Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 50, No. 1, March 2017

SITE CHARACTERISATION OF GEONET STATIONS FOR THE NEW ZEALAND STRONG MOTION DATABASE

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(Submitted *June 2016*; Reviewed *September 2016*; Accepted *November 2016*)

ABSTRACT

The New Zealand Strong Motion Database provides a wealth of new strong motion data for engineering applications. In order to utilise these data in ground motion prediction, characterisation of key site parameters at each of the ~497 past and present GeoNet strong motion stations represented in the database is required. Here, we present the compilation of a complete set of site metadata for the New Zealand database, including four key parameters: i) NZS1170.5 site subsoil classification, ii) the time-averaged shear-wave velocity to a depth of 30 m (Vs30), iii) fundamental site period (Tsite) and iv) depth to a shear-wave velocity of 1000 m/s (Z1.0, a proxy for depth to bedrock). In addition, we have assigned a quality estimate (Quality 1 – 3) to each numerical parameter to provide a qualitative estimate of the uncertainty. New high-quality Tsite, Vs30 and Z1.0 estimates have been obtained from a variety of recent studies, and reconciled with available geological information.

This database will be used in efforts to guide development and testing of new and existing ground motion prediction models in New Zealand, allowing re-examination of the most important site parameters that control site response in a New Zealand setting. Preliminary analyses, using the newly compiled data, suggest that high quality site parameters can reduce uncertainty in ground motion prediction. Furthermore, the database can be used to identify suitable rock reference sites for seismological research, and as a guide to more detailed site-specific references in the literature. The database provides an additional resource for informing engineering design, however it is not suitable as a replacement for site-specific assessment.

INTRODUCTION

Local site conditions strongly influence earthquake ground motion and need to be accounted for in seismic design. Currently in New Zealand, site effects are conventionally incorporated in design standards (NZS1170.5:2004, Standards New Zealand 2004) through spectral shape factors for a given subsoil classification (Site Class). These spectral shape factors are based on smoothed approximations to hazard spectra calculated using the McVerry et al. (2006) [1] ground motion prediction equation (GMPE), which characterises site effects using indicator variables for Site Class C and D sites (sites located on shallow and deep or soft soil respectively). Effectively, this is modelling the average period-dependent amplification of Site Class C and D strong-motion sites relative to the average amplification from Site Class B (weak rock) sites, based on a set of New Zealand strong motion records described in McVerry et al. [1]. Site Class E sites (very soft soil) are not directly modelled, and the Site Class E spectral shape factors in NZS1170.5:2004 are derived from engineering judgement [2]. Future revisions to the NZS1170.5:2004 loadings standard are likely to incorporate more detailed site effect modelling than the current Site Class factors.

There are now alternative GMPEs being used in New Zealand [3-6] which use time-averaged shear-wave velocity to 30m depth (Vs30) and the depth to a shear-wave velocity of 1000 m/s (Z1.0) to characterise site effects. These GMPEs include New Zealand-based Bradley (2013) [3] model. Other models use fundamental site period (Tsite) in place of Vs30, i.e. the New Zealand model of McVerry (2011) [7] and recent overseas work by Hassani & Atkinson [8].

Accurate knowledge of these key site parameters (Site Class, Vs30, Z1.0, Tsite) is critically needed in order to test and develop GMPEs for New Zealand conditions. With the recent expansion of the GeoNet strong motion network (www.geonet.org), site parameters for a large number of newly installed stations have to date been unavailable or scattered across multiple references in the literature. Furthermore, in the development of current New Zealand GMPEs, site parameters at a given strong motion station (SMS) have largely been estimated from surface geology or sparse geotechnical information. In practice numerical parameters Vs30 and Z1.0 have also been assigned based on Site Class and are thus not independently measured, such as in development of the Bradley (2013) GMPE [3]. Fundamental site period (Tsite) has also largely been inferred from estimated geological profiles without direct measurements, e.g. in development of the McVerry (2011) model [7]. Here, we describe the compilation of a complete set of new site metadata for GeoNet SMS, including key site parameters and estimates of parameter 'quality' or uncertainty.

In recent years, a wealth of new strong motion data has become available for engineering applications. The New Zealand strong motion database, detailed in the companion article of Van Houtte et al. [9], provides a significantly expanded strong motion dataset with updated processing strategies and a suite of source metadata from significant New Zealand earthquakes. The site metadata compiled here are an important component of the database and describe the local

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Table 1: Key site parameters compiled for the 2016 database.

Site Classification	Tsite (s)	Z1.0 (m)	Vs30 (m/s)
NZS1170.5 Site Class [12] following the implementation of Wotherspoon et al. [13])	Fundamental Site Period*	Depth to a shear-wave velocity (Vs) of 1000 m/s	Time-averaged shear-wave velocity (Vs) in the uppermost 30 m, as defined by: $Vs30 = \frac{30}{\sum_i \frac{d_i}{Vs_i}}$ Where d_i and Vs_i are the thickness of the i-th layer

**Note, that rock sites are assigned Tsite either according to the observed longest period amplification peak (if present and assumed to be due to topographic and/or material effects) or a value of -1 if flat response can be assumed. This also provides a useful flag to identify good quality rock reference stations for seismological research.*

site conditions and site response at the 497 GeoNet strong motion stations that have recorded significant historical ground motions. The four key parameters compiled for the New Zealand database are i) NZS1170.5 site classification, ii) Tsite iii) Vs30 and iv) Z1.0. A summary of these parameters is given in Table 1. The site metadata compilation draws on the previous site database of Cousins et al. [10], with the inclusion of many additional GeoNet SMS and many more recent site-specific investigations, such as in Canterbury following the Canterbury earthquake sequence and in Wellington as part of the ongoing *It's Our Fault* project [11]. An important new feature of this metadata compilation is the inclusion of qualitative estimates of uncertainty for the three numerical site parameters.

