Subsoil-class determination using surface-wave techniques in the Wellington region.

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ABSTRACT: As part of the It's Our Fault project, twenty five sites were investigated in the Greater Wellington Region using passive microtremor techniques, to assist with regional estimation of earthquake ground shaking subsoil-class determination, and an assessment of liquefaction potential. At each site, Spatial Autocorrelation (SPAC) and Horizontal to Vertical Spectral Ratios (HVSR) were used to estimate the velocities and thicknesses of the shallowest subsurface layers (typically < 100 m), the site period and subsoil classification in terms of New Zealand Standard NZS1170.5, and liquefaction potential. A geological layer model for all sites was constructed from available information and jointly interpreted with the layer models derived from the SPAC and HVSR analysis. The quality and reliability of SPAC and HVSR results depend on a number of factors including the distribution of coherent noise sources and the presence of horizontal soft layers overlying stiff material. A 1D shear-wave model was successfully applied in nearly all cases, but confidence in the derived models was variable depending on the site conditions. We examine how environmental factors including proximity to the coast, urbanisation and soil conditions affected the quality of the SPAC and HVSR results.

1 INTRODUCTION

1.1 Aim

The work outlined in this paper forms a component of the It's Our Fault project (http://www.gns.cri.nz/Home/IOF/Its-Our-Fault). It was undertaken to assist with regional estimation of earthquake ground shaking subsoil-class determination, and assessment of liquefaction potential (Dellow et al, 2014). It builds on earlier work for It's Our Fault, (Fry et al, 2010; Semmens et al, 2010, Perrin et al, 2010, Boon et al, 2011, Semmens et al, 2011) undertaken in the CBD area of Wellington City and the Lower Hutt Valley.

The project also provided the opportunity to test the retrievablity of a 1D structure using our combined HVSR and SPAC (Spatial Autocorrelation) approach (Stephenson et al, 2011) on a range of materials likely to be thick, dense or stiff materials within subsoil-class C and D (Wairarapa & Upper Hutt sites) as well as those sites with thick softer sediments overlying stiffer dense materials (Kapiti Coast and parts of the eastern suburbs of Wellington City).

The SPAC method can provide the shear-wave velocity and thickness of the top layer, and the shear-wave velocity of an underlying (second) layer. It is possible to determine the thickness of the underlying (second) layer but this always has a lesser level of certainty. The depth and accuracy to which the shear-wave velocity profile can be determined are dependent on the spacing that can be obtained for a regular seismograph array, as determined by the availability of open ground space at and near the site, together with the extent to which the site profile conforms to a model of flat layers with clear velocity contrasts. If the soil profile varies appreciably across the site, or there are no clear-cut velocity contrasts, it may not be possible to identify a well-defined site period and velocity profile using the SPAC technique alone.

1.2 Sites

Twenty one sites were selected initially to be representative of the dominant ground materials around the urban areas in the Greater Wellington Region. Sites were selected in Upper Hutt, Kapiti Coast, Wairarapa, Porirua basin, and the eastern suburbs of Wellington City. At the request of Wellington City Council, four additional sites in the Kilbirnie and Miramar suburbs were included. The site locations are shown in Figure 1 and detailed in Table 1.

