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Estimating the shear velocity profile of Quaternary silts using microtremor array (SPAC) measurements

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Key Words: microtremor method, Rayleigh waves, sediment thickness, shear velocities, Yarra Delta, SPAC, spectral ratio

ABSTRACT

We have used the microtremor method, with arrays of up to 96 m diameter, to carry out non-invasive estimation of shear-wave velocity profiles to a depth of 30 to 50 m in unconsolidated Quaternary Yarra Delta sediments. Two silt units (Coode Island Silt, and Fishermans Bend Silt) dominate our interpretation; the method yields shear velocities for these units with precision of 5%, and differentiates between the former, softer unit (V_s = 130 m/sec) and the latter, firmer unit (V_s = 235 m/sec). Below these silts, the method resolves a firm unit correlating with known gravels (V_s 500 to 650 m/sec).

Using surface traverses with the single-station H/V spectral ratio method, we show that the variation in thickness of the softer silt can be mapped rapidly but only qualitatively. The complexity of the geological section requires that array methods be used when quantitative shear-wave velocity profiles are desired.

INTRODUCTION

This paper is a study of the use of the microtremor method in characterising the shear-wave velocity profile of Quaternary sediments (and in particular, near-surface silts) using non-invasive passive seismic methods.

Geology of the Yarra Delta, Australia

The Yarra Delta in Victoria, Australia, comprises a sequence of Quaternary sediments deposited at the northernmost extent of Port Phillip Bay during previous periods when sea level was higher than at present. Beneath the Quaternary sediments lies an embayment of Tertiary sediments, basalts, and Silurian mudstones at variable depth beneath the present, low-relief ground surface (Cupper et al., 2003). During successive periods of sea level fluctuation, a range of sediment types has been deposited in the Yarra Delta, representing a range of depositional environments.

The most recent unit is known as the Port Melbourne Sand (PMS), which consists of predominantly clean, fine- to medium-grained sands. Beneath the PMS lies Coode Island Silt (CIS) – a dark grey-brown silty clay of soft to firm consistency – which has presented many geotechnical challenges because of its low shear strength and high compressibility, resulting in highly variable settlement characteristics (Neilson, 1992; Ervin, 1992). Underlying the CIS is the Fishermans Bend Silt (FBS), a stiff to very stiff silty clay. At the base of the Quaternary sequence lie the Moray Street Gravels (MSG), consisting predominantly of fine- to medium-grained gravels. A cross-section taken from Cupper et al. (2003) passing through the survey area is shown in Figure 2.

Both the CIS and FBS generally occur as silty clay according to the Universal Soil Classification system, but they have distinctly different geotechnical characteristics. Coode Island Silt is generally of soft to firm consistency and experiences significant primary and secondary settlement, even under relatively low applied stresses. Fishermans Bend Silt is, by contrast, stiff to very stiff in consistency, and exhibits relatively little settlement under modest loading, making it a favourable founding material for foundation piles (Ervin, 1992). Identification of the difference in shear velocity between the softer CIS and firmer FBS silts is a principal result of this paper.

The microtremor method

"Microtremor" is the name given to the background, low-amplitude seismic waves which are present everywhere at the Earth's surface. With amplitudes of the order of 10^{-4} to 10^{-2} mm (Okada, 2003), microtremors represent a low-energy wave field consisting of interfering waves propagating from a range of different sources and directions, at many frequencies. Microtremors with frequencies above 1 Hz are generally associated with man-made, cultural sources (such as road traffic, trains, machinery, etc.), while those below 1 Hz are associated with natural phenomena such as wind and wave action and variations in atmospheric pressure.

The spectral characteristics of microtremor energy vary in both space and time. Hence, the amplitude and frequency content of measurements made at a fixed location will likely vary at different times of the day. Likewise, these characteristics are also likely to vary between two separate locations measured simultaneously, depending upon the relative proximity of each site to seismic sources. Despite these variations, when considered over suitably short time periods (e.g., a few minutes at a time) at a fixed location, the wave field can be considered stationary in time (Okada, 2003).

Although the microtremor wave field consists of both body waves and surface waves, at sufficient distance from any source of seismic energy, most of the energy propagates as surface waves (Toksöz and Lacoss, 1968). The vertical component of such wave motion can be assumed to correspond to Rayleigh wave modes. In all layered media except a uniform half-space, Rayleigh wave motion is dispersive; velocity of (horizontal) propagation is a function of the velocity structure beneath the Earth's surface. In simple terms, seemingly random ambient ground vibrations carry significant information about the velocity structure (and associated physical properties and geological character) of the subsurface. High-frequency (short wavelength) vibrations have propagation characteristics governed by elastic properties of the near surface, while lower frequencies (longer wavelengths) are influenced by properties at greater depth.

