1. INTRODUCTION

The 1989 Newcastle earthquake has resulted in an extensive focus on earthquake risk assessment in the area. Prior to this event the area was considered to be a minimal risk zone, but this and the following 1994 earthquake resulted in the area being reclassified as moderately seismically active. The 1989 earthquake was the first in Australia to cause considerable damage to engineered structures. In Newcastle and the surrounding areas, where unweathered bedrock is overlain by a weathered profile and sediments, the presence of regolith as well as the condition and location of particular building types appear to be the main reasons for the amount of damage experienced as a consequence of the earthquake.

Focused interest on the Newcastle area has resulted in a relatively large collection of geotechnical data. Earlier studies in the area include the creation of regional seismicity, attenuation and site response models, determined mainly from historical seismicity and geotechnical data (Jones and Dhu 2002). However, commonly used geotechnical methods for site response models are relatively expensive and the need exists for a cheap and rapid method to obtain information about amplification effects of sediments.

The objectives of this study are firstly to use the Spatial Autocorrelation (SPAC) microtremor method to generate shear wave velocity (SWV) profiles at six different locations in Newcastle and surrounding areas. Secondly, to compare the SWV profiles to Seismic Cone Penetrometer Testing (SCPT), horizontal to vertical spectral ratio measurements (HVSR) and information from drill holes.

This paper provides a summary of the SPAC and HVSR methods. It briefly describes the study area incorporating six SPAC localities. The SWV profiles obtained from the six SPAC datasets are outlined and compared to the SCPT shear wave velocity profiles, and an example is given of the comparison to HVSR data. The SWV SPAC profiles agree well with existing geotechnical information, but the SPAC method proves to be superior to more invasive methods for resolving greater bedrock depths.

2. METHODS

The microtremor methods are based on measurements of the natural microtremor field. These ground movements are produced by a range of different sources such as road traffic, industrial machinery and natural phenomena such as wind and wave-action. These low amplitude seismic movements are generally in the 1-40 Hz range.
Two different ways of using the microtremor wave field have been widely applied.
In the HVSR method (Nakamura 1989, Asten and Dhu 2004, Tokimatsu 1997, Bodin *et al.* 2001), three components of the wave field are measured at single stations and the horizontal to vertical particle motion ratio is calculated. This approach is a particularly useful tool for mapping shear wave site amplification effects used in earthquake hazard assessments, since spectral peaks near shear wave resonance of unconsolidated sediments overlying hard basement are obtained.

The spatial autocorrelation method, or spatially averaged coherency method (SPAC), is the array processing technique first introduced by Aki (Aki 1957). This method is based on measuring the vertical component of the wave field, which restricts the velocity analysis to Rayleigh waves. The geophone array makes it possible to measure energy from multi- or omnidirectional sources, given that the method does not need to determine the direction of the wave. By calculating the coherency of waves between two different geophones in the array and azimuthally averaging the coherencies for geophones with the same separation distance, a coherency curve for the array location can be obtained. This curve can ideally be described by a zero order Bessel Function, the shape of which depends on the station separation and the dispersion characteristics of the earth.

In a layered earth, wave motion is dispersive and the velocity of propagation is a function of the velocity structure beneath the Earth's surface.

The model parameters (thickness, velocities and density) can be determined by using a manual iterative method to compare the coherency curves obtained from the field measurements to a theoretically computed coherency curve.

Long wavelength responses are influenced by structures at greater depth while shorter wavelength ones are influenced by structures at shallower depths. More details about the SPAC technique can be found in Okada (2003) and examples of applications in Roberts and Asten (2004) and Apostolidis *et al*. (2004).

3. STUDY AREA

The locations of the six SPAC measurement sites within the Newcastle city area are shown in figure 1. The area is extensively covered by Quaternary alluvial deposits frequently up to 30 m in depth.