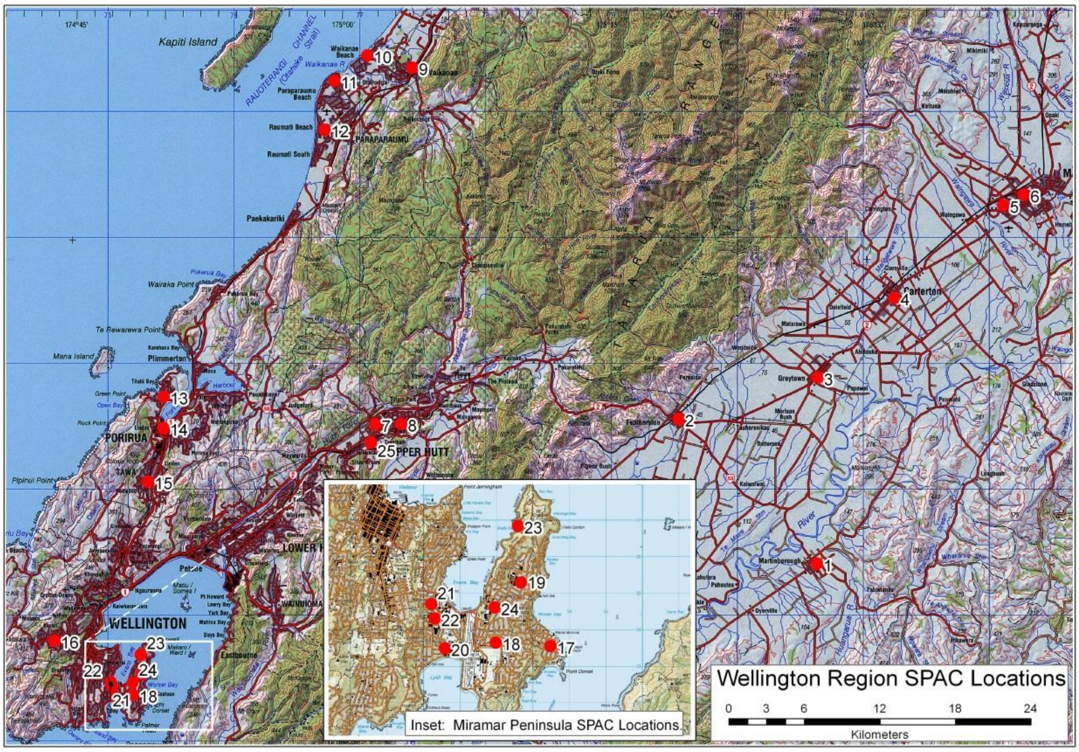

Figure 1 - Map showing locations of Wellington Region SPAC sites. See Table 1 for details regarding site name and geographic co-ordinates. Sites within the Wellington, Lower Hutt and Kapiti coast area were generally most tractable to the SPAC and HVSR techniques, while the deeper sites within the Wairarapa area were less amenable to SPAC analysis.

Table 1. Location details of the Wellington Region SPAC sites shown in Figure 1.

Site	Location	Latitude	Longitude
1	Corner Strasbourge & Texas Streets, Martinborough	41°13'06.74" S	175°27'41.36" E
2	Corner Lyon & Fitzherbert Streets, Featherston	41°07'04.15" S	175°19'36.80" E
3	Greytown Rugby Club, East Street, Greytown	41°05'07.85" S	175°27'25.80" E
4	Carrington Park, High Street South, Carterton	41°01'36.84" S	175°31'38.61" E
5	Solway Show Grounds, Judds Road, Masterton	40°57'30.56" S	175°37'39.85" E
6	Wairarapa College, Pownall Street, Masterton	40°57'01.73" S	175°38'48.88" E
7	Upper Hutt College, Moonshine Road, Upper Hutt	41°07'37.61" S	175°02'24.37" E
8	Upper Hutt Primary School, Brown Street, Upper Hutt	41°07'34.69" S	175°03'53.23" E
9	Vacant section behind 10 Sylvan Cres, Waikanae	40°52'16.93" S	175°04'01.24" E
10	St Michaels Church, Ngapaki Street, Waikanae Beach	40°51'48.42" S	175°01'27.79" E
11	Te Atiawa Park, Donovan Road, Paraparaumu	40°52'55.70" S	174°59'37.67" E
12	Weka Park, Weka Street, Raumati	40°55'02.34" S	174°59'08.58" E
13	Kura Park, Kura Street, Titahi Bay	41°06'38.37" S	174°50'21.58" E
14	Te Rauparaha Park, Lyttleton Ave, Porirua	41°07'58.63" S	174°50'22.30" E
15	Coronation Park, Oxford Street, Tawa	41°10'17.63" S	174°49'33.77" E
16	University grounds, Campbell Street, Karori	41°17'12.07" S	174°44'25.76" E
17	Seatoun Park, Corner Ludlam & Monro Streets, Seatoun	41°19'29.37" S	174°50'02.29" E
18	Crawford Green, Broadway, Strathmore	41°19'27.26" S	174°48'57.83" E
19	Miramar Park, Darlington Road, Miramar	41°18'33.43" S	174°49'25.92" E
20	Rongotai College grounds, near Bowling Club, Lyall Bay	41°19'33.30" S	174°47'58.03" E
21	Kilbirnie Park, Bay Road, Kilbirnie	41°18'54.37" S	174°47'40.83" E
22	6 – 10 Onepu Road, Kilbirnie	41°19'07.02" S	174°47'45.60" E
23	Shelly Bay Road, Shelly Bay	41°17'43.46" S	174°49'20.97" E
24	69 – 71 Miramar Avenue, Miramar	41°18'56.21" S	174°48'55.76" E
25	Hutt International Boys School, Granville St., Trentham	41°08'24.25" S	175°02'11.20" E

