Site class determinations (NZS 1170.5) in Wellington using borehole data and microtremor techniques

2010 NZSEE
Conference

N.D. Perrin & W.R. Stephenson
GNS Science Ltd, Avalon, Lower Hutt.

S. Semmens
Canterbury University.

ABSTRACT: Wellington has a high seismic hazard due to its close proximity to several major fault systems, with the Wellington Fault crossing the north-western central city, and deep sedimentary basins in which amplification of incident bedrock shaking can be expected during earthquakes. Under the "It's Our Fault" project, a 3D geological model of Wellington's central business district has been constructed and used to define areas of different seismic subsoil class as defined in NZS 1170.5, and depth to rock, at a scale useful for site-specific analysis (e.g. 1:5,000). This model to based on a compilation of 1025 borelogs and surface geology. Shear wave velocity (Vs) estimates have been made for the geological materials present in central Wellington, including greywacke bedrock, based on ~20 direct measurements of shear wave velocities by means of seismic CPT, vertical seismic profiling and seismic refraction. These Vs determinations have been correlated/substantiated with results from three microtremor techniques: SPAC (SPatial AutoCorrelation), ReMi (Refraction Microtremor), and HVSR (Horizontal to Vertical Spectral Ratio, commonly referred to as the "Nakamura Method"). Generally the near-surface deposits (typically loose to dense silt, sand and gravel) have Vs in the order of 150 m/sec, but the deeper sediments (silt/sand/gravel mixtures) range from about 300 to 700 m/sec. Weathered bedrock has velocities around 600 m/sec, but 1000 to 1100 m/sec is more typical for unweathered rock.

1 INTRODUCTION

The five site classes as defined in New Zealand Standard 1170.5 are based partly on the low amplitude natural site period, which is taken as approximately equal to 4 times the shear wave travel time from surface to rock, and partly on the average shear wave velocity over the top 30 m (Vs30). Therefore, where direct measurements are not available at a specific site, establishment of the shear wave velocity (Vs) profile at the site may be achieved by correlating shear wave velocities and layer physical properties, particularly density or stiffness.

The site classes are *A, strong rock* (not present in Wellington); *B, rock*; *C, shallow soil sites*; *D, deep or soft soil sites*; and *E, very soft soil sites*. The Standard (Standards New Zealand 2004) prescribes structural design actions on the basis of site class to accommodate likely increased earthquake loadings due to amplification of shaking.

An NZS 1170.5 site class map for central Wellington has been derived (Semmens 2010), based on a new compilation of geological and geotechnical information combined with geophysical methods to establish shear wave velocity profiles and site period. The methodology for the compilation of this map (Figure 1) is presented below.

The geological and geotechnical model on which the map is based was derived from a compilation of 1025 borehole logs and other data, including existing geological maps, geotechnical properties and geophysical measurements. The model is a refinement of previous models (presented in Grant-Taylor et al 1974, Perrin & Campbell 1992, Kingsbury & Hastie 1992), incorporating some recent drilling information and geophysical test results combined with new three-dimensional modelling.

Paper Number 22

2 CHARACTERISATION OF GEOLOGICAL MATERIALS

For this modelling a representative stratigraphic column of five geological units (including bedrock) has been established for the central Wellington city area on the basis of material type, geotechnical properties and geological age (from Begg & Mazengarb 1996).

The ranges of geotechnical properties for each of these units is derived from 1025 bore log descriptions, the more recent ones utilise the guidelines for the field description of soil and rock for engineering purposes (NZ Geotechnical Society Inc. 2005). In older logs with less-rigorous descriptions, a high degree of local knowledge aids interpretation, but the Standard Penetration Test (SPT) has been used almost universally, and provides a reliable method of making correlations between boreholes, inferring geotechnical properties, and extrapolating shear wave velocity measurements.

