SHEAR WAVE VELOCITY PROFILING IN MELBOURNE SILURIAN MUDSTONE USING THE SPAC METHOD

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ABSTRACT:

A passive seismic investigation technique known as the spatial auto-correlation (SPAC) method has been used to measure shear wave velocity profiles down to depths of approximately 100m around the Melbourne metropolitan area. A series of surveys have been carried out in different suburbs in Melbourne to develop an average shear wave velocity profile for the bedrock formation. This paper presents details of the surveys including geometries of the geophone arrays, measured auto-correlation spectra, theoretical spectra derived from layered earth models, and the resulting shear wave velocity profiles. These shear wave velocity profiles can be used to assist in modelling the seismic attenuation relationship and radiation damping properties of the bedrock in the area as demonstrated by companion papers presented at this conference.

A passive seismic surveying technique known as the Spatial Auto-Correlation (SPAC) method has been used to measure shear wave velocity (SWV) profiles down to a depth of up to 100m into Silurian mudstone around the Melbourne area. The SPAC technique appears to be well suited to the measurement of SWV profiles in urban areas. Its advantages include its non-invasiveness (no drilling required), speed of data acquisition, low cost and the ability to be able to provide shear wave velocity information over a wide range of depths. In a recent study undertaken jointly by the *Centre for Environmental and Geotechnical Applications of Surface Waves* (CEGAS) at Monash University and the *Earthquake Engineering Research Group* at the University of Melbourne, a series of SPAC surveys were undertaken at five sites around the Melbourne Metropolitan area to develop an average shear wave velocity profile from the surface to an approximate depth of 100-120m.

Major mechanisms amplifying seismic waves as they are transmitted to the ground surface are controlled by the SWV gradient of the earth crust. The effect of this amplification is particularly pronounced on sites covered by soft soil sediments. Consequently, SPAC has been used in previous studies in identifying high hazard sites and modelling the somewhat localised amplification effects of near-surface sediments. The objective of this study, which is distinguished from most of these previous studies (Asten et al, 2003; Asten, 2004), is to model the potential amplification and attenuation properties of seismic waves for the entire region based on measuring and analysing the SWV profiles recorded through thin overburden overlying Silurian mudstone (the basement rock in this region). This new approach of developing regional attenuation relationships is an attractive alternative to conventional modelling methods for regions of low and moderate seismicity where strong motion data is typically lacking.

This paper presents an outline of the basis of the SPAC technique (Section 2); a brief description of the varying geologic conditions within the Melbourne area (Section 3); details of the geophone arrays used (Section 4); measured and theoretical auto-correlation spectra obtained for the Monash University site (Section 5); and a summary of the SWV profiles obtained from each site covered by the study (Section 6). The companion paper (Lam et al, 2004a) presented at this conference, describes the analyses of measured SWV profiles towards the development of the regional attenuation relationship for the Melbourne region. Lam et. al (2004b) [submitted for review to ACMSM conference at Perth, Dec-2004] has presented a methodology to develop seismic attenuation relationships for any region around the globe, based on earth's crustal thickness. The methodology requires information on rock SWV profiles in the top 100m or so. Thus the influence of varied rock SWV profiles at the near surface, on attenuation of seismic waves has now been addressed.

1. BASIS OF THE 'SPAC' METHOD

The SPAC technique measures the propagation of microtremors – very low amplitude ground motions – that occur as the result of both natural (wind, wave action, atmospheric variations) and man-made (road traffic, trains, industrial noise) phenomena. Although the amplitude and frequency content vary with both space and time, microtremors form a background 'field' of (low-amplitude) seismic waves, with most of the energy transported as surface waves. Surface waves are dispersive (i.e. velocity of propagation is dependant upon frequency), with the velocity-frequency relationship being governed (principally) by the shear-wave velocity structure of the earth.

