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Shear wave velocity characteristics of Nelson-Tasman regional deposits

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ABSTRACT

This paper presents proposed shear wave velocity-depth relationships for six prominent geological formations from the Nelson-Tasman area. Shear wave velocity profiles were developed for a selection of sites across the Nelson-Tasman Region using a combination of active source and passive source surface wave testing methods. A-priori subsurface geotechnical investigation data was used to define preliminary constraints for these subsurface profiles when carrying out surface wave inversions to define a suite of shear wave velocity profiles for each site. These subsurface geotechnical investigation records and published geologic information were used to assign a geologic formation to each depth range across all sites. By combing the data for each geologic formation across the region, power-law shear wave velocity-depth relationships were developed, with shear wave velocities much higher than those from velocity-depth relationships from regional and international studies. The application of this data includes uses in site characterisation and potentially liquefaction assessment processes, as well as providing the basis for regional ground motion simulation and visualization.

1 INTRODUCTION

An earthquake source and path to the site provide the ‘input’ motion but seismic/dynamic site effects dictate the representation of seismic shaking at the ground surface for a given site. The importance of these effects is important both for design and assessment of structures on a given site, as well as regional modelling of seismic events. This paper presents the development of representative shear wave velocity profiles for the major geologic formations in the Nelson-Tasman region. The motivation for this research was to collect region-specific data that could be used to inform dynamic site characterisation, as has been completed for other regions in New Zealand. Wherever possible, guidance from similar regional studies was referred to so that a reasonably consistent approach was adopted across the country. This information was used to refine the testing methods and processing techniques adopted in this research.

2 GEOLOGIC SETTING AND SEISMIC HAZARD OF THE NELSON TASMAN REGION

The Nelson-Tasman region is located in the north-west of the South Island of New Zealand shown in Figure 1. Basement rocks exposed immediately to the east of the Nelson urban area include Brook Street Volcanics Group of Permian age and Richmond Group Sedimentary rocks of Triassic age. The terranes were accreted at the Paleozoic-Early Cretaceous convergent margin of Gondwana prior to Late Cretaceous rifting (110-85 Ma), with opening of the Tasman Sea (Laird and Bradshaw 2004; Mortimer et al. 2017). These units have been exposed by uplift along the Flaxmore and Waimea Faults and dip steeply which is likely a consequence of a long history of superposed deformation (Ghisetti et al, 2019).

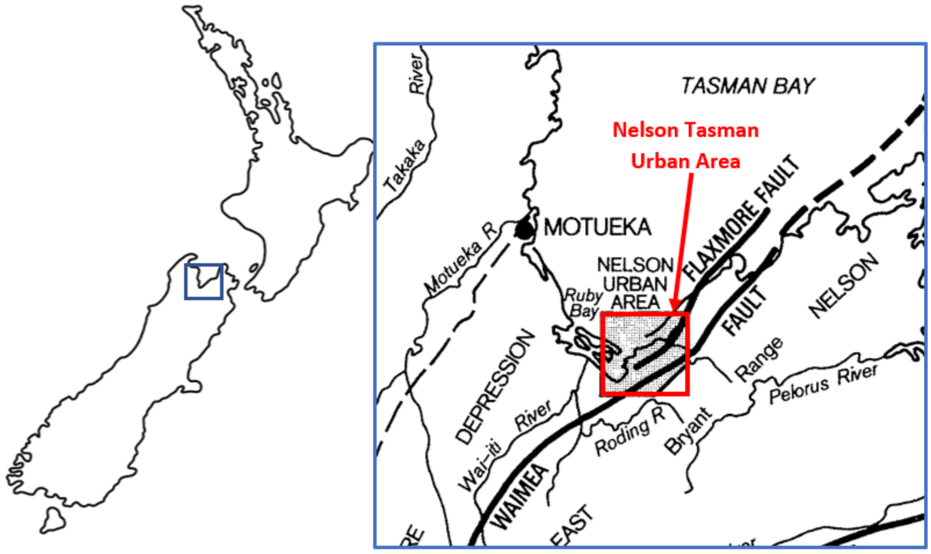

Figure 1: Location of Nelson-Tasman in New Zealand, Inset: Map showing the location of WFFS and Alpine Fault relative to main urban areas of Nelson and Richmond (Fraser, 2005)

The steep rocky mountain ranges that enclose the region have supplied huge volumes of gravel to the lower lying areas. Over time, the relatively flat areas of Nelson and Richmond have been formed on outwash gravels. The majority of the Nelson-Tasman sediments comprise unconsolidated sands, partly consolidated river gravels and minor areas of soft peat (Rattenbury at al., 1998). Alluvial gravels are widespread and well preserved in flood plains.