The units and their properties established in this study comprise:

> **Unit I -** Artificial fill, landfill, reclamation. These fill materials are generally weathered rock and soil, but in a few areas there is hydraulic fill. Thickness up to 20 m. Depending on their nature, they range from very loose to medium dense (non-cohesive) and very soft to firm (cohesive). SPT N values are typically 0 to 20, rarely up to 40 in coarse gravelly material.
>
> **Unit II** – Holocene age unconsolidated, loose to medium dense granular sediments including marginal marine (e.g. beach) deposits. Thickness up to 10 m. SPT N values of 10 to 30 are typical.
>
> **Unit III** – Holocene and upper Pleistocene age soft to firm clays, silts, topsoil etc. Thickness usually <10 m. SPT N values range from 0 to 15 (see note below).
>
> **Unit IV** – Pleistocene age (here 12,000 to 400,000 years old – Begg & Mazengarb 1996), mainly dense to very dense sand/gravel alluvial and colluvial deposits, commonly weathered in-situ to form complex mixtures and discontinuous lenses of silt/sand/gravel with minor clay, and thin (<1 m), stiff paleosol layers. There are up to four paleosol layers separated by beds of relatively uniform silt/sand/angular gravel mixtures in the order of 10 to 25 m thick. Rounded gravels are very rare. Thickness of this unit is up to 200 m. The top 10 to 20 m of this unit (corresponding to a Last Glacial age) contains marginal marine sediments and organic layers that are generally not present in deeper layers, and is not as stiff or dense as the deeper part of this unit. A scatter of SPT N values between 30 to >50 are diagnostic of the top of this unit, and N >50 is typical for the deeper parts, with the exception of a few N values of 10 to 20 where paleosol layers are encountered.
>
> **Unit V** – greywacke bedrock of Paleozoic to Mesozoic age, commonly deeply chemically weathered (up to 30 m below the surface). At the most extreme degree of weathering the rock is reduced to a stiff to hard sandy silt/clay with a visible relict rock texture (e.g. stained joint surfaces). SPT N values of <50 are rare even in the most intensely weathered bedrock.

Note - SPT is such a widely-used and well-understood method that even more sophisticated tests such as cone penetration testing (CPT) results are often converted to equivalent SPT values, and NZS 1170.5 prescribes SPT N values (blows per 300 mm) for a guide to the shear wave characterisation of non-cohesive materials.

Although the SPT was developed specifically for non-cohesive materials to provide density information, it is used indiscriminately, often in cohesive materials. Although such usage is outside the standards for the SPT, it can provide an indication of stiffness of cohesive materials. While an SPT N >40 implies dense sand or sandy gravel, N ~ 20 is indicative of stiff to hard cohesive materials.

