Using 3D geological models to create maps of estimated V_s30 and site period

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ABSTRACT

The 30-m time-averaged shear-wave velocity (V_s30) and the fundamental site period (T_0) are useful parameters for understanding site conditions, informing geotechnical and seismic hazard studies as well as infrastructure planning. Unfortunately, sites where these data are measured can be sparse or poorly distributed posing challenges in mapping these properties over an entire city. To help resolve the spatial problem, this study has used a detailed 3D geological model and assigned shear wave velocity values for the modelled subsurface material units to create maps of estimated V_s30 and T_0 for the Wellington City CBD. We compare the model estimated values with measured site parameters from surface or down-hole geophysical data and explore the variability of the model results using Monte Carlo Simulations.

1 INTRODUCTION

In this study we test forward modelling of sediment thickness data from a detailed 3D geological model of Wellington City to estimate the 30-m time-averaged shear-wave velocity (V_s30) and the fundamental site period (T_0, referred to hereon as site period). These parameters are useful for understanding site conditions, informing geotechnical and seismic hazard studies, as well as infrastructure planning. In most New Zealand cities, measured values of V_s30 and T_0 are sparse or poorly distributed so are usually insufficient for 2D interpolation of point data to create continuous maps of these properties. Modelling of these parameters from a detailed geological model (e.g. Nastev et al. 2016), and careful testing and correlation with measured site data, may provide a solution for understanding regional variation. The results also support creation of continuous maps and help resolve some of the spatial problems related to limited geophysical datasets.

This project used a detailed three-dimensional (3D) model of geological and geotechnical properties for Wellington that encompasses the Thorndon, Wellington central business district (CBD), and Te Aro areas (see Hill et al. 2022 and references therein). The model was created using the latest geomorphic and geological map data as well as thousands of borehole data interpretations (see Figure 1A) and results from geophysical studies that help control the subsurface interpretation. The model interprets the accumulation of loose to dense Quaternary sediment deposited on weathered Rakaia Terrane greywacke (basement) rocks. It models nineteen lithological units: one water, four anthropogenic fill, four Holocene sedimentary, nine glacial and interglacial sedimentary, and the greywacke basement. The glacial and interglacial sedimentary units are divided into Late Pleistocene and mid-Pleistocene time-period units and are also divided into loose, dense, a loose-dense transition layer, and very dense sediments. These sediments are in a fault-controlled basin structure that varies in depth from a few to several hundred metres. Average shear-wave velocities have been assigned to each geological unit from empirical estimates, geophysical studies and down-hole geophysics.

2 ESTIMATING SITE PERIOD AND VS30 FROM THE 3D GEOLOGICAL MODEL

Estimates of site period have been obtained from the sediment thickness and shear-wave velocity values determined from the geological model, as in Kaiser et al. (2019) and Hill et al. (2022). The fundamental site period (T_0) was calculated based on the 1D velocity profile below the site using the quarter wavelength approximation (QWL, sometimes referred to as the four-way travel-time [FWTT] approximation). Each geological unit was exported from the 3D modelling software as a thickness grid across the study area, and calculations of the site period used Equation 1 and the assigned shear wave velocity (V_s) for each geological unit (Figure 1C) at every 10 x 10 m surface cell. The resulting data can be plotted as a map of estimated site period (Figure 2A) and compared with geological data and measured values of site period using geophysical techniques such as the horizontal to vertical spectral ratio (HVSR).

$$t = 4\sum\left(\frac{d_i}{Vs_i}\right) \qquad (1)$$

where d_i = unit thickness (metres); Vs_i = shear-wave velocity of the unit (m/s); $t = T_0$ (seconds).