Recent Quaternary deposits in the Nelson-Tasman area include alluvial gravels and fan deposits, marine deposits, swamp deposits and sands (Johnston, 1979). Prominent formations including Stoke Fan Gravel, Appleby Gravel, Hope Gravel, Nelson Alluvium and Tahunanui Sand, make up a vast majority of the surficial deposits in the region. These formations are the focus of the research presented in this paper and are discussed in more detail in later sections.

The Nelson-Tasman region is considered a ‘moderately’ seismic area, due to the proximity to the Alpine Fault and the local Waimea-Flaxmore Fault System. The Waimea-Flaxmore Fault System is a pronounced feature of the Nelson-Tasman area and extends for approximately 150km north-east from the Alpine Fault near St Arnaud to the western side of D’Urville Island (Figure 1). The area is characterised by shallow seismicity (<15km) largely concentrated in the west, an absence of mid-depth seismicity (15-40km) and deep seismicity (>40km) in central and eastern parts related to subducting Pacific Plate (GNS, 2016).

3 SURFACE WAVE TESTING METHODOLOGY

A combination of active-source (MASW) and passive-source microtremor array measurements (MAM) surface wave, testing techniques was utilised at chosen locations around the Nelson-Tasman region to collect dynamic site information. These surface wave testing methods utilise sensors set out on the ground surface to record signals from either active or passive energy sources. This information can then be processed and interpreted along with constraints from a priori information to provide inferred relationships for the subsurface ground profile.

3.1 Acquisition

Both active and passive surface wave testing methods were employed as part of this study. Active methods utilise an excitation source and receivers at known locations while passive methods rely on ambient noise in the environment. Both active and passive methods are based on the propagation of surface waves, called as such as they travel along the ground surface. This study employed the use of geophones and broadband seismometers as sensors set out in a 1D (geophones) or 2D (geophones or seismometers) array. Active and passive source surface wave testing methods currently do not have standardised methodologies. The testing was completed based on technical references and methods which have been refined by other researchers for the equipment used in this study and for site conditions in New Zealand, as detailed later in this section.

3.2 Processing and Inversion

By processing the acquired data from surface wave testing, experimental dispersion data representative of the soil/rock below the ground surface is extracted. The experimental dispersion curve resulting from this process relates the Rayleigh wave velocity (i.e. phase velocity) to the wavelength or frequency. The dispersive nature of Rayleigh waves means that different wavelengths travel at different velocities and therefore wavelength/frequency can be used to characterise a range of depths through the soil profile.

The experimental dispersion curve was processed for each of the testing methods applied at each site (MASW, L-array and circular array testing) using Geopsy (www.geopsy.org, Copyright 2002-2011 by Marc Wathelet). The three resulting dispersion curves after processing and the removal of poor quality data were then combined for further analysis. Dinver open-source software, which is part of the Geopsy package, was used to carry out the inversion process. The uncertainty in the shear wave velocity profile is represented as a ‘minimum misfit’ and is an important piece of information for site-response analyses. A-priori geotechnical and geological information and empirical shear wave velocity data was used to constrain the layering where possible and shear wave velocity profiles for different materials. This methodology is covered in more detail in Teague et al. (2015). For each of the 29 Nelson-Tasman sites tested, the 1000 "best" ground models with lowest misfit to the experimental dispersion curves were kept to capture the epistemic uncertainty in shear wave velocity, underscored by the non-uniqueness of surface wave inversion

4 SHEAR WAVE VELOCITY-DEPTH MODELS

For each test sites the 1000 shear wave velocity profiles were extracted, discretised into metre-thick layers, and subsequently combined and organized by geologic units to develop regional representative shear wave velocity profiles. As noted by Lin et al. (2014), for a given homogenous soil, the shear wave velocity is proportional to the quarter power of the mean effective stress normalized by one atmosphere of pressure. This is described by the following generalized functional form:

$$V_s = A_s\,(\sigma'_m/Pa)n_s \qquad (1)$$

Where A_s= the shear wave velocity corresponding to an effective mean stress equal to 1 atm,n_s= the exponent of normalised effective mean stress, σ'_m= mean effective stress, Pa = 1 atm.