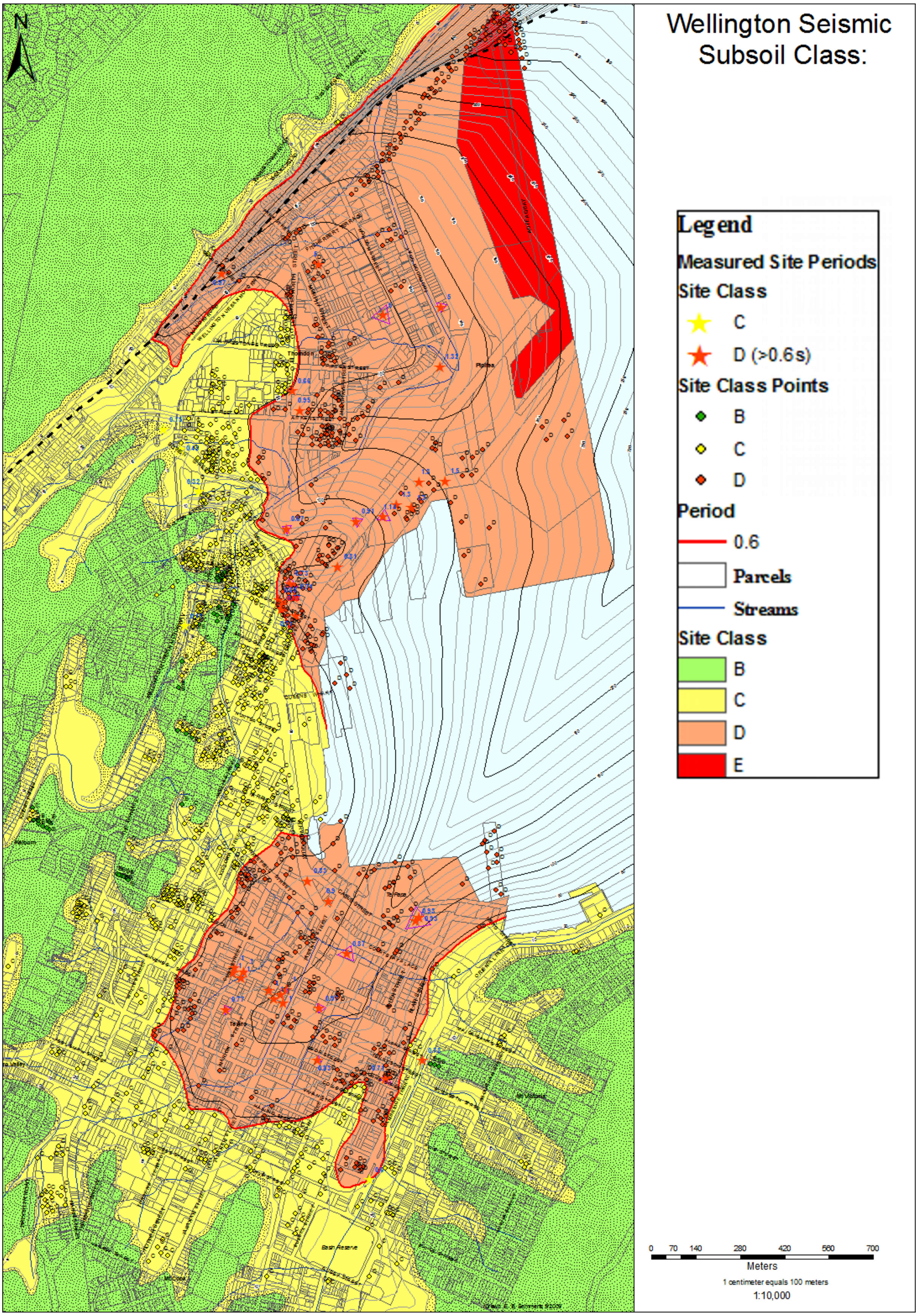

Figure 1. Central Wellington site class map (from Semmens 2010). Contours interval on depth to bedrock is 10 m, and bold every 50 m. SPAC sites are shown as stars within triangles. ReMi and other determinations shown as stars.

3 SHEAR WAVE VELOCITY PARAMETERISATION OF GEOLOGICAL UNITS

3.1 Estimates based on material properties

Shear wave velocities are dependant on the stiffness and density of a soil. The loosest and softest soils may have shear wave velocities as low as 50 m/s while very dense/hard soil velocities may be up to 1000 m/s.

In the absence of direct measurements of shear wave velocities at a site, the methods in Borcherdt 1994 and NZS 1170.5 may be used to estimate shear wave velocities, guided by the ranges of measured shear wave velocities established for the same geological units.

3.2 Direct measurements of shear wave velocities

Seismic Cone Penetrometer testing provides the best measurement of Vs profiles, but its use is limited on the basis of cost and limited ability to penetrate gravelly materials. Fewer than 10 SCPT results were available for this study, mainly from unpublished commercial jobs.

Downhole Vs measurements can be made using a shear wave-generating source at the top of a borehole and first arrivals measured by geophones at various depths in the borehole. This is also expensive and difficult, and few boreholes have been drilled deep enough to characterise the full Vs profile at sites where bedrock is over 100 m below the surface. Only about 5 downhole Vs results were available for this study, also mainly from unpublished commercial jobs.

Seismic refraction measurements in bedrock in The Terrace Tunnel by Ingham (1971) provided Vs data for the complete range of degrees of weathering by correlation with greywacke bedrock material descriptions by Perrin (1971).

3.3 Microtremor methods to measure Vs and site period

3.3.1 Horizontal to vertical spectral ratio (HVSR)

Also known as the Nakamura method, this microtremor technique can be used to give a direct measurement of site period, provided there is a strong Vs contrast between the surface layer and substrate. It does not provide a shear wave velocity profile, and the necessary Vs contrast may not be present, or may be confusing because the subsurface interfaces may be irregular and sloping. The method is non-invasive and can yield a reliable result in suitable conditions. About 20 HVSR results have been used in this study, 12 in conjunction with SPAC (see section 3.3.2 below).

