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RESEARCH ARTICLE

3D models of Quaternary-aged sedimentary successions within the Canterbury, New Zealand region

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ABSTRACT
A 3D high-resolution model of the Quaternary geological stratigraphic sequence in the Canterbury, New Zealand region is developed utilising datasets of over 500 high-quality water well logs from a database of 29,985, and over 370 near-surface cone penetration test (CPT) records from a database of 13,670. The model, developed using geostatistical Kriging, represents the complex interbedded regional Quaternary geology by characterising the boundaries between significant interbedded geological formations as 3D surfaces. The model is examined in the form of both geological surface contour maps and vertical cross sections, where the most evident trend identified is the easterly dip caused by the dominant alluvial deposition of terrestrial sediments. The developed 3D interbedded Quaternary stratigraphy model has several applications for hydrologic modelling, earthquake-induced ground motion simulations and seismic site characterisation. For the latter case, the role of the model in constraining surface wave analysis-based shear wave velocity profiling is illustrated.

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Canterbury; New Zealand; Quaternary model; interbedded geology; geological surfaces

Introduction

The 2010–2011 Canterbury earthquake sequence produced severe ground motions which caused widespread geotechnical and structural damage throughout the Canterbury, New Zealand region (Kaiser et al. 2012; Bradley et al. 2014). The complex Quaternary geology underlying the Canterbury region was likely a salient factor in the observed structural and geotechnical damage, as the soft sedimentary deposits resulted in both basin and nonlinear near-surface soil response effects (Bradley and Cubrinovski 2011; Bradley 2012). The development of a 3D high-resolution model of the Quaternary geological stratigraphic sequence in Christchurch and the wider Canterbury region will therefore provide an improved understanding of its contributions to the severe ground motions observed in the 2010–2011 Canterbury earthquake sequence as well as improving predictions of future events which can cause strong ground shaking (local moderate magnitude earthquakes, e.g. M_w 5.5–6.5 similar to the event on the 22 February 2011, or larger, regionally significant events, e.g. Alpine Fault ruptures). In addition, such a geological model can also provide valuable information for hydrologic modelling, seismic site characterisation, seismic site response analyses and earthquake-induced ground motion simulations as a part of the wider Canterbury velocity model (CantVM) (Lee et al. 2017).

The Quaternary geological stratigraphic sequence of the Canterbury region has a complex interbedded nature with alternating terrestrial gravels, resulting from fluvial deposition from the Southern Alps and marine sediments deposited in times of marine transgression (Talbot et al. 1986; Brown and Weeber 1992). Figure 1 illustrates the formations which comprise the Canterbury Quaternary stratigraphy. Previously, documentation of the Quaternary geology was limited to the shallower stratigraphy: i.e. the Christchurch and Springston Formations, Riccarton Gravel and Bromley Formation (Suggate 1958). However, advancements in recent decades have identified and documented several deeper formations, referred to as the Linwood Gravel, Heathcote Formation, Burwood Gravel, Shirley Formation and Wainoni Gravel (Talbot et al. 1986; Brown et al. 1988; Brown and Weeber 1992). Beneath the identified formations, there are also several additional terrestrial and marine formations which are currently not well-documented and thus undifferentiated (Brown et al. 1988). Although the exact lithology of each formation varies, the marine formations generally consist of gravel, sand, silt, clay, peat, shell and other organic material, while the gravel formations are predominantly gravel with some sand, silt, clay and lesser quantities of organic material (Brown and Weeber 1992). As a result of the lithological differences, the marine formations

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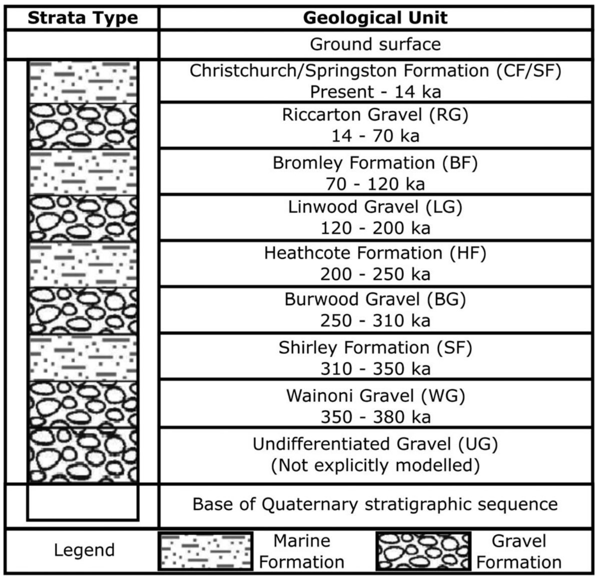


Figure 1. Schematic well log detailing the geological formations comprising the Canterbury Quaternary stratigraphy in the vicinity of Christchurch city, which generally alternate between terrestrial gravel and marine sedimentary deposits and their respective ages. The undifferentiated gravel (UG) is not explicitly modelled. Modified from source: Brown and Weeber (1992). Near the Port Hills, the Quaternary formations onlap against the unconformity resulting from the Banks Peninsula volcanics.

are typically less dense and have lower seismic shear wave velocities than the gravel formations which produce complex seismic wave propagation (and also a series of confined aquifers). Beneath Christchurch city, the thickness of the marine and gravel layers usually varies between 10 and 30 m, although the Linwood Gravel thickness is generally over 30 m (Brown and Weeber 1992).

Talbot et al. (1986) first presented a comprehensive overview of the Christchurch artesian aquifers, detailing the geology of the principal aquifers and presenting diagrammatic cross sections of the subsurface geology and groundwater system across Christchurch city. The results were primarily inferred from available water well logs, both public and private, at the time of development. However, the physical model developed was a simplified 2.5D fence model of the subsurface geology, from the inland plains to the eastern offshore, consisting of several cross sections (three serial lines and one tie-line) that do not now translate into a modern, spatially continuous, digital 3D environment. Efforts to characterise the Canterbury Quaternary geological stratigraphic sequence through 3D modelling include work conducted by Murray et al. (1998), Harfoot and White (2000), White (2007), Weeber (2003) and Begg et al. (2015). Murray et al. (1998) and Harfoot and White (2000) produced 3D lithological and formation models of the Christchurch city area which consisted of several geological formations down to the Burwood Gravel (i.e. roughly 100 m below sea level). Over 1244 water well logs containing lithological descriptions were used to develop the models for hydrologic modelling applications. White (2007) followed up on the previous work by producing revised lithological models of the near surface Christchurch and Springston Formations, which have a complex relationship of interfingering; these models were of a higher resolution and employed a larger well log dataset comprising 4596 wells, although the extent that the well logs were utilised and their quality were not well documented. Weeber (2003) produced a stratigraphic model of the south Christchurch to Rakaia River area utilising around 1750 well logs with the purpose of documenting recent geological work in the study area. The model represented all of the Quaternary formations down to the Wainoni Gravel and presented the top of each formation as contour elevation surfaces and isopachs, and several cross sections across the study area. However, the model was noted to have limitations relating to location and altitude inaccuracies, as well as inherent well logging inaccuracies. Begg et al. (2015) developed a 3D model of the urban Christchurch area for geotechnical applications using lithological definitions from water well logs, and cone penetration test (CPT) data obtained following the 2010–2011 Canterbury earthquake sequence. The near-surface Christchurch and Springston Formations are modelled in high detail, utilising a small but homogeneous dataset of 198 water well logs and 1340 CPT records. While these existing models were adequate for the purposes of their initial development, the Canterbury Quaternary geological model presented subsequently aims to:

1. expand the scope of previous models beyond the urban Christchurch city area; and
2. explicitly model all of the currently documented formations, while utilising a more consistent and improved high-quality dataset.

In this paper, the details of a new 3D high-resolution interbedded Quaternary stratigraphy model of the Canterbury region that characterises seven geological formation boundaries based on over 500 high-quality water well logs and 370 CPT records are presented. A detailed seismic site characterisation application for surface wave analysis is also provided to highlight the practicality and capability of the developed model. In this example, the developed Quaternary model is used to provide geological formation boundaries to constrain the surface wave analysis to produce geologically feasible shear wave velocity profiles which are important in such a geologically complex setting. The shear wave velocities developed can be subsequently used with the developed Quaternary model for further seismic applications.

Summary of adopted datasets

The adopted datasets for modelling the interbedded Canterbury Quaternary stratigraphic sequence comprise a widespread, high-density network of hydrologic well logs and near-surface CPT records which provide a previously unparalleled level of information on the spatial variation of the Quaternary stratigraphic sequence in the region. The base of the Quaternary stratigraphic sequence is constrained by the top of the Pliocene unit or Banks Peninsula volcanics from the CantVM inferred principally via seismic reflection interpretations (Lee et al. 2017). The physical data sources are supplemented by additional constraints (in the form of artificial data points for surface regularisation) in areas where a lack of physical data can lead to a geologically inconsistent model via the application of Kriging alone. The following subsections present the details of the various data sources which comprise the adopted datasets used to develop the model and the quality controls undertaken to ensure the suitability of the data for the aims of this study.

Environment Canterbury water well logs

The principal data source for the interbedded Quaternary geological surfaces developed herein is a database consisting of 29,985 Environment Canterbury (ECan) water well logs (http://canterburymaps.govt.nz/). The ECan water well logs are primarily used to document and utilise groundwater in underground aquifers, and provide information on the sediment colour, type (e.g. gravels, silts, etc.), particle description (e.g. grain size, roundness, etc.) and fabric (e.g. fractured, weathered, etc.) as a function of log depth (Brown 1990) and hence allowing identification of specific geological formations. A significant percentage of these ECan water well logs have geological strata codes already assigned in the metadata based on the soil descriptions, as interpreted by Weeber (2003), which were used to identify depths to the boundaries of significant geological formations at each respective well. This subset of interpreted well logs provided good spatial coverage of the interbedded region, as shown in Figure 2 which illustrates the spatial distribution of 1505 water wells that encounter the Riccarton Gravel, and Figure S1 in the electronic supplement which illustrates the spatial distribution of high-quality water wells which encounter all the other modelled geological formations (where the number of wells that intersect deeper layers reduces, as elaborated upon subsequently). It is also shown that the well logs are also most spatially dense in urban areas. Therefore, only this subset of well logs was used to preserve consistency in the interpretations. The black outline highlights the interbedded Quaternary stratigraphic sequence boundary which specifies the area where marine formations exist. The maximum depth of the ECan water well logs varies significantly, the deepest being the Bexley bore (M35/6038) which has a depth of 433 m.

Several filters were applied to the database of ECan water wells to obtain wells which had information relevant to the development of the model. The first filter applied was to remove wells which were not within, or

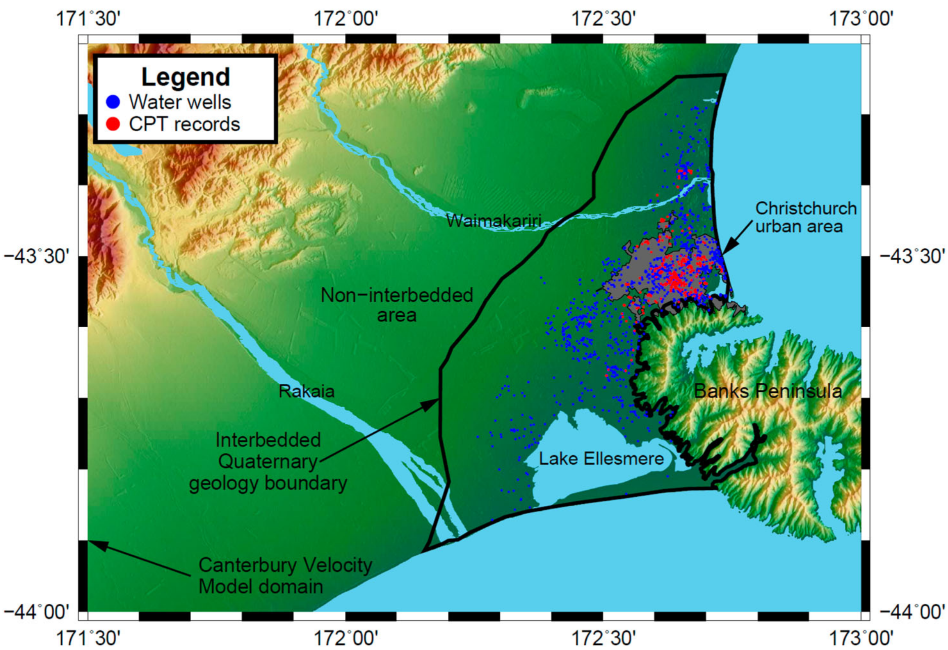


Figure 2. The Canterbury, New Zealand region showing the boundary within which the interbedded Quaternary stratigraphic sequence is considered and highlighting, as an example, the distribution of 1505 water wells and 377 CPT records which encounter the Riccarton Gravel.

