1. INTRODUCTION

Knowledge of local site response is a necessary part of earthquake hazard classification. Single-station measurements of particle motion horizontal/vertical spectral ratios (HVSR) of background seismic noise (microtremor noise), acquired over a grid (regular or otherwise) are a popular method for determining shear-wave resonances relevant to the modelling of site response. SESAME (2004) and references therein contain a major review and results of current studies with the method. However the HVSR spectra and resonances alone are insufficient to determine quantitative site response.

2. PREVIOUS STUDIES OF RESONANCE-EQUIVALENT MODELS

Asten et al (2002) who considered three resonance-equivalent models for a site at Blacksmith, near Newcastle. The site (discussed in greater detail by Sorensen and Asten, 2005, this volume) has a thickness of 44-50 m of dense sands and clays with shear-velocities in the range 140-250 m/sec, overlying sandstone bedrock. The three resonance-equivalent models considered the preferred model, a "thick" model with twice the shear velocities (velocities which would be typical of thick gravels), and a "thin" model with shear velocities halved (velocities which would be typical of soft muds and silt). Non-linear shear-wave modelling showed that the displacement demand of the "thin"silt model exceeded the "preferred" model by 19% while the "thick" gravel model showed demand reduced by 25%.

Asten and Dhu (2004) considered three sites in the Botany Bay area, Sydney where the velocity profiles were established through microtremor array studies. The geology is similar to the Blacksmith area discussed above. One site on the edge of Botany Bay atypically showed a shear-velocity profile in the top 5 m of low values in the range 98-125 m/sec (typical of silts). Computation of amplification of acceleration response for the three sites showed that the last of these sites had a shear-wave resonance at 6 Hz associated with the previously-unknown soft top layer, not obvious in HVSR. Equivalent linear site response modelling predicted that this site will have acceleration amplification 70-100% above that for the other two "comparable" sites.

The difficulty of resolving shear-wave velocity profiles from single-site microtremor data is also evident in quantitative modelling studies by Scherbaum et al (2003) who found that inversion of H/V spectral ratios for layered-earth models suffers from velocity-thickness trade-offs, ie. the phenomenon of resonance-equivalence as discussed above. This may not always prevent extraction of SWV profiles from H/V data; Lang and Schwartz (2005) present one such example.

3. CURRENT SITE – HVSR

The site surveyed is located north-west of the Melbourne CBD. A series of single-station microtremor measurements (Figure 1) showed a dominant natural period of order 0.3 sec, with some subsidiary peaks of order 0.9 sec. A geotechnical drill-hole in the locality showed 5 m of fill over 6.5 m of Coode Is silt, with a siltstone basement (the expected bedrock in this locality is Melbourne Mudstone). This relatively thin cover, coupled with the 0.3 sec HVSR peak, would normally result in a site classification "C" according to the new Australian Standard for earthquake actions (AS/NZS 1170.4 Draft no.D5212-5.1, 2005), but the weak 0.9 sec peaks in the HVSR raise the question