By assuming reasonable values for the unit weight of the soil, the at-rest lateral earth pressure coefficient, and depth to groundwater table (γ_S = 18 kN/m3, k_0 = 0.5 and, GWL = 0 m, respectively), regional representative shear wave velocity profiles were used to develop relationships for each geologic unit. Specifically, the generalized functional form (Eqn 1) was fitted to each representative velocity profile using a linear least squares regression.

Table 1 presents the coefficients for the relationships developed using this equation (Eqn 1) for the Nelson-Tasman geological formations, along with references from literature for comparison. The overall trend being that the Nelson-Tasman relationships present a higher estimated shear wave velocity compared with deposits of a similar description from literature. These same equations are then presented in Figure 2 by plotting these deposits with depth in the generalised groupings based on soil-type description.

Comparing the equation coefficients from the Moutere Gravel and Port Hills Gravel with the 'Dense Gravel, Menq (2003)' data in Table 1, the value of n_s is greater than that of the dense gravel deposits documented in the literature references. Figure 2(a) presents these relationships for Port Hills Gravel and Moutere Gravel along with the gravel deposit relationships from Menq (2003) and Deschenes (2018). This indicates that the Nelson-Tasman Port Hills Gravel and Moutere Gravel deposits have a comparable estimated shear wave velocity to around 5m - 15m below ground level to that of the 'gravel only' and 'interbedded gravel' deposits presented in Deschenes (2018). Below this range of 5m - 15m below ground level, the Nelson-Tasman deposits then show a more significant increase in estimated shear wave velocity with depth, compared to the other considered deposits from literature.

Table 1: Summary of the derived coefficients for Nelson-Tasman formations and information from literature by Menq (2003), Lin et al (2008) and Deschenes (2018).

Soil Type	**Estimated unit weight (kN/m3)**	**As (m/s)**	**n_s**
Moutere Gravel	18.0	734	0.471
Port Hills Gravel	18.0	576	0.391
Stoke Fan Gravel	18.0	458	0.264
Hope Gravel	18.0	395	0.117
Tahunanui Sand*	18.0	305	0.331
Nelson Alluvium	18.0	357	0.338
Dense Gravel (Menq, 2003)	18.0	312	0.331
Dense Sand (Menq, 2003)	18.0	255	0.261
Imperial Valley Soft Sands, Silts and Clays (Lin et al, 2008)	17.0	192	0.273
Canterbury Gravel only gravel sites (Deschenes, 2018)	19.6	547	0.15
Canterbury Interbedded gravels sites (Deschenes, 2018)	19.6	369	0.26
Canterbury Interbedded sites, soft soils (Deschenes, 2018)	17.3	229	0.44

Similarly, the Hope and Stoke Fan Gravel coefficients are slightly higher than the comparative ‘interbedded gravel’ information by Deschenes (2018). In Figure 2(b) the shear wave velocity relationships of Nelson-Tasman Hope Gravel and Stoke Fan Gravels are compared against the same literature deposits. The Hope and Stoke Fan Gravel deposit relationships sit between the ‘gravel only’ and ‘interbedded gravel’ deposit relationships by Deschenes (2018). This result makes sense based on the material descriptions for the Hope and Stoke Fan Gravel deposits being generally gravelly and interbedded gravel deposits.

The Tahunanui Sand and Nelson Alluvium are the Nelson-Tasman deposits with the highest proportion of sand and fines content, considered in this study. The coefficients of these formations are also slightly higher than the similarly described ‘soft soil sites’ of Deschenes (2018) and ‘Dense Sand’ by Menq (2003). Figure 2(c) presents these Nelson-Tasman with the Lin et al (2014) ‘Dense sand’ and Deschenes (2018) ‘soft soils’. The Nelson-Tasman formations are shown to have a higher estimated shear wave velocity for a given depth when compared to the similarly described literature units. It is deemed that this comparison of geological units is reasonable based on the published geology and descriptions of the formations provided by the referenced literature. Both Tahunanui Sand and Nelson Alluvium either have a component of gravel, or have been derived from gravel deposits, which is expected to influence the overall shear wave velocity of the deposits.