The SPAC technique has as its basis, a mathematical formulation first put forward by Aki (1957) which shows that the azimuthally averaged signal coherency measured using an array of geophones is related to the velocity-frequency characteristics of the ground beneath the array. By measuring microtremor signal coherency in the field, it is therefore possible to estimate the shear-wave velocity structure in the subsurface over a wide range of depths. Okada (2003) provides a detailed overview of the SPAC technique, while recent studies in Australia (Asten, et al, 2003; Roberts and Asten, 2004) and overseas (Asten, 2004; Apostolidis et al, 2004) have demonstrated the effectiveness of the method in providing shear-wave velocity profiles in a number of different cities.

2. SITE DESCRIPTION

The surveys were carried out at five locations distributed around the Melbourne metropolitan area as shown in Figure 1.

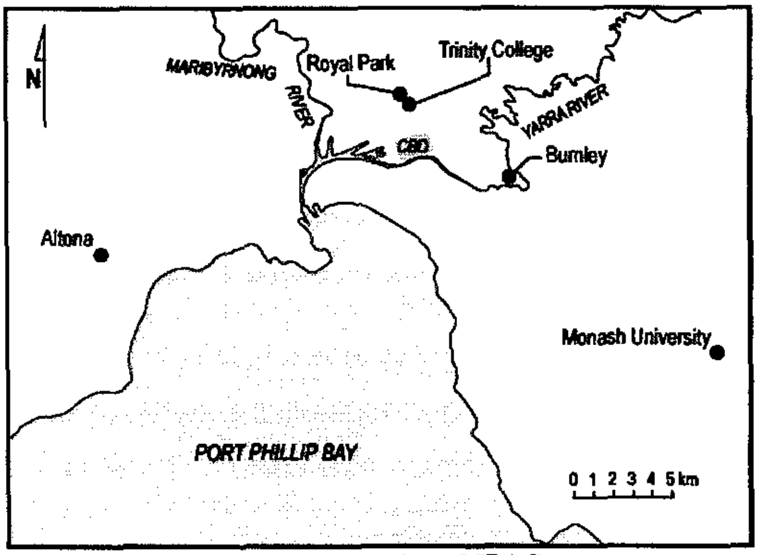


Figure 1: Location of SPAC surveys

The geology of Melbourne and surrounding areas is both complex and variable (Archbold, 1992). Basement rock across Melbourne and surrounding suburbs consists of folded sandstone and siltstone sequences of early to mid-Palaeozoic age (approximately 400 to 450 million years). Although the basement rock is relatively uniform in character, the depth of weathering and extent of jointing is variable (Haustorfer, 1992).

In parts of Melbourne (north, east and northeast of the CBD), this 'basement' rock outcrops at the surface, with no overlying geologic material. This geology is expected at the Royal Park and Trinity College sites indicated in Figure 1. To the north, west and northwest of the CBD, sheets of extrusive basalt rock of variable thickness overly the older basement rocks. The Altona site (Figure 1) is located within this geologic region of Melbourne, while the Burnley survey was undertaken over basalt that constitutes the extreme eastern extent of the basalt. The southeastern suburbs are characterized by significant Tertiary and Quaternary age sediments, consisting of variably consolidated sand, clay and silt which overly the Silurian basement rock. The Monash survey is located in an area that is close to the boundary between these recent sediments and the outcropping basement rock.

3. GEOPHONE CONFIGURATION

SPAC field data consists of time-domain recordings of (vertical, and hence Rayleigh wave) ground motion as measured by an array of geophones. For an array of seven geophones, a hexagonal geometry provides even azimuthal sampling (60 degree spacing) of microtremor energy and is best for situations where microtremor energy is assumed to be propagating evenly from all directions. In situations where a particular direction is likely to account for a greater proportion of the microtremor energy (such as in proximity to a freeway), the array can be placed to 'aim' at the source to better sample the dominant directions of propagation. The 'folded hemisphere' consists of a semi-circular array, consisting of pairs of geophones aligned with an azimuthal spread of 30 degrees. To make this array more compact, one 'half' of the array is offset to lie over the other half in such a way that the most central geophone is common to both halves of the semicircle (as shown in Figure 2).