3.3.2 SPatial AutoCorrelation (SPAC)

Naturally-occurring ground vibrations are simultaneously recorded on an array of seismometers, arranged in an equilateral triangle, and converted to azimuthally-averaged coherency as a function of station separation and vibration frequency. This can yield a shear wave velocity profile where conditions are suitable - e.g. horizontally stratified site with low shear wave velocity and high Poisson's ratio materials in the surface layer and a large velocity contrast at the soil/rock interface (Fry et al 2010, Beetham et al 2010). Such conditions have been found to be present in the Te Aro and part of the Thorndon area.

As part of the microtremor recording process, the horizontal to vertical spectral (HVSR) ratio can be determined from the records from single geophones. Provided there is a very high shear wave velocity contrast between the surface layer and the substrate, there will be a peak at what is known as the site period. Coupled with SPAC, HVSR allows both the shear wave velocity profile and the natural site period to be calculated, because the natural period of a site is approximately four times the shear wave travel time from surface to rock.

The SPAC and HVSR determinations used in this study comprise several commercial jobs and 12 research arrays undertaken for the "It's Our Fault" project (Fry et al 2010).

3.3.3 *Refraction Microtremor (ReMi)*

This method uses a linear array of vertical geophones spaced at intervals of a few metres, to synchronously record microtremors and thus to obtain Rayleigh wave dispersion curves, which can be inverted to become a shear wave velocity profile (Louie 2001). The ReMi data used in this study come from unpublished work by Louie in 2003 and 2006, held by GNS Science Ltd. Unlike SPAC, which requires deployment of 3 geophones and recorders at the apices of an equilateral triangle, ReMi uses 15 to 20 geophones and recorders in a linear array.

3.4 **Shear wave velocities ranges assigned to geological units**

Table 1 shows the range of shear wave velocities for the individual units defined above. These have been based on calibration of empirical methods such as Borcherdt 1994 against Vs measurements by the other methods outlined above, and where more than one method has been used at a site, consistency of results has been assessed. For example, Figure 2 shows a Vs layer model for the Te Papa site as determined by both SPAC (with HVSR) and ReMi.

There are ranges of values of Vs shown for each unit because of lateral and vertical variations in geological material types and physical properties. Selection of a Vs value for analysis at a specific site requires judgement based on extrapolation from nearby sites. An alternative is to construct both a worst-case (based on the lower Vs value) and a best-case (based on the higher value). If even the worst-case indicates, for example, class C, then we can be confident that it is class C. Conversely, if the best-case indicates class D, then we can be reasonably sure class D is appropriate. In the event that a ground class cannot be assigned with confidence because subsoil conditions may be close to the boundaries of an NZS 1170.5 class, more detailed examination of borehole information should be undertaken. Guidance from any nearby SPAC, ReMI or HVSR sites should aid the selection of appropriate values. If a ground class still cannot be applied with confidence, direct site-specific Vs determinations would be required.