2 METHOD

2.1 Microtremors and Spatial Autocorrelation

Microtremors are the ubiquitous ground motions caused by wind, traffic and other minor random sources, and are predominantly composed of Rayleigh and Love surface waves. Of these, it is Rayleigh waves that are of interest due to their vertical component, which Love waves lack. By using only the vertical component we can focus on Rayleigh wave effects, and hence ignore Love wave effects. However, some "near-field" signals from sources close to the motion sensor may not be propagating surface waves, and they can mask the sought-after effects.

The SPAC method (Aki, 1957; Roberts & Asten, 2005) method uses an array of seismographs to simultaneously record microtremors. Analysis assumes the dominant energy is from Rayleigh waves traversing the array, and data processed in the domains of space and time can provide a shear wave velocity profile averaged over the array. The technique requires a relatively laterally homogeneous site (layered, 1D structure) and uses the dispersive nature of Rayleigh waves, i.e.: waves with different frequencies travel at different velocities. Longer wavelengths (lower frequencies) penetrate deeper, so their velocities across the array are a function of the shear-wave velocity profile. Given a shear-wave velocity profile, the use of a propagator matrix allows the dispersion (and derivative properties such as coherency) to be evaluated (Aki & Richards, 1980; Hermann, 2001).

In the SPAC method used here (Stephenson, 2010; Stephenson et al, 2011), values of azimuthally-averaged coherency are obtained and the shear-wave velocity profile is determined by inverting these values. In this approach (typified by Roberts & Asten, 2005), we calculate synthetic coherency from a trial model of the area which assumes plane layers of soil and incorporates guessed values for shear wave velocity (Vs), pressure-wave velocity (Vp) and density (ρ) for each layer. We then compare the synthetic and measured values of coherency. The trial model is then iteratively adjusted to minimize the misfit between field coherency and theoretical coherency.

Incoherent noise will depress all coherencies. We therefore match in the coherency domain, with an emphasis on the shape of the coherency curve, rather than its amplitude. In practice, we assume three sensor arrays are sufficient to geometrically define average azimuths of wavefront propagation (Okada, 2006). We have subsequently verified this result with numerical testing. We also assume that the shallower materials are underlain by a half-space with a contrasting high shear wave velocity material to represent a greywacke basement prevalent throughout the Wellington region.

We have attempted to characterise each shear wave velocity profile as a sequence of horizontal layers, each with a constant shear-wave velocity. We assign each layer a p-wave velocity either as that of water (1500 m/s) or as that of a Poisson solid ($\lambda=\mu$), whichever is the higher. The SPAC method provides an accurate characterisation of a surface layer lying upon a stiff substrate in terms of both layer thickness and layer velocity to within a few percent. The velocity of the layer is generally better defined than its thickness. In multi-layer situations, deeper layers are more poorly defined and for each layer, velocity is better constrained than depth because of the depth-frequency dependence of Rayleigh waves. Higher frequency waves are sensitive to near-surface properties. Frequencies higher than 20 Hz in general do not penetrate deeper than about 4 m.

2.2 Combined use of SPAC and Horizontal to Vertical Spectral Ratio (HVSR/Nakamura's ratio)

Rayleigh waves travelling in a soil layer lying upon a substrate have a frequency at which their ellipticity changes from retrograde to prograde, going through purely horizontal motion at that frequency. The frequency concerned is very close to that associated with the quarter-wave travel time in the layer, and so there is a concentration of Rayleigh wave energy at that frequency, and a lack of energy associated with the vertical component of motion at that frequency. Thus if microtremors are recorded for sufficient time, and the ratio of the horizontal to vertical spectra is computed, there will be a peak at the frequency of any prograde/retrograde transition. At sites with a very high contrast in shear-wave velocity between the upper layer and the substrate, there can also be a trough in the horizontal-to-vertical spectral ratio for which the motion will be purely vertical. The frequency of this trough is usually around twice the frequency of the peak. When used in seismic microzonation, the HVSR is often referred to as Nakamura's ratio, after its populariser (Nakamura, 1989). The particle orbit associated with a Rayleigh wave travelling in a given set of layers is easily computed, and it follows that in cases where a distinct peak in the HVSR is observed, the layer model must correctly give the particle orbit as well as the coherency. We have made use of this principle with SPAC layer modelling by conceding that the thickness of the lowest modelled layer is ill-defined, allowing us to vary that thickness until the modelled HVSR agrees with the observed field value (Stephenson, 2010; Stephenson et al, 2011). This is not always possible because there may be no HVSR peak where there is no strong velocity discontinuity in the shallow subsurface geological materials.