4. PROCESSING METHODOLOGY

Detailed explanations of the SPAC processing technique are not included in this paper. Readers are directed to references such as Okada (2003) or Asten et al (2004) for general details of the SPAC technique and Asten et al (2003) or Roberts and Asten (2004) for description of the processing and interpretation methodology.

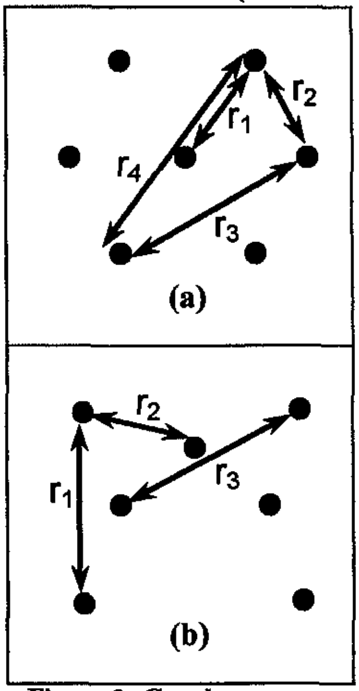


Figure 2: Geophone array geometries – (a) hexagonal array and (b) "folded hemi" array.

The interpretation of SPAC data consists of fitting the spectra of averaged coherencies measured in the field with the theoretical spectra corresponding to a horizontally layered earth model as governed by equation (1) below.

Routines by Hermann (2001) allow for the dispersion relation, $V(f)$ (Rayleigh wave phase velocity as a function of frequency) to be determined from layered-earth model parameters. Although layer density and compressional (P-wave) velocity contribute to the dispersion relation, shear velocity and layer thickness are the most sensitive model parameters. It can be seen from equation (1) that the resulting (theoretical) coherency spectra should have a form corresponding to a Bessel function, which has the appearance of a decaying sinusoidal waveform.

Model parameters (shear velocity and layer thickness) are iteratively varied until the 'best-fit' is achieved between theoretical and measured coherency spectra, as shown in Figure 3 below for data collected on the grounds of Monash University. The solid black line is the field (averaged) coherency curve obtained by processing of the ground motions at each station in the array. The dashed line represents the theoretical coherency curve for the 'best-fit' layered earth model, based upon *fundamental* mode Rayleigh wave motion, which is assumed to be dominant in the frequency range of interest and in the absence of near-sources.

$$\bar{c}(f) = J_0\left(\frac{2\pi f r}{V(f)}\right) = J_0(k.r) \qquad (1)$$

where: f is frequency,

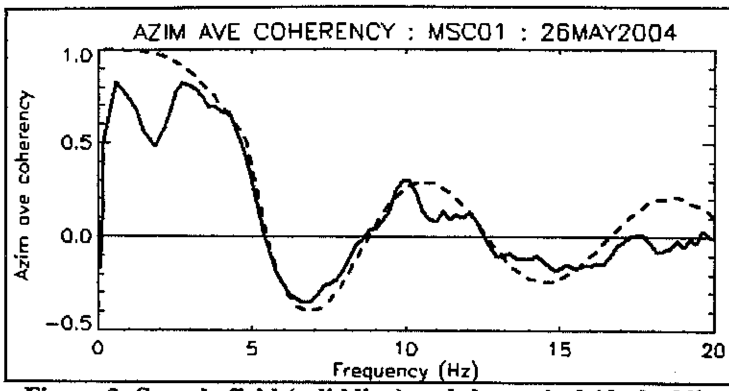
$\bar{c}(f)$ is the azimuthally averaged coherency,

J_0 is the zero-order Bessel function,

k is the scalar wavenumber,

$V(f)$ is the velocity dispersion relationship, and

r is the station separation in the circular array.



Layer thickness (m)	V_P (m/s)	V_s (m/s)	Bulk density (g/cm^3)
2	800	400	1.6
4	900	450	1.7
12	900	450	1.7
16	1000	550	1.8
20	1300	650	1.9
20	2000	1400	2.4
200	3000	2000	2.5
3900	4670	2696	2.6

Figure 3: Sample field (solid line) and theoretical (dashed line) autocorrelation spectra [left]; and corresponding layered earth model parameters for Monash University [right]. Array used was hexagonal (see Figure 2a) with $r_1 = 48$m.