In this paper, we explore two techniques that utilise observations of microtremor ground motion to deduce shear wave velocity structure and to qualitatively assess variations in the thickness of recent sediment in the Port Melbourne area. By using only

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naturally occurring background seismic noise, both methods qualify as passive seismic techniques, requiring minimal equipment and permitting for their operation in an urban area.

Two classes of processing methodologies are commonly applied to microtremor data; Tokimatsu (1997) provides a valuable review of both. The first class consists of single-station methods, where a three-component record from a single geophone is processed to yield a spectrum of the horizontal to vertical particle-motion ratio. Such data shows spectral maxima near resonances associated with notional vertically propagating shear waves, and thus provides indications of sediment thickness and shear velocity.

The second class of microtremor methodology employs array techniques to measure propagation velocities of the Rayleigh waves. The most common processing technique is the Spatial Autocorrelation (SPAC) method. This method relies on averaging of inter-station coherency spectra over a range of azimuthal directions to obtain wave velocity.

Horizontal to vertical spectral ratio (HVSR) method

Measurement of high frequency seismic "noise" (i.e., microtremor) is a well-established means of assessing resonance frequencies of relatively thick (tens of metres) unconsolidated sediments overlying a stiff basement. The approach described by Nakamura (1989) utilizes measurements of ground motion made using a single three-component sensor to determine the fundamental period (T_s) of a site. Tokimatsu (1997) examines the relationship between natural site (resonance) period for alluvium overlying basement rock and the frequency (period) at which a maximum is observed in a plot of the horizontal to vertical (H/V) ground motion versus frequency spectral ratio (HVSR). The amplitude and shape of the maxima in the HVSR plot are also characteristic of the shear velocity structure of the subsurface. Sites displaying a sharp shear-velocity contrast between a soft layer (e.g., recent sediment) overlying a hard basement generally have a distinct peak of high amplitude in the H/V spectra. For a steady increase in velocity (e.g., a deep soil site with gradual increase of V_s with depth, or a rock site), the H/V spectra will not display a significant peak. A theoretical estimate of H/V spectra can be made (analytically) for a horizontally layered earth model, enabling some estimate of velocity structure from a single-station measurement. Tokimatsu (1997) notes several limitations in the use of this approach for establishing layered-earth structure. Bodin et al. (2001) provides an example of use of the method, and Stephenson (2003) and Asten (2004) discuss some of the physical conditions affecting the shape of the HVSR spectrum.

Despite the potential for ambiguity and complexity in HSVR measurements, the technique is a widely accepted means of obtaining (principally) qualitative comparisons of subsurface structure at different sites.

Spatial autocorrelation (SPAC) processing

If, at any given frequency, wave energy propagates with only one (scalar) velocity, it can be shown (Aki, 1957; Asten, 1976; Okada, 2003) that the azimuthally averaged coherency for a circular array is given by

$$\bar{c}(f) = J_0\left(\frac{2\pi fr}{V(f)}\right) = J_0(kr) \ , \qquad (1)$$

where $\bar{c}(f)$ is the azimuthally averaged coherency, f is frequency, J_0 is the zero-order Bessel function, k is the scalar wave number, $V(f)$ is the velocity dispersion relationship, and r is the station separation in the circular array.

In this work, we use a variant of SPAC, in which the simultaneous use of averaged coherency spectra acquired over multiple array station separation distances allows recognition of multiple-mode Rayleigh wave propagation (Multiple Mode SPAC or MMSPAC; Asten et al., 2003; Asten et al., 2004).

PORT MELBOURNE MICROTREMOR STUDIES

This paper presents the results of a series of microtremor measurements undertaken in the Port Melbourne, Australia, area, at locations indicated in Figure 1. The field measurements were made with two seven-station hexagonal array recordings using Mark L4C 1 Hz geophones, and 32 single station recordings using a three-component geophone. The first array location was on vacant land immediately adjacent to Lorimer Street (hereafter referred to as the "Lorimer Street array") and consisted of recordings taken with array radii of 48 and 15 m. A second array was situated at Westgate Park ("Westgate Park array"), with an array radius of 21 m. A larger array was not possible at this site due to space and access limitations within Westgate Park.