Table 1. Geographic location quality assurance rating (QAR) identification methods and accuracy levels.

Geographic location quality assurance rating		
QAR code	Indication method	Accuracy
1	Differential GPS (advanced) or geodetic land survey	1–2 m
2	Standard handheld GPS	2–15 m
3	Site visit, driller's GPS or checked location sketch using GIS	10–50 m
4	Old grid reference ±100 m, no location sketch or location not checked	50–300 m
5	Proposed location, should be within 50 m for a well requiring water take consent	<50 m

near the border of the CantVM domain (Lee et al. 2017), which encompasses the entire area shown in Figure 2. The well logs were also filtered based on depth, only retaining well logs that had depths greater than 30 m, as shallow wells were unlikely to contain useful information on the Quaternary formation boundaries. Following these two steps, 7196 well logs were retained.

A quality filter was applied to the remaining well logs. The water well logs have several quality assurance rating (QAR) codes corresponding to various measurements. Although none of the QAR codes specifically detail the accuracy of the well log stratigraphic assignments, the QAR code for the geographic location of the well was used as a proxy based on the assumption that a more accurate location (often correlated with well log investigation date and well logging quality procedures) will result in higher quality well drilling and logging. It is recognised that the link between the QAR location code and well log quality may not be the strongest correlation, and quality is inherently better linked to the procedures of the driller and logger, but in the absence of this direct information the available information has been used to estimate the well log quality. The QAR values for location vary from 1 to 5, with 1 being the most accurate. Table 1 details the identification methods and corresponding accuracy levels. The assertion that newer wells were expected to have a higher quality rating appears reasonable as the higher quality ratings, 1, 2 and 3, utilise more recent technology for location determination such as global positioning systems (GPS) compared to the lower quality ratings, 4 and 5, which use older methods such as grid references (which were noted to be problematic by Weeber 2003). Newer interpretations also naturally draw on the greater understanding of the stratigraphy present, and therefore are more likely to correctly delineate different stratigraphic units. Based on the identification methods provided, QAR codes 1–3 ('high-quality wells'), which utilise GPS or digital locations were retained while wells with a QAR code of 4 or 5 ('low-quality wells') were discarded.

The aforementioned filtering process, and variable maximum depth of each well, produced datasets with a different number of wells for each geological formation boundary. Figure 3 shows the number of high- and low-quality wells which encounter the top of each modelled formation, and the mean depth and depth distribution at which the formations are encountered. It can be seen that a large proportion of the low-quality wells are shallow in nature relative to the high-quality wells. The reduction in the number of wells penetrating deeper formations reflects both the distribution of maximum well depths, as well as the fact that fewer existing data in the deeper formations can lead to difficulties in their identification (i.e. it may be possible in several cases that the deeper formation may have been physically encountered in the water well but remained un-interpreted because scientific knowledge of such formations was lacking at the time). Both high- and low-quality wells see a significant decrease in the number of well logs encountering formation boundaries below the Linwood Gravel. This is likely due to the nature of gravel layers being more difficult to drill through, as well as the Linwood Gravel being generally the thickest Quaternary formation considered, as illustrated by the large difference between the mean depths of the top of the Linwood Gravel and Heathcote Formation. It can also be seen that for each formation the number of low-quality well logs are greater than the number of high-quality well logs, as most well logs have a QAR code of 4. Despite the decrease in the number of well logs following the filtering processes, a reasonable spatial distribution of wells is maintained over the considered area (as previously shown in Figure S1).

Cone penetration test (CPT) data

The considered CPT dataset consists of 13,670 individual CPT records extracted from the Canterbury Geotechnical Database (CGD, https://canterburygeotechnicaldatabase.projectorbit.com) on 1 February 2014 from sites located throughout Christchurch and the surrounding towns and suburbs (McGann et al. 2017). Because the CPT is specifically utilised in the geotechnical characterisation of sands and fine-grained soils, the CPT records generally characterise the surficial Christchurch Formation and cover a range of depths from the ground surface to the upper surface of the Riccarton Gravel or Banks Peninsula volcanics (BPV), the latter of which was expected to be the cause of CPT refusal near the BPV outcrop where the Riccarton Gravel does not exist (McGann et al. 2017). A large percentage of the CPT tests were terminated at a pre-defined target depth (typically 20 m) or prematurely on cobbles, boulders, or dense gravelly material that was not the Riccarton Gravel or BPV (e.g. the Springston Formation), resulting in CPT records which were too shallow to identify the Riccarton Gravel or BPV (McGann et al. 2017). Therefore, for the purposes of this study, the raw CPT data were passed through several filters to obtain additional

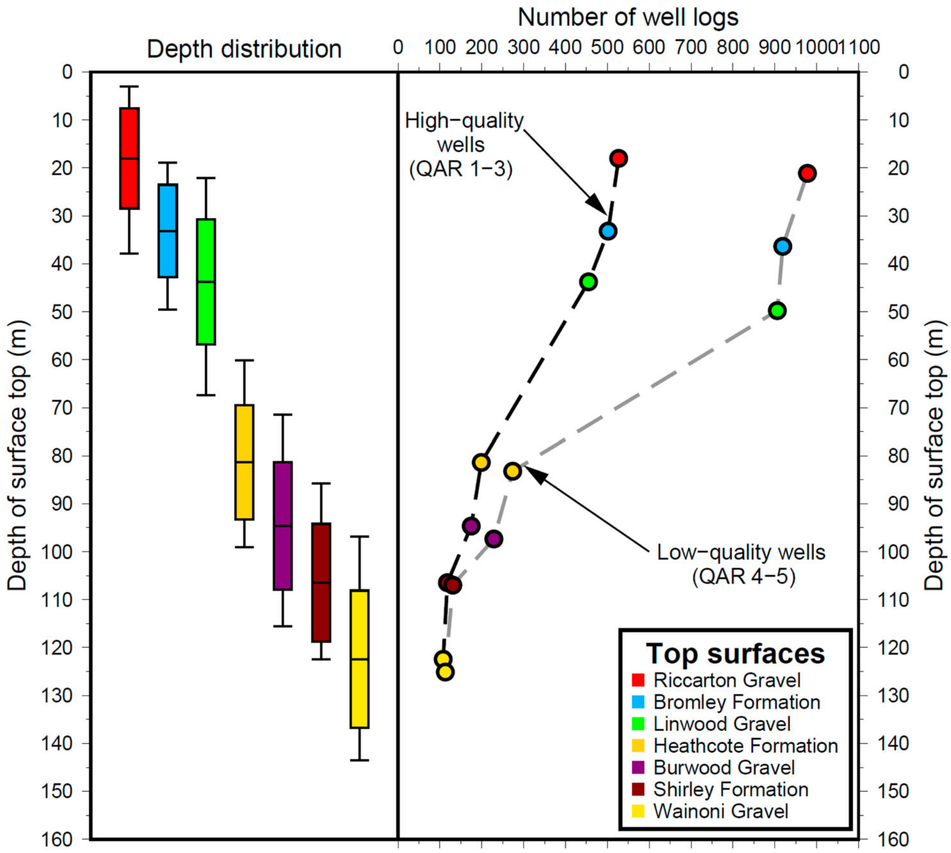


Figure 3. Depth and formation distribution of high- and low-quality well logs which encounter the top of each geological formation. In the left panel, the box plots illustrate the depth distribution of each surface based on the high-quality logs for perspective. The boxes indicate the mean ±1 standard deviation and the error bars indicate the 5th and 95th percentiles. In the right panel the depicted depths are mean values for the high- and low-quality datasets.

data representing the top of the Riccarton Gravel to supplement those from ECan water well logs, or the top of the BPV for the development of the BPV surface in the work by Lee et al. (2017). The ground surface elevations for the CPT are obtained from light detection and ranging (LiDAR) surface models where available and from the 25 m land resource information systems (LRIS) digital elevation model otherwise.

Initially, 10,550 CPT records from McGann et al. (2017), which were quality assured based on the larger dataset of 13,670 CPT records, were considered. Additional filtering steps were then required to determine which CPT records had encountered the Riccarton Gravel or BPV. The process compared CPT refusal measurements against provisional surfaces developed from water well log data alone. Two surfaces were considered, one characterising the Riccarton Gravel and one characterising the BPV. CPT logs which are inferred to have encountered either of these units were identified based on:

1. a normalised tip resistance of $q_{c1N} > 200$ and a soil behaviour type index of $I_c \leq 1.31$; and
2. refusal depths which are within 3 m of the relevant provisional geological surface based on water well log data only.

The second criteria was based on the expected error in the provisional water well log-based models in constrained areas. In areas with less constraint from well logs, the automatic CPT evaluation criteria were superseded by manual inspection of the available CPT records. The resultant filtered dataset contains 377 CPT records which were interpreted to have terminated on the top of the Riccarton Gravel, were used to supplement the water wells in the development of the Riccarton Gravel top surface, and whose spatial distribution is shown in Figure 2. Only five CPT records were found to have been refused on the BPV.

Constraints for base of the Quaternary stratigraphic sequence

The base of the Quaternary stratigraphic sequence delineates sediments deposited in the Quaternary period (roughly <2.6 Ma) with those in the Tertiary period (roughly >2.6 Ma) (Forsyth et al. 2008; Gibbard et al. 2010). Geologically, this delineation represents the top of the uppermost geological unit in the Tertiary sequence which corresponds to the Pliocene unit, or the BPV where the Pliocene unit does not exist (e.g. in the vicinity of BPV surface outcrops), as defined in the CantVM (Lee et al. 2017). Surfaces representing the elevation of the top of the Pliocene unit and BPV from the CantVM were used to provide this constraint, where complete details of these surfaces can be found in the work by Lee et al. (2017). The CantVM Pliocene unit was primarily constrained by seismic reflection lines (Lee et al. 2017) and almost exclusively consists of the Kowai Formation, a brown, weathered, greywacke-clast conglomerate with interbedded sandstone, siltstone, mudstone and carbonaceous layers (Forsyth et al. 2008). The BPV unit consists of high-velocity basaltic and trachytic lava flows in the upper regions, and rhyolite and andesite lava flows in the deeper regions (Forsyth et al. 2008). This delineation has seismological importance as the seismic velocities, and hence impedance, of the Tertiary period deposits are often much higher than those of the Quaternary period deposits. Large impedance contrasts can lead to complex wave propagation through reflected and guided waves, resulting in amplified and longer duration ground motions (Joyner 2000; Graves and Wald 2004; Frankel et al. 2009; Bradley and Cubrinovski 2011; Bradley et al. 2014). The large stiffness contrast between the BPV and Quaternary formations can also lead to significant basin edge effects, where the earthquake induced shaking effectively results in the stiffer volcanics pounding against the softer sedimentary deposits increasing the intensity of ground shaking (Graves et al. 1998; Bradley 2012, 2016). In the 2010–2011 Canterbury earthquake sequence, for example, this effect was most apparent at the Heathcote Valley strong motion station (HVSC), located adjacent to the BPV outcrop (Bradley 2012).