5. SHEAR WAVE VELOCITY PROFILES FOR CASE STUDY SITES

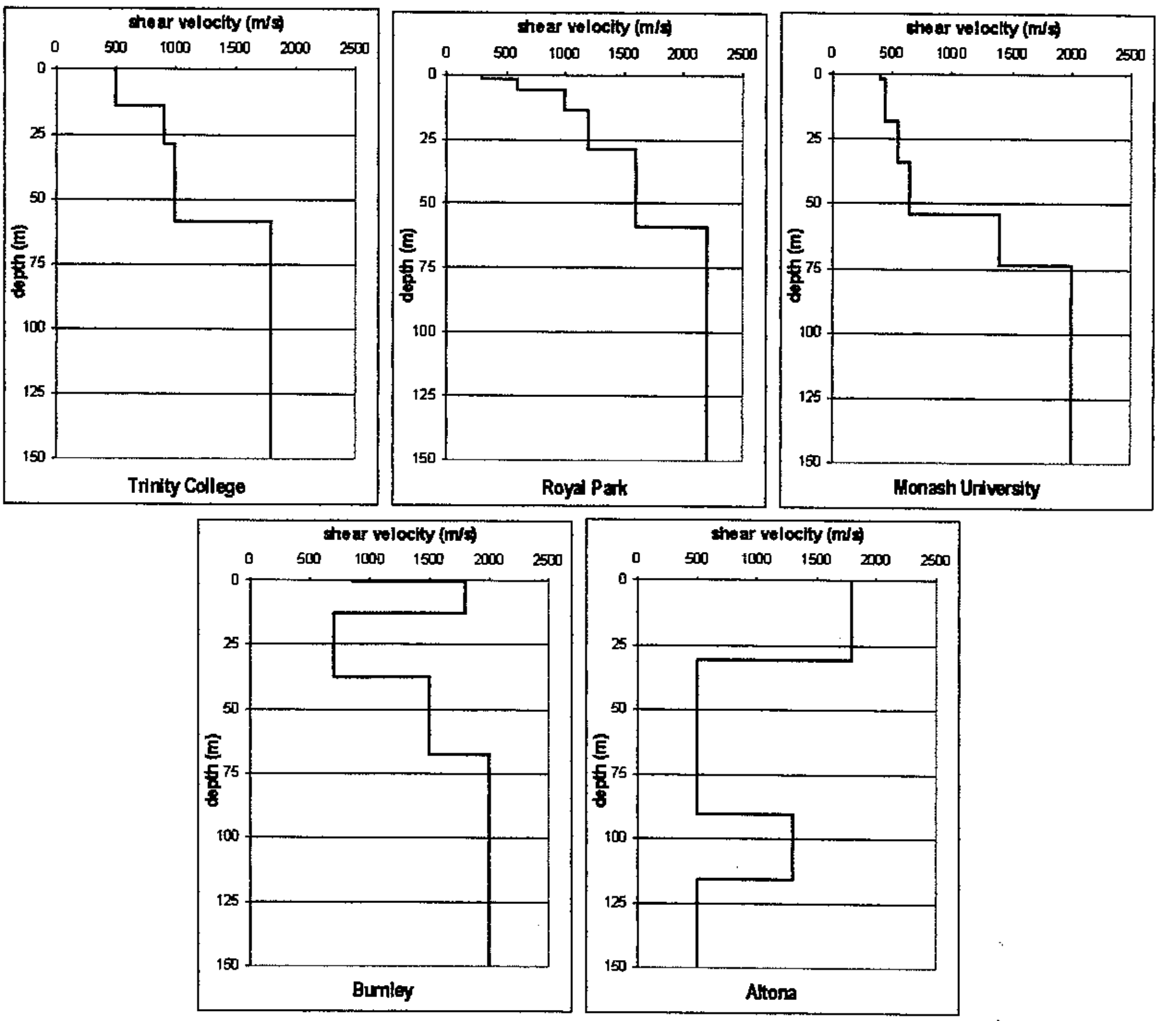


Figure 4: SWV profiles obtained from SPAC microtremor surveys in the Melbourne area.