Shear velocity profiles from SPAC processing of array recordings

Multiple seven-channel records of vertical component ground motion were made at each site, using a sampling rate of 200 samples per second and data lengths of 200 seconds. The data were corrected for the transfer characteristics of each geophone using pre-established calibration data, and SPAC spectra were computed for each recording for the four station-separation distances allowed by the hexagonal array geometry (Asten et al., 2004). Each of the SPAC spectra computed for a given array size and site showed a consistent coherency curve over each of the multiple records. The smoothest curve from each set of records was then selected for interpretation.

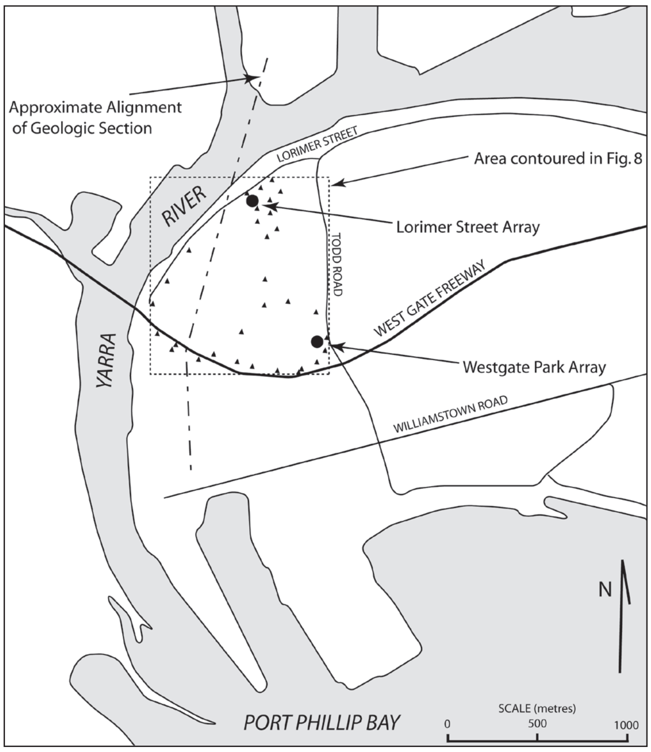

Fig. 1. Site location map indicating survey locations, proximity to major roads, and the position of the geological section shown in Fig 2. SPAC array locations are as indicated. The small triangles represent locations of single-station, 3-component recordings for H/V spectral ratios.

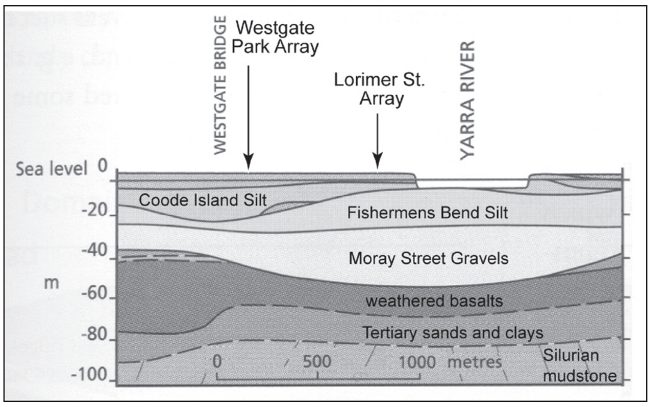

Fig. 2. Geological section through Port Melbourne and Fishermans Bend. (Reproduced from Cupper et al. (2003), Figure 11.19).

The interpretation procedure used was similar to that used in a previous engineering-scale investigation (Roberts and Asten, 2003). This consists of a manual, iterative comparison of analytically computed model coherency curves (computed for a 1D or layered-earth model) with those obtained from the field measurements. The response of the resulting "best-fit" model for each of the three array configurations is shown in Figures 3, 4, and 5.

Lorimer Street Array

Figures 3 and 4 show both the field and modelled coherency spectra for each of the array sizes recorded at this site. Both the modelled spectra are computed using equation (1) based upon a layered-earth model corresponding to the shear-wave velocity (SWV) profile shown in Figure 6 for Lorimer Street. While only the shear wave velocity and layer thicknesses are indicated here, compressional velocities and densities were chosen to be physically consistent with the chosen shear velocities.