Although we give the properties of all best-fit layers overlying a model rock basement representing greywacke, we strongly caution against summing these layer thicknesses to obtain a depth to rock. Such a result can be considerably in error due to the inherent non-uniqueness of the generated layer models. We believe that we have provided accurate near-surface velocities, useful average shear-wave velocity values in the top 30 metres (Vs30), and guidance-only values for the thicknesses of deeper layers, particularly at sites where a well defined HVSR frequency is not present to calibrate the model. We believe that we have isolated and quantified the properties most relevant to amplification of earthquake motion.

2.3 Deep Stiff Sites

Earlier SPAC survey work carried out in the Wellington area (Fry et al, 2010) generally involved sites with a well-defined series of soil layers starting with a low-velocity near-surface layer, and with deeper layers having velocities that increased with depth. Such situations are well suited to the SPAC method. However, where sites are within a deep basin, but also comprised of stiff gravelly alluvium, SPAC does not always work well. For a small-aperture array on stiff soil the coherency curve is shifted off scale to high frequencies, but for a large-aperture array on stiff soil, recordings at individual array sites can involve motion which is local to each site, and the coherency becomes meaningless.

Many of the sites used in the current survey (e.g. all Wairarapa sites – sites 1 - 6 in Figure 1 and Table 1) are situated on stiff gravel, and SPAC often merely confirms this, adding little in the way of reliable velocity or depth information. It is difficult to characterise such sites in a satisfactory manner using the SPAC technique, although the high near surface velocities modelled in such cases can be of use in informing subsoil-class decisions, a satisfactory layer model and site period is unlikely to be retrievable.

2.4 Liquefaction

The relevance of SPAC analysis to assessing liquefaction potential is that the shear-wave velocity of a granular material depends mainly upon the voids ratio of the material, such that a low shear wave velocity is associated with high porosity. If the pore spaces of a low shear-wave velocity layer are filled with water, and the soil particles are uniform sands or silts, the layer is likely to liquefy on being shaken. This approach is well-established e.g. Andrus & Stockoe (2000), where a confinement-stress-adjusted shear-wave velocity of 200 m/s was the liquefaction threshold in sands and silts with low fine silt content (≤5%) and 215 m/s in soils with more than 35% of fine silt.

Thus using SPAC to measure the shear-wave velocity at the ground surface, and although less accurately, the thickness of the surface layer, can provide a cost-effective way of providing information relevant to identifying liquefiable and non-liquefiable materials.

In Christchurch, a shear-wave velocity of 190 m/s constituted the boundary value between potentially liquefiable and non-liquefiable materials (Stephenson et al, 2011). We assume that this is because of the nature of the predominant materials. Adopting 200 m/s as a boundary value is a conservative approach in that clays can inhibit liquefaction even though velocities are less than 200 m/s. Accordingly, where the depths of low velocity layers defined by SPAC measurements are known to intersect with saturated sandy and silty sediments, it is prudent to treat such sites as liquefiable until proven otherwise.

2.5 Subsoil Class

NZS 1170.5 subsoil-class determinations are made on the basis of the measured (by HVSR) site natural low-amplitude period, or are estimated by incorporating geological models of depth to bedrock.

2.6 Vs30

The average shear-wave velocity over the top 30 m (Vs30) is derived from the SPAC layer model results where the layer model reaches to 30 m or deeper.