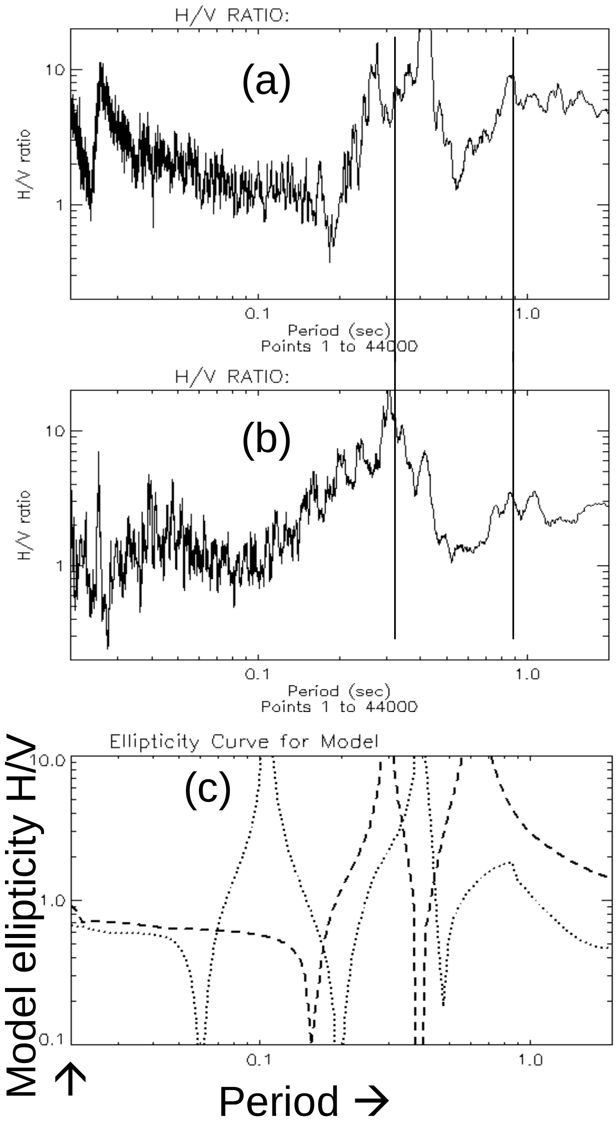


Fig. 1. (a) and (b): HVSR plots for two sites in the study area. Peaks in the range 0.25-0.4 sec are associated with a known thickness of 11.5 m of Quaternary sands and silts. Lesser peaks at periods of order 0.9 sec indicate underlying unconsolidated sediments.

(c) Modelled elipticity ratios for the fundamental (dashed line) and 1st higher (dotted line) Rayleigh modes, for the shear-wave velocity model velocity developed in Figs. 2 and 3, shown as inset in Fig. 4b.

whether alternative classification is warranted. Uniform silts would need to have a hypothetical thickness of 21.5 m to result in a HVSR peak at a period of order 1 sec. Recognising the importance of the soil shear-velocity, not just resonance frequency (period), as demonstrated by Lam and Wilson (2004), Tsang et al (2005) and by examples in the previous section, an array microtremor survey was performed to determine the soil shear-wave velocity profile.

4. CURRENT SITE – VELOCITY MODEL FROM ARRAY MEASUREMENT

The microtremor array survey closely followed methods described by Asten and Dhu (2004), Roberts et al (2004), Roberts and Asten (2005) and Asten et al (2005). Two hexagonal arrays of radius 20 m and 48 m were used. As shown in Figure 2 the SPAC spectra acquired with the smaller array resolve the shear velocities of the upper 5 m of sand/silt, and the underlying 6.5 m of Coode Is silt. These velocities are resolved with an accuracy of order 5% and the fact that there is a velocity inversion at this site (higher shear-velocity overlying a layer of lower shear velocity) is explicitly resolved.

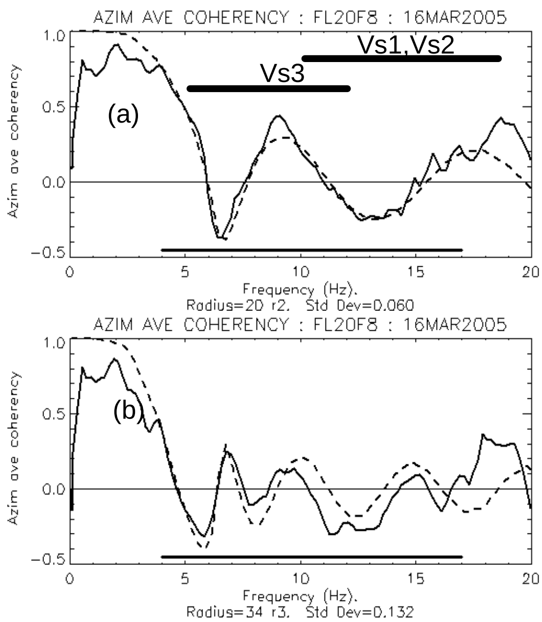


Fig. 2. SPAC spectra acquired with the small (20 m radius) array, station separations (a) 20 m and (b) 34.6 m.

Thick black curve: SPAC spectrum from field data. Dashed curve: model SPAC spectrum, computed from layered earth model shown in Fig. 4b.

The useful band of frequencies in the field data is 4-17 Hz. Frequencies 10-20 Hz resolve shear velocities Vs1,Vs2 of the upper two layers (fill) to 5%. Frequencies 5-12 Hz resolve Vs3 the shear velocity of layer 3 (Code Is silt) to 5%.