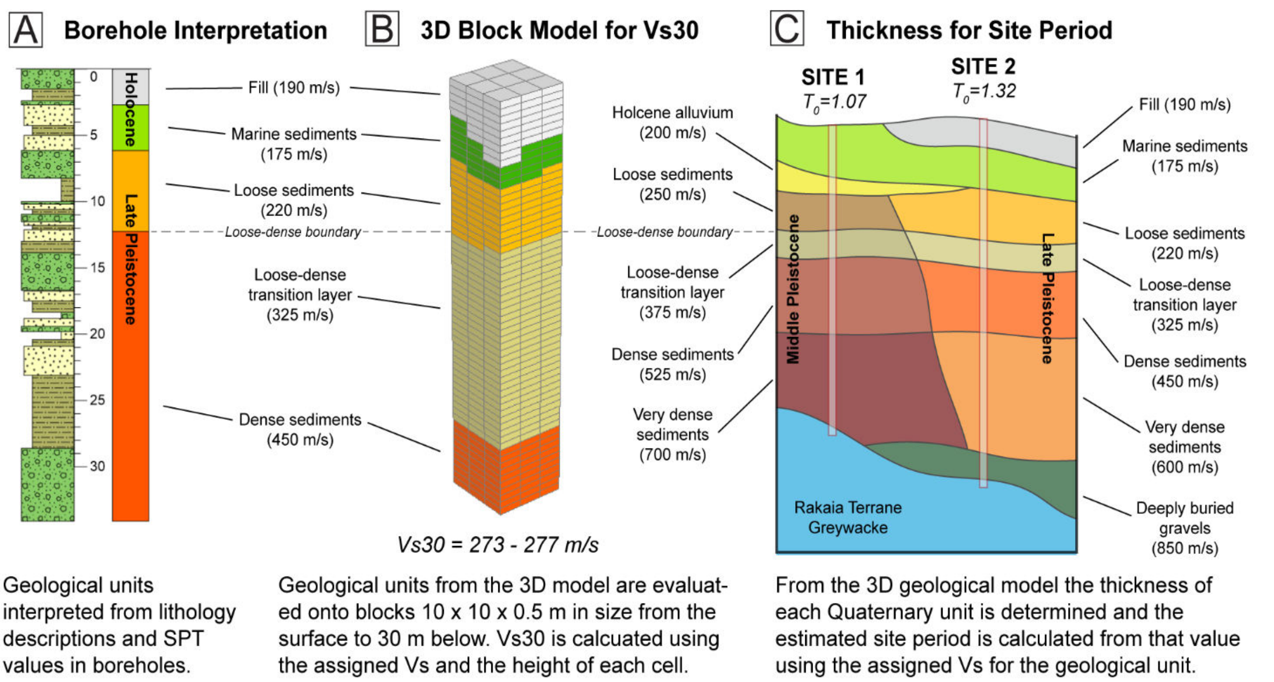

Figure 1: Process for estimating the site period and V_s30 from geological model data. A) example classification of borehole data for the models; B) example of block model used to calculate V_s30; C) cartoon cross-section of 3D geological model units and the V_s values used with thickness to estimate site period.