Artificial data points for surface regularisation

In addition to the aforementioned well log and CPT data used for the interbedded Canterbury Quaternary stratigraphic model development, several sets of artificial data were also produced to constrain the model in areas that had either no physical data constraint, or required additional interpolation or extrapolation constraint to adequately represent the regional geology (i.e. to provide regularisation in the subsequent geostatistical Kriging process).

Figure S2 in the electronic supplement illustrates the artificial data used as well as the water wells and CPTs which encounter the Riccarton Gravel to highlight the need for surface regularisation. These data points are primarily located near the perimeter of the interbedded Quaternary boundary in order to guide the surface extrapolation to be geologically consistent. The non-interbedded region points were introduced to enforce the marine formations to taper to zero thickness beyond the maximum inland extent while the maximum inland extent buffer points, located roughly 1–2 km on the coastal side of the perceived maximum inland extent, guide the convergence of the top and base of marine formations as they approach the maximum inland extent. The offshore points are included to reduce boundary and edge effects at the shoreline which would occur in the absence of offshore constraints. The Banks Peninsula points are located just inside Banks Peninsula and are used to model the Quaternary formations onlapping against the BPV. Lastly, the Lake Ellesmere points are produced to provide a smooth transition over the Lake Ellesmere area, owing to the fact that water well drilling does not occur in lacustrine environments. The elevation of the points was developed through different techniques, dependent on the proximity and availability of surrounding data, such as neighbouring high-quality well logs, linear spatial interpolation and extrapolation, and general understanding of the regional geology.

Geological surface model methodology

The datasets discussed in the previous section were utilised in geostatistical Kriging to develop 3D surface models which characterise the elevation of the top of each significant Quaternary geological formation. Several novelties of Canterbury's regional geology were explicitly considered in the development of the surfaces to ensure the model adequately represents the existing regional geology. The following two subsections discuss the salient features of the regional geology and the Kriging interpolation method employed in the model development, as well as some inherent model limitations.

Considerations of regional geology and model limitations

Canterbury's regional Quaternary geology is complex, consisting of interbedded terrestrial and marine formations with specific depositional patterns (Brown et al. 1988; Brown and Weeber 1992; Browne and Naish 2003; Forsyth et al. 2008). The top of the geological formations shown in Figure 1 are explicitly developed as the components which comprise the Canterbury Quaternary geological model, the output of this particular study, with the exception of the top of the surficial Christchurch and Springston Formations, since this is simply equivalent to the ground surface and is obtained from a digital elevation model (DEM). The depths between the Wainoni Gravel and base of the Quaternary stratigraphic sequence lacks documented data to provide adequately constrained characterisation as deep wells which penetrate these depths are sparse and methods of exploring deep stratigraphy (e.g. seismic reflection surveying) are generally of lower resolution in these shallower areas. The depth between the Wainoni Gravel and base of the Quaternary stratigraphic sequence is therefore modelled as an undifferentiated gravel despite the expected presence of thin marine formations. As the primary purpose of the Quaternary geological model is the analysis of seismic problems, such as surface wave analysis and 1D seismic site response analysis, as detailed in a subsequent section, the consequences of this modelling assumption are reasonably minor as lithological differences become less important with increasing confining stress. As confining stress increases, the differences between velocities of terrestrial and marine formations, which are the important parameters required for the aforementioned seismic problems, diminish and therefore the errors introduced from this assumption are less significant.

As previously discussed, Figure 2 shows the 'interbedded Quaternary geology boundary' which encloses the area where modelling of the interbedded geological stratigraphic sequence is considered. The northwest edge of the boundary is the maximum inland extent of marine formations, and the southeast edge is the BPV outcrop. The delineation of the maximum inland extent was produced considering previous research on paleo-coastlines (Brown et al. 1988) and examination of the location and formation depths of the furthest inland wells encountering the various marine formations. The southeast edge of the boundary, the BPV outcrop, limits the extent of the sedimentary deposits which rest unconformably on the BPV. The non-interbedded area (also shown in Figure 2) comprises a series of fluvial gravel units only and is therefore effectively modelled as a single continuous undifferentiated gravel unit, again in the context of seismic problems where seismic velocity variations are of principal concern.

As the Quaternary formations overlie the Tertiary geological sequence, the raised elevation of the tertiary sediments as a result of the Pliocene–Miocene BPV leads to unconformities in the vicinity of the Banks Peninsula (Brown and Weeber 1994) which must be explicitly considered. The unconformities are modelled using surfaces representing the top of the Pliocene unit and BPV (where the Pliocene unit does not exist) from the CantVM (Lee et al. 2017). The interaction between the Quaternary formation, Pliocene unit and BPV surfaces naturally lead to onlapping of the Quaternary formations against the unconformities. Therefore, the modelled Quaternary geological surfaces abruptly transition from a relatively horizontal inclination, constrained by the well logs, CPT and surface regularisation constraints, into a steep slope, constrained by the top Pliocene unit and BPV surfaces, as they approach the BPV outcrop (Brown and Weeber 1994).

Interpolation method

Kriging, a generalised least squares regression algorithm for geostatistical interpolation, was utilised to develop the geological surfaces based on the aforementioned data using the Move geological modelling software provided by Midland Valley (http://www.mve.com/). The Kriging method is linear, unbiased and more conservative with estimation of minima and maxima compared to other interpolation methods (Isaaks and Srivastava 1989; Olea 1999). An exponential transition model, which determines the Kriging algorithm's spatial autocorrelation, was used for the theoretical variogram as it was found to provide the best fit to the adopted datasets amongst considered transition models. Variogram parameters (i.e. nugget, partial sill and range) were developed for each surface based on the data used as constraints. The theoretical exponential variogram was produced by visually adjusting parameters to provide a good fit to the empirical variogram for 0–20 km lag distances (with larger distances considered unimportant given the scope of the interbedded Canterbury Quaternary geological stratigraphic sequence).

The modelled geological surfaces were Kriged onto a rasterised grid of 500 m $\times$ 500 m spacing, which was chosen to balance the resolution of the interpolation with the spatial density of the underlying data. As the interpolation grid points do not necessarily coincide with the water well or CPT locations, the exact elevations of the constraints are not precisely honoured but a weighted average is assigned at the grid points instead. Therefore, a subsequent assessment of the surfaces is required to assess the integrity of the model with respect to the underlying data. However, it is also important to note that the aim of this study is to have a model that is region-specific and captures large-scale variations but not necessarily localised fluctuations. Hence, the developed model is not intended to replace the value in obtaining site-specific information.

Quaternary geological surface models

This section examines the resulting geological surfaces produced from Kriging, including a comparison with the distribution of the underlying well log and CPT data from which they are derived from. Figure 4 provides a 3D isometric view of the developed surfaces in the interbedded area which highlights their interbedded nature and stratigraphic sequence. A detailed examination of the surfaces is carried out by evaluating elevation contour maps of each surface which include the locations of the physical data used as constraints, as well as north–south and east–west oriented vertical geological cross sections through the Christchurch city area, presented as cross section 1 and 2 in Figure 4, respectively.

Geological surface elevation contour maps

Figures 5 and 6 present elevation contour maps (relative to the mean sea level) of the top of the Riccarton

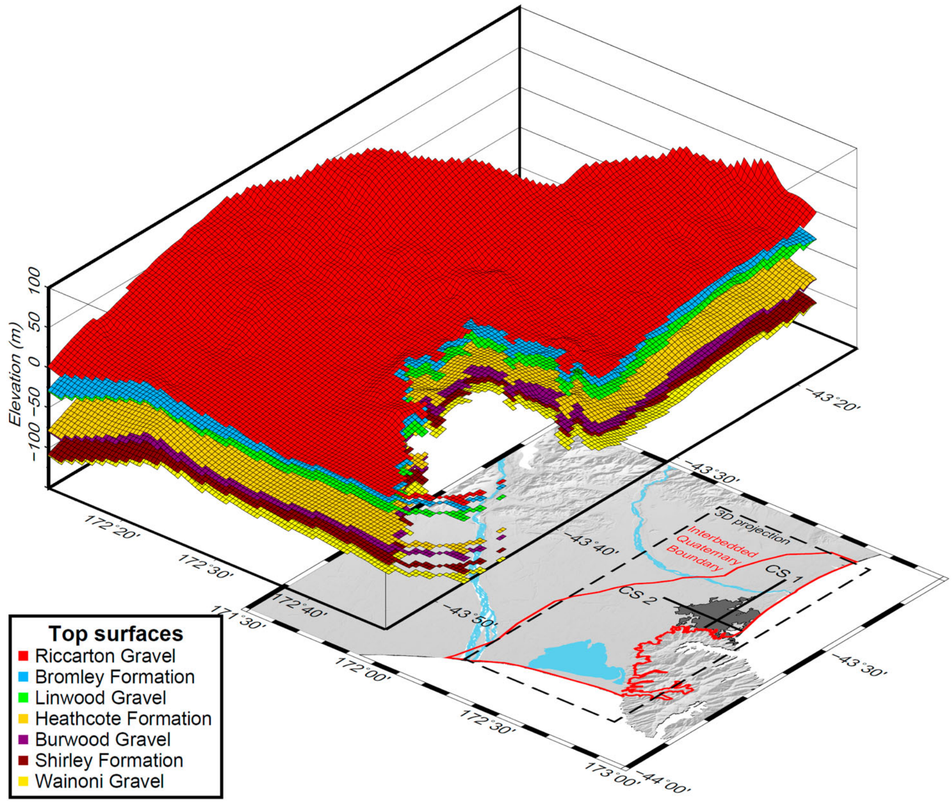


Figure 4. Isometric view of the modelled interbedded Quaternary formation surfaces overlying the Canterbury, New Zealand region highlighting their interbedded nature and stratigraphic sequence. The location of cross sections examined in subsequent sections, cross section 1 (CS1) and cross section 2 (CS2), are also shown on the basemap.

Gravel and top of the Heathcote Formation, respectively, which highlight the essential features of the Quaternary formation surfaces. All other developed surfaces are presented in the electronic supplement. The most apparent trend in all surfaces is the general dip (downward slope) in the easterly direction, which is expected given the dominant alluvial deposition of sediments in the Canterbury Plains from the inland Southern Alps (principally from the Waimakariri River) (Brown and Weeber 1992). One feature that is apparent in each of the surfaces is the interaction of the Pliocene unit and BPV edifice on the surface depths. Near the Pliocene and BPV surface outcrop (shown by the dashed line), each surface onlaps on the unconformity shown by the cropped area with deeper surfaces having a larger area affected as the surfaces onlap further from the outcrop. Several deeper surfaces (i.e. the Heathcote Formation and below) also onlap with the Pliocene unit surface near its outcrop north of Kaiapoi in the Ashley Forest area leading to thin Quaternary deposit thicknesses (Lee et al. 2017). These deeper surfaces (below the Heathcote Formation) also feature the saddle northwest of the Banks Peninsula and the Pegasus Basin southeast of Kaiapoi, which are also observed in the Tertiary geological formations in the same area (Lee et al. 2017). These features become more prevalent with increasing surface depth. Marine formations also appear more irregular than the terrestrial formations near the eastern coastline, particularly the Bromley Formation, which is a consequence of the corresponding marine depositional processes being less uniform than the fluvial deposition of gravels.