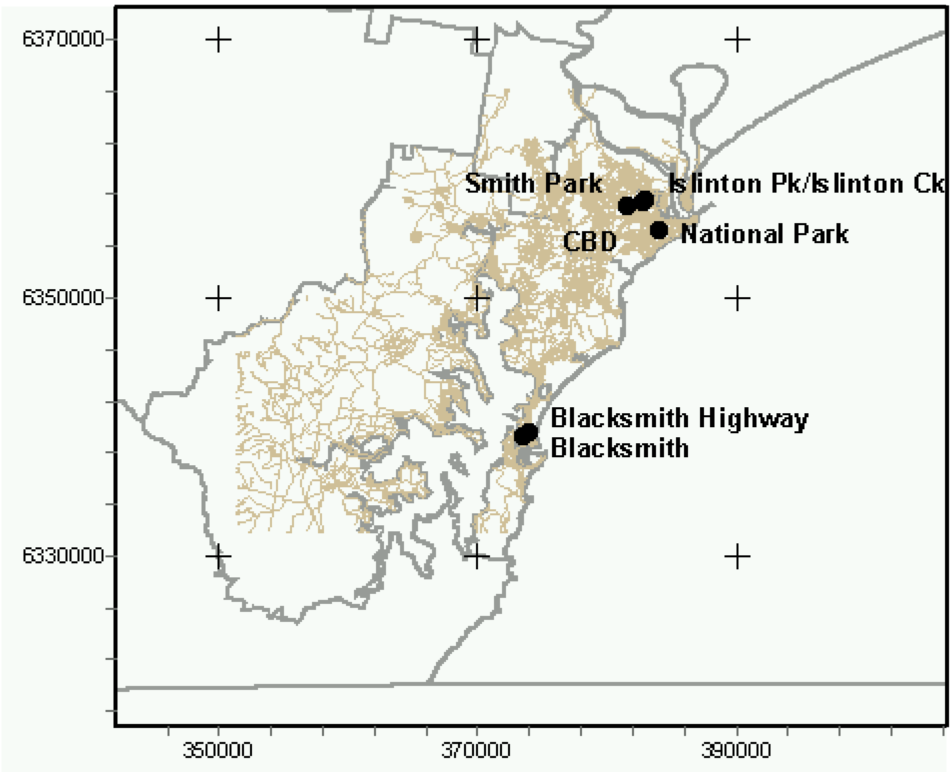

Figure 1: Location of the SPAC measurement sites.

These blanket a large area associated with the Hunter River, which includes the CBD and several industrial areas. Similar deposits are also found on the Belmont Peninsula extending from Redhead to Swansea. Consequently, all SPAC sites are located in areas of alluvial cover.
Profiles within the alluvium zones are characterised by a 0.5-2.0 m thick surface layer comprising loose fill, underlain by 1.5-3.0 m of soft clay. Loose to medium dense sand typically occurs below this down to depths of 15 m. Clays underlie this sand in most areas, typically at depths of 10-15 m, but with some occurrences extending to 30 m (Douglas, 1995).

4. RESULTS

Several SPAC measurements were conducted at each location (Figure 1) using a hexagonal array. The locations of the measurements were chosen according to a criterion of easy access to large open areas and therefore not necessarily in the immediate vicinity of an existing drill hole or SCPT measurement. Three different array sizes were employed; 20, 25 and 50 m, allowing for computation of SPAC spectra for station separation values of [20, 20, 34, 40], [25, 25, 43, 50] and [50, 50, 86, 100] respectively (Asten et al, 2004). The typical time required for a SPAC measurement is 2 to 3 hours for layout, readings and removal of the array. Initial processing of data in the field can be performed for purposes of quality control and verification of correct survey design. The coherency curve for each location was compared to a theoretically computed curve and a best-fit model was obtained. Figure 2 is an example from the Blacksmith Highway site and shows the theoretically obtained curve fitted to the measured curve. From this it can be seen that a fairly close fit is obtained between the two curves, particularly for frequencies below 10 Hz and above 15 Hz.

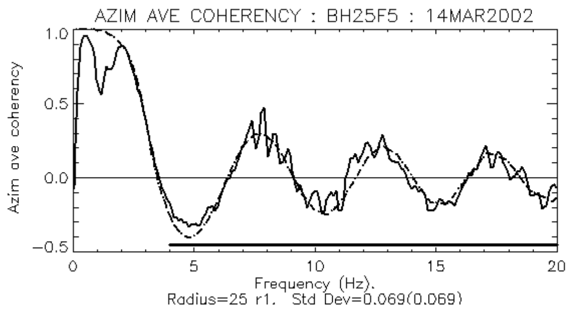

Figure 2: Measured coherency curve for a station separation of 25 m (black line), plotted against the theoretically obtained coherency curve for the fundamental mode (dashed line).