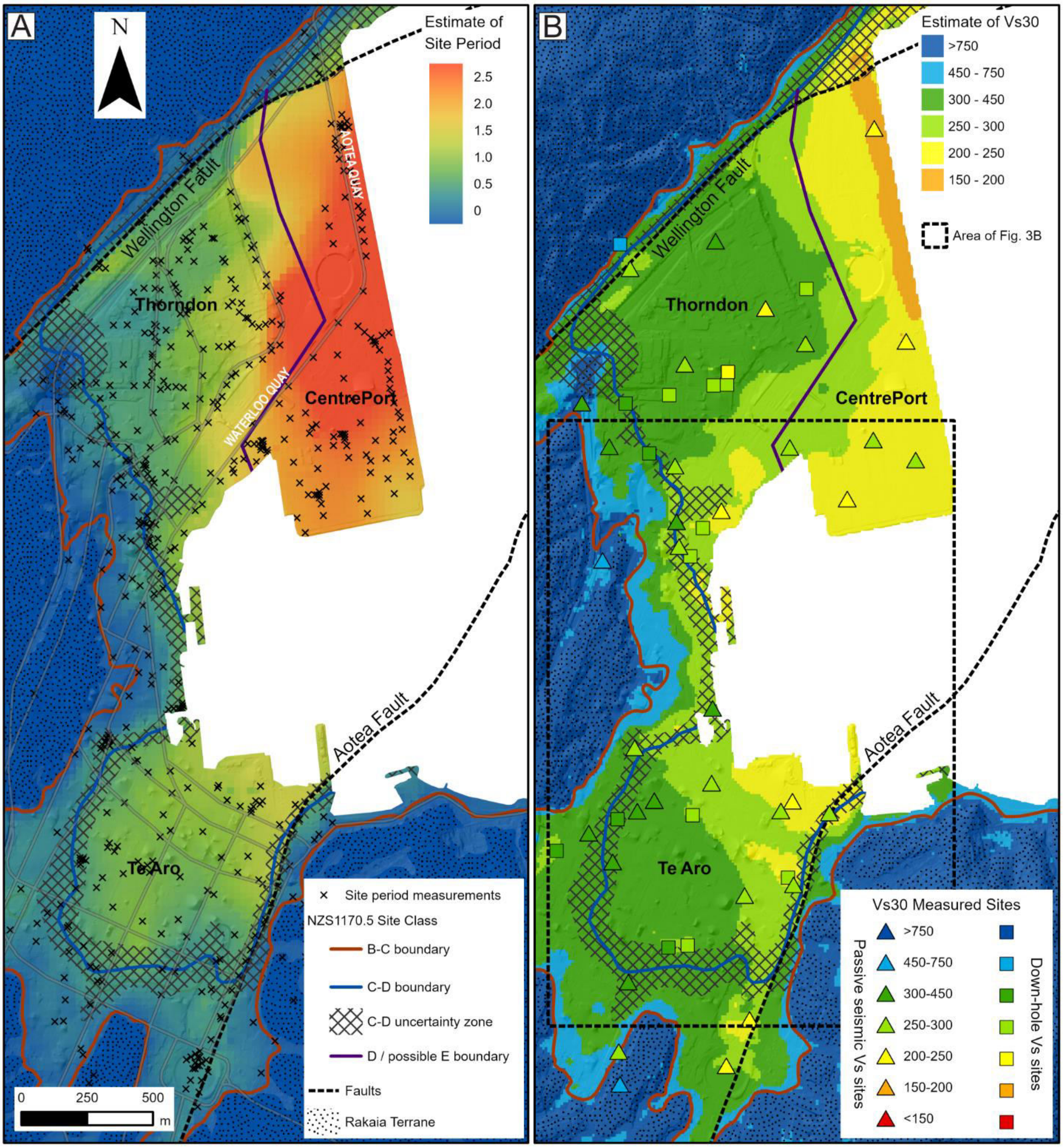

Figure 2: Maps of estimated site period and V_s30 for the Wellington CBD area. A) approximate site period calculated from 3D geological thickness data; location of measurement sites also shown; and B) approximate Vs30 calculated from the assigned V_s values in the top 30 m of the ground profile (after Kaiser et al. 2022). Both maps include interpretations of NZS1170.5 site class from Kaiser et al. 2019 as reference.

The 30-m time-averaged shear-wave velocity (V_s30) is estimated in a similar way to the site period. Rather than using the thickness grids determined above, the technique evaluates the geological model onto a 10 x 10 x 0.5 m cell sized grid that occupies a volume 30 m below the ground surface. V_s30 was calculated based on the 1D velocity profile using the QWL approximation applied to average shear-wave velocities assigned to each geological unit for every cell in the block model (Equation 2, Figure 1B). The resulting data for each 10 x 10 m surface cell can be plotted as a map of estimated V_s30 (Figure 2B) and compared with geological data and other estimated values of V_s30 using geophysical techniques such as surface wave and down-hole V_s measurements at borehole sites.

$$Vs_{30} = \frac{\sum d_i}{\sum\left(\frac{d_i}{Vs_i}\right)} \tag{2}$$

where d_i = cell vertical thickness (metres); Vs_i = shear-wave velocity of the unit (metres per second).