The modelled Quaternary surfaces are smooth in areas with few well log or CPT data constraints, as expected considering the properties of Kriging and objectives of the surface regularisation. However, areas which are highly constrained, such as the Christchurch city area, are also reasonably smooth and regular, suggesting the level of smoothing in weakly constrained areas based on the theoretical variogram is suitable. Small-scale features which differ from the general trends generally occur in areas which are constrained by few data points or a single data point, such as the area south of Rolleston in the deeper surfaces, as data which deviates from the general trends can have a large influence in these data sparse areas.

Vertical geological cross sections

Two cross sections, whose locations are shown in Figure 4, of the Quaternary formations and their corresponding shear wave velocities (V_s) are presented here to highlight the trends and thicknesses of the various formations simultaneously. Figures 7 and 8 show north–south (cross section 1) and east–west (cross section 2) oriented cross sections passing through the Christchurch city area, respectively. The V_s prescribed

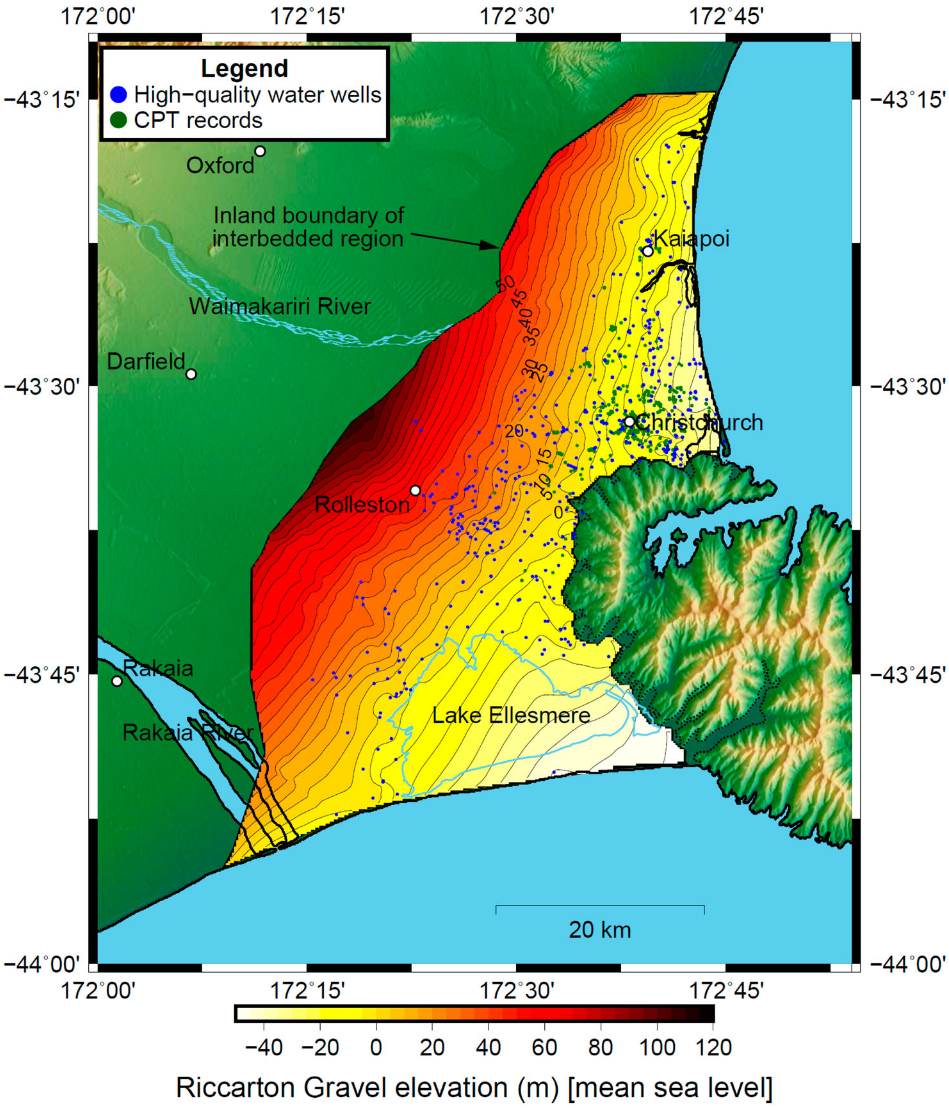


Figure 5. Top of the Riccarton Gravel surface elevation contour map with high-quality well log and CPT locations plotted.

for each unit are based on the depth-dependent shear wave velocity variations from surface wave analyses by Teague et al. (2015). In short, all the resulting V_s profiles from Teague et al. (2015) are firstly separated into gravel and marine formations. A mathematical correlation following the functional form of the Faust equation (Faust 1951), is then independently regressed against each respective subset, gravel or marine, producing depth-dependent velocity correlations for gravel and marine formations, respectively. The two resulting depth-dependent velocity correlations are used in the cross sections presented in this section. Both cross sections show that the marine formations are relatively thick across the Christchurch city area as a consequence of being adjacent to the coastline. The southern end of Figure 7 onlaps with the BPV at a steep gradient, possibly a result of weathering from prehistoric sea levels. The beginning of the basin structure can also be seen in the deeper formations (Heathcote Formation and below) at roughly 12 km along the cross section where the deeper formations begin to dip into a regional depression. Figure 8 highlights the trend of thicker marine formations on the eastern, coastal end, and thinner marine formations on the western, inland end. Conversely, the gravel formations are thick on the western, inland end and thinner on the eastern, coastal end. The thinner thickness of Quaternary deposits on the western end of cross section 2 is a consequence of the elevated structural saddle of the Pliocene unit (Lee et al. 2017). The eastern end of Figure 8 has a protrusion producing a thinner thickness of Quaternary deposits resulting from the Pliocene unit resting on the BPV edifice (Lee et al. 2017).

Assessment of surfaces via residual analysis

In this section, a residual analysis of the high-quality water wells and CPT data is performed to assess the integrity of the Quaternary geological model. Such an analysis is necessary because the use of geostatistical Kriging in developing the geological surfaces does not explicitly enforce that the surface elevations honour the underlying data, instead yielding a conservative estimate of minima and maxima to provide a surface

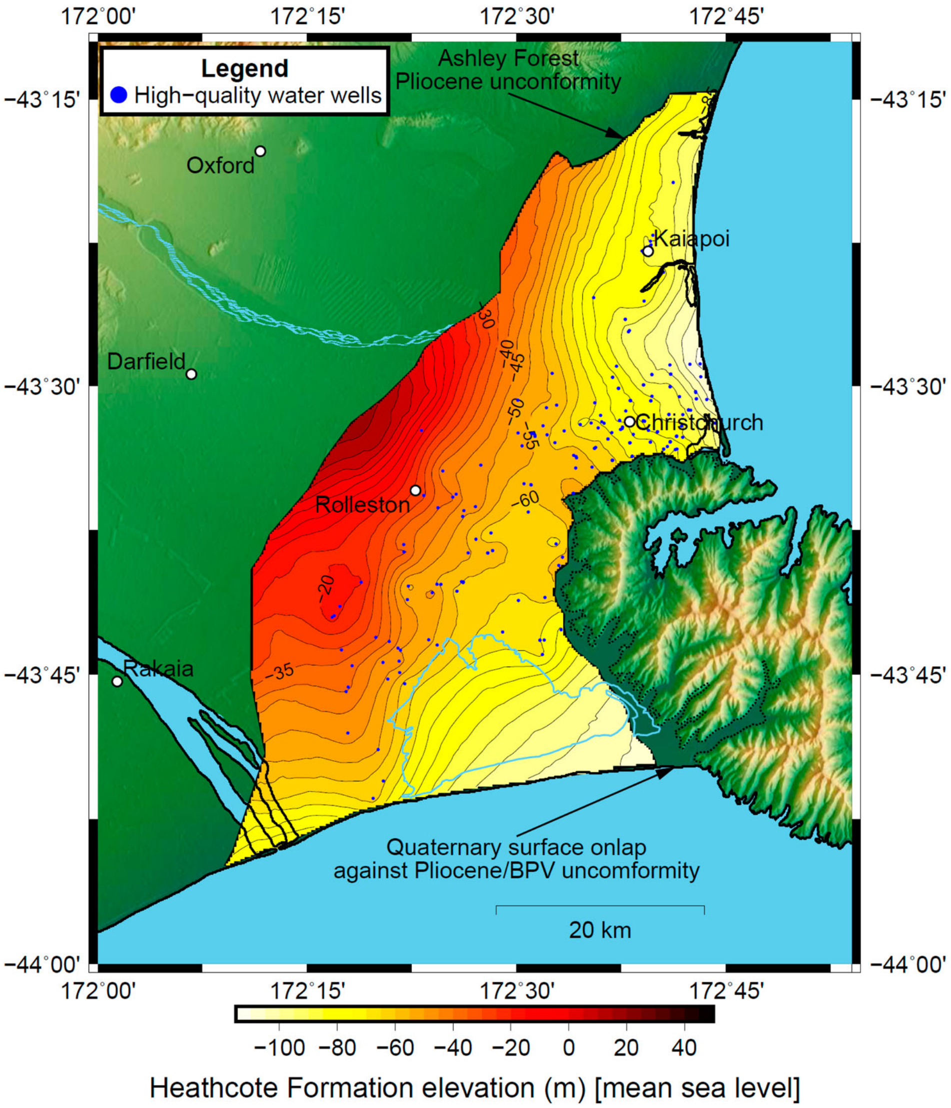


Figure 6. Top of the Heathcote Formation surface elevation contour map with high-quality well log locations plotted.

without excessive extrema (Isaaks and Srivastava 1989). As a result, it is insightful to understand the discrepancy between the Kriged surfaces and the underlying data points they are based on. The residuals are calculated by subtracting the Kriged surface value from the measured depth at each respective data point location for each surface encountered.

$$\delta_i = z_{i,\mathrm{Data}} - z_{i,\mathrm{Surface}} \tag{1}$$

where δ_i is the residual at the ith location, $z_{i,\mathrm{Data}}$ is the data elevation at the ith location and $z_{i,\mathrm{Surface}}$ is the surface elevation at the ith location. Cross sections with well log depth interfaces through the Christchurch central business district (CBD) (whose locations are shown in Figure 4) are also plotted to schematically assess the agreement between the well data and model.

Water well log data residuals

Figure 9 illustrates the histograms for the high-quality well log data residuals. It can be seen that the histograms of the residuals for the high-quality wells have a mean bias of approximately zero, with the vast majority of residuals within ±1 m, for both shallow surfaces, which have more data constraints, as well as deeper surfaces which have less data constraints. The standard deviation for the high-quality well residuals vary between 1.4 m and 0.9 m, which is small compared to the range of surface elevation values, indicating that the spread of residuals from the mean is relatively small. The minimum and maximum residuals, −7.59 m and 8.26 m, respectively, are likely caused by localised variations which are unable to be captured by the developed model. Overall, the standard deviations and maximum and minimum residuals are considered to be acceptable for the high-quality well logs given that the objective of this study was to develop a regionally consistent model which is not intended to replace the value in obtaining site-specific information.

