Characterizing GeoNet strong motion sites: Site metadata update for the 2015 Strong Motion Database

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ABSTRACT: The 2015 New Zealand strong-motion database provides a wealth of new strong motion data for engineering applications. An important component of this database is the compilation of new site metadata, describing the soil conditions and site response at GeoNet strong motion stations.

We have assessed and compiled four key site parameters for the ~460 GeoNet stations that recorded significant historical ground motions. Parameters include: site classification (NZS1170.5), Vs30, fundamental site period (Tsite) and depth to bedrock (Z1.0, i.e. depth to material with Vs > 1000 m/s). In addition, we have assigned a quality estimate (Quality 1 – 3) to these parameters to provide a qualitative estimate of the uncertainty. New high-quality Tsite estimates have largely been obtained from newly available HVSR amplification curves and spectral ratios from inversion of regional strong motion data that has been reconciled with available geological information. Good quality Vs30 estimates, typically in urban centres, have also been incorporated following recent studies. Where site-specific measurements of Vs30 are not available, Vs30 is estimated based on surface geology following national Vs30 maps. New Z1.0 values have been provided from 3D subsurface models for Canterbury and Wellington.

This database will be used in efforts to guide development and testing of new and existing ground motion prediction models in New Zealand. In particular, it will allow re-examination of the most important site parameters that control and predict site response in a New Zealand setting. Furthermore, it can be used to provide information about suitable rock reference sites for seismological research, and as a guide to site-specific references in the literature. We discuss compilation of the database, preliminary insights so far, and future directions.

1 INTRODUCTION

Local site conditions strongly influence earthquake ground motion and need to be accounted for in earthquake-resistant design. Currently in New Zealand, site effects are conventionally incorporated in design standards (e.g. NZS1170.5:2004) through spectral shape factors that reflect, in a general way, normalised hazard spectra for a given site classification calculated using the McVerry et al. (2006) ground motion prediction equation (GMPE). This equation characterises site effects by relating the amplification observed at New Zealand strong motion stations with the NZS1170.5 site classifications (McVerry 2003). However, the definition of site class at a given location is often estimated from sparse site information. In addition, there are alternative GMPEs now being used in New Zealand (e.g. Bradley, 2013) which use Vs30 and Z1.0 to predict site effects, although these parameters are mostly unknown at strong motion stations. Moreover, with the recent expansion of the GeoNet strong motion

network, accurate site parameters for new stations are only available at limited numbers of sites, and where they are available, they tend to be scattered across multiple references in the literature. Knowledge of these parameters is critical to test and develop GMPE in New Zealand. Here, we describe the compilation of a new site database for GeoNet strong-motion stations, including four key parameters for ground motion prediction as well as estimates of 'quality' or uncertainty.

In recent years, a wealth of new strong motion data has become available for engineering applications. The 2015 New Zealand strong motion database (Van Houtte et al. 2016) provides a significantly expanded strong motion dataset with updated processing strategies. The site database is an important component of this wider project and describes the soil conditions and site response at the ~460 GeoNet strong motion stations that have recorded significant historical ground motions. The four key parameters compiled for the 2015 database include i) NZS1170.5 Site Classification, ii) site period, Tsite, iii) time-averaged shear-wave velocity to 30m depth, Vs30 and iv) the depth to a shear-wave velocity of 1 km/s, Z1.0 (see Table 1). The site database draws on the previous work of Cousins et al. (1996), with the inclusion of many recent site-specific investigations (e.g. in Canterbury following the Canterbury earthquake sequence and in Wellington as part of the *It's Our Fault* project). An important new feature of the database is the inclusion of qualitative estimates of uncertainty for the three numerical parameters.

The database is 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. It can also be used to provide links to existing site data, as well as target new investigations where they are most needed. We are currently working on making the database publically available through the GeoNet website, and our intention is to provide ongoing maintenance and expansion to cover the entire GeoNet strong-motion network.

Table 1. Key site parameters

Site Classification	NZS1170.5 Site Class (as defined in Standards New Zealand, 2004 and discussed in Section 2.2 of Wotherspoon et al. 2015c)
Tsite (s)	Fundamental Site Period*
Z1.0 (m)	Depth to shear-wave velocity (Vs) of 1000 m/s
Vs30 (m/s)	Average shear-wave velocity (Vs) in the uppermost 30 m, as defined by: $$Vs30 = \frac{30}{\Sigma_i \frac{d_i}{Vs_i}}$$ Where d_i and Vs_i are the thickness of the ith 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.