A reasonably good fit was obtained for each SPAC location with the exception of the National Park site. Here it was not possible to obtain a model with a consistent fit for the whole frequency range. Instead either a model well fitted to the 2-8 Hz range or a model well fitted to the >10 Hz range was obtained. The model fitted to the low frequency range incorporates a layer with a velocity of 65 m/s. This layer is not seen by the higher frequencies, probably due to dominant higher modes at these higher frequencies.
The corresponding SWV profiles for all sites are shown in Figure 3 (bold lines). For five of the six sites, it was possible to compare the obtained SWV profiles to nearby

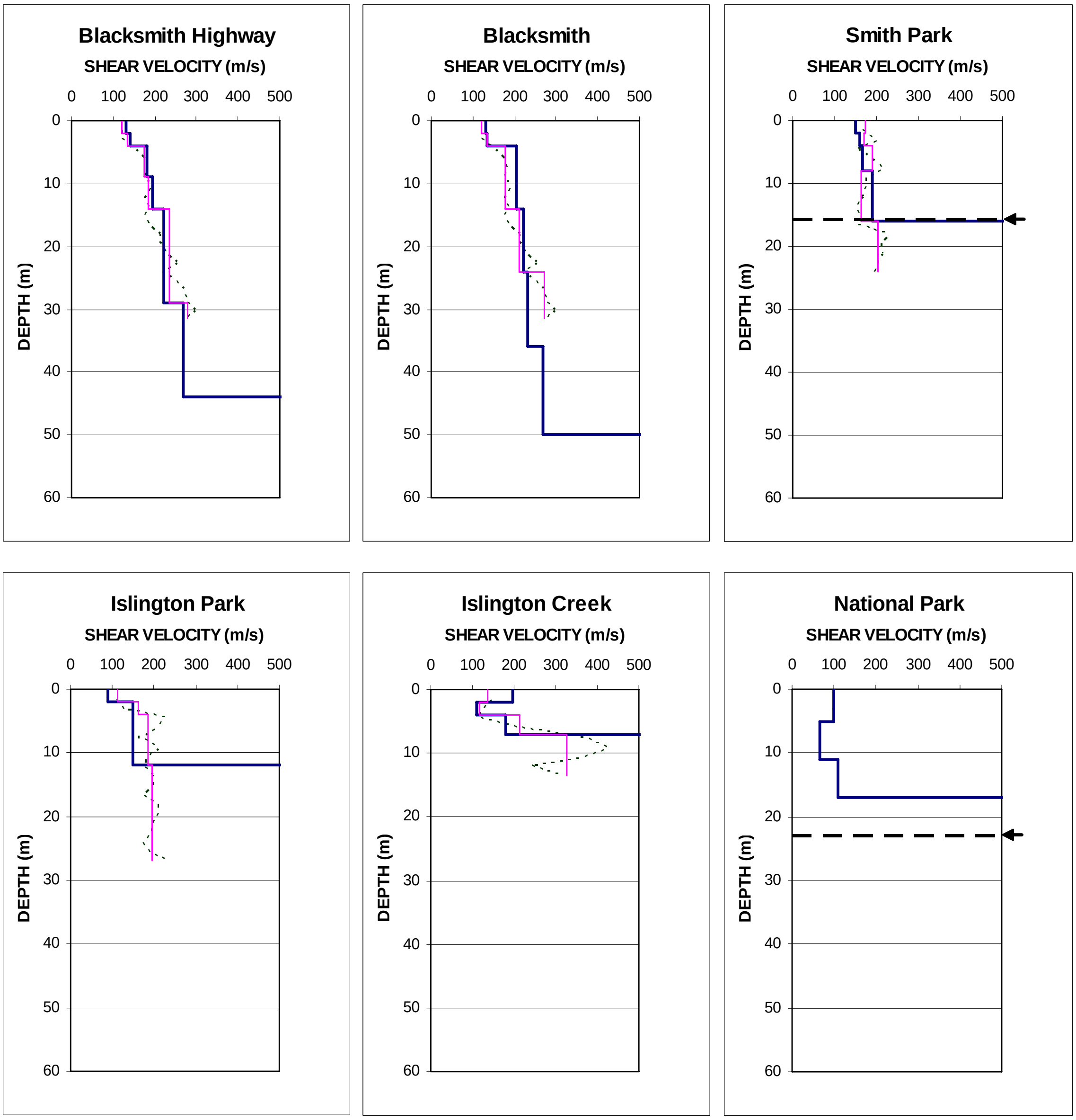

Figure 3: Shear wave velocity profiles for the six SPAC locations. Thick black line is the SPAC model, thin grey line is the SCPT model with same layer intervals as the SPAC model. Dotted line is the original SCPT model. Arrows denote the interpolated depth to bedrock from surrounding boreholes.

SCPTs (dotted lines Figure 3). Also shown are the SCPT profiles in layer thickness intervals corresponding to the intervals from the SPAC models (thin lines Figure 3).

The two Blacksmith sites show an overall good agreement between the shear wave velocities from the SPAC model and the SCPT model. For the Blacksmith Highway site which is situated 35 m from the SCPT site this level of agreement is expected. For the second Blacksmith site, the velocities disagree at some depths, probably due to the horizontal distance of 440 m on bearing 065 from the SPAC to the SCPT location. The SCPT was stopped at 31.5 m depth, but did not reach bedrock. The SPAC models suggest that the depth to bedrock is 44 and 50 meters respectively for the Blacksmith Highway and the Blacksmith sites.