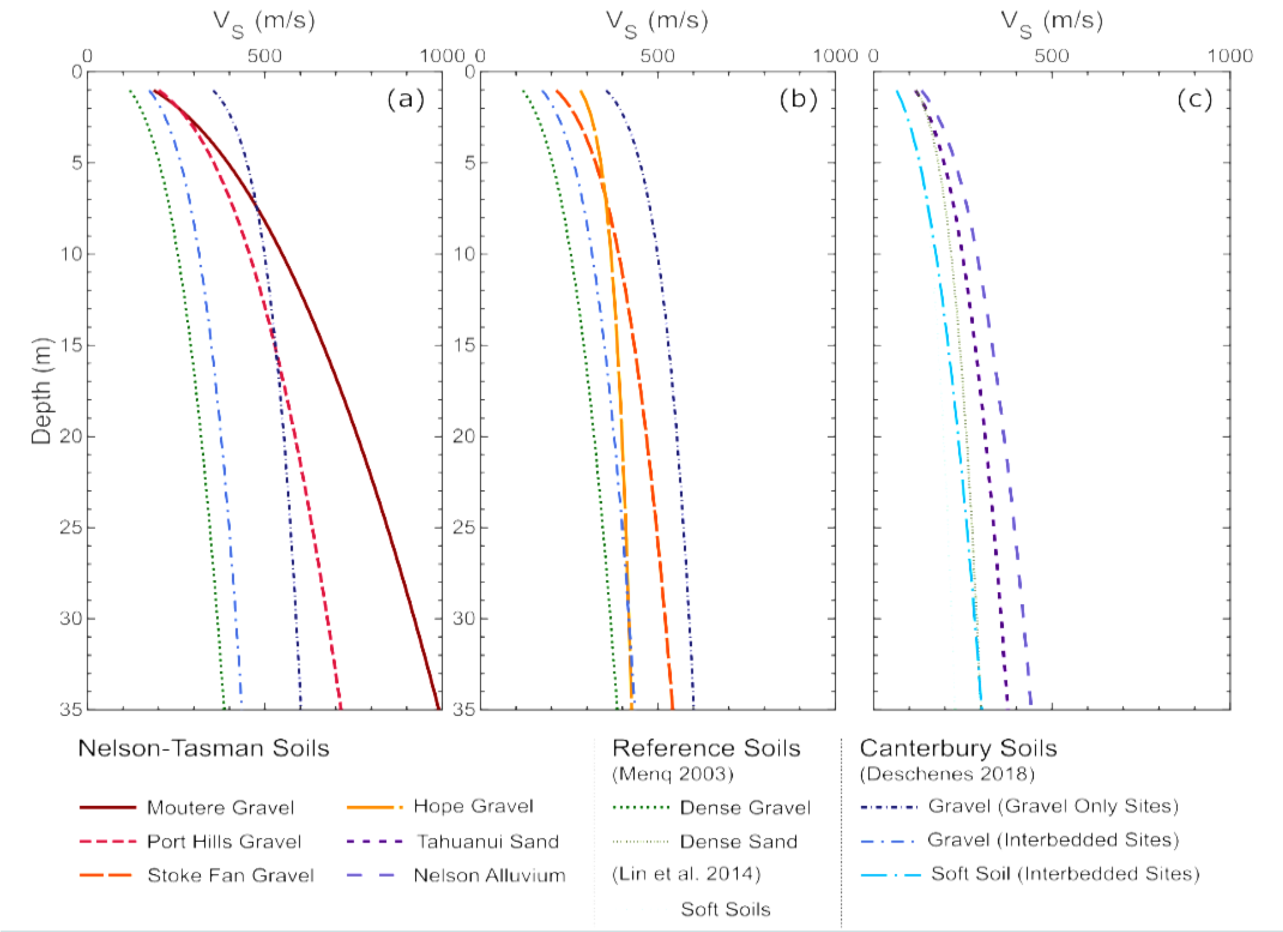

Figure 2 (a): Shear wave velocity relationships of predominantly gravel formations. (b) Shear wave velocity relationships of interbedded gravel formations (c) Shear wave velocity relationships of fine grained and sand formations