2 SITE PARAMETERS

Site parameters compiled for the 2015 database (Table 1) include those utilised in existing New Zealand GMPEs as well as most overseas models (see summary in Stewart et al., 2013). In New Zealand, the McVerry et al. (2006) GMPE uses discrete site classification, whereas the Bradley (2013) GMPE uses a combination of Vs30 and Z1.0, following closely the Chiou and Youngs GMPE (2008) developed for the Next Generation of Attenuation (NGA) project in the United States (Power et al., 2008). The addition of the Tsite parameter is intended to allow testing of an additional continuous parameter that has been proposed as a viable alternative to the more commonly used Vs30, as well as being the parameter that defines the boundary between two of the NZS1170.5 site classes. For example, McVerry (2011) proposed a new method using Tsite to replace spectral shape factors of the

New Zealand design standard NZS1170.5, allowing for a gradual transition between Site Class C (shallow soil) and Site Class D (deep or soft soil) spectral shapes. Based on a small local dataset, they concluded that Tsite provided a more suitable parameter than Vs30, given that Vs30 may not adequately account for long-period amplification at sites with high Vs30, but thick sequences of stiff gravels down to considerable depth. The use of both Vs30 and Z1.0 within the Bradley (2013) GMPE may allow greater flexibility in handling these sites. However, in development of Bradley (2013) and its application in New Zealand, Vs30 is often simply estimated based on Site Class, with Z1.0 then inferred from the assigned Vs30 value. Hence, further benchmarking and validation of GMPE methods based on more complete knowledge of site parameters is valuable. In future, other site parameters may be considered for inclusion in the database, but are not the focus of the present effort.

Significant datasets used in this data compilation effort included i) the previous site data compilation work of Cousins et al. (1996) and references therein, ii) recent efforts to define Tsite through spectral ratio methods (e.g. Kaiser et al. 2013a,b; Wotherspoon et al. 2015a; Van Houtte et al. 2012, unpublished data), iii) Christchurch borehole, CPT and active and passive surface wave investigations following the Canterbury earthquakes (Wotherspoon et al. 2015b,c), including compilation of a new 3D velocity model (Lee et al. 2015), iv) *It's Our Fault* project 3D geological models from the Wellington and Hutt Valley region (e.g. Semmens et al. 2010) including Vs measurements (Fry et al. 2010; Kaiser & Louie unpublished data, Perrin et al. 2010) and v) estimated soil profiles at selected national sites compiled for the McVerry (2011) model under the *It's Our Fault* Project, vi) national maps of Vs30 and site class developed by Perrin et al. (2015), based on surface geology.

An important new component of this database is the provision of quality (Q) 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 Q is estimated qualitatively based on the type and result of investigations at the site (see Table 2). Table 2 also illustrates the typical quality assessment for different types of site investigation methods underlying our work.

In practice, the Z1.0 parameter, is often assumed to be equal to depth to rock without direct measurement of Vs, but where rock Vs is assumed to reach 1000 m/s. 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) ≈ 1800 m/s; Unweathered, very strong greywacke, basalt ≈ 1500 m/s; Moderately strong greywacke ≈ 1300 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.

Note, that the site parameters given in the database are intended for use in broad statistical studies. While they provide a guide to local site conditions, the database is not intended as a replacement for site-specific assessment for engineering design. The determination of site parameters for engineering design and hazard assessment requires detailed site-specific assessment; the references listed in the database and contained in the earlier work of Cousins et al. (1996) may serve as a starting point for available information.

3 EXAMPLE SITES

In Figure 1 we present examples of Q1, Q2 and Q3 sites according to Tables 1 and 2.

3.1 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.

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, hard 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 non-invasive surface-wave methods or borehole Seismic Cone Penetrometer Testing (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

* Please refer to guide for the Z1.0 parameter depth-to-rock and velocity assumptions in above text.

** Spectral ratio methods include horizontal-to-vertical (HVSR) or standard site-to-reference (SSR) with a suitable reference station demonstrated to have flat response.