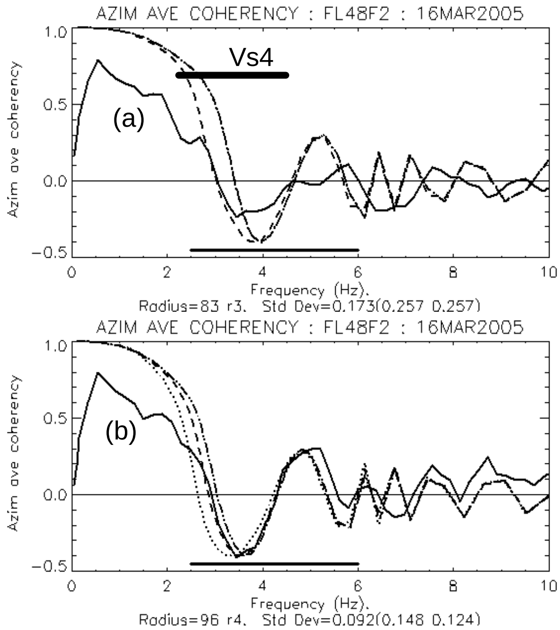


Fig. 3. SPAC spectra acquired with the large (48 m radius) array, station separations (a) 83 m and (b) 96 m. The thick dashed line is the model spectrum using Vs1,Vs2 and Vs3 as resolved in Figure 2, with Vs4 for underlying gravels 600 m/sec.

The useful band of frequencies in field data is 2.5-6 Hz. Frequencies 2-4.5 Hz resolve Vs4 shear velocity of layer 4 (interpreted as gravels) to +-10% or better.

In (a), the dash-dot line shows the model spectrum for Vs4=900 m/sec, which is a very poor fit and rules out Melbourne mudstone as a possible bedrock material immediately under the Coode Is Silt.

In (b) the dash-dot and dotted lines show model spectra for Vs4=600+-10%. These are significantly poorer fits than the preferred model (Vs4=600 m/sec).

TABLE 1

Velocity model for best-fit Figs 2 and 3.

Layer	h (m)	Vp (m/sec)	Vs (m/sec)	RHO t/m^3	GEOLOGY
1	2	800	190	1.8	sand/silt
2	3	1600	190	2	sand/silt
3	6.5	1600	140	2	Coode Is silt
4	95	2100	600	2.4	gravels
5	300	3100	1500	2.4	bedrock

Notes: Compressional velocities Vp and densities Rho are assumed values.

Layer 1 is a guess, representing position of a nominal water table.

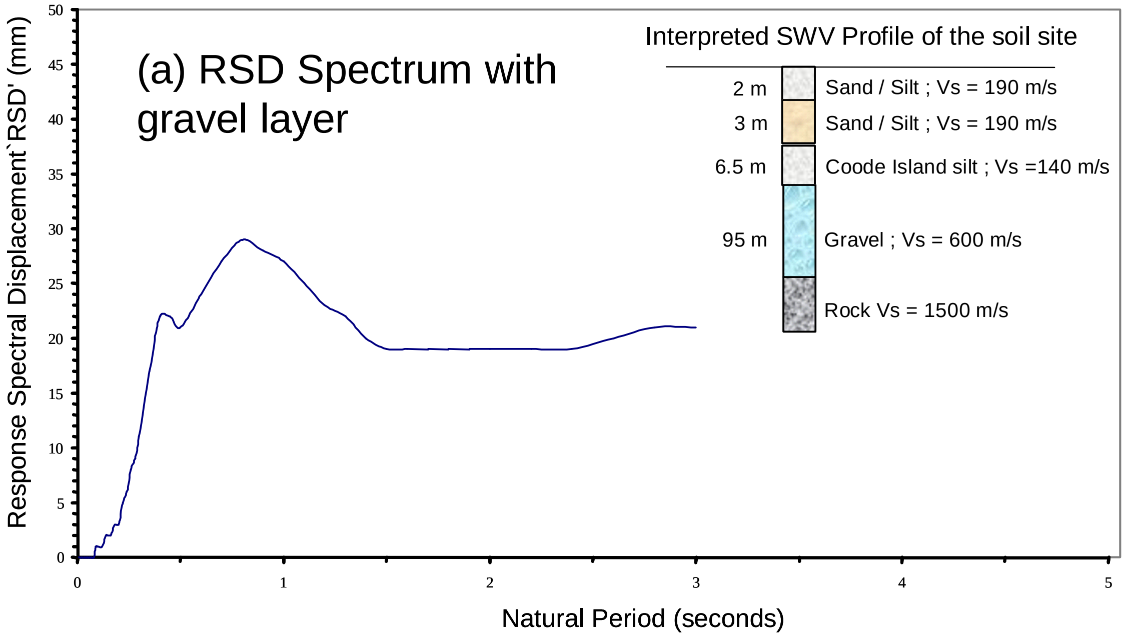
Base of of layers 2 & 3 is fixed, using drill-hole data.