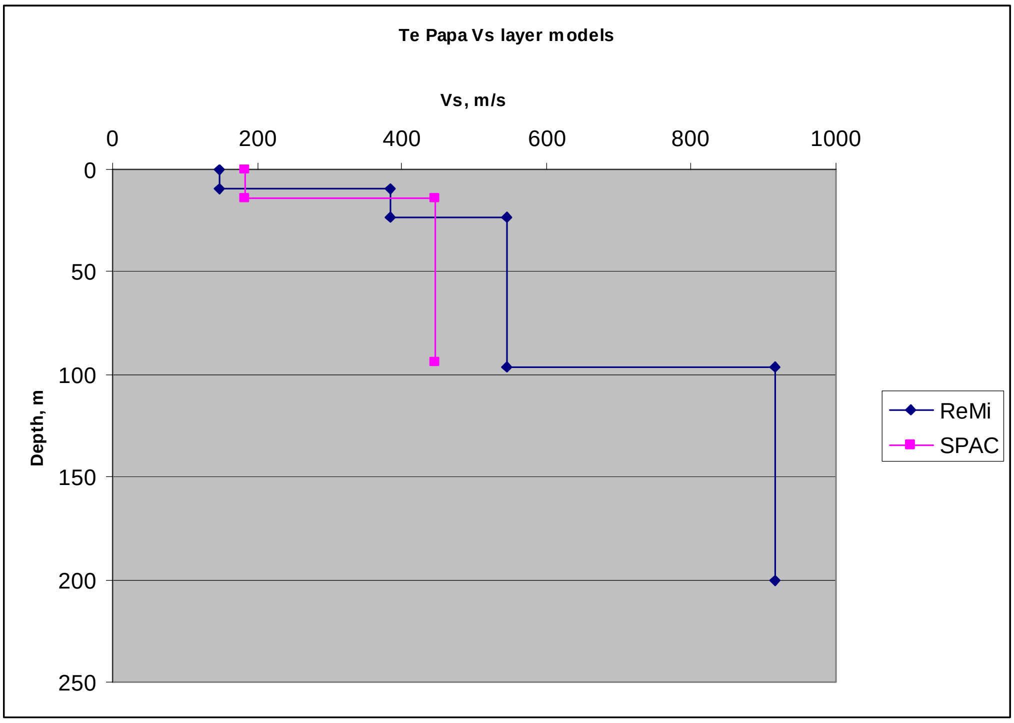

Figure 2. Shear wave velocity profiles for the Te Papa site derived from SPAC and ReMi. Both results suggest bedrock is at 94.2 to 96.2 m depth. A deep drillhole at the site proves bedrock is at about 137 m depth, but that the material 45 m above that depth is almost indistinguishable from the underlying bedrock and should be taken as “effective bedrock”. Note that SPAC produces only shear wave velocities down to “rock”, the depth of which is derived from the HVSR natural period.

The relationship of SPT N values to Vs has been investigated (e.g. by Imai & Tonouchi 1982). Application of their formula may yield useful results provided only N values from non-cohesive materials are used, because those from cohesive materials will indicate Vs values much lower than the real values. Figure 3 plots SPT N values against measured shear wave velocities from three holes in Wellington in which Vs was measured directly. The large scatter of results is inferred to come from anomalously high N values on large gravel clasts in otherwise loose material, broad averaging of Vs in downhole measurements, and the fact that many of the tests are in silt and clay materials. However, it is expected that useful results could be obtained with further analysis and the taking into account of these factors, given the almost universal use of the SPT in site investigations.

Table 1. Stratigraphic units and range of Vs.

Unit	**Description**	**Vs (min)** (m/sec)	**Vs (max)**	**Typical location**
I	Hydraulic Fill	50	150	Aotea Quay
	Rock Fill	125	250	Railway yards/ Te Papa
	Other Fill	200	300	Subdivisions
II	Holocene lake silt, swamp, peat	50	200	Thorndon (rare)
	Holocene sand/gravel, loose	150	300	small stream channels
	Holocene sand/gravel, med dense	250	350	
	Holocene sand/gravel, dense	350	450	
	Holocene sand/gravel, very dense	400	500	
	Historical beach sand/gravel	150	250	Under reclamation, thin
III	Holocene silt/clay, soft-firm	100	200	
	Holocene silt/clay, firm-stiff	200	350	
	Older Silt/clay, v stiff	400	700	Paleosols (v thin) - in unit D
IV	Pleistocene gravel/sand/silt, dense	250	400	Thorndon/Te Aro
	Pleistocene, deeper, v dense	400	700	
	Pleistocene, deepest, v dense	700	1000	(effective bedrock – e.g. Te Papa)
V	Bedrock CW	200	700	Terrace Tunnel
	Bedrock, crushed (fault breccia)	500	900	
	Bedrock HW	600	1000	
	Bedrock MW	700	1100	
	Bedrock SW	900	1300	
	Bedrock UW	1200	1750	
	Bedrock, deep, UW	1500	2000	