*** 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.

Table 3 Examples of 2015 database entries from three GeoNet strong motion sites

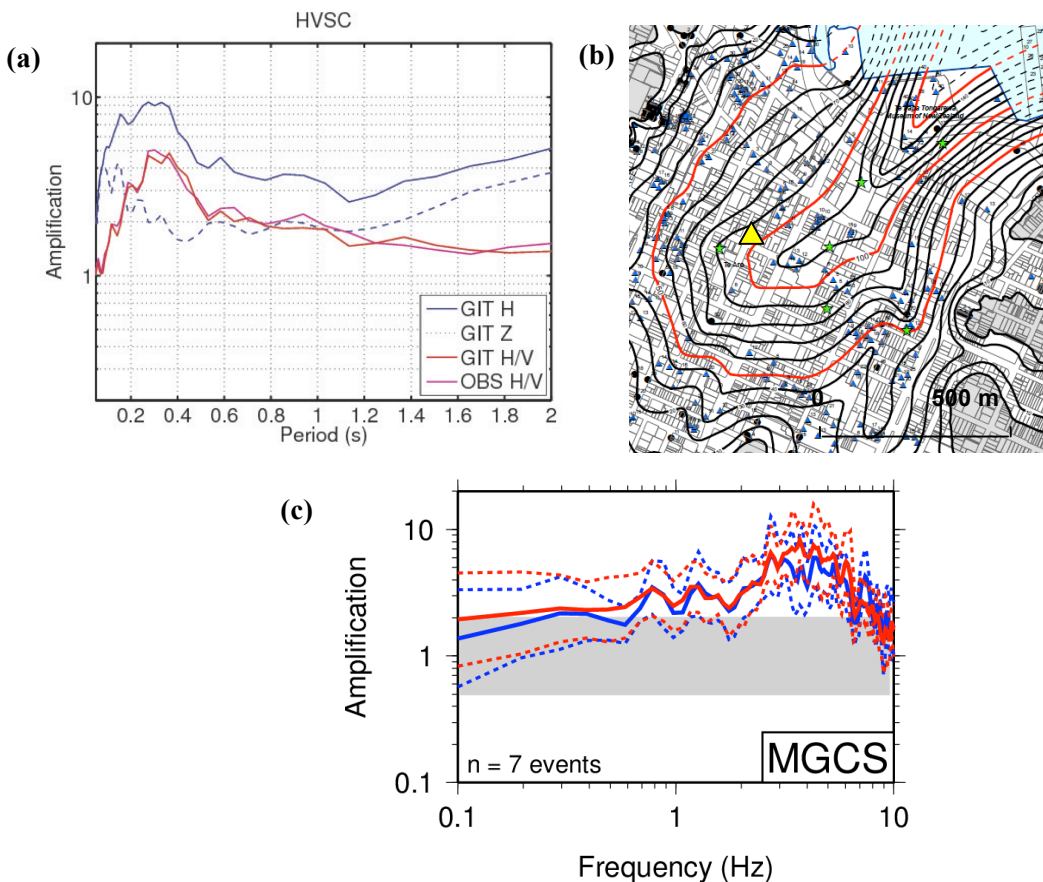| GeoNet Station	Site Class	Vs30	Tsite	Zb	Q Vs30	Q Tsite	Q Zb	References
HVSC	C	348	0.27	19	Q1	Q1	Q1	Wotherspoon et al. 2015c; Kaiser et al. 2013a; Jeong et al. 2015; Van Houtte et al. 2012
919A	D	307	0.85	96	Q2	Q2	Q2	McVerry 2011; Semmens et al. 2010
MGCS	D	210	1	70	Q3	Q3	Q3	Unpublished HVSR (A. Kaiser & C. Van Houtte); Perrin et al. 2015

Figure 1. Examples of different types of data used to compile the 2015 site database. (a) SSR spectral ratios for the horizontal and vertical components (GIT H and GIT Z respectively) at station HVSC based on aftershock data from Kaiser et al. (2013a). Observed and modelled HVSR ratios are shown as pink and red lines respectively. (b) Extract from the bedrock depth map for Wellington city published by Semmens et al. (2010). 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. (c) HVSR amplification curves for two horizontal components at station MGCS (Van Houtte, unpublished data) show multiple low amplitude amplification peaks.

Figure 1a illustrates the spectral ratio results (HVSR and SSR) based on earthquake data of Kaiser et al. (2013a) which illustrate a clearly defined site period of 0.27 s. This is in agreement with the HVSR result from Van Houtte et al. (2012), and the investigations of Wotherspoon et al. (2015c) who conducted both HVSR from ambient noise and MASW Vs profiling constrained by available CPT borehole data down to rock. Furthermore, 2D modelling of site response has been conducted by Jeong

et al. (2015). All studies and methods are in good agreement, providing well-constrained values for each of the site parameters.

3.2 Q2 Site: 919A

Station 919A was located at Te Aro Post Office in central Wellington until 1974 and is an example of a Q2 site. We used the 3D geological model of Wellington compiled under the *It's Our Fault* Project presented in Semmens et al. (2010) to infer site parameters at this station. The model uses a large database of point constraints (boreholes and passive seismic investigations) to interpolate 3D lithology over the central Wellington region (Figure 1b). 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 (e.g. Fry et al. 2010; Perrin et al. 2010), as well as iii) standard correlations with material type of Borcherdt et al. (1994). Based on the 3D model, a 1D soil profile has been prepared for the 919A site and used in the McVerry (2011) 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. (2010) model currently considered at GNS Science. The Q2 assessment 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.