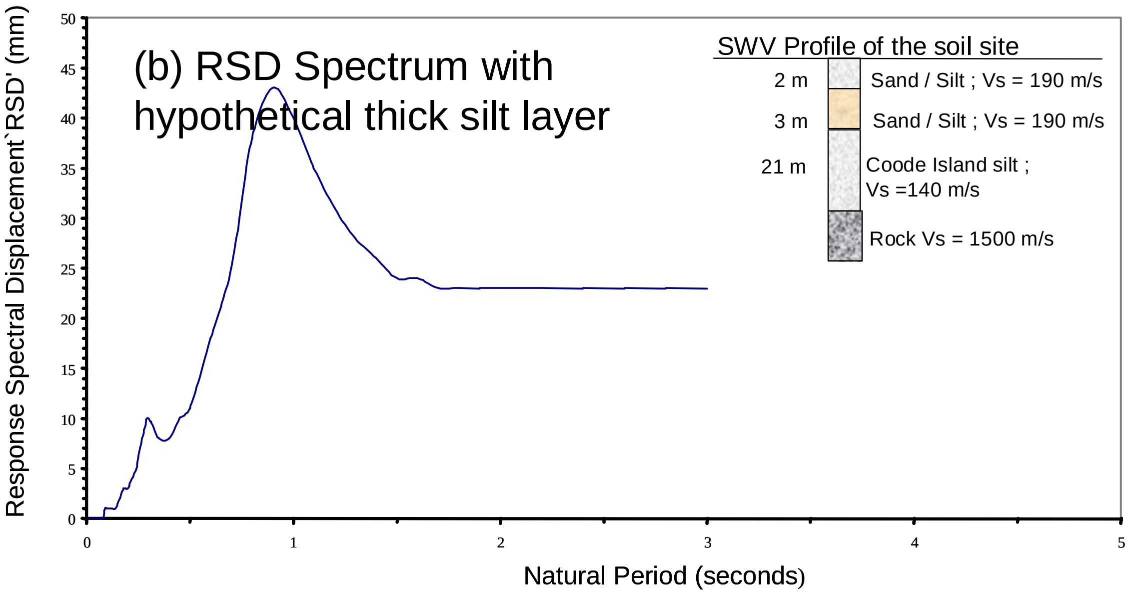
Bedrock is assumed but not resolved.

Figure 3 shows observed and modelled SPAC spectra for the larger array. The shear-wave velocity for Melbourne Mudstone has been measured in other surveys at three sites north-west of the Melbourne CBD, and found to be in the range 1800-2000 m/sec (Roberts et al, 2004; Lam et al, 2005). It is clear that rock beneath the Coode Is Silt at the current site is very much softer than mudstone. Model fitting shown in Figure 3 gives a shear-velocity of 600 m/sec +-10%, with a thickness of 95 m, overlying bedrock. This shear velocity is less than that expected for rock or weathered rock, and is similar to that for known gravels such as the Pleistocene-Holocene gravels of the Auckland (New Zealand) area reported in Asten et al (2005). The full set of parameters used in modelling is given in Table 1.

5. SITE-AMPLIFICATION MODELS

Figure 4 shows the displacement response spectra (RSD) computed for the velocity model developed in Figures 2 and 3, and for the resonance-equivalent model whereby a uniform thick silt layer is used to obtain a site natural period to match the secondary peak observed on the HVSR at 0.9 sec. The RSD spectra were computed by one dimensional non-linear shear wave analysis using program SHAKE based on the soil shear wave velocity profile inferred from the SPAC measurements (refer inset diagram of Figure 4a).





The excitations from the bedrock required for input into the analysis was obtained from stochastic simulations (Lam et al, 2000) based on a hypothetical magnitude 6.5 earthquake at a distance of 45 km. This hypothetical earthquake has a peak ground velocity of approximately 60 mm/sec on rock sites and hence corresponds to a 500 year return period earthquake risk for both Melbourne and Sydney (Lam and Wilson, 2005).

The amplitude demand for the shear-wave velocity (SWV) profile interpreted from microtremor array measurements is 30 mm, which lies well within the design bounds of an average building structure. However the amplitude demand for the resonancequivalent model, which assumes a hypothetical thick silt layer as the cause of the observed HVSR peak at 0.9 sec, is 43% greater at 43 mm (refer Figure 4b). The hypothetical case would indicate a Class D site which is associated with a stipulated seismic demand some 60 % higher than that of a Class C site (as inferred from the SPAC survey). This demonstrates the advantage of obtaining microtremor array data and a quantitative SWVP rather than relying on single-station site resonance data alone.

6. ACKNOWLEDGEMENTS

Data in this paper is used with permission from the Office of Housing of the State Government of Victoria, Department of Human Services. MWA is supported in the development of microtremor methods by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 05HQGR0022. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either express or implied, of the U.S. Government.