The site metadata are intended to provide a tool for statistical analysis to guide development of ground motion prediction models in New Zealand, in particular allowing re-examination of the most important site parameters that control and predict site response in a New Zealand setting. The metadata can be a resource for engineering design, however they are not suitable as a replacement for site-specific assessment. The determination of site parameters for engineering design and hazard assessment requires detailed site-specific assessment; the references listed in the database may serve as a starting point for available information. The site database can also be used as a guide to target new site investigations where they are most needed to build on existing knowledge.

SITE PARAMETERS

Site parameters compiled for the New Zealand database (Table 1) include those utilised in existing New Zealand GMPEs as well as most overseas models for tectonically active regions [summaries in 14, 15]. In New Zealand, the McVerry et al. (2006) GMPE [1] uses discrete site classification, whereas the Bradley (2013) [3] GMPE uses a combination of Vs30 and Z1.0, following closely the Chiou and Youngs (2008) GMPE [16] developed for the Next Generation of Attenuation project for the Western United States [17] (NGA-West). We note, that almost all GMPEs developed in the follow-up NGA-West2 project [15] for tectonically active regimes also use Vs30 and Z1.0. The sole exception is the Campbell and Bozorgnia equation [18], which uses the depth to Vs=2.5 km/s. This parameter is not defined in this site database, as it would be unknown, or highly uncertain, almost everywhere in New Zealand. This is because it generally lies within the basement rock unit, in contrast to the Z1.0 parameter, which is often associated with a lithological boundary delineating bedrock depth.

In addition to Vs30 and Z1.0, we also include the Tsite parameter to allow testing of an additional continuous parameter that has been proposed as a viable alternative to the more commonly used Vs30. Tsite is also the parameter that defines the boundary between two of the NZS1170.5 site classes. For example, McVerry [7] proposed a new method using Tsite to replace the spectral shape factors of the New Zealand design standard NZS1170.5, thus allowing for a gradual transition between Site Class C (shallow soil) and Site Class D (deep or soft soil) spectral shapes. Note that Tsite was assigned only for Class C and D sites, with no assignment to rock sites, and records from Class E sites were not included in the study. Based on a small local dataset, McVerry [7] concluded that for Class C and D sites, Tsite provided a more suitable parameter than Vs30 alone, given that Vs30 may not adequately account for long-period amplification at sites that have high Vs30, but thick sequences of stiff gravels down to considerable depth. However, the Tsite parameter values used to develop McVerry (2011) model [7] were often estimated based on 1-D geological profiles derived from surface geology and limited subsurface knowledge, and not direct site-specific measurements.

The use of both Vs30 and Z1.0 within the Bradley (2013) [3] and other NGA-West2 GMPEs [4-6] may also allow greater flexibility in handling these deep-soil high-Vs30 sites. However, in Bradley's (2013) [13] examination of the Chiou et al. (2010) model for New Zealand, Vs30 values were estimated based on Site Class, and Z1.0 was then inferred from the assigned Vs30 value (see Table 2 of Bradley [13]). The dependence of the Bradley (2013) GMPE expressions on these parameters was adopted directly from the NGA-West Chiou et al. (2010) model upon which it is based. Hence, testing and validation of both local and international GMPEs based on more complete knowledge of site parameters is valuable. The database will also allow examination of whether internationally-derived correlations between these parameters (currently commonly applied in New Zealand due to lack of site-specific data) are applicable in New Zealand conditions.

In future, other site parameters may be considered for inclusion in the database, but are not the focus of the present effort.

DATASETS

The starting point for this data compilation effort was the previous work of Cousins et al. [10] and references therein, which contains geological descriptions of the GeoNet SMS network sites existing at the time, as well as some site-specific investigation data. Significant new datasets used in the 2016 database are outlined below.

Nation-Wide Spectral Ratio Studies

Spectral ratio investigations have been used to derive Tsite for a significant number of national SMS by numerous different studies [e.g. 20-23].

Standard spectral ratios (SSR) calculated from earthquake recordings attempt to capture the resonant periods of the site by taking the ratio of recorded horizontal component Fourier amplitude spectra at the site to the equivalent horizontal rock reference spectra [24]. To provide high quality measurements, this method requires a nearby rock reference station that can be reasonably assumed to have 'flat' response or negligible amplification itself. We have also used SSR calculated using generalized spectral inversion of regional strong motion data [21, 25] which calculate site amplification compared to regional average rock reference motions, after taking into account source and path effects, i.e. they do not require a locally situated reference station.

Horizontal-to-vertical spectral ratios (HVSR) compare the horizontal spectra to the vertical spectra at the site, under the assumption that in a flat-layered media, vertical motions are not amplified by local soil structures [26, 27]. HVSR also do not require a nearby rock reference station, and have been calculated based on earthquake recordings and/or background microtremor or 'noise'.

Canterbury Datasets

Numerous site-specific investigations have been undertaken in Canterbury following the start of the Canterbury earthquake sequence in 2010, in addition to spectral ratio investigations. These include invasive borehole measurements, i.e. seismic cone penetrometer testing (SCPT), as well as non-invasive active and passive seismic investigations based on surface wave analysis. For example, multi-channel analysis of surface waves (MASW) has been used to derive Vs profiles, with depths constrained by cone penetrometer testing (CPT) [13, 22, 28]. Surface wave methods used alone can yield Vs profiles that are highly non-unique, due to trade-offs between layer thickness and layer Vs. The combined use of surface wave methods and constraints from invasive boreholes yields well-constrained estimates of both Vs and bedrock depth. Other surface wave techniques used in Canterbury include the Spatial Autocorrelation method (SPAC) [29], which when combined with ambient noise HVSR can also yield well-constrained estimates of Vs and shallow layer thickness [30]. A new 3D basin velocity model for the Canterbury region has been compiled [31], drawing on a variety of sources, including surface wave investigations [32], regional tomography [33], and seismic reflection lines [e.g. 34]. Based on this information, we adopt the depth to material of Miocene age extracted from the Canterbury 3D model as a proxy for Z1.0. This surface follows similar spatial trends, but is deeper than the base of Quaternary-age sediments inferred in the regional map of Jongens [35].