Trinity College: Two separate SPAC surveys have been undertaken at this site. An initial survey conducted in September 2003 with hexagonal arrays of 'radius' 17 m and 35 m provided data of insufficient quality to provide definitive results. A more recent survey using the folded hemi array geometry, with a radius of 45 m, provided a significant improvement, allowing the interpretation of the SWV profile, which is indicated for this site in Figure 4. This profile is consistent with the earlier data, but enables determination of the SWV to a depth of approximately 100m. A lack of coherent low frequency microtremor energy and the size of the array limit the reliability of the interpretation below this depth.

Royal Park: Although this site is located less than 1km from the Trinity college site, a significant variation in the interpreted SWV profile can be observed between the two sites. This corresponds with available geological information, which indicates that while Trinity College is located on outcropping Silurian mudstone basement, Royal Park lies in an area where the surface geology is dominated by unconsolidated Tertiary age sandy sediments. A hexagonal array of 48 m radius was adopted for this site to provide the profile in Figure 4.

Monash University: Hexagonal array of 48 m was adopted at this location on a soccer ground. The interpreted SWV profile indicates a significant thickness (<50 m) of relatively soft sediment overlying a higher velocity basement at this site. This result is consistent with geologic maps that indicate that the site lies in an area of poorly consolidated sandy sediments of Tertiary age overlying Melbourne Mudstone.

Altona: At this site, adjacent to Laverton Bowling Club, both a 48 m radius hexagonal array and a coincident 48 m radius folded hemi array were adopted during a SPAC survey undertaken in May 2004. Initial interpretation (under the assumption of fundamental mode Rayleigh wave motion) of this data proved difficult, due to a sharp discontinuity in the coherency curve at a frequency of approximately 4–5 Hz. After more detailed analysis, which identified and addressed the presence of higher mode Rayleigh wave motion, the SWV profile indicated in Figure 4 allowed for a strong agreement between the measured and theoretical coherency curves. This SWV profile is also consistent with geologic cross sections available in this area. This site displays an unusual SWV structure due to a complex geologic structure of alternating layers of (hard) basalt and (soft) sediment.

Burnley: A 48 m radius hexagonal array was adopted for SPAC measurements at this site during October 2003. The resulting SWV profile is quite precisely constrained by relatively high data quality at this site, with velocity and thickness of both the high-velocity layer at the surface and the lower velocity underlying sediments being constrained to within 10-20% of the listed values. More detail on the interpretation of this data can be found in Roberts and Asten (2004). It is observed that the SWV profile (along with that interpreted for the Altona site) shows a high shear velocity layer (basalt) in the upper ten or more meters. In the companion paper however, the basalt layer will be removed in order to provide a general picture of the bedrock structure in Melbourne.

6. CLOSING REMARKS

The usefulness of the SPAC technique in modelling the basement SWV profiles has been demonstrated in this paper based on surveys undertaken on five sites around the Melbourne metropolitan area. The SWV profiles measured from these sites represent considerable variability in the velocity structure of the upper 100 m of the crust around Melbourne. In the companion paper, these SWV profiles are adopted to develop a regional attenuation model for the area. The series of surveys described in this paper represent the first of ongoing attempts to utilize the SPAC technique to measure SWV profiles for use in earthquake hazard studies. Unfortunately, no cone penetrometer results are available for comparison with the SWV profiles obtained using the SPAC technique at the sites in this study. Furthermore, resolution of shear velocities within the basement rock was limited by thickness of cover and the array size used. With further research and experience in this application of SPAC along with the implementation of larger array sizes, it is expected that more detailed definition of SWV profiles can be developed for the Melbourne area.

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