3 TESTING THE SITE PERIOD AND VS30 MODELS

Results of the estimated site period data in this study (Figure 3A) illustrate that site periods up to approximately 1.2 s derived from the model correlate well with only a minor under prediction of the measured values for Wellington compiled by Kaiser et al. (2019). However, a suite of samples (circled in green in Figure 3A) from the Aotea and Waterloo quay areas in Wellington illustrate a divergence of the modelled site period from the measured values. These data are in deeper parts of the basin where the Quaternary sediment thickness (QST or commonly referred to as depth to basement) is 150 to 500 m. This indicates that there could be a potential impedance contrast in the Quaternary sediments related to a Middle Pleistocene erosion surface or older Pliocene sediments in the bottom of the basin that is stronger than the impedance contrast at the greywacke basement interface, and therefore produces a dominant site response in the HVSR data. In other words, the HVSR may pick up the site period associated with ‘engineering bedrock’, whereas the model estimates the site period down to deeper greywacke basement. The estimated site period map is considered to be well constrained where the sediment profile down to basement is well-known and less than 150 m, i.e., in shallow parts of the basin where more boreholes reached basement. However, we note that the 3D model estimates are based on simple 1D average layer assumptions and will therefore not capture any 2D or 3D ‘basin effects’ or consider detailed site-specific velocity structure.