***It's Our Fault* Wellington Regional Datasets**

The *It's Our Fault* project in the Wellington region [11] involved constructing a 3D geological model of the Wellington and Hutt Valley regions [36, 37] based on borehole data (including SCPT) and geophysical investigations. Layer Vs information is available from passive seismic measurements, including noise cross-correlations [38], refraction microtremor (ReMi) studies [39], and SPAC [30, 40, 41] assessed along with newly available spectral ratio Tsite measurements [23].

1D Geological Profiles and National Maps

Development of the McVerry (2011) Tsite model [7] involved collating a series of 1D geological profiles at ~150 SMS GeoNet locations nationwide, based largely on Cousins et al. [10] and profiles for Wellington city and the Hutt Valley developed by Semmens *et al.* [36] and Boon *et al.* [37, 42] as part of the *It's Our Fault* project [11]. These profiles were estimated on a site-by-site basis, drawing on geotechnical investigations where available, mapped local surface geology and geological intuition. Vs was assigned to each geological unit in a consistent manner following the scheme outlined in Semmens et al. [36]. The complete set of profiles and their assigned velocities are held as unpublished supplementary data to McVerry (2011) [7] at GNS Science.

In addition, national maps of Site Class and Vs30 were developed by Perrin et al. [43]. Although these coarse-scale maps (estimated accuracy to within ± 250 m) are not intended to be used for site-specific assessment, they provide an initial guide to site conditions at each SMS.

PARAMETER ASSIGNMENT AND QUALITY

An important new component of this database is the provision of quality assessments of Q1 (well-constrained), Q2 (reasonably constrained) or Q3 (poorly constrained) for each numerical site parameter. These categories correspond to approximate uncertainties of < 10%, 10 – 20% and > 20% respectively. However, in most cases quantitative estimates of uncertainty are unavailable, such that quality is estimated qualitatively based on the type and result of investigations (see Table 2). Table 2 also illustrates the typical quality assessment for different types of site investigation methods underpinning our work.

The Tsite parameter can be estimated either from direct spectral ratio measurements or based on a 1D layer model with appropriate Vs assigned to each layer. In many cases Tsite values derived from these two approaches are similar, but this is not always the case. For the 1D model approach, depth-to-bedrock (proxy for Z1.0) is assumed to be equal to the depth of the soil column responsible for the fundamental resonance (Tsite). However, particularly in deep basins, it is possible that velocity contrasts below the assumed Z1.0 depth (e.g. those associated with deeper basement rock units), contribute to site resonance and are captured by the spectral ratio approach. Differences in the Tsite values from the two approaches could also be due to inaccuracy of the 1D profile parameters, or complex amplification effects (e.g. 2D and 3D effects) that are not captured by a simple 1D model.

Given the above, we infer that Tsite values from spectral ratios are in most cases a more accurate description of site resonance and these values are used preferentially in the database, where they are available. However, for Site Class C and D SMSs with no clear resonant peak in the spectral ratios, Tsite is inferred based on geological layer models or nearby measurements. For some very deep soil SMSs (Class D), Tsite cannot be meaningfully estimated due to both lack of spectral ratio information (or poor resolution) in the relevant frequency range, and very high uncertainty in the parameters of the deep soil profile. These stations are assigned a default value of Tsite > 2 s. Site Class A and B rock stations are either flagged as reference stations with flat response and assigned Tsite = -1, or assigned Tsite according to the greatest amplification peak if present. This allows us to record observed amplification due to topographic effects and/or material contrasts within material assumed to be rock. Where spectral ratio measurements are unavailable, Tsite is generally assigned a default value of < 0.1 s at rock sites.

In the case of the Tsite parameter, it is important to note that strongly resonant sites may be over-represented in the Q1 and Q2 categories, due to the clear amplification peaks, whereas sites exhibiting smaller or more ambiguous amplification peaks are more likely to be classified as Q3. This may have implications when quality factors are used in statistical testing of GMPEs. In order to provide more clarity, we have included a Tsite Descriptor (D_Tsite) following the guide in Table 3. This descriptor indicates whether direct Tsite measurements from spectral ratios are available at the site, and if so, provides a crude marker of the degree of amplification of the

Table 2: Quality criteria for site parameters.

Quality	Approx. Uncertainty	Tsite	Z1.0	Vs30
Q1	< 10 %	Well-constrained spectral ratio result compatible with known geology *AND/OR* Geological model with measured well-constrained Vs structure	Direct measurements (i.e. borehole, rock outcrop) *AND/OR* Well-constrained measurements of rock depth & Vs soil profile from non-invasive surface-wave methods or seismic reflection/refraction*	Well-constrained measurements of Vs30 from shear wave velocity measurements using non-invasive surface-wave methods or invasive methods using boreholes or SCPT.
Q2	10 - 20 %	Reasonable spectral ratio result *AND/OR* Well-constrained spectral ratio that is not in agreement with estimated geological model *AND/OR* Geological model with estimated layer velocities & thicknesses based on reasonable assumptions	Estimates compatible with well-constrained Tsite and partly known geological structure, *AND/OR* Well-constrained measurements at nearby geologically similar sites.	Estimates based on partly constrained near-surface Vs structure (i.e. well-constrained to depths less than 30 m) *AND/OR* Estimates from known local strata and Vs approximated using established correlations *AND/OR* Well-constrained measurements at nearby geologically similar sites
Q3	> 20%	Ambiguous or poorly constrained spectral ratio result *AND/OR* Best – guess geological model with poor constraints	Estimates from broad-scale national Z1.0 maps *AND/OR* Estimates at site with poor constraints	Estimates from broad-scale national Vs30 maps *AND/OR* Estimates at site with poor constraints

**Note, that non-invasive surface wave methods of estimating bedrock depth (e.g. MASW, ReMi, SPAC) are often subject to strong trade-offs between layer thickness and layer velocity, such that bedrock depth is not well-constrained. Additional information is often required to meet Q1 standard, i.e. CPT/known nearby structure etc.). This also affects Vs30 measurements to a lesser degree.*

fundamental peak, if present. In practice, it is problematic to assess the amplitude of spectral ratio measurements across all studies, because differences in data type, processing and smoothing parameters can lead to differences in ratio amplitude. Hence, we only assess the amplitude based on the most comprehensive studies of earthquake recordings by Kaiser et al. [21] and Van Houtte [23], which show compatible results in the large majority of cases. Where spectral ratios are determined from ambient noise or other smaller earthquake-based studies, they are not evaluated in terms of amplitude.