The two Islington sites have been compared to different SCPT measurements. The SPAC and the SCPT at the Islington Park site shows an acceptable agreement in SWV profiles, although depth to bedrock is in disagreement by 15 m. This may be attributed to paleo-topographic variations over the 110 m (bearing 188) of horizontal separation between the SPAC and SCPT locations. This is supported by drilling information which suggests considerable variation in depth to bedrock over short distances in this particular area.

The SWV profiles from each of the two methods at Islington Creek are also in close agreement, except for the top 2 m. The SCPT is located 380 m on bearing 293 from the SPAC array, but in a similar geological environment, next to the creek. A disagreement in depth to bedrock also exists, but the 7 m obtained from the SPAC model seems to accord well to bedrock depths obtained from drilling.

The SPAC velocities acquired at Smith Park appear to be less compatible with velocities derived from the SCPT, and the difference in bedrock depth is 8 m. The horizontal distance from the SPAC to the SCPT site is 130 m, bearing 176, but information from drilling suggests that over this distance, changes of this magnitude are possible. Linear interpolation of surrounding depth to bedrock values indicates that the depth at the SPAC site should be 15.9 m, very close to the 16 m suggested by the SPAC model.

The National Park site was not located near any SCPTs, but a Cone Penetrometer Test (CPT) exists 200 m away on bearing 226. The model obtained from the SPAC data is therefore compared to this as well as log data retrieved from drill holes located 200-400 m from the SPAC site. Linear interpolation of surrounding depth to bedrock values suggests a value of 23 m. Given that extensive paleo-topographic variations over fairly short distances are likely within this area, a bedrock depth of 17 m obtained from the SPAC model is probably realistic. Furthermore, the measured SWV profile corresponds well to soil types deduced from the CPT which showed 5 m of clay followed by 6 m of sand underlain by 10 m of clay.