7. REFERENCES

Asten,M.W., Lam, N., Gibson, G. and Wilson, J. (2002) Microtremor survey design optimised for application to site amplification and resonance modelling, *in* Total Risk Management in the Privatised Era, editted by M Griffith, D. Love, P McBean, A McDougall, B. Butler, Proceedings of Conference, Australian Earthquake Engineering Soc. , Adelaide, Paper 7.

Asten, MW, and Dhu, T., (2004) Site response in the Botany area, Sydney, using microtremor array methods and equivalent linear site response modelling . *Australian Earthquake Engineering in the New Millennium*, Proceedings of a conference of the Australian Earthquake Engineering Soc., Mt Gambier South Australia, Paper 33.

Asten , M.W., Stephenson, W.R., and Davenport, P., (2005) Shear-wave velocity profile for Holocene sediments measured from microtremor array studies, SCPT, and seismic refraction, Journal of Engineering and Environmental Geophysics, Vol 10 (3), pp. 235-242.

AS/NZS 1170.4 Draft no.D5212-5.1, (2005) Structural Design Actions - Part 4 Earthquake Actions, sub-committee BD-006-11, Standards Australia.

Lam, N.T.K., Venkatesan, S, Wilson, J.L., Asten, M.W., Roberts, J., Chandler, A.M., & Tsang, H.H., (2005) Generic Approach for Modelling Earthquake Hazard, *Advances in Structural Engineering*, in press.

Lam, N.T.K., Wilson, J.L., Hutchinson, G.L., (2000) Generation of synthetic earthquake accelerograms using seismological modeling: a review, J Earthquake Engineering, Vol 4, No 3, pp 321-354.

Lang, D.H. and Schwarz, J., (2005) Identification of the Subsoil Profile Characteristics at the Coyote Creek Outdoor Classroom (CCOC), San José, from Microtremor Measurements - A Contribution to the CCOC Blind Comparison Experiment, *in* Asten, M.W., and Boore, D.M., eds., Blind comparisons of shear-wave velocities at closely spaced sites in San Jose, California: U.S. Geological Survey Open-File Report 2005-1169. [available on the World Wide Web at http://pubs.usgs.gov/of/2005/1169/].

Lam, N.T.K. and Wilson, J.L., (2004) Displacement Modelling of Intraplate Earthquakes, in International Seismology and Earthquake Technology Journal (special issue of invited papers on Performance Based Seismic Design; Ed Nigel Priestley), 2004. Indian Institute of Technology, Vol.41(1), paper no. 439: pp. 15-52.

Lam, N.T.K., Wilson, J.L., (2005) Accelerograms for dynamic analysis under the New Australian Standard for Earthquake Actions, Proceedings of the Australasian Structural Engineering Conference (ASEC), Newcastle, NSW, Australia, September 2005. Paper ref. 321.

Roberts, J., Asten, MW., Hing Ho Tsang, Srikanth Venkatesan, and Lam, N., (2004) Shear Wave Velocity Profiling in Melbourne Silurian Mudstone using the SPAC Method. *Australian Earthquake Engineering in the New Millennium*, Proceedings of a conference of the Australian Earthquake Engineering Soc., Mt Gambier South Australia, Paper 15.

Roberts, J., and Asten, M.W., (2005) Estimating the shear velocity profile of Quaternary silts using microtremor array (SPAC) measurements, Exploration Geophysics, vol. 36, pp. 34-40.

Scherbaum F., Hinzen K.-G. and Ohrnberger M., (2003) Determination of shallow shear wave velocity profiles in the Cologne, Germany area using ambient vibrations, Geophys. J. Int., vol. 152, pp. 597-612.

SESAME, (2004) Site effects assessment using ambient excitations: Final Report, European Commission – Research General Directorate, Project EVG1-CT-2000-00026 SESAME. Available online at http://sesame-fp5.obs.ujf-grenoble.fr/ .

Sorensen, C., and Asten, M., (2005) Comparison of shear wave velocity profiles of Quaternary sediments in the Newcastle area estimated from SCPT, microtremor spectral ratios and array studies, and drilling. Australian Earthquake Engineering in the New Millennium, *Earthquake engineering in Australia,* Proceedings of the annual technical conference of the Australian Earthquake Engineering Soc., Albury NSW., Paper 9.

Tsang H.H., Lam N.T.K. and Chandler A.M., (2005) Displacement Models for Site Effects, *Earthquake engineering in Australia,* Proceedings of the annual technical conference of the Australian Earthquake Engineering Soc., Albury NSW., Paper 30.