In practice, unless there is information to the contrary, the Z1.0 parameter is often assumed to be equal to depth to bedrock, without direct measurement of Vs, but with an assumption that Vs reaches 1000 m/s within this unit. Vs measurements within rock are very rare, and we use the following approximate guide established from discussions at the July 2014 Site Metadata Workshop held at GNS Science: Hard unweathered rock (e.g. Class A, Fiordland) or unweathered, very strong greywacke/ basalt ≈ 1500 m/s; Moderately strong greywacke ≈ 1200 m/s; Moderately weathered greywacke or moderately strong mudstone/sandstone/siltstone/limestone) ≈ 1000 m/s; Completely/highly weathered greywacke, weak rock/stiff hard soil (e.g. siltstone/mudstone/sandstone) ≈ 800 m/s. For rock sites, we have adopted a default Vs30 of 1000 m/s and Z1.0 of 0 m where no other assessment can be made. At soil stations, depth-to-bedrock (Z1.0) values in the current version of the database have largely been estimated from geological intuition based on slope angle of the bordering terrain and consideration of basin-specific depth morphology. Future updates to the database will also consider default Z1.0 measures from new national Z1.0 maps currently in development [43]. Given the

Table 3: Tsite descriptors.

D_Tsite	Description
I	Inferred from 1D layer model with assigned velocities and thicknesses.
Mn	HVSR or SSR shows no clear amplification (max ratio < 3). Site is therefore either flagged as reference station (if rock site class A or B) or Tsite is inferred from 1D layer model (if soil site class C or D).
Mw	HVSR or SSR shows weak amplification peak (max ratio 3 - 5).
Ms	HVSR or SSR shows strong amplification peak (max ratio ≥ 5).
Mu	HVSR or SSR amplification is unknown.
Ma	Tsite inferred from microtremor-based HVSR (amplification is not assessed or compared to earthquake-based HVSR here).

above assumptions and general lack of well-constrained site-specific data down to bedrock depth, there are currently few high quality measures of Z1.0 in the database.

Generally, site class is assigned here according to NZS1170.5 based on Tsite, with consideration of the Vs and Z1.0 parameters where appropriate. These parameters relate directly to the site response; however as discussed by Wotherspoon et al. [13], we note that other parameters not considered here can also be used in NZS1170.5 to determine site class (e.g. undrained shear strength (s_u) and SPT N). The Site Class parameter is not assessed for quality here, given it is a discrete parameter that is not directly measured. However, if needed, it would be possible for users of the metadata to devise a scheme to assign a quality factor to the Site Class parameter based on the value and quality of the other continuous parameters as they see fit.

At stations where no site-specific data were available, we have adopted Site Class and Vs30 from the national maps of Perrin et al. [43], and adjusted these parameters if necessary after a visual check against aerial photographs, geological maps and nearby station data. As part of this visual check, Z1.0 was also estimated qualitatively (as described earlier). If shear-wave velocity profiles were available at nearby stations and were considered a good representation of the geological structure beneath the site, we adopted this profile (adjusted for the new Z1.0 parameter if appropriate) for the calculation of Tsite. If there were no existing nearby V_s estimates for this geological setting, we based Tsite on a very simple 1D V_s profile compiled based on the velocity assignment in Perrin et al. [43]. In the absence of other information, this was generally done by assigning the Vs30 value down to 30 m (or Z1.0 depth, whichever is shallower), and assigning an appropriate average V_s (default 400 m/s, indicating reasonably stiff/dense deposits) from this depth down to the Z1.0 depth.

EXAMPLE SITES

In Figures 1-3 and Table 4 we present examples of Q1, Q2 and Q3 sites from the 2016 database.

Q1 Site: HVSC

Following the Canterbury earthquakes, detailed site investigations at GeoNet station HVSC (Heathcote Valley School) have been conducted by numerous geotechnical and research groups. Figure 1a illustrates the spectral ratio results (HVSR and SSR from spectral inversion) of Kaiser et al. [21] based on earthquake data. The results illustrate a strong amplification peak and a clearly defined site period of 0.27 s.

Table 4: Example station entries in the 2016 site database.

GeoNet Station	Site Class	Vs30 (m/s)	Tsite (s)	Zb (m)	Q Vs30	Q Tsite	D Tsite	Q Zb	References
HVSC	C	348	0.27	19	Q1	Q1	Ms	Q1	Wotherspoon et al. 2015c; Kaiser et al. 2013; Jeong and Bradley 2015; Van Houtte et al. 2012
919A	D	307	0.85	95.6	Q2	Q2	I	Q2	McVerry 2011; Semmens et al. 2010
MGCS	E	150	1	70	Q3	Q3	Mw	Q3	Unpublished HVSR (A. Kaiser & C. Van Houtte); Perrin et al. 2015