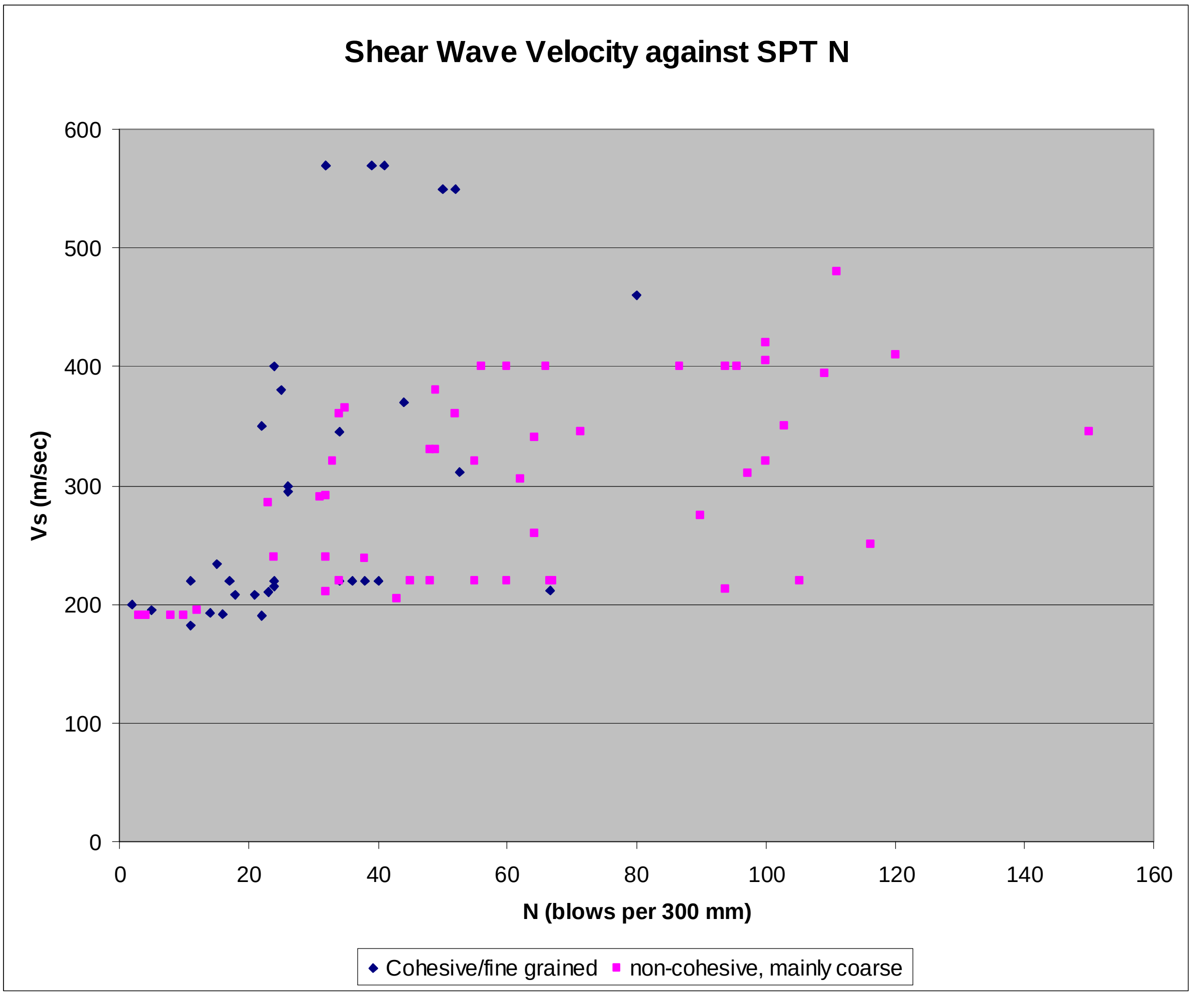

Figure 3. Plot of shear wave velocity measurements against Standard Penetration Test (SPT) N values from three sites in Wellington city. N values >50 have been scaled-up by calculating number of blows that would be required for 300 mm of penetration from the actual penetration after 50 blows (the test usually terminates after 50 or 60 blows if 300 mm penetration is not achieved).

4 METHODOLGY FOR CONSTRUCTING THE SITE CLASS MAP

The three dimensional geological model and the compiled geological unit Vs ranges have been used to generate the NZS 1170.5 site class map (Figure 1) by taking point-data natural period and Vs determinations from all of the geophysical methods above. Extrapolation from the measured sites was achieved by generating 48 cross sections from the three dimensional model and establishing synthetic point Vs profiles at intervals along these cross sections to calculate site periods or Vs30 (average shear wave velocity in top 30 m). The site periods and Vs30, both measured and synthetic were contoured and the boundaries between the various NZS 1170.5 classes were outlined. The most important of which is probably the class C/D boundary at a natural period of 0.6 s.