2.7 Geological Correlation

Independently derived geological profiles for each site have been constructed from available information, including published geological maps. It is generally found that shear-wave velocity contrasts identified by SPAC analysis compare well with inferred subsurface geology, and therefore could be used to refine estimates of soft sediment thicknesses and depth to bedrock in many cases. The SPAC determined layer shear-wave velocities are associated with particular lithological units, allowing extrapolation to other areas of similar geology, and for estimates to be made in cases where lack of coherency or velocity inversions produce equivocal SPAC interpretations. In other words, the SPAC layer models and geological layer models can be used as mutual cross-checks.

3 DISCUSSION AND CONCLUSIONS

3.1 Discussion

The sites investigated are five separate geographical areas: Wairarapa, Upper Hutt, Kapiti Coast, Porirua and Wellington City (Figure 1). Results are given in Table 2; good to satisfactory SPAC data were obtained at 15 sites while 10 sites gave poor but useful data. All could be assigned to subsoil-class C or D based on the SPAC/HVSR data or on geological information. At some sites it was not possible to obtain a subsoil-class or site period directly from the HVSR and SPAC data. In these cases, conditions were not ideal for SPAC and HVSR, such as very stiff soils, dipping layers, or a lack of strong velocity contrast between soil and inferred rock. However, the shear-wave velocity values from SPAC combined with archival drill hole or other geological information allowed interpretation at these sites. Ideal conditions exist on the Kapiti Coast, while tractable conditions were present in Wellington City and Lower Hutt, while the ground was most difficult in stiff sites in Upper Hutt and the Wairarapa. A satisfactory result is considered to have been achieved at most sites and the quality of the SPAC/HVSR results have been rated for reliability in Table 2.

The Wairarapa sites (sites 1 to 6; Figure 1, Table 1) gave satisfactory results typical of very stiff sites not well suited to the SPAC method. However, at each of these sites, with the exception of site 5 (Solway Showgrounds), results indicated the presence of thick soil material with relatively high shear-wave velocities typical of Quaternary alluvial surficial deposits in the region. Because of the appreciable thickness and relatively high shear-wave velocity of the soil material these sites are classified as subsoil-class D. These sites are also considered unlikely to liquefy.

The three Upper Hutt sites (sites 7, 8 and 25) also gave satisfactory but uninformative SPAC results typical of stiff soils dominated by gravelly alluvium. Site 7 (Upper Hutt College) had poor coherencies possibly due to a velocity inversion and has been interpreted as subsoil-class D from pre-existing geological information, while site 8 can be attributed to subsoil-class D from both the SPAC models, site period and geological information. Site 25 (Hutt International Boys School) gave a marginal result possibly because of very high near surface velocity and possible basin-margin effects, and could be regarded as either subsoil-class C or D, although D is more likely given the geological setting . These sites are considered unlikely to liquefy based on their relatively high measured (or inferred) shear-wave velocities.

The Kapiti Coast sites (sites 9 through 12) are dominated by softer soils with the exception of site 9 (Sylvan Crescent, Waikanae). The interpretation at Waikanae was very difficult because of possible basin-margin effects, with dense gravel wedges and shallow, sloping bedrock – as suggested by the geological interpretation. The site is stiff, with high to very high near surface velocity, but also a possible thin low-velocity layer directly at the surface, and is assigned to subsoil-class D on geological interpretation, but may be near class C. Based on the (inferred) shear-wave velocity, there may be potential for this site to liquefy. In contrast, the remaining Kapiti Coast sites (10, 11 and 12) were well suited to SPAC analysis, with good layer models obtained. These three sites are dominated by coastal dune sands, marginal marine deposits and swamp deposits over deep alluvium and gravel, and can be assigned to subsoil-class D from both SPAC models, HVSR results and geological interpretation. Surface velocities are below 200m/sec and it is prudent to regard liquefaction as possible.

The three sites in the Tawa - Porirua area (sites 13 – 15) gave useful results but were limited due to the shallow depths of alluvium and soil giving poor coherencies. Both site 13 (Kura Park) and site 14 (Te Rauparaha Park) could be modelled with thin low velocity layers at the surface, reflecting the shallow nature of the Holocene sediments, and while they can be assigned to subsoil-class C, the low to very low surface velocities make liquefaction a possible consideration. Site 15 (Coronation Park), in contrast, was limited by possible shallow bedrock producing a poor coherency result. The site is very stiff, and is assigned to subsoil-class C on geological interpretation only, and while liquefaction is unlikely, a very thin low velocity surface layer may be present above the stiff material.