The coherency spectra of Figure 3 (15-m radius hexagonal array) shows a strong agreement between the observed and model curves over the frequency range 4 to 20 Hz, although in some regions of the curve the data is noisy. The SWV profile is well constrained by particular attention to the matching of curve crossovers (points of zero coherency) and the location of apparent local maxima and minima in the field data.

For the larger (48-m radius) Lorimer Street array (Figure 4), there is somewhat better resolution of coherencies below 4 Hz down to approximately 2 Hz. This is at the expense of precision at higher frequencies (as for the smaller array mentioned above), underlining the advantages of using multiple array radii at a given location. The modelled coherency curve for the 48-m radius array shows good agreement with the field data in terms of the location of crossovers and minima and maxima locations.

The interpreted SWV profile corresponding to the coherency curves for Lorimer Street indicates two very low-velocity layers in the top 10 metres, with shear velocities of 140 and 130 m/s. The velocity of the five-metre thickness of 130 m/s material is resolved with a high level of precision (±5%); alternative models with 140 or 120 m/s show clearly poorer fits to the field data. Underlying the very-low velocities in the upper 10 metres is a similar thickness of 235 m/s material. Again, this velocity is quite well constrained by the data. At depths below 25 to 30 m, the data begins to lose sensitivity, owing to the relatively long wavelengths resulting from the very low velocities. Despite this, a 'basement' velocity on the order of 650 m/s is resolvable to order ±20%. The extent of this 'basement' layer is not interpretable from the field data and would require additional observations with a larger array.

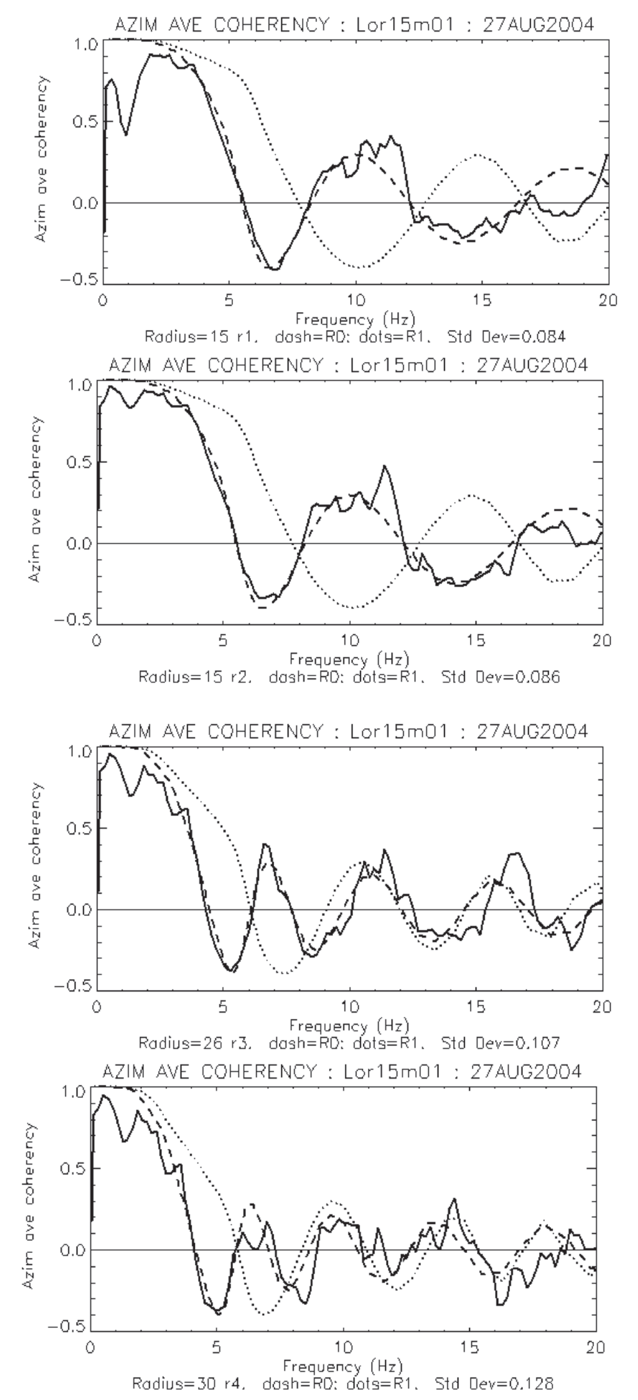

Fig. 3. Results of iterative interpretation procedure for Lorimer Street 15 m radius array. Station separations are (a) 15 m, (b) 15 m, (c) 26 m, (d) 30 m. Solid black line: field data SPAC spectrum; Dashed line: model SPAC for the layered earth shown in Figure 6, fundamental Rayleigh mode, used for iterative fitting to field data; Dotted line: model SPAC for the first higher Rayleigh mode; shown for reference purposes only since higher modes appear to be absent in this sample of field data.