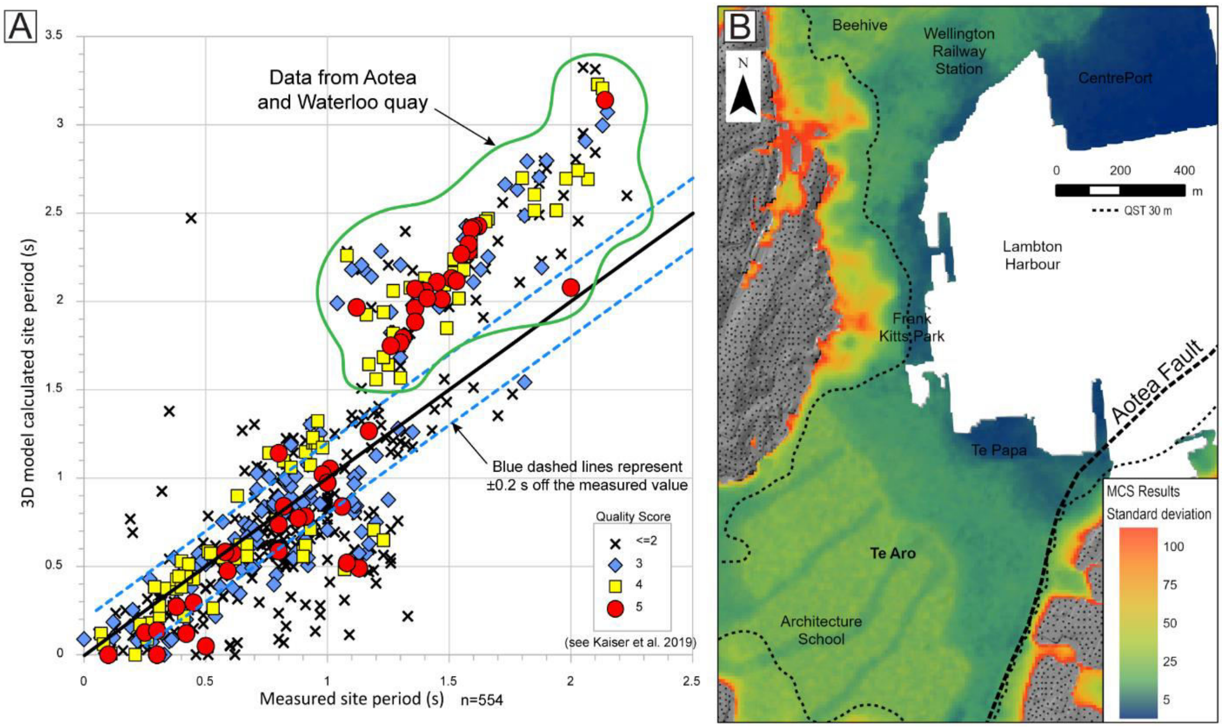

Figure 3: Results from testing the estimated site period and V_s30 models A) Plot comparing the site period measured from geophysical studies (Kaiser et al. 2019) and the site period calculated based on the 3D geological model; B) Standard deviation of V_s30 from Monte Carlo Simulations after 300 model runs using variable V_s and loose-dense boundary values in the area of Wellington City (see Figure 2). Quaternary sediment thickness (QST) contour of 30 m thickness shown for reference (dotted line in B).

To evaluate the estimated V_s30 data from this study, results are compared to measured values from surface wave studies and down-hole V_s data (Kaiser et al. 2022) as well as a Monte Carlo Simulation (MCS) undertaken to test model variability. Figure 2B shows that the estimated V_s30 calculated from the 3D geological model correlates well with sites of measured V_s30 from MASW or down-hole V_s measurements. However, measured data are sparse, and more data should be collected for detailed correlation analysis.

The MCS evaluation of the V_s30 model varied the V_s within each geological unit and the depth of the loose-dense boundary in the 3D model (see Figure 1B). Values were sampled at random within a normal distribution of values in each geological unit for the V_s and the loose-dense boundary depth in Pleistocene sediments. The normal distribution of V_s values was determined from down-hole V_s surveys and values of V_s assigned to classified geological units; and the loose-dense boundary data were sample from the borehole database (see Hill et al. 2022). The MCS was carried out for 300 variations of the 1D V_s profile at each site to test the sensitivity of the V_s30 results to the assigned shear-wave velocity and the loose-dense boundary. Figure 3B maps the standard deviation of the V_s30 model results from the MCS; the map shows that in absolute terms the largest standard deviations in the model are in areas where the Rakaia Terrane greywacke basement is included in the 1D profile (i.e., in locations where the QST is <30 m). This can be explained by the diverse range of V_s values estimated for the basement (700 – 1,300 m/s) related to their weathering and varied lithological composition. The large uncertainties in the V_s30 MCS model reflect the lack of constraint on shallow greywacke V_s from unweathered to completely weathered rock within 30 m of the surface. Further work will advance this analysis by investigating V_s30 as a non-normally distributed parameter.

4 CONCLUSIONS

Modelling of site period and V_s30 from detailed 3D geological models is a useful tool to estimate site parameters where direct geophysical measurements are sparse. For Wellington, modelled estimates correlate well with measured data and enable us to map these parameters across areas where the 3D geology is well known. The modelled site period correlates well with measured values in areas of the basin where the QST is <150 m. The modelled estimates are systematically longer than measured values in areas where the basin is deeper; this could be caused by older sedimentary deposits or erosion surfaces causing a strong impedance contrast within the sedimentary sequence (e.g., a measured site period associated with 'engineering bedrock' rather than greywacke basement). The V_s30 modelling correlates well with the measured values in the basin; however, sparse data prevent a detailed correlation analysis. Monte Carlo Simulation of the V_s30 calculation tested the effect of V_s uncertainties in the model and highlighted the poor constraints on 'rock' velocities which arise from the highly variable material properties of the Rakaia Terrane greywacke due to weathering and composition. Estimates of site period and V_s30 from detailed 3D geological models are a useful tool for understanding regional variation and can be used to create continuous maps of these properties as well as resolve some of the spatial problems related to limited datasets of measured sites.

5 REFERENCES

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