Figures 10 and 11 present stratigraphic cross sections from the Quaternary model with well log depth interfaces corresponding to the top 150 m of cross section 1 (CS1) and cross section 2 (CS2), respectively, which were previously detailed. Well logs located

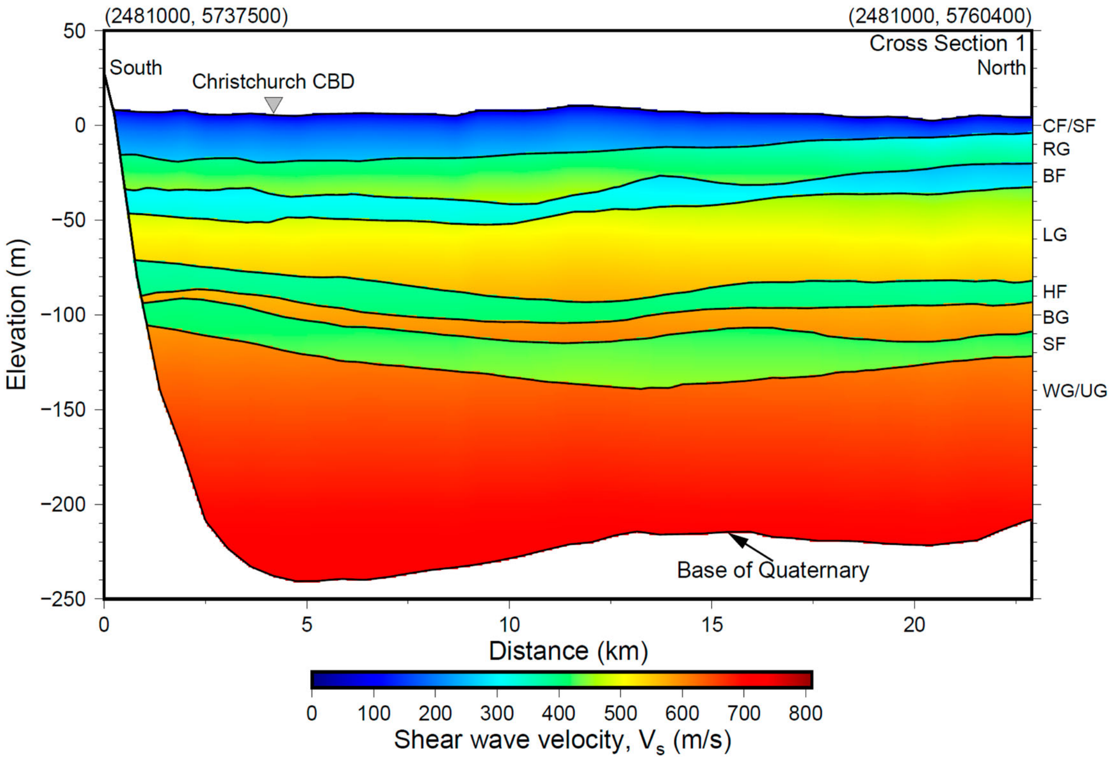


Figure 7. North–south oriented cross section 1 (CS1) of the Canterbury Quaternary geological model and corresponding shear wave velocities, through the Christchurch CBD. 47× vertical exaggeration. Coordinates of the end points in New Zealand Map Grid (NZMG) are included above the plot.

within 500 m of the cross section transects are plotted, although many wells were omitted to prevent congestion in areas with high well density. Under these circumstances, deeper wells were prioritised in the plot. The comparison between wells and modelled formations mostly show good agreement with generally small residuals for all formations. Figure 11 shows that both wells and the model illustrate the dominant

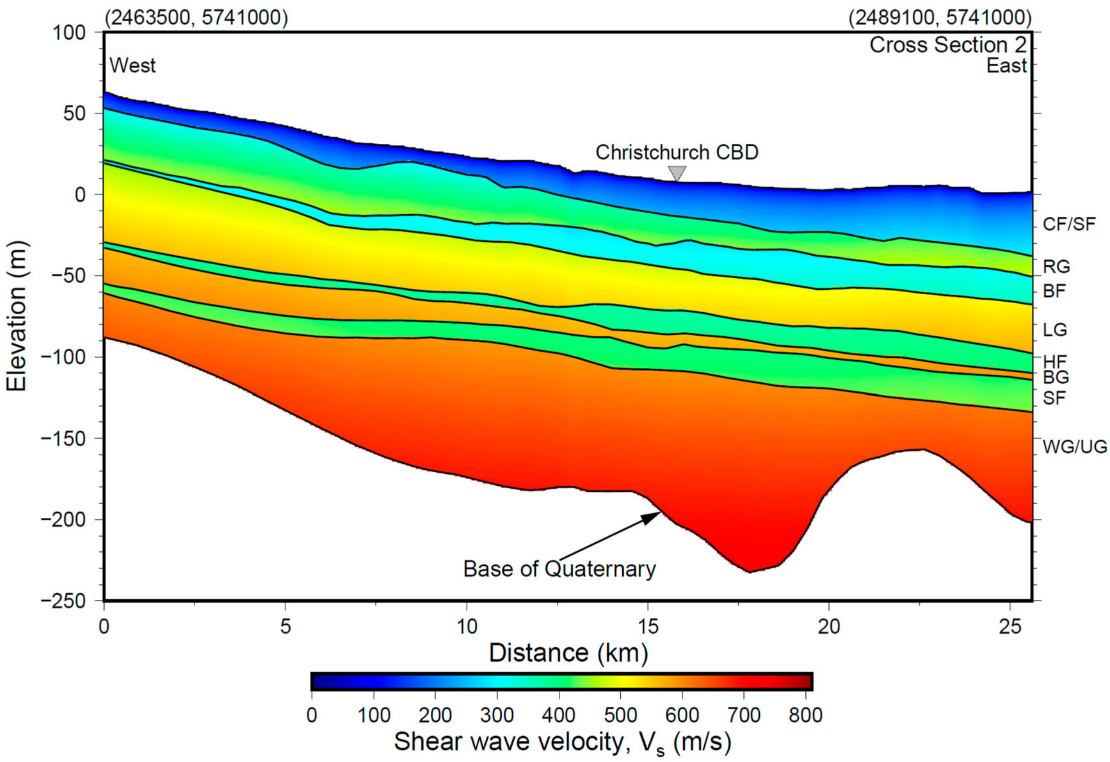


Figure 8. East–west oriented cross section 2 (CS2) of the Canterbury Quaternary geological model and corresponding shear wave velocities, through the Christchurch CBD. 45× vertical exaggeration. Coordinates of the end points in NZMG are included above the plot.

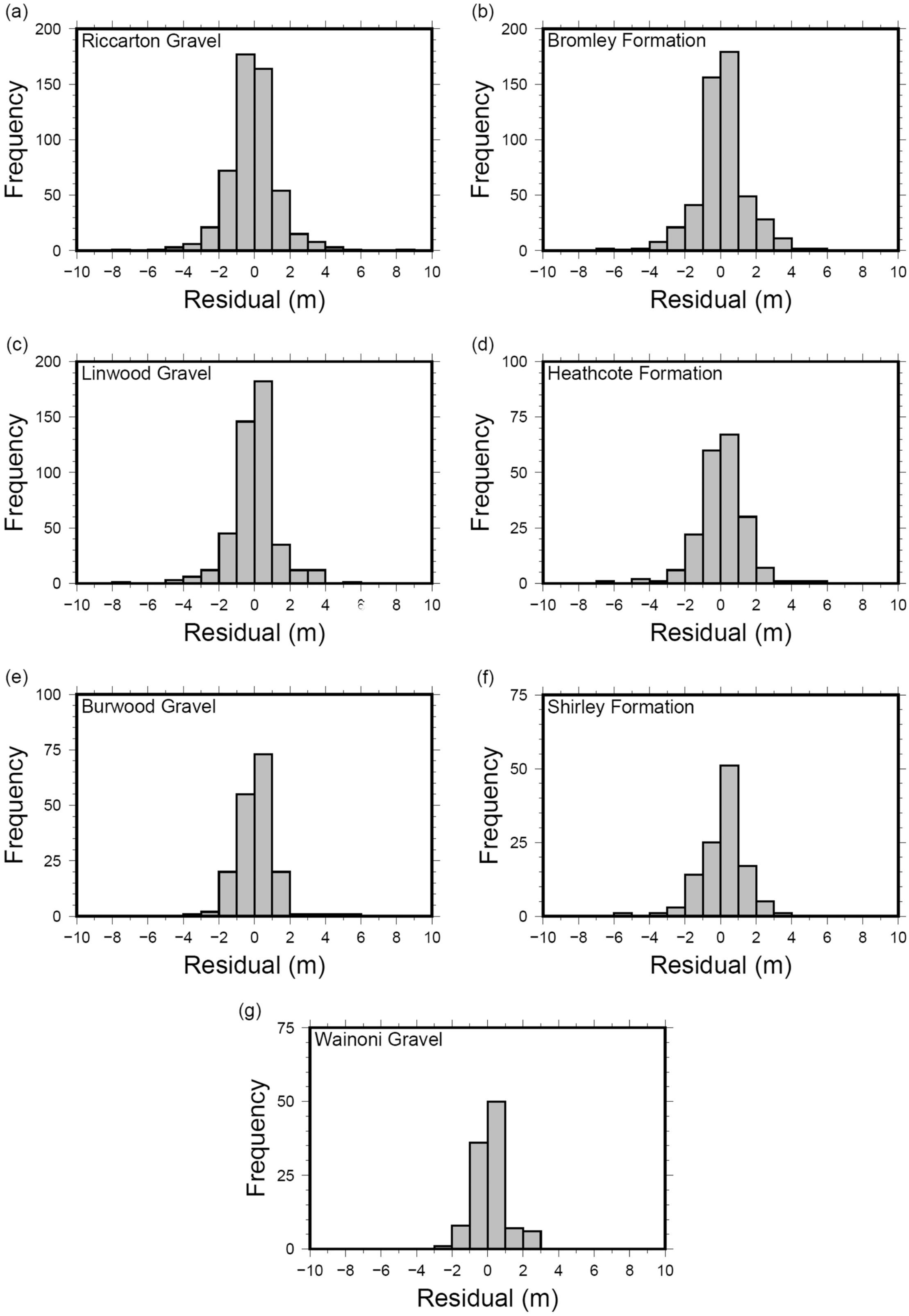


Figure 9. Histograms of high-quality well log residuals illustrating the difference between the Kriged surfaces and the underlying data utilised in their development. The relevant geological surface is noted in the top left of each figure panel.

trend of thick gravel and thin marine formations in the west, and thin gravel and thick marine formations in the east. It should be noted that some (but not all) of the errors evident between the wells and model result from lateral offsets up to 500 m from the cross section transects (as is reflected by the top of the wells not exactly matching the model's ground surface).

CPT data residuals

Figure 12(a,b) illustrates the histograms for the CPT-based elevation data residuals compared with:

(a) the final Kriged surface of the Riccarton Gravel with CPT data explicitly utilised; and