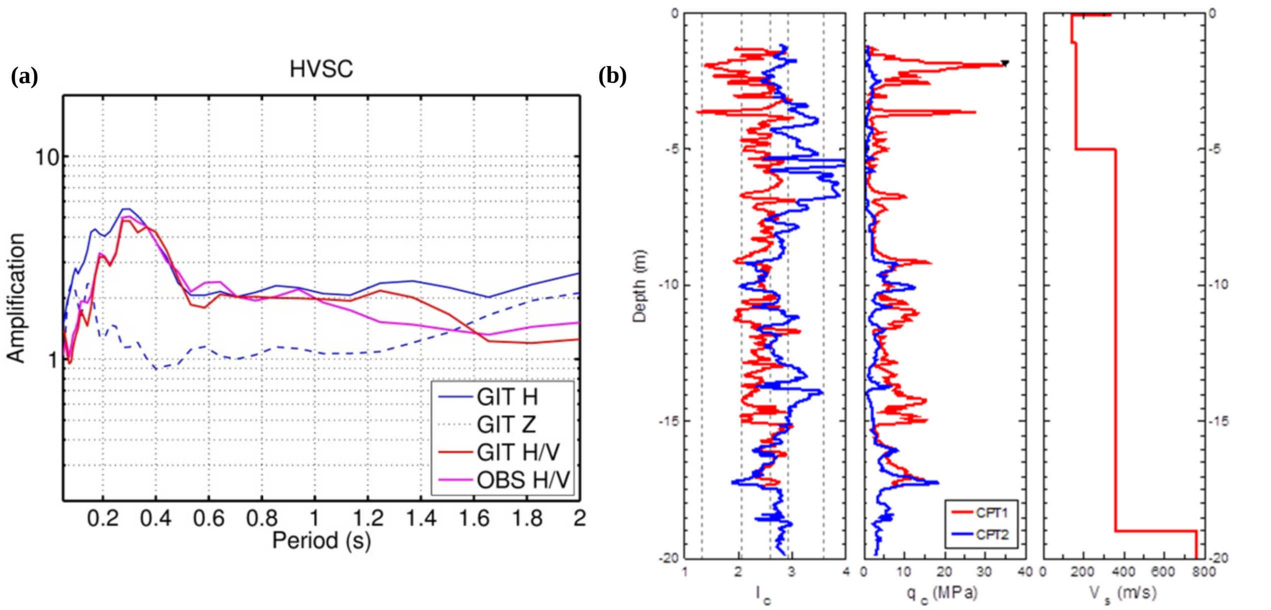

***Figure 1:** Examples of well constrained (Q1) Tsite and Vs30 measurements. (a) SSR spectral ratios of Kaiser et al. [21] derived from generalized spectral inversion (GIT) of aftershock data for both the horizontal (H) and vertical (Z) components relative to the horizontal reference spectra. Horizontal component is the root-mean-square average of the two components. Observed and modelled (GIT) HVSR ratios are shown as pink and red lines respectively. (b) Soil profile at HVSC from Wotherspoon et al. [13] showing i) soil behaviour type index (left); ii) CPT tip resistance (middle) and iii) shear-wave velocity derived from MASW measurements.*

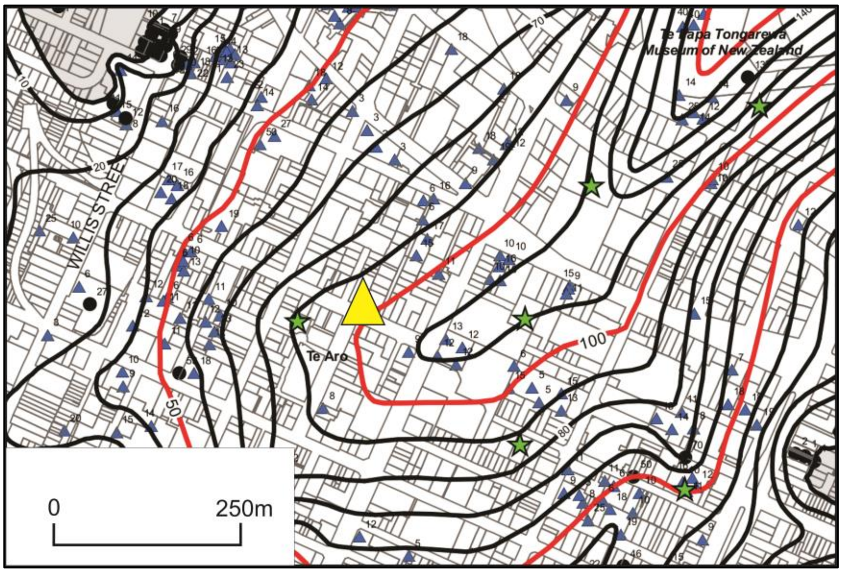

Figure 2: Example of Q2 Z1.0 measurement. Extract from the bedrock depth map for Wellington city published by Semmens et al. [36]. Yellow triangle shows the location of station 919A, contours indicate greywacke bedrock depth, blue triangles indicate boreholes that did not reach bedrock, black dots indicate boreholes reaching bedrock Green stars indicate locations of SPAC and HVSR surveys that estimate bedrock depth.

This is in agreement with the HVSR result from Van Houtte et al. [20], and the investigations of Wotherspoon et al. [13] using both HVSR from ambient noise and MASW Vs profiling constrained by available CPT borehole data down to rock (shown in Figure 1b). Furthermore, 2D modelling of site response has been conducted by Jeong and Bradley [44]. All studies and methods are in good agreement, providing well-constrained Q1 values for each of the site parameters.

Q2 Site: 919A

Station 919A was located at Te Aro Post Office in central Wellington until 1974. We used the 3D geological model of Wellington compiled under the *It's Our Fault* Project presented in Semmens et al. [36] to infer site parameters at this station. The 3D model uses a large database of point constraints (boreholes and passive seismic investigations) to interpolate 3D lithology over the central Wellington region (Figure 2). Vs values in the 3D model have been assigned to each layer based on information from i) SCPT, ii) surface-wave methods applied to the Wellington region [38-40], as well as iii) standard correlations with material type [45]. Based on the 3D model, a 1D soil profile (Table 5) has been prepared for the 919A site and used in the McVerry (2011) [7] model. Although site-specific investigations at 919A have not been used to determine site parameters, we can consider the values extracted from the 3D model to be reasonably constrained, and they are not expected to change significantly in revisions to the Semmens et al. [36] model currently considered at GNS Science. The Q2 assessment for this site accounts for uncertainty due to the fact that values at this site are interpolated between measured locations and may not capture local variations of the steeply dipping bedrock interface below Wellington.