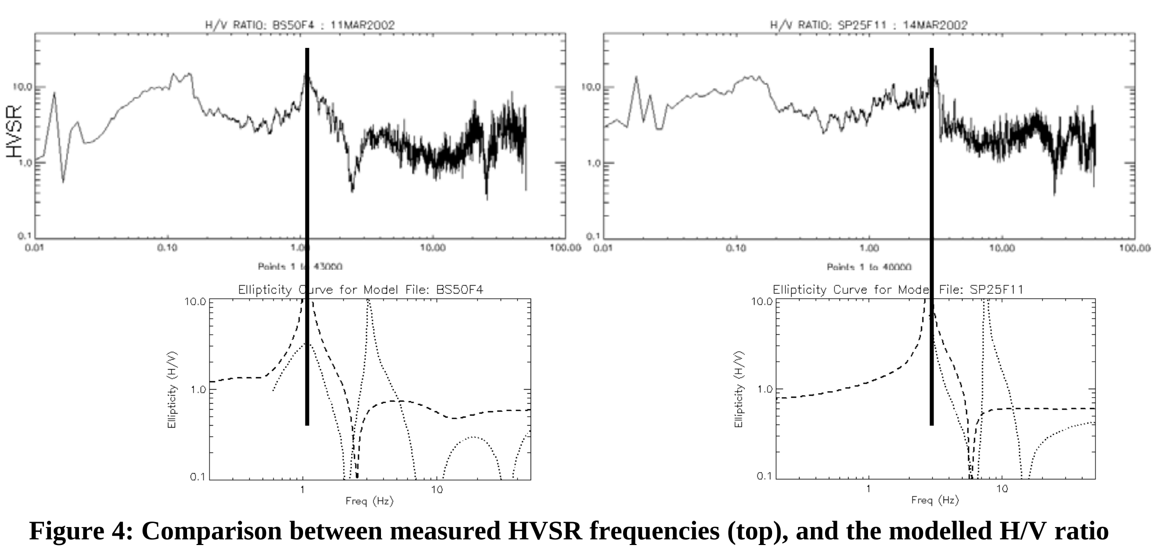

Figure 4: Comparison between measured HVSR frequencies (top), and the modelled H/V ratio (bottom) for Blacksmith (left) and Smith Park (right). The dashed line is the fundamental mode and the dotted line is the first higher mode.

At each SPAC location a HVSR measurement was conducted in addition to the SPAC measurement. This allows both the measured and the SPAC modelled horizontal to vertical Rayleigh wave particle motion ratio to be compared using the method given in Asten *et al*. (2004). Figure 4 provides two examples and shows that the measured and the modelled spectral ratio have coincident frequency peaks. This indicates that the model obtained from the array data is compatible with the HVSR data and increases confidence in the model.

For the Smith Park site, where there was a lack of agreement between the SPAC and SCPT data, the HVSR comparison is important for testing whether the SPAC derived model is sound. As seen on figure 4 to the right, the measured and modelled HVSR shows a close correlation between the frequency peaks.
The comparison can also be used as a basis for distinguishing between two potential models. Comparisons have been undertaken for all sites and generally a good agreement was found.

5. DISCUSSION

The results of the current study indicate that there is an overall close correlation between SWV profiles obtained using the two different methods of SCPT and microtremor arrays with SPAC processing. This is particular the case when distances between site locations are reasonably small, or when the measurements are conducted in geologically similar environments. However, for Smith Park and Islington Park at depth ranges of 4-16 m and 2-12 m respectively the shear wave velocities are not in close agreement. The discrepancy is approximately 15% for Smith Park and 20% for Islington Park, despite fairly short horizontal distances between the locations of the SCPT and the SPAC sites. One reason for this could be that the geology changes quite rapidly over short distances, an assumption that is supported by the geotechnical data. Alternatively the model obtained from the SPAC data is in fact not the best possible model. However, using the SCPT data as an input model for fitting the measured SPAC data, confirmed that the SCPT model did not fit the SPAC data. Consequently the SCPT model was not a more likely model. Although it is difficult to determine which of these factors contribute most to this problem, a comparison with the other sites suggests that a geological heterogeneity is the more likely explanation.

6. CONCLUSION

The SPAC measurements have shown that the method is a reliable way to obtain information about depths to bedrock and shear wave velocities over that depth range. Comparisons with seismic cone penetrometer tests exhibited a close agreement between shear wave velocities. The depth to bedrock was in most instances well resolved, but to make a direct comparison to the SCPT the horizontal distance between the SPAC and the SCPT should be as small as possible. Paleo-topographic variations over short distances are quite common. Furthermore the SPAC method is clearly better at resolving depths to bedrock in areas of thicker cover such as Blacksmith where the SCPT failed to reach bedrock and the alternative become invasive and costly conventional drilling methods.

The horizontal to vertical spectral ratio is a useful and important tool for confirming the validity of the model obtained from the SPAC data.

7. ACKNOWLEDGMENTS

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