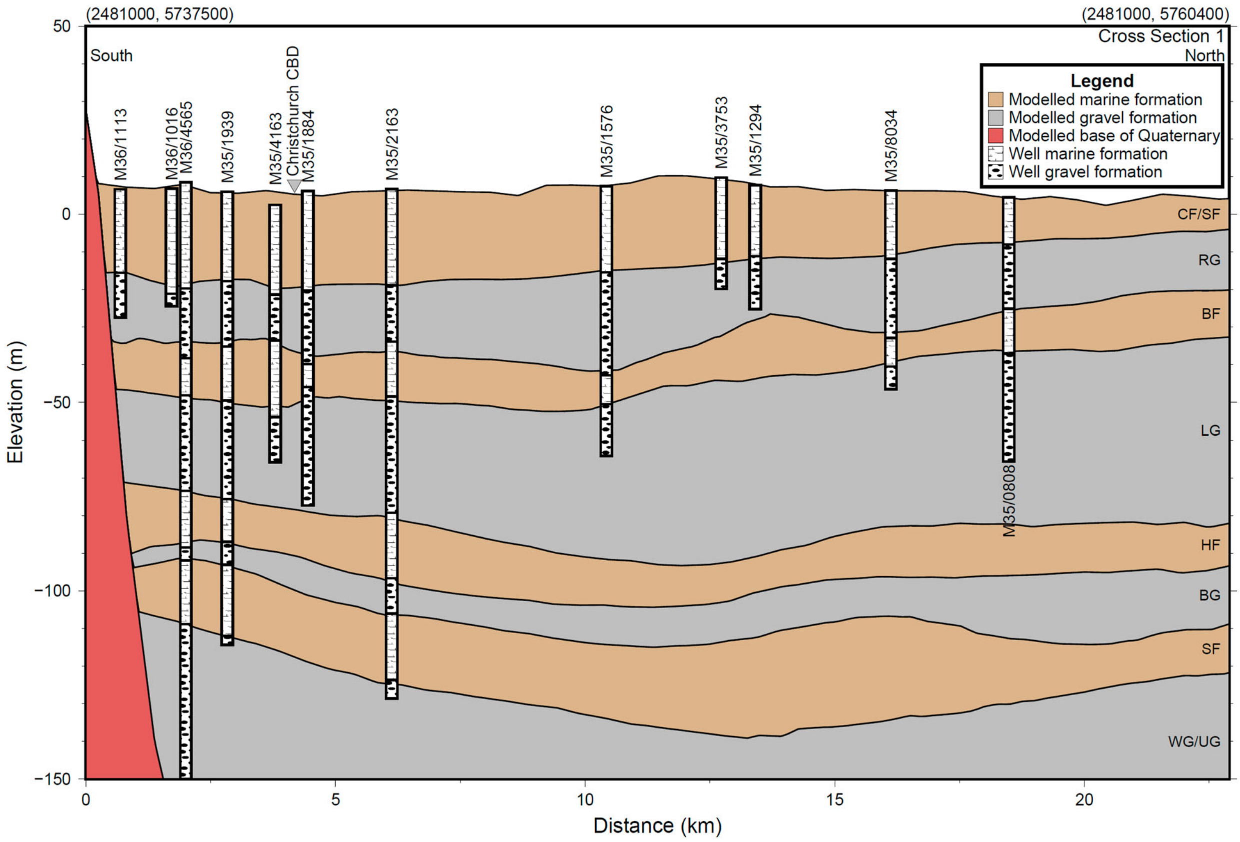


Figure 10. Stratigraphic cross section 1 (CS1) with well logs located within 500 m of the cross section transect plotted.

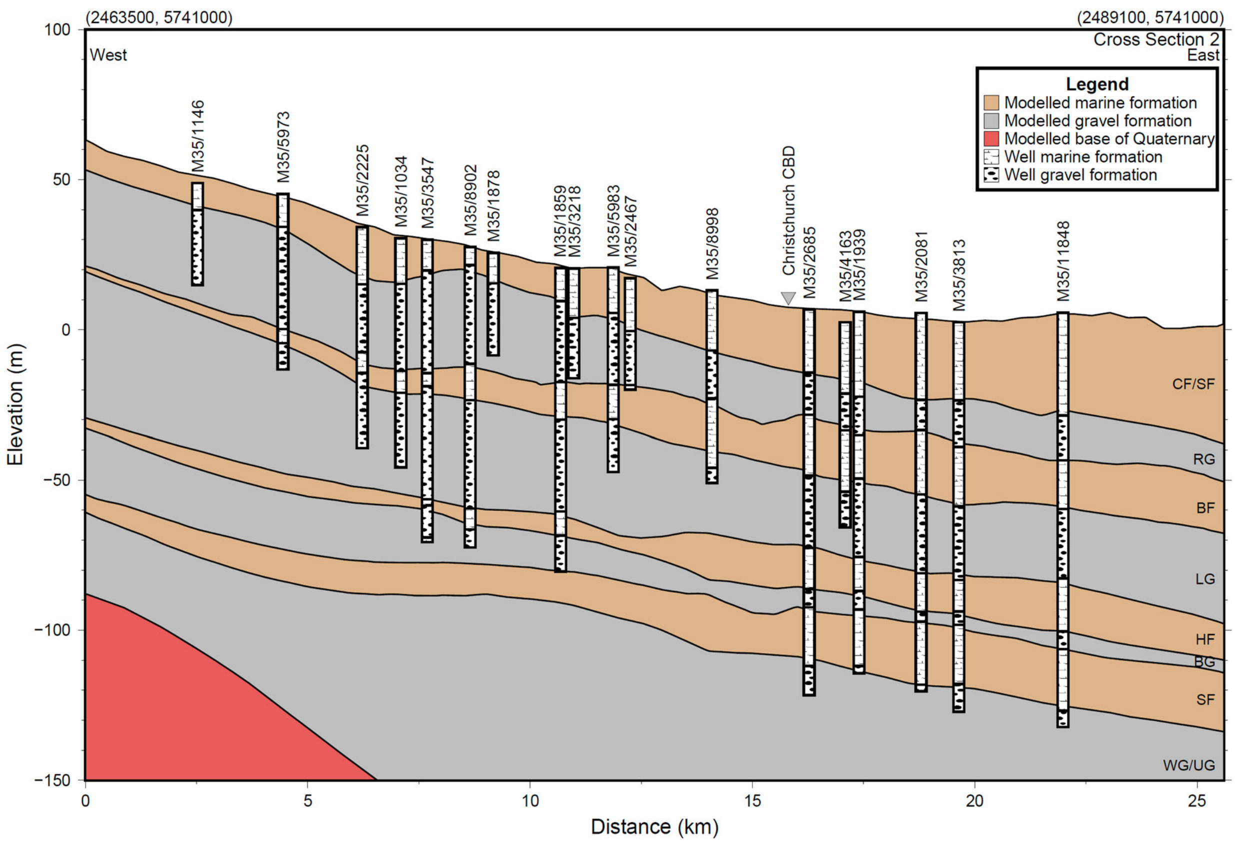


Figure 11. Stratigraphic cross section 2 (CS2) with well logs located within 500 m of the cross section transect plotted.

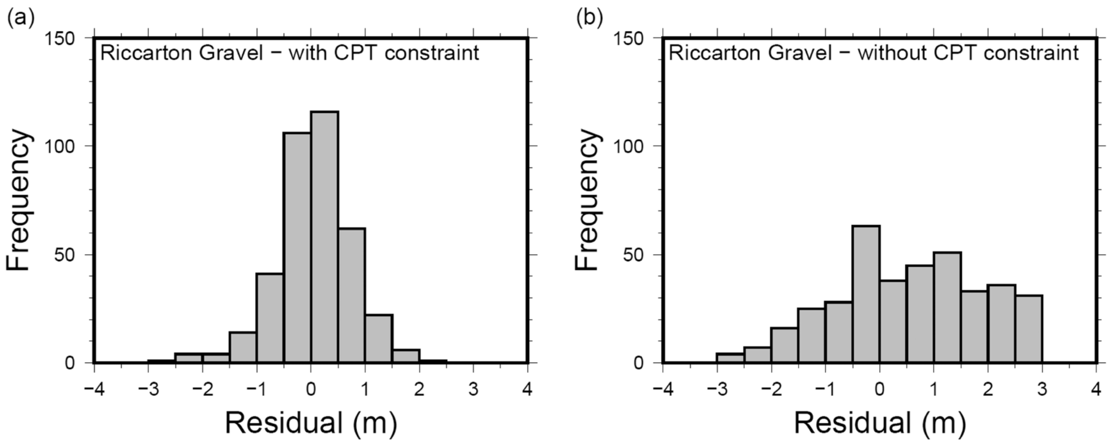


Figure 12. Histograms of CPT-based elevation residuals illustrating the difference between the CPT data with a: (a) Kriged Riccarton Gravel surface with a CPT data constraint; and (b) Kriged Riccarton Gravel surface without a CPT data constraint.

(b) a Kriged Riccarton Gravel surface constrained by well logs but not CPT data.

The residuals for the Riccarton Gravel surface with CPT data constraint have a mean value of 0.06 m indicating there is no bias, and a standard deviation of 0.69 m indicating the spread of residuals from the mean is small. The small mean and standard deviation are expected as the CPT data is used directly as a constraint in this case. When comparing the same CPT data with the Riccarton Gravel surface not constrained by CPT data, the residual histogram is negatively skewed and has a mean value of 0.56 m and standard deviation of 1.34 m, almost double the standard deviation of the Riccarton Gravel surface with the CPT constraint. The negatively skewed distribution of residuals is a result of CPTs terminating upon refusal on the upper surface of, or possibly prematurely above, the Riccarton Gravel and not being able to penetrate into the gravel. On the other hand, well logging is capable of drilling through the Riccarton Gravel and therefore has less bias towards shallower interpretations. The minimum and maximum have been explicitly limited by the CPT filtering process which required CPT refusal to be within 3 m of the Riccarton Gravel surface without the CPT constraint. A comparison between the two histograms show that the Riccarton Gravel surfaces with and without the CPT data constraint are distinctly different at the CPT data locations; thus, emphasising the importance of implementing the CPT data to supplement the water wells in producing a high-resolution Riccarton Gravel surface.

Comparison with previous models

A comparison of the Kriged surfaces against previous geological models specifically highlights improvements of the model developed in this study, as well as similarities and differences between them. In this section, the model developed in this study is specifically compared against the Weeber (2003) Quaternary stratigraphic model and the White (2008) top and bottom of Riccarton Gravel surface models through a qualitative comparison of their elevation contour plots. Other models were either superseded by those analysed here, presented in a way which is difficult to carry out an accurate comparison, or not directly comparable (i.e. Christchurch and Springston Formation models which are not explicitly characterised in the model developed in this study).

The Weeber (2003) model was developed using an earlier version of the water well log database utilised in this study and the modelled domain of each surface was dependent on the spatial extent of the well log constraints used. As a result, areas of the model developed in this study and the Weeber (2003) model which are constrained by similar data have a strong resemblance. Generally, large-scale, regional trends and elevations are consistent between the models but small-scale, local differences between the models arise as a result of differences in the adopted Kriging methodology, well quality filters and processing, and where new data is included in the model developed in this study (i.e. recent well logs and CPT). A dataset exclusively comprised of high-quality data with corrected wellhead elevations used in the model developed in this study has ubiquitously resulted in small-scale differences and corrections to anomalies in the Weeber (2003) model. In particular, the top of the Riccarton Gravel surface developed in this study also utilises numerous CPT records in the Christchurch city area contributing to small-scale differences. The Wainoni Gravel surface developed in this study has some noticeable regional differences; firstly, the saddle structure northwest of the Banks Peninsula is narrower and more elongated, and secondly, the eastern coastline is approximately 5 m shallower. These differences are also attributed to more deep well logs being available since the development of the Weeber (2003) model, in addition to the other aforementioned factors. Overall, the model developed in this study improves on the Weeber (2003) model by utilising a higher quality and more consistent dataset with greater scope resulting in smoother surfaces with less anomalies from inconsistencies.

The White (2008) top and bottom of Riccarton Gravel surfaces utilised lithological codes in the well logs, as the purpose of the model was hydrologic applications such as identifying distributions of hydraulic conductivity, and are compared to the top of the Riccarton Gravel and Bromley Formation surfaces of the model developed in this study, respectively. Although both models have the dominant inland to offshore dip, the model developed in this study has steeper slopes and deeper elevations across both the Christchurch and Kaiapoi areas. Both models are relatively smooth, suggesting there are no significant inconsistencies within the models. Differences between the models are primarily attributed to the different interpretations of the subsurface geology in addition to differences in interpolation methods and datasets employed.

Application of the developed Quaternary geological model for surface wave analysis-based site characterisation

As alluded to previously, the developed Quaternary geological model has several applications for seismic and hydrologic problems. Here, attention is given to a seismic problem for which the model was specifically developed, which is the characterisation of the seismic velocities of the Quaternary formations.