Q3 Site: MGCS

GeoNet station MGCS (Blenheim Marlborough Girls College) is currently assigned Q3 for each parameter. Site Class D and Vs30 of 210 m/s have been inferred based on the national coarse-scale maps of Perrin et al. [43], hence Vs30 is poorly constrained and assigned Q3. HVSR investigations (Figure 3) show multiple amplification peaks, none of which can be confidently interpreted as corresponding to the fundamental site period (likely to lie above 1.7 Hz, or below 0.6s period if Class D is correct). Note that very few records have been used to calculate the HVSR below 0.4 Hz (i.e. above 2.5s), and hence the HVSR is not well constrained in this frequency range. A value of 1 s is adopted, which is consistent with the

Table 5: 1D soil profile assumed for Station 919A. The profile represents a pseudo-borehole extracted at the site from the 3D geological model of Semmens et al. (2010) for the development of the McVerry (2011) model.

Depth (m)	Description	Vs (m/s)
0 – 3	Soft/Loose Deposits	190
3 – 15	Soft/Loose Deposits	270
15 – 60	Stiff/Dense Deposits	400
60 – 95.6	Stiff/Dense Deposits	900
> 95.6	Greywacke Bedrock	

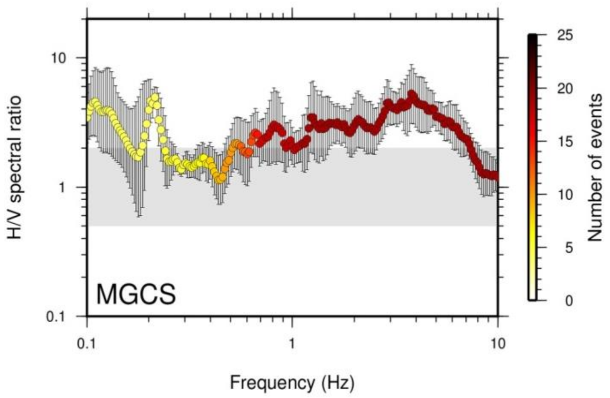

Figure 3: Example of Q3 Tsite measurement at station MCGS [23]. HVSR amplification curves using the geometric mean of the two horizontal components. Shaded area represents the standard deviation above and below the mean.

lowest-frequency (longest-period) well-constrained peak, the national maps of Perrin et al. [43] and the Z1.0 value of ~70 m estimated in Cousins et al. [10] based on geological maps.

METADATA STATISTICS

Metadata Composition

Figure 4 shows the distribution of Site Class of stations in the New Zealand strong motion database [9]. The majority of GeoNet stations are located on deep or soft soil (Class D), with smaller numbers on shallow soil (Class C) or weak rock (B). Very few stations are located on strong rock (Class A) or very soft soil (Class E). However, the number of Class E sites is likely underestimated due to a lack of site-specific investigations that are generally needed to confirm Class E. For example, recent observations of severe liquefaction and site-specific investigations in Christchurch identified additional Class E sites [13].

Figure 5 shows a summary of the quality factors for each site parameter in the database. The majority of sites are Q3, indicating the need for further targeted site investigations and compilation of site-specific data going forward. However, 180+ sites have Tsite values of Q1 or Q2 following recent spectral ratio analyses of strong motion data [13, 21-23]. Good quality (Q1 or Q2) values of Vs30 and Z1.0 are concentrated in urban centres, particularly Wellington and Christchurch, with site parameters elsewhere largely estimated based on geological maps and insight (Q3).

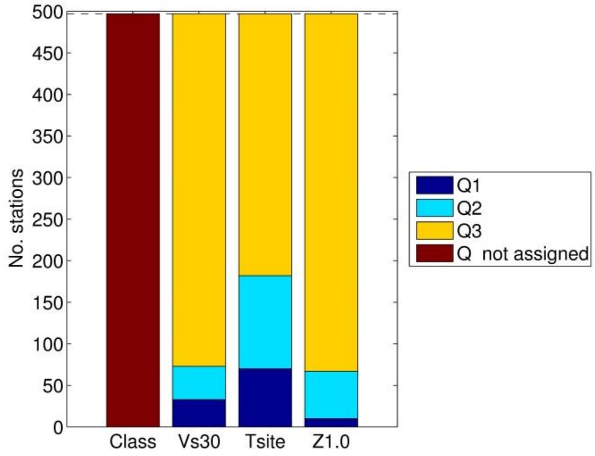

Figure 5: Site parameter quality factors for the 497 GeoNet strong motion stations in the database.