5 DISCUSSION

5.1 Shear wave velocity-Depth Relationships

In general, the shear wave velocities of the Nelson-Tasman are relatively high at relatively shallow depths, with the Moutere Gravel and Port Hills Gravel formations exceeding 750 m/s within 30m below ground level. The high shear wave velocity of Moutere Gravel is likely because it is highly over-consolidated as discussed further below. The very high shear wave velocity inputs from the Moutere Gravel results in both the A_s and n_s coefficients which are much higher than that of the Menq (2003) 'Dense Gravel'. The UCS of Moutere Gravel is expected to be less than 1MPa and therefore is not considered to be rock according to NZS1170.5 classifications (reference NZS). Because of this, while the shear wave velocity is comparable to site classification of bedrock, Moutere Gravel cannot be considered seismic bedrock.

For the purposes of comparison between units, only the inferred weathered or 'soil-like', portion of the Port Hills Gravel was included in the development of the modelled shear wave velocity relationships. Even with the data-points selected only from the material which is inferred to be a clay-bound gravel, it is evident that the shear wave velocity equation coefficients are still higher than those of Menq (2003) 'Dense Gravel'.

Stoke Fan Gravel, Hope Gravel and Nelson Alluvium are all relatively young deposits. While all contain a reasonable proportion of gravel, these would not generally be classified as a 'dense gravel'. Therefore, the similarity between these units and the Menq (2003) Dense Gravel equation coefficients highlights the need for both geotechnical and geophysical information to allow fair comparison of geological units. This may also indicate higher shear wave velocity for Nelson-Tasman subsoil units, compared with other parts of New Zealand.

One possible explanation is the understanding that the Nelson-Tasman area is thought to have undergone cycles of geological uplift which has produced much denser, over-consolidated units that are likely to have relatively high shear wave velocities. For example, the Moutere Gravel Formation is aged from late Pliocene – lower Pleistocene (approx. 3.5 – 1 Ma). The geology indicates that NW-SE compression across the Nelson region and the Moutere Depression has been undergoing continued uplift for at least 17Ma and increased during the last few million years and uplifted the Richmond Range and Kahurangi ranges which are both young mountain ranges (Ghisetti et al, 2019). With additional geotechnical characterisation information of the regional deposits, this suggested explanation could be explored further.

The Tahunanui Sand formation includes silt, sand and gravel at depth, so the equation coefficients are also deemed to be reasonable for the expected materials within this unit. However as there were only three sites tested with this Tahunanui Sand present, the data may potentially be biased due to the lack of data points to capture the true range of the formation. Tahunanui Sand shear wave velocity profile is comparable to the 'soft silt/sand/clay' of Lin et al (2014), and the Canterbury interbedded site soft soils as well as the 'dense sand' from Menq (2003). Based on the published geology it is inferred that the Tahunanui Sand formation (excluding deeper gravel deposits) is a comparable material to these units.

6 CONCLUSIONS

This project is the first regional study of Nelson-Tasman utilising active and passive surface wave methods to assess the dynamic characteristics of the subsoil materials. Relationships for estimated shear-wave velocity with depth were derived prominent regional formations by combining a range of geotechnical and geophysical investigation techniques.

It is noted that the Nelson-Tasman area is thought to have undergone cycles of geological uplift which has produced much denser, over-consolidated units that are likely to have relatively high shear wave velocities. This highlights the need for soil characterisation of the Nelson-Tasman units both through geotechnical and geophysical testing methods, rather than relying on geological descriptions alone. The younger deposits of Stoke Fan Gravel, Hope Gravel, Tahunanui Sand and Nelson Alluvium, the shear wave velocities are similar to that expected for a 'Dense Gravel' deposit presented in Lin et al (2014). While all of these deposits contain proportions of gravel, they would not typically be labelled as a 'dense gravel', indicating that the shear wave velocities are higher than expected when compared to literature.

Shear wave velocity along with site period are the two fundamental parameters for seismic site classification, however it was found in Nelson-Tasman that traditional site period estimation techniques were often not conclusive due to the uncertainty around depth to seismic bedrock.

Further research is required into the depth to seismic bedrock and how this characteristic might influence seismic shaking in an earthquake event. Once a depth to seismic bedrock is established, the estimated relationships of shear-wave velocity with depth presented in this study for regional formations could be used to better refine site characterisation and therefore dynamic site response of specific locations in the Nelson-Tasman region.

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