Surface wave testing is a non-intrusive field method which utilises the dispersive nature of surface waves to determine local shear wave velocity profiles (Park et al. 1999). The V_s profiles are obtained by solving an inverse problem which is inherently non-unique. To circumvent the non-uniqueness of the problem, it is possible to define several independent constraints (with their corresponding uncertainties) for the solution, such as estimated velocities and/or depths of significant velocity changes corresponding to geological formation boundaries (Roberts and Asten 2004; Wood et al. 2014). The resulting inversion thus finds solutions which not only reproduce the recorded surface wave dispersion data but also satisfies a priori information (Wood et al. 2014)

In early 2013, surface wave testing was carried out at 14 sites across the Christchurch area in a collaborative effort between the University of Canterbury, University of Texas at Austin and University of Auckland, as shown in Figure 13 (Wood et al. 2014). Based on the geographic coordinates of the surface wave testing sites, the developed Canterbury Quaternary geological model was utilised to independently provide the

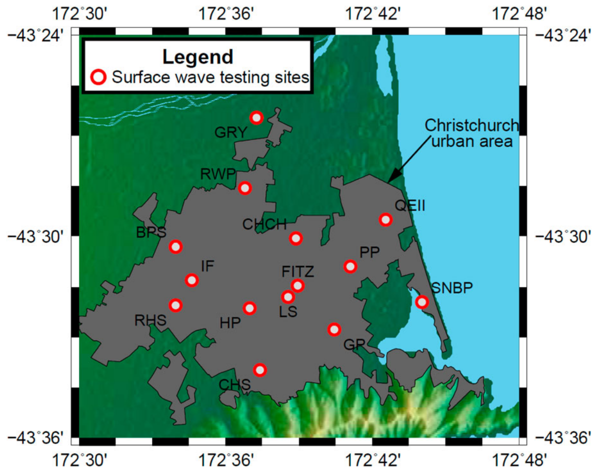


Figure 13. 14 sites across the Christchurch area where surface wave testing was carried out in March 2013 (Wood et al. 2014).

stratigraphic depths to constrain the surface wave analysis by interpolating depths for each surface so geologically plausible velocity profiles can be produced. Uncertainties in the stratigraphic boundary depths were also determined for use in the surface wave inversion analysis and were based on the number and consistency of neighbouring water wells logs which were used in the development of the surfaces with depth uncertainties generally being assigned values in the range of 2–7 m. The development of V_s profiles for the Ilam fields (IF) and Hagley park (HP) sites are presented here as an example.

Figure 14(a,b) illustrates the experimental dispersion data (and uncertainty) and the median theoretical dispersion curves resulting from the surface wave analyses at the IF and HP sites, respectively (Teague et al. 2015). Three solutions are provided here which highlights the logical progression from a blind analysis to one which is well constrained and geologically feasible:

1. unconstrained;
2. constrained by formation depths without velocity reversals allowed; and
3. constrained by formation depths with velocity reversals allowed.

The theoretical dispersion curves for the fundamental and first higher modes fitted to the experimental dispersion data are shown. The fundamental and first higher modes are the Rayleigh wave modes of vibration corresponding to the lowest and second lowest natural frequencies of the site, respectively, and are generally the largest contributors to the surface ground motion amplitudes (Tokimatsu et al. 1992; Kramer 1996). All theoretical dispersion curves fit the experimental dispersion data relatively well and are therefore all considered acceptable solutions based on misfit alone. However, it is important to note that a lower dispersion

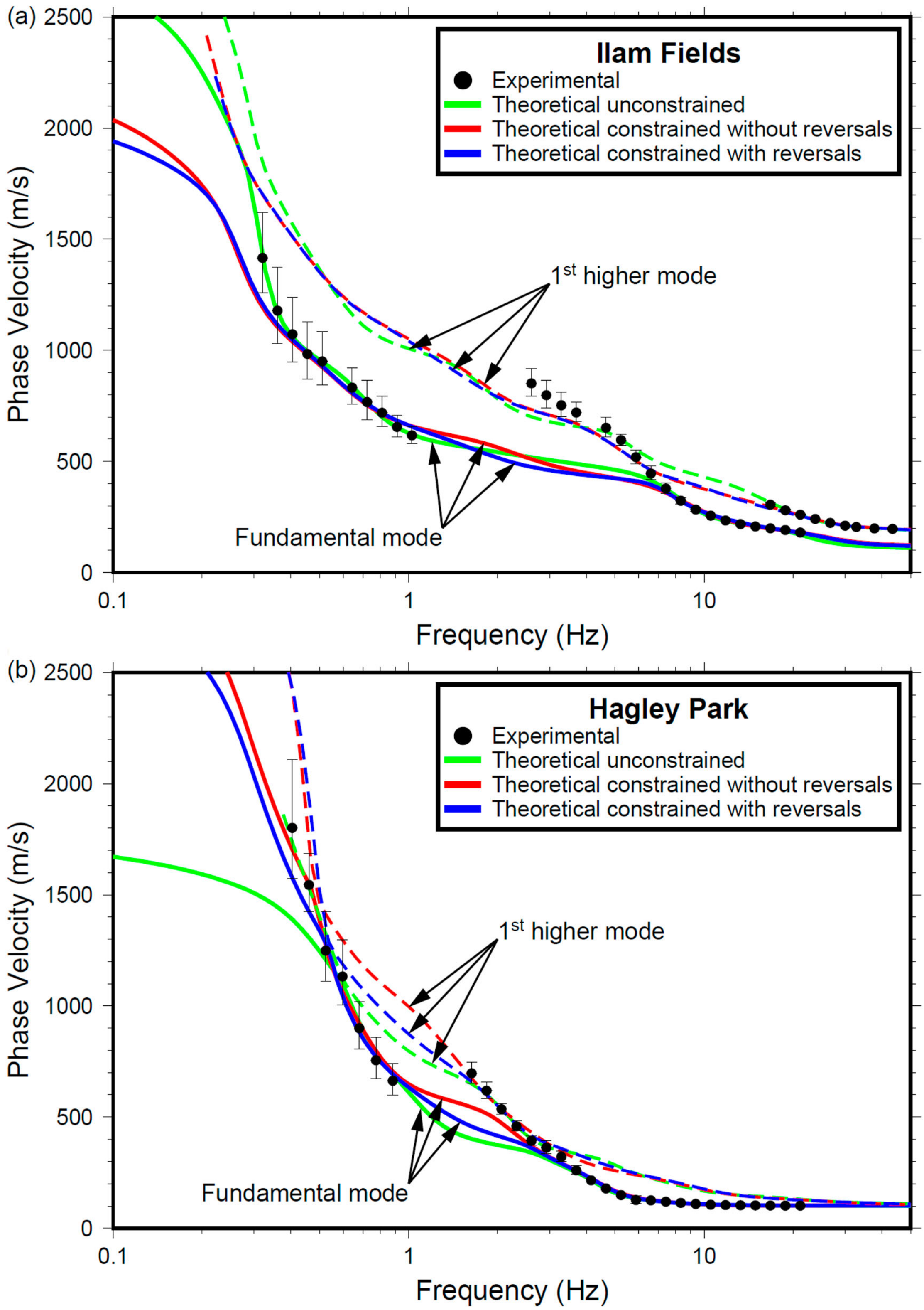
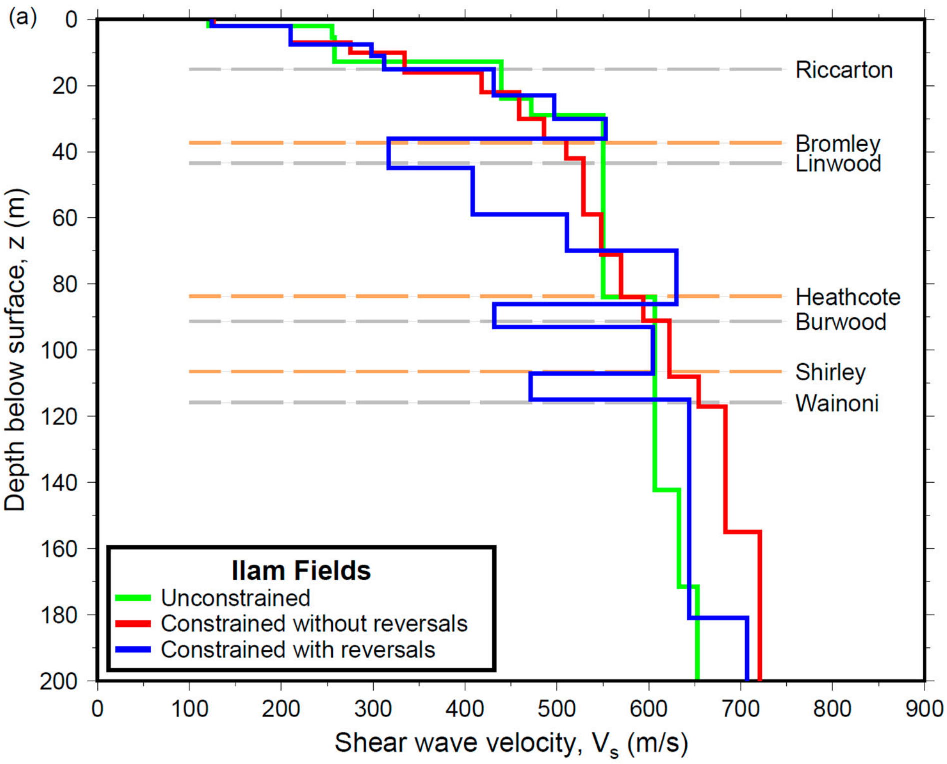


Figure 14. Experimental and theoretical dispersion curves resulting from surface wave analyses at the: (a) Ilam Fields; and (b) Hagley Park sites.

misfit was achieved with the 'unconstrained' solution which does not realistically match the expected subsurface conditions and geology, shown subsequently. On the other hand, the constrained solutions have a larger misfit as the solutions are local minima of constrained parameter domains as opposed to global minima (Teague et al. 2015).

Figure 15(a,b) illustrate the V_s profiles resulting from the surface wave analyses carried out at the IF and HP sites, respectively, corresponding to the theoretical dispersion curves presented in Figure 14 (Teague et al. 2015). The V_s profiles shown are the median profiles selected from over 1000 solutions based on the neighbourhood algorithm (Teague et al. 2015). Plotted



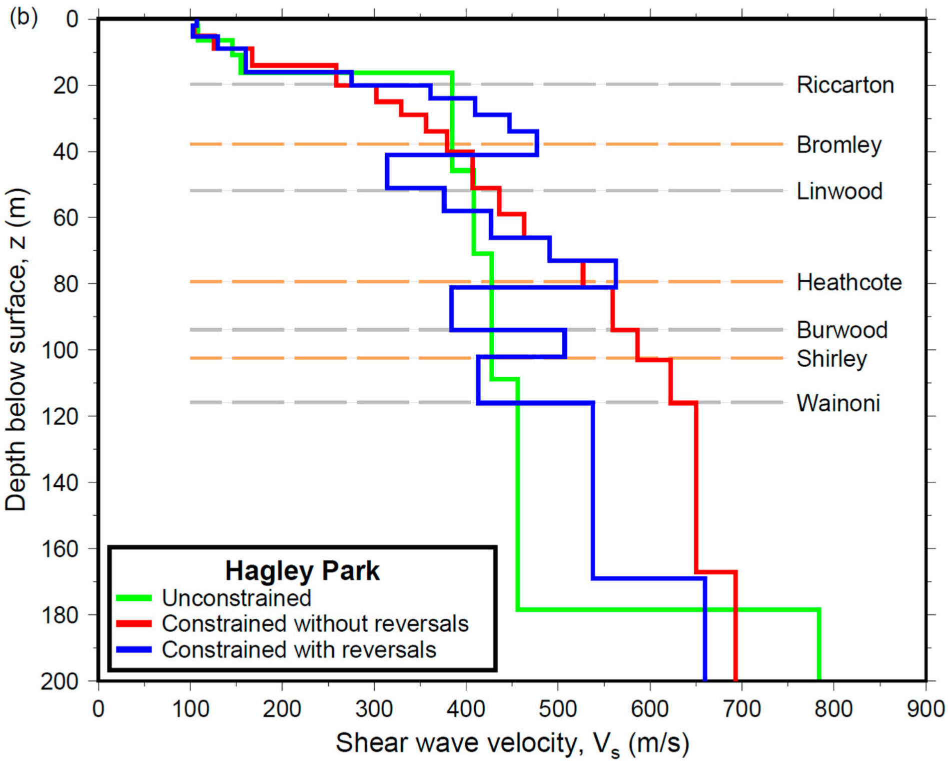


Figure 15. Shear wave profiles of the: (a) Ilam Fields; and (b) Hagley Park sites produced from forward modelling of surface wave analyses, including stratigraphic boundaries provided by the Canterbury Quaternary model.