3.3 Q3 Site: MGCS

GeoNet station MGCS (Blenheim Marlborough Girls College) is currently assigned Q3 for each parameter. HVSR investigations (Figure 1c; Van Houtte, unpublished data) show multiple amplification peaks of low amplitude from a small number (7) of earthquake recordings. Tsite is estimated to be approximately 1 s based on the lowest frequency (longest period) peak, which is reasonably consistent with the Z1.0 value of ~70 m estimated in Cousins et al. (1996) based on geological maps. Vs30 is estimated from coarse-scale national Vs30 maps of Perrin et al. (2015) using surface geology and is poorly constrained.

4 DATABASE SUMMARY

Figure 2a shows the distribution of Site Class of the ~460 sites in the 2015 strong motion database. The majority of GeoNet stations are located on deep or soft soil (Class D), with smaller numbers on shallow soil (Class C) or soft rock (B). Very few stations in 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 (Wotherspoon et al. 2015c).

Figure 2b 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, 150+ sites now have Tsite values of Q1 or Q2 following recent spectral ratio analyses of strong motion data (e.g. Kaiser et al. 2013a, 2013b; Van Houtte, unpublished data; Wotherspoon et al. 2015c) and this number is expected to increase when results from further studies in progress become available. 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). It is also 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 broader amplification peaks are more likely to be classified as Q3. This may have implications when quality factors are used in statistical testing of GMPEs.

One interesting feature highlighted by the database is the prevalence of site amplification at stations classed as soft rock (Site Class B). Of the Site Class B sites assessed with spectral ratios methods, almost 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

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importance of amplification effects in hillside areas traditionally assumed to have 'flat' site response The database can be used to identify suitable reference stations with 'flat' site response for seismological studies (currently 20 suitable reference stations have been identified with Q1 or Q2).
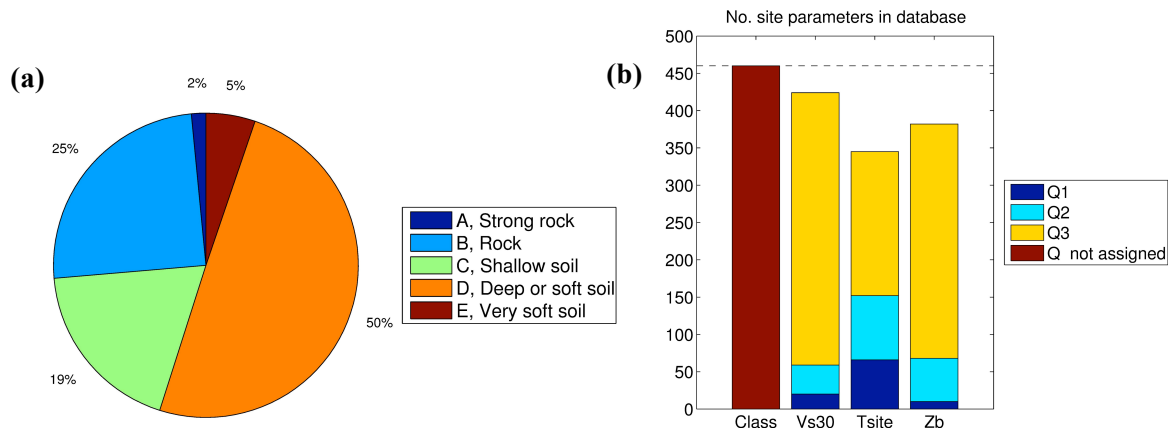

Figure 2. Summary of site database values. (a) Site Classification as a percentage of total stations. (b) Site parameter quality factors for the ~460 GeoNet strong motion stations in the database.

5 CONCLUSIONS AND FUTURE DIRECTIONS

We have compiled four key site parameters (Site Class, Tsite, Vs30 and Z1.0) for the ~460 GeoNet stations that recorded significant historical ground motions. In addition, we have assigned a quality estimate (Quality $1 - 3$) to these parameters to provide a qualitative estimate of the uncertainty. The best-quality Tsite estimates have largely been obtained from newly available HVSR amplification curves or spectral ratios from inversion of regional strong motion data, which 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. (2015).

This data is intended to guide efforts to develop and test new and existing 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. Furthermore, it provides useful information on suitable rock reference stations for seismological studies. However, it is not intended to replace site-specific assessment for structural design purposes. We are currently working on making the database publically available through the GeoNet website. It is intended to be incorporated within a wider project to update and maintain the existing GeoNet DELTA system. We also encourage researchers to submit the results of their site-specific investigations to future versions of the database.

6 ACKNOWLEDGEMENTS

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