Table 2. Summary of the significant test results. Twenty five sites were occupied in the Greater Wellington Region (Figure 1, Table 1), using triangular seismograph arrays with apertures from 5m to 30m. Satisfactory azimuthally-averaged coherency curves were obtained for most apertures of each array, and at each site a theoretical coherency curve was able to be modelled for at least one aperture. "n/d" indicates no data for that parameter.

Site No	Location	Quality*	Preferred Shear wave velocity (Vs) & layer thickness model						Vs30 (m/sec)	Sub soil class	Site Period (sec)	Liquefaction Potential
			Layer 1		Layer 2		Layer 3					
			Depth (m)	Vs (m/sec)	Depth (m)	Vs (m/sec)	Depth (m)	Vs (m/sec)				
1	Martinborough	ii	7	292	7 - 227	402			369	D	n/d	None
2	Featherston	ii	12	338	12 - 125	473			406	D	1.1	None
3	Greytown	ii	11	369	11 - 118	587			482	D	0.9	None
4	Carterton	ii	17	450	17 - 151	700			532	D	0.9	None
5	Solway Show Gds	iv	?	>400					n/d	D	n/d	None
6	Wairarapa Coll	ii	90	390					390	D	0.9	None
7	UH College	iv	?	n/d					n/d	D	0.9	None
8	UH Primary Sch	ii	138	449					449	D	1.25	None
9	Sylvan Cres	iv	n/d	>400					n/d	D(C?)	n/d	Low
10	St Michaels	i	8	168	8 - 25	264	25-201	359	237	D	2.4	Moderate
11	Te Atiawa Park	i	12	156	12 - 205	321			223	D	2.7	Moderate
12	Weka Park	i	12	185	12 – 15	267	15-175	353	252	D	2.1	Moderate
13	Kura Park	ii	7	117	7 – 12	259	12 - ?	~500	>400	C	0.3	Moderate
14	Te Rauparaha Pk	i	1.6	79	1.6 - 12	172	12-32	450	251	C	0.27	High
15	Coronation Park	iii	?	>400					>400	C/D	n/d	Low
16	Karori	iii	8±2	240 - 300	8±2 - 150	500 - 700			420-540	C/D	n/d	None
17	Seatoun Park	iii	2.6	180 - 230	2.6 – 4.6	130 - 150	4.6-64	350-400	263	D	0.8	Moderate
18	Crawford Green	iii	>40	203					203	D	0.8-1.2	Low
19	Miramar Park	i	8	154	8 – 80	341			257	D	n/d	Moderate
20	Rongotai	iii	5-50	250-350	8	150	40-70	250-600	n/d	D	1.1	Moderate
21	Kilbirnie Park	iii	10	505					>500	C	n/d	Low
22	Onepu Road	i	1.6	144	1.6 – 12	213			508	C	0.2	Moderate
23	Shelly Bay	ii	11	200					n/d	C	n/d	Low
24	Miramar Avenue	i	44	199					>199	D	0.87	Low
25	Hutt Intl Boys Sch	iii	30	505					>500	C/D	n/d	None

*Quality estimate is shown using the following non-quantitative scale			
i Good – Very good	ii Satisfactory	iii Poor	iv No Result

Within the Wellington City suburbs, (sites 16 – 24) the results cover a variety of ground types with useful results returned for all sites. At site 16 (Karori), near surface velocities were high, but the lack of clear HVSR data precluded refining the deeper structure, so the site is assigned to subsoil-class C, based on the geological interpretation of stiff Pleistocene sediments overlying deeply weathered bedrock, although subsoil class D cannot be ruled out. Model results with low velocity surface layers were common, with site 17 (Seatoun Park), site 18 (Crawford Green), site 19 (Miramar Park), site 20 (Rongotai), site 21 (Kilbirnie Park), site 22 (Onepu Road), site 23 (Shelly Bay) and site 24 (Miramar Avenue), all able to be modelled with surface layers near or below 200m/s. Of these, sites 17 to 20 and site 24 were assigned to subsoil-class D on the basis of both SPAC models and geological interpretation, although a site period could not be resolved for site 19 (Miramar Park), while sites 21 to 23 were assigned to subsoil-class C, with shallow SPAC layer models and geological information. It is prudent to regard liquefaction as possible at these sites.