alongside the profiles are the depths of the stratigraphic boundaries, showing alternating high-velocity gravel formations followed by low-velocity marine formations corresponding to the interbedded Quaternary geological stratigraphic sequence of the Canterbury region. The ‘unconstrained’ V_s profile is normally dispersive (monotonically increasing with depth) and does not have layer depths and velocity changes consistent with the Quaternary formation boundaries and thus incorrectly representing the local geology. The two V_s profiles constrained by the stratigraphic boundaries have velocity changes at depths consistent with the Quaternary formation boundaries, where the profile without reversals is also normally dispersive while the profile with reversals allowed has distinct low velocity marine layers present. The shallowest high-velocity formation is the Riccarton Gravel which underlies the lower-velocity Christchurch Formation for the majority of Christchurch city. Proper characterisation of these two formations to produce representative velocities is very important for a near-surface seismic site response (Wood et al. 2011). As demonstrated, the absence of stratigraphic information does not explicitly allow for velocity reversals in the inversion and the resulting V_s profiles exhibit a normally dispersive nature which would be expected when the lithology does not change unexpectedly with depth. This suggests that the data obtained from surface wave testing, Quaternary surface depths and other preferred characteristics/a priori information are consistent. Despite the theoretical dispersion curves of the 'unconstrained' solution displaying the best fit to the experimental dispersion data, and the 'constrained without reversals' dispersion curves showing acceptable misfit, the corresponding V_s profiles do not resemble the regional Quaternary geology; thus, providing the stratigraphic constraints is imperative in obtaining geologically correct solutions.

In order to quantify the effect of the interbedded Quaternary geology on seismic waves, transfer functions are derived for the IF and HP sites, shown in Figure 16(a,b), respectively. Transfer functions represent the extent of amplification or deamplification of waveforms which propagate through multilayered stratified media. The transfer functions shown here are calculated using the Thomson–Haskell matrix method (Thomson 1950; Haskell 1953). For the purpose of illustrating the effect of the interbedded Quaternary geology, only the strata above the top of the Wainoni Gravel is considered in the calculation of these transfer functions and a damping ratio of 5% is prescribed to all layers. For the IF site, the three

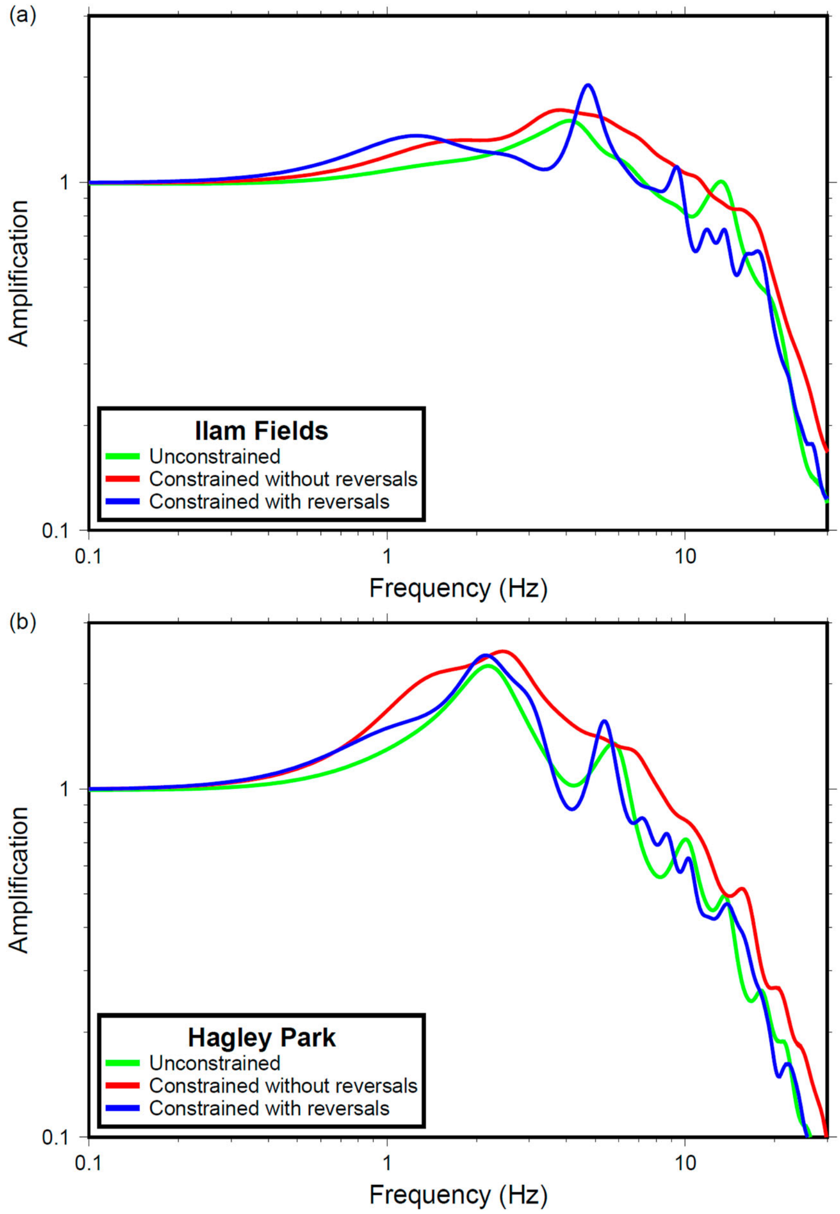


Figure 16. Transfer functions of the: (a) Ilam Fields; and (b) Hagley Park sites for 'unconstrained', 'constrained without reversals' and 'constrained with reversals' shear wave profiles.

solutions are significantly different. The 'unconstrained' and 'constrained with reversals' transfer functions both have relatively pronounced amplification at several frequencies, although the frequencies at which they occur and degrees of amplification differ. The largest peaks of the 'unconstrained' and 'constrained with reversals' transfer functions occur at 4.10 Hz with 1.50× amplification and 4.72 Hz with 1.90× amplification, respectively, a 13% difference in frequency and 21% difference in amplification. The bandwidth of the peak in the 'constrained with reversals' transfer function is also narrower than the bandwidth of the peak in the 'unconstrained' transfer function. The 'constrained with reversals' transfer function also has several more peaks than the 'unconstrained' transfer function at higher frequencies. The 'constrained without reversals' transfer function is the simplest solution with no distinguishable amplification of specific site vibration modes. For the Hagley Park site, the three solutions are more similar. The largest peaks of the 'unconstrained' and 'constrained with reversals' transfer functions occur at 2.19 Hz with 2.25× amplification and 2.15 Hz with 2.42× amplification, respectively, a 2% difference in frequency and 7% difference in amplification. In this case, the 'unconstrained' and 'constrained with reversals' solutions have very similar transfer functions despite significant differences in geology, thus highlighting the issue of non-unique solutions in optimisation problems with and without physical constraints. The 'constrained without reversals' transfer function is also much simpler at the Hagley Park site which is attributed to the absence of strong impedance contrasts.

Discussion and conclusions

A 3D high-resolution model of the interbedded Quaternary stratigraphic sequence that characterises seven geological formation boundaries was developed for the Canterbury, New Zealand region utilising datasets consisting of over 500 high-quality water wells and over 370 CPT records, a previously unparalleled high-quality dataset. The top of the Riccarton Gravel and Heathcote Formation surfaces were presented as elevation contour maps, to highlight the essential features of the surfaces where the most prevalent trend observed was the downward dip from inland to the eastern coastline as a result of the dominant fluvial depositional environment of the terrestrial gravel formations. A residual analysis of the Kriged surfaces to the underlying physical data validated the adequacy of the model as the high-quality water wells and CPT records displayed small residuals. The developed Quaternary model has several applications due to the broad extent of the model and high level of characterisation. A surface wave analysis application was specifically examined, where the Quaternary model provided depths to significant geological formations at 14 sites across the Christchurch urban area to constrain the forward modelling of seismic shear wave velocity profiles to explicitly capture seismic velocity reversals, which are important in seismic wave propagation. Subsequently, transfer functions were calculated for the profiles to highlight the effect of the interbedded Quaternary geology on seismic wave propagation.

The Canterbury Quaternary model developed in this study has several key limitations, which have been briefly mentioned previously. These include the depths below the Wainoni Gravel being modelled as an undifferentiated gravel despite the expected presence of thin marine formations, the decreasing level of constraint for the surfaces with increasing depth and not explicitly modelling the Christchurch and Springston Formations. The result of these limitations is a reduction in the accuracy of the model representation of the real geological stratigraphic sequence in the relevant subregions. For seismic site response analyses, the appropriate lithological representation of the shallow stratigraphic sequence (i.e. Christchurch and Springston Formations, Riccarton Gravel and Bromley Formation) has the most importance and is mostly well-constrained in the Canterbury Quaternary model. Properties of deeper sediments are also less lithologically dependent and more dependent on the increasing confining pressure, mitigating the consequences of the assumed undifferentiated gravel below the Wainoni Gravel. The Springston and Christchurch Formations have a complex relationship of interfingering beneath Christchurch city with significant variations in lateral facies (White 2007; White et al. 2007). At the eastern, coastal side of Christchurch there are no significant interbedded gravels above the Riccarton Gravel as the area is dominated by the Christchurch Formation comprised of marine fine sediments with some alluvial silts and peats. At the western side of Christchurch, the Springston Formation is vertically adjacent and continuous with the Riccarton Gravel as the Christchurch Formation does not exist. Beyond the maximum inland extent of marine formations, only gravels overlie gravels (without marine formations) often resulting in difficulties interpreting marker beds in well logs to accurately determine the formation boundaries. In the central region of Christchurch, a complex zone of interfingering between the Springston and Christchurch Formations exist, including significant gravel lobes (Weeber 2008). The Springston Formation is also often distinguished between upper and lower Springston Formations, predominantly separated by the Christchurch Formation, in the complex central Christchurch zone (Weeber 2008). However, the intention of the model developed is to provide a regional representation of the Canterbury Quaternary stratigraphic sequence which is widely applicable to Christchurch. Hence, the model does not attempt to explicitly capture these localised subsurface features although it is an area of potential future research. Ultimately, an adequate level of accuracy and characterisation is provided by the Canterbury Quaternary model in constraining surface wave analyses to obtain geologically realistic velocity reversals that are consistent with observed dispersion data.

Data and resources

Water well data was provided by Environment Canterbury (http://canterburymaps.govt.nz/). The Canterbury QMap can be obtained through GNS Science (http://www.gns.cri.nz/). The CPT data was obtained from the Canterbury Geotechnical Database (now known as the New Zealand Geotechnical Database: https://www.nzgd.org.nz/). Topography digital elevation models were obtained from the Land Research Information Systems, LRIS, portal (https://lris.scinfo.org.nz/).

Figures were prepared using Generic Mapping Tools (http://gmt.soest.hawaii.edu/) and the geological surface development was carried out using the Move geological modelling software suite (http://www.mve.com/).

The 3D model for the interbedded Quaternary stratigraphy is provided in a separate zip file archive in the World Geodetic System 1984 (WGS84) coordinate system in the electronic supplement.

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Disclosure statement

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