5 DISCUSSION

While the compilation scale of the map (1:5000) makes it useful for site-specific determinations, it should be taken as a guide rather than a substitute for site-specific investigations. This methodology has application in other areas, provided the nature, distribution and shear wave velocities of the subsurface materials can be characterised.

The reliability of the results of this study are strongly dependant on the quality of the borehole information. There are fewer boreholes, and even fewer that reached bedrock in the northern part of the study area, consequently the class determinations in that area are more speculative. In this area HVSR failed to indicate a natural period, and the depth to rock is not well constrained. It appears there may not be a strong Vs contrast on the soil/rock interface, and some of the deeper Unit IV material may be “effective bedrock” as appears to be the case at Te Papa. Even so, the inferred great depth to bedrock in the northern area would probably preclude class C in this area.

Clearly, more detailed work is needed in the northern part of the study area (i.e. Thorndon), and this site class map should be taken as subject to revision as more detailed data becomes available from future investigations. A large part of Thorndon had previously been considered to be “intermediate” with respect to amplification of earthquake shaking, which would correlate with NZS 1170.5 class C, but it now appears that this classification is no longer supportable, and class D is indicated.

6 ACKNOWLEDGEMENTS

We thank Russ Van Dissen of GNS for reviewing this paper, and acknowledge those from the industry who have shared data and supported the compilation of Wellington data over many years, especially Tonkin & Taylor Ltd and Connell Wagner Ltd.

7 REFERENCES:

Begg, J.G., Mazengarb, C., 1996. Geology of the Wellington area, scale 1:50,000. *Institute of Geological & Nuclear Sciences geological map 22.*

Beetham, R.D., Stephenson, W.R., Perrin, N.D., Barker, P.R., 2010: A non-invasive site investigation method for determining site class from microtremor records. (in prep) *IAEG 2010 Conference proceedings*

Borcherdt, R. D. (1994). Estimates of site-dependent response spectra for design (methodology and justification). *Earthquake Spectra* 10**:** 617-654.

Fry, B., Stephenson, W.R. & Benites, R. 2010. It’s Our Fault – Seismic instrumentation and inversion for velocity structure of the Wellington region. *GNS Science Consultancy Report* 2010/18.

Grant-Taylor, T.L.; Adams, R.D.; Hatherton, T.; Milne, J.D.G.; Northey, R.D.; Stephenson, W.R. 1974: Microzoning for earthquake effects in Wellington, New Zealand. *Department of Scientific and Industrial Research Bulletin 213.*

Imai, T. and Tonouchi, K. 1982: Correlation of N value with S-wave velocity and shear modulus. – *Proceedings of the 2nd European Symposium on Penetration testing, Amsterdam,* 24-27 May 1982, pp 67-72

Ingham, C.E. 1971: Elastic properties of rock, Wellington urban motorway tunnel. *Department of Scientific and Industrial Research, Wellington, Geophysics Division report* 71

Kingsbury, P.A.; Hastie, W.J. 1992: Sheet 1 Wellington (1st Ed.). Wellington Regional Council, Wellington, New Zealand. Ground shaking hazard map (with notes), scale 1:40,000.

Louie, John N., 2001: Faster, better; shear-wave velocity to 100 meters depth from refraction microtremor arrays, *Bulletin of the Seismological Society of America*, 91 (2), p. 347-364.

NZ Geotechnical Society Inc, 2005: Field Description of soils and rock- Guideline for the field classification and description of soil and rock for engineering purposes.

Perrin, N.D. 1971: Geology of test drives for Terrace tunnels. Lower Hutt: New Zealand Geological Survey. *New Zealand Geological Survey report EG 108/A.*

Perrin, N.D.; Campbell, H.J. 1992: Regional natural disaster reduction plan - seismic hazard. Compilation of geological data, Wellington area (Part 3 of 1991/92 study). *DSIR Geology and Geophysics contract report 92/24.* 13 p. figures

Semmens, S., 2010: An engineering geological investigation of the seismic sub-soil classes in the central Wellington area. *Unpublished MSc thesis, University of Canterbury, Christchurch, New Zealand*

Standards New Zealand, 2004: Structural design actions. Part 5: Earthquake actions – New Zealand. *NZS 1170.5*