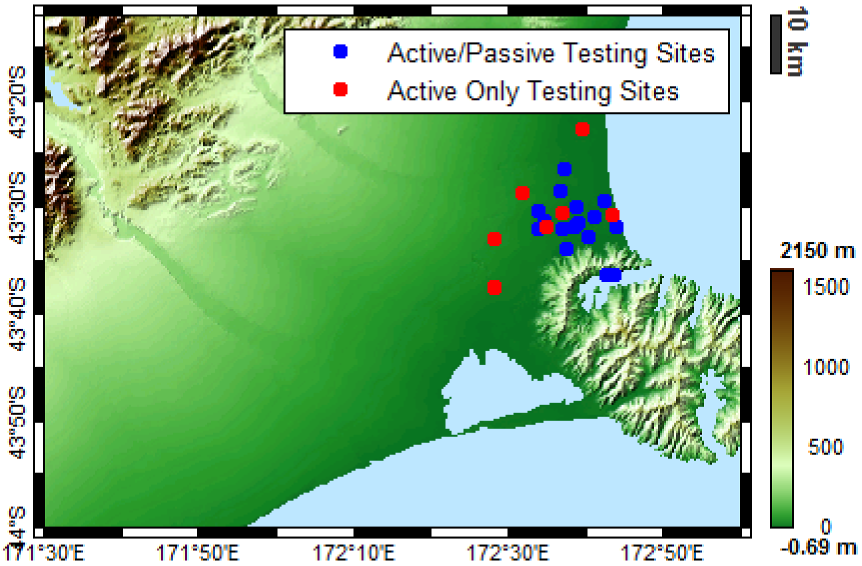

Figure 8. Active and passive surface wave testing locations.

Figure 9 shows one resulting shear wave velocity profile inverted from surface wave testing at the Queen Elizabeth II (QEII) site on the eastern side of Christchurch. As illustrated in Figure 9(a) the profile extends to a depth of 1.5km, clearly showing several significant velocity contrasts and velocity inversions, while Figure 9(b) illustrates the uncertainty in V_s obtained from the inversion. The large velocity contrast at approximately 1km depth indicates basement rock, which is broadly consistent with results obtained at nearby seismic reflection lines. Figure 9(c), shows that there are several noteworthy velocity contrasts at shallow depths, the first at roughly 40m corresponding to the Riccarton Formation, while the velocity inversions resulting from the inter-bedded layers (in particular, the Linwood, Burwood, and Wainoni Gravels, and the Bromley, Heathcote, and Shirley Formations) are less well resolved and are still being improved.

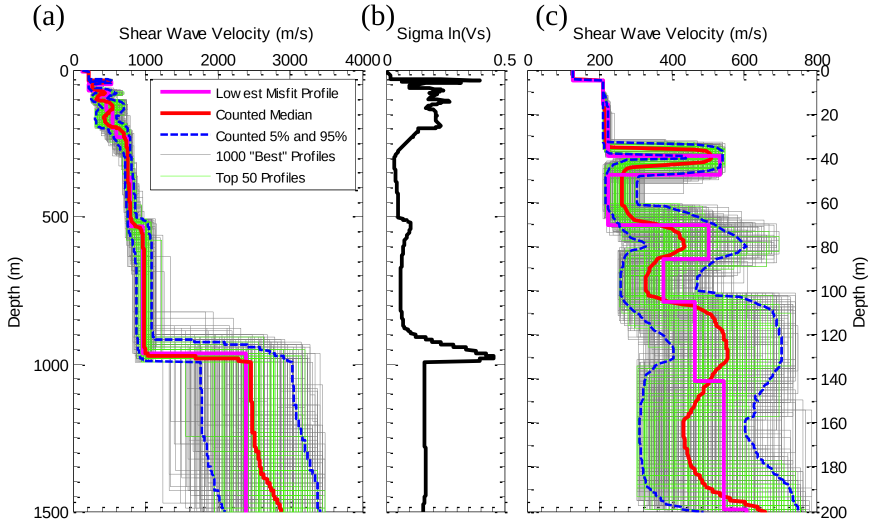

Figure 9. Shear wave profile results from the QEII site (a) the entire shear wave profile, (b) the uncertainty, and (c) a near surface close-up of the shear wave profile (Wood et al., 2013).

3.6 Christchurch-Specific CPT-V_S Correlation

The abundance of CPT data available in the Canterbury region following the 2010-2011 Canterbury earthquake sequence is a great asset for shallow geotechnical characterization. Using seismic CPT data (i.e. co-located CPT and V_S measurements), McGann et al. (2014) have developed a region-specific CPT-V_S correlation which can be used to develop an estimate of the V_S values of the near surface (depth<30m) throughout urban Christchurch (which has dense CPT coverage). A region-wide shallow V_S model from this CPT data is currently under development and will be utilized in the present Canterbury velocity model.

3.7 Topography

A ground surface model has been produced to constrain the upper bounds of the velocity model by stitching together numerous available digital elevation models (DEMs), making use of higher resolution models where possible. The majority of the surface model is produced from the South Island 25m DEM, while in the Christchurch city area a 15m DEM and LIDAR DEM were also utilized.

4 CONCLUSIONS

A 3D seismic velocity model for the Canterbury region is currently being developed for use in hybrid broadband ground motion simulation. The model follows a rule-based approach which prescribes P- and S-wave velocities, and density values to a point in 3D space from the appropriate data set depending on which geologic surfaces the point lies between. Numerous data sets are employed to ensure that the velocity model represents the critical aspects of the crustal structure of the region. These datasets include 3D regional seismic tomography, seismic reflection lines, well and borelogs, shear wave profiles from surface wave analysis, and results from CPT geotechnical investigations. The 3D seismic velocity model of the Canterbury region will enable synthetic ground motions to be computed using hybrid broadband ground motion simulations which will provide a means to understand the salient physical processes which resulted in the ground motions observed in the 2010-2011 earthquakes as well as predict future seismic scenarios of interest in this region.

5 ACKNOWLEDGEMENTS

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