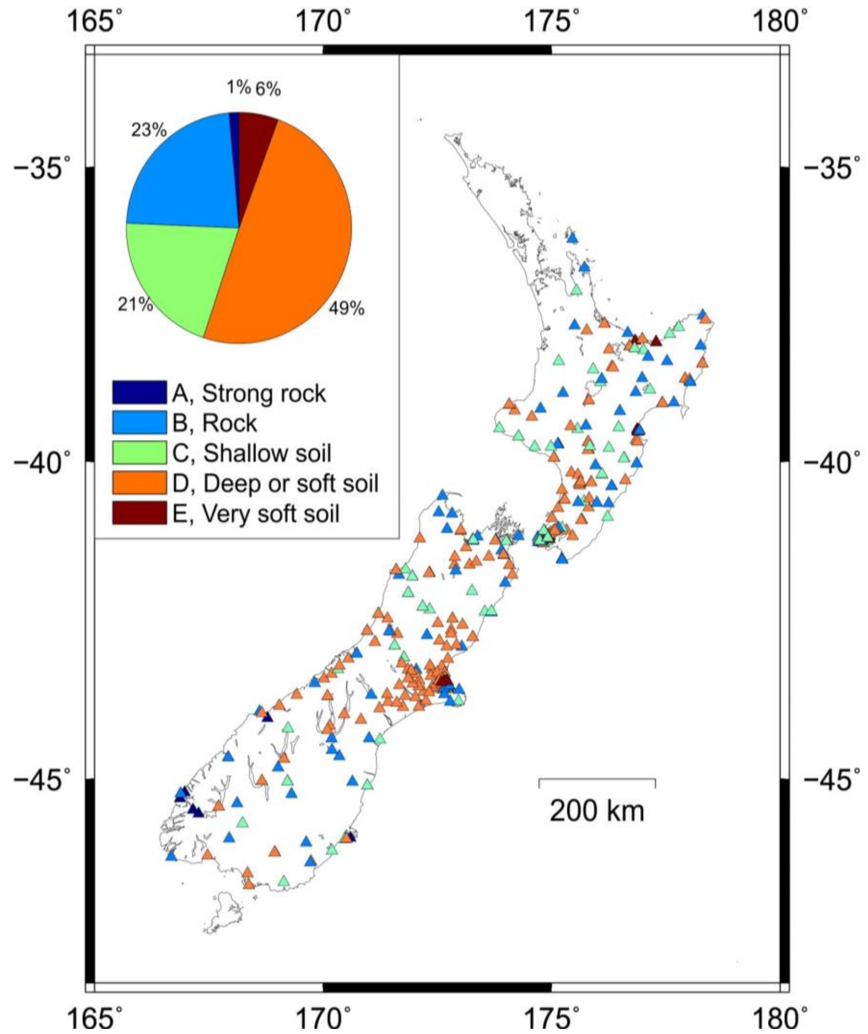

Figure 4: Summary and geographical distribution of site classes for strong motion stations in the strong motion database.

Rock Site Amplification

One interesting feature highlighted by the database is the prevalence of site amplification at stations classed as weak rock (Site Class B). Of the Site Class B sites assessed with spectral ratio methods, one half were assigned Tsite greater than 0.2 s, indicative of significant amplification effects due to topography and/or the presence of local softer deposits in the near-surface. This highlights the importance of amplification effects in hillside areas traditionally assumed to have 'flat' site response [see also 20, 46, 47]. An example of strong amplification up to a factor of 6 at a Class B site (PARS) is shown in Figure 6. This site is situated at the crest of a narrow ridge derived of Miocene-age volcanic material in the Port Hills of Christchurch. Amplification effects are inferred to be due to a combination of topographic shape combined with the presence of relatively low-velocity material in the Port Hills [46, 48].

Importantly, the database can be used to identify suitable reference stations with 'flat' site response for seismological studies. Currently 23 suitable reference stations have been identified with Q1 or Q2.

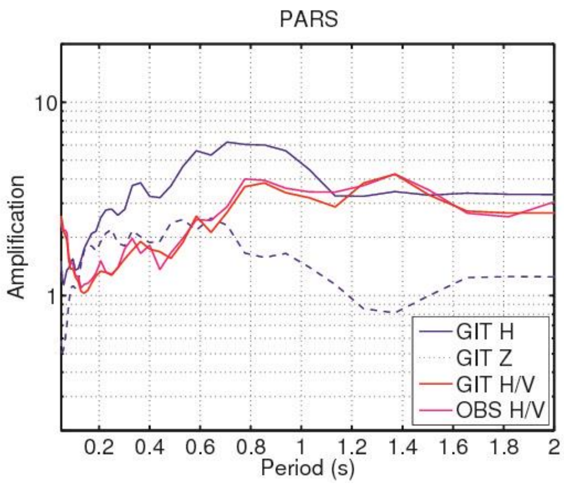

Figure 6: Spectral ratios from Kaiser et al. [21] for Class B rock station PARS showing significant amplification effects. As in Figure 1a, SSR is derived for the horizontal (H) and vertical (Z) components using generalised spectra inversion (GIT) of aftershock data. Horizontal component is the root-mean-square average of the two components. Observed and modelled (GIT) HVSR ratios are also shown as pink and red lines respectively. The Tsite value for this site is 0.8s and the quality assessment is Q1, based on the GIT H result, which is able to define the amplification peak more clearly than the HVSR result, which we infer may be somewhat biased by amplification of the vertical component.

Implications for Ground Motion Prediction

The importance of site parameter quality for ground motion prediction can be investigated by comparing GMPE predictions using poorly constrained versus well-constrained parameters against observed data from the New Zealand strong motion database [9].

Figures 7 and 8 show a comparison of station residuals for different site and quality parameters using PGA predictions from the Boore et al. (2014) GMPE [5]. Note that the Boore et al. model [5] uses Vs30 and Z1.0 site parameters, which is consistent with most NGA-West2 models. Station residuals are calculated as the average within-event residual for

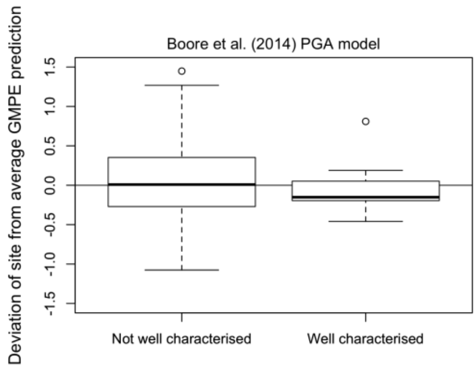

Figure 7: Distribution of PGA site-to-site residuals using the GMPE of Boore et al. (2014) [5], in natural log units. Thick black line represents the median residual, box the upper and lower quartiles and whiskers the range (excluding outlier given by circles). Observed data is compared to the GMPE for a site with the given database parameters after removal of event residuals. The comparison is for well-characterised sites (Q1 or Q2 for both Vs30 and Z1.0 parameters) and poorly characterised sites (all other sites).

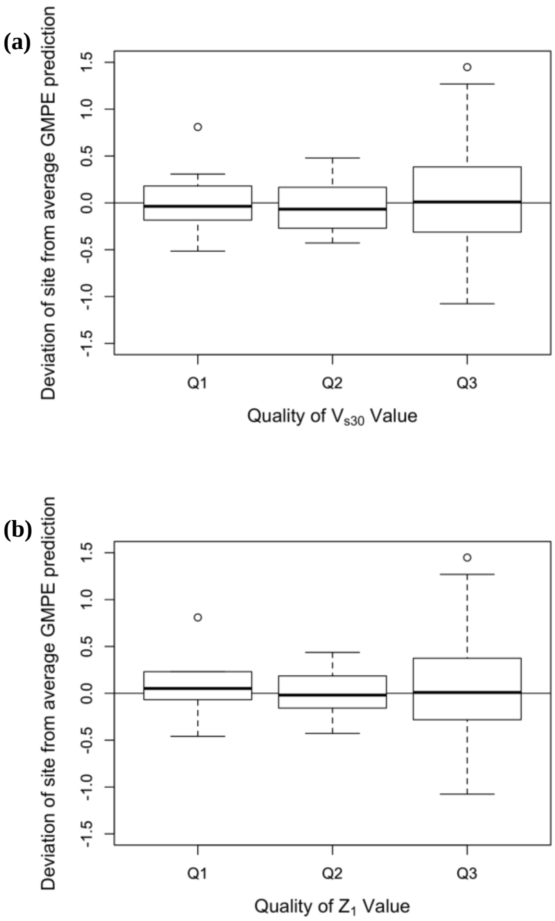

Figure 8: As for Figure 8, but PGA station residuals are broken down by quality factor for (a) Vs30 and (b) Z1.0.