Modelling at site 23 (Shelly Bay) was limited by basin-edge effects of dipping soil layers, while site 17 (Seatoun Park), site 20 (Rongotai) and Site 21 (Kilbirnie Park) show velocity inversions, making interpretation complex, although it is likely that the velocity inversions at Rongotai and Seatoun Park are due to compacted beach or dune sands over soft, low velocity estuarine or peat swamp deposits.

3.2 Conclusions

The combined use of SPAC and HVSR as a surface wave site investigation technique is useful within the Wellington region, although care must be taken in both choosing sites and interpreting the results.

- As expected, the technique is best used on soft, horizontally stratified sites;
- The presence of steeply dipping or wedge shaped sediments near coastal regions or basin margins will reduce the utility of the technique, as will the presence of stiff, gravelly soils;
- Partial automation of the data processing is useful, but experienced operators in SPAC modelling and good geological background and interpretation are essential in assigning subsoil-class.

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REFERENCES

Andrus, D.R. & Stokoe, K.H. 2000. Liquefaction Resistance of Soils from Shear-Wave Velocity, ASCE, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 126, No. 11, November, pp 1015-1025.

Aki, K. 1957. Space and time spectra of stationary stochastic waves, with special reference to microtremors, Bull. Earthquake Res. Inst. 35, 415–456.

Aki, K., Richards, P. Quantitative Seismology: Theory and Methods. (1980).

Boon, D., Perrin, N.D., Dellow, G.D., Van Dissen, R., Lukovic, B., 2011, NZS1170.5:2004 site subsoil classification of Lower Hutt. *in proceedings*, 9th Pacific Conference on Earthquake Engineering, Auckland, New Zealand, 14-16 April, 2011: Paper 013, 8 p.

Dellow, G.D., Perrin, N.D. & Ries, W. 2014. Liquefaction hazard in the Wellington Region, GNS Science Report 2014/16. 54 p.

Fry, B., Stephenson, B., Benites, R. & Barker, P. 2010. It’s Our Fault – Seismic instrumentation and inversion for physical parameters of Wellington and the Hutt Valley. GNS Science Consultancy Report 2010/18.

Hermann, R. B. 2001. Computer programs in seismology – an overview of synthetic seismogram computation Version 3.1: Department of Earth and Planetary Sciences, St Louis University.

Nakamura, Y. 1989. A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. Quarterly Report Railway Technical Research Institute, 30(1), 25–30.

New Zealand Standards. 2004. NZS 1170.5 Supplement 1:2004 Structural design actions - Part 5: Earthquake actions - New Zealand Commentary.

Okada, H. 2006. Theory of efficient array observations of microtremors with special reference to the SPAC method. Exploration Geophysics 37: 73-85.

Perrin, N.D., Stephenson, W.R. & Semmens, S. 2010. Site class determinations (NZS 1170.5) in Wellington using borehole data and microtremor techniques. New Zealand Society for Earthquake Engineering 2010 Conference Proceedings, paper No 22.

Roberts, J.C. & Asten, M. 2005. Estimating the shear velocity profile of Quarternary silts using microtremor array (SPAC) measurements, Exploration Geophysics, Vol 36, 1. Australian Society of Exploration Geophysicists, Innaloo City WA, Australia, pp. 34-40.

Semmens, S., Perrin, N.D. & Dellow, G. 2010. It’s Our Fault – geological and geotechnical characterisation of Wellington City. GNS Science Consultancy Report 2010/176: 48p.

Semmens, S., Perrin, N.D., Dellow, G., & Van Dissen, R. 2011. NZS 1170.5:2004 site subsoil classification of Wellington City. Proceedings of the 9th Pacific Conference on Earthquake Engineering. Auckland, New Zealand, 14-16 April, 2011: Paper 007, 8 p.

Stephenson, W.R. 2010. Microtremor coherency: simultaneous recording with arrays having different apertures. Bulletin of the New Zealand Society for Earthquake Engineering, 43(1): 1-6.

Stephenson, W. R., Barker, P. R., Bruce, Z. & Beetham, R. D. 2011. Immediate report on the use of microtremors (SPAC measurements) for assessing liquefaction potential in the Christchurch area. GNS Science Report 2011/25.

Stephenson, W.R., Barker, P.R. & Beetham, R. D. 2011. Microtremor-based determination of shear wave velocity of soft soils using the SPAC method. GNS Science Report 2009/62.