recordings at a given station (i.e. no pooling of data from multiple stations), and to use the notation of Al Atik et al. [49], corresponds to the site-to-site residual δS2S. Note, that we have used only sites with at least three recordings from events of magnitude Mw > 5.

Figure 7 shows that the range and inter-quartile range of PGA station residuals is less for well-characterised sites than for poorly characterised sites. In fact, the inter-quartile range is reduced by ~50% when only well-characterised sites are considered (based on natural log units). Or alternatively, the standard deviation is reduced by ~30% for well-characterised sites compared to poorly characterised sites. In general, better constrained site parameters reduce the scatter in residuals, however, some sites will still behave uniquely due to other factors not taken into account in the GMPE. For example, the outlier in the well-characterised site category is station HVSC (Figure 1), which is likely affected by 2D/3D amplification effects within the narrow loess-filled valley [44]; this site may therefore behave differently than a typical Site Class C site.

We also note, that the median PGA residual for well-characterised sites indicates that the NGA-West2 Boore et al. GMPE [5] overpredicts the New Zealand observations in this category. Further investigation is needed to determine whether the features discussed above hold in a robust manner for New Zealand site conditions in general, or are a feature of the sites currently represented in the database (e.g. currently well-characterised sites are predominantly located in Christchurch and Wellington).

When comparing PGA residuals for each site parameter and quality factor individually (Figure 8), a significant reduction in residuals is seen for Q3 sites compared to Q2, whereas Q2 and Q1 sites show a similar residual distribution.

The station residuals have also been analysed for GMPE predictions at 1 s period (Figure 9). At this period, there is also a significant reduction in the range of residuals, but no significant reduction in the inter-quartile range for well-characterised sites. The standard deviation is reduced by ~15%.

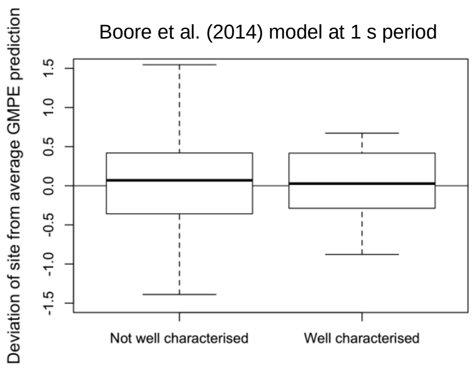

Figure 9: Distribution of 1 s period site-to-site residuals when observations are compared to the Boore et al. (2014) [5] GMPE predictions (in natural log units). See description of Figure 7.

In general, our preliminary analysis suggests that the use of high-quality continuous site parameters (at least Q2 standard) in New Zealand GMPE development may significantly reduce epistemic uncertainty associated with GMPEs, particularly at short periods, and therefore enable more accurate ground motion predictions. Given that the majority of current quality assessments are Q3 (Figure 5), future updates to the database incorporating new well-constrained site-specific surveys are expected to add further value for ground motion prediction.

CONCLUSIONS

We have compiled four key site parameters (Site Class, Tsite, Vs30 and Z1.0) for the 497 GeoNet stations in the New Zealand strong motion database [9] that recorded significant historical ground motions. In addition, we have assigned a quality estimate (Quality 1 – 3) to the latter three continuous parameters to provide a qualitative estimate of the uncertainty. Well-constrained Tsite estimates have largely been obtained from newly available HVSR measurements and SSR amplification curves from inversion of regional strong motion data, and have been reconciled with available geological information. Good quality Vs30 and Z1.0 estimates, typically in urban centres, have also been incorporated following recent studies using both active and passive seismic methods. Where site-specific measurements of Vs30 are not available, Vs30 is estimated based on surface geology following the national Vs30 maps of Perrin et al. [43].

These data are intended to guide efforts to develop and test new and existing ground motion prediction models in New Zealand, in particular allowing statistical re-examination of the most important site parameters that control site response in a New Zealand setting. Preliminary analysis using the New Zealand strong motion database suggests that improved site characterisation (at least quality 2) can reduce uncertainty in ground motion prediction, particularly at short periods. Furthermore, the site metadata provide useful information on suitable rock reference stations for seismological studies, and demonstrate the prevalence of amplification effects at stations classified as rock. Although the site metadatabase is not intended to replace site-specific assessment for structural design purposes, it can be used as a guide to site-specific studies in the literature.

The database and any updates are available upon request to the corresponding author, and through the following link on the GeoNet website at the time of publication of this article: http://info.geonet.org.nz/x/TQAdAQ. Users are encouraged to check for updates to the database, which will be carried out as new survey results become available in the future.

ACKNOWLEDGEMENTS

This work has been funded under GNS Core Funding, the Natural Hazards Research Platform project 2012-GNS-08 “Rethinking PSHA” and the EQC/NZSEE Ivan Skinner Award. We sincerely thank those who have contributed local data to this project, including: Brendon Bradley and Robin Lee of University of Canterbury for contributing Z1.0 values in Canterbury from their 3D regional model; Zane Bruce and Sandra Bourguignon for providing results of microtremor site investigations conducted at GNS Science; Jim Cousins for sharing his earlier site data compilation work and database. We also thank Sally Dellow of GNS Science and Erin Lindsay who contributed to the data handling. We are grateful for the project support of Matt Gerstenberger and Stephen Bannister of GNS Science and their internal reviews of this manuscript.

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