Examination of the cross section (Figure 2) from Cupper et al. (2003) shows that beneath the approximate location of the Lorimer Street array there is about 5 m of Port Melbourne Sand over a similar thickness of Coode Island Silt. These layers are interpreted to correspond to the 10 m thick section of very low velocities discussed above. Beneath the Coode Island Silt, the section shows approximately 15 m of Fishermans Bend Silt overlying at least 20 m of Moray Street Gravels. As noted earlier, the Fishermans Bend Silt is known to be stiffer than the Coode Island Silt, so an

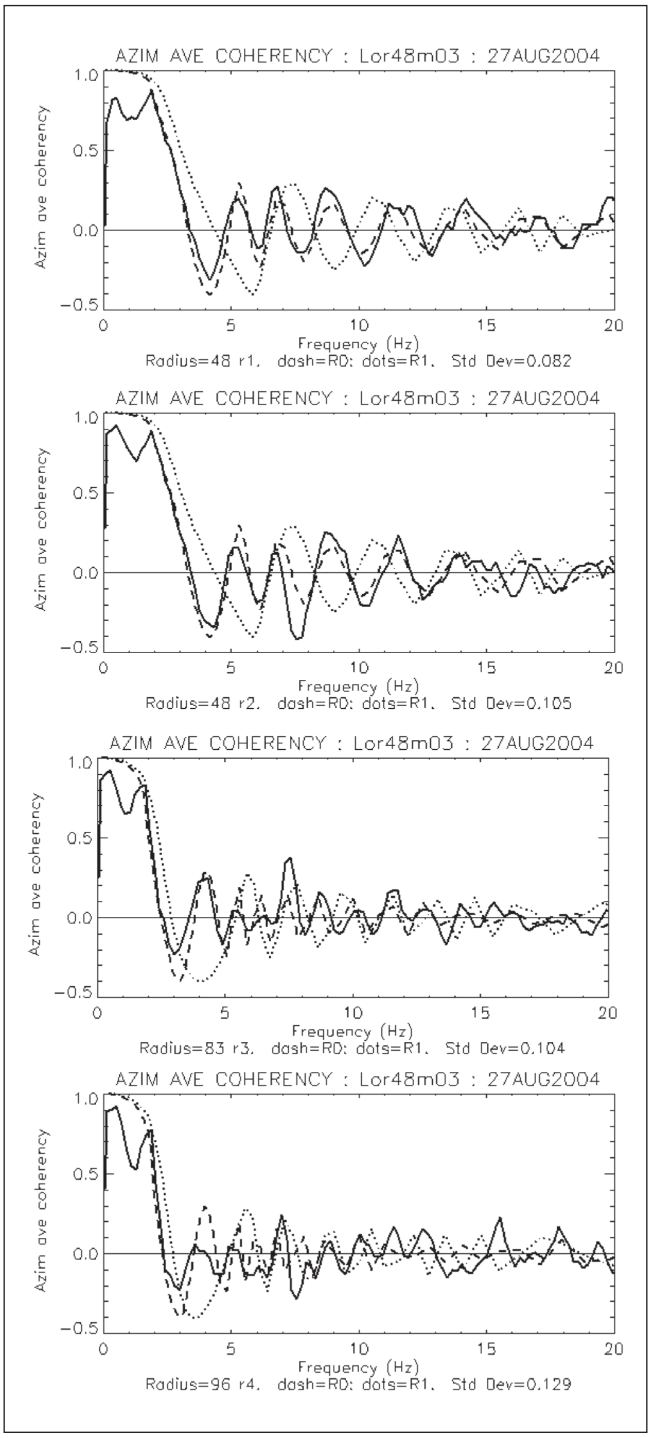

Fig. 4. Results of iterative interpretation procedure for Lorimer Street 48 m radius array. Station separations are (a) 48 m, (b) 48 m, (c) 83 m, (d) 96 m. Line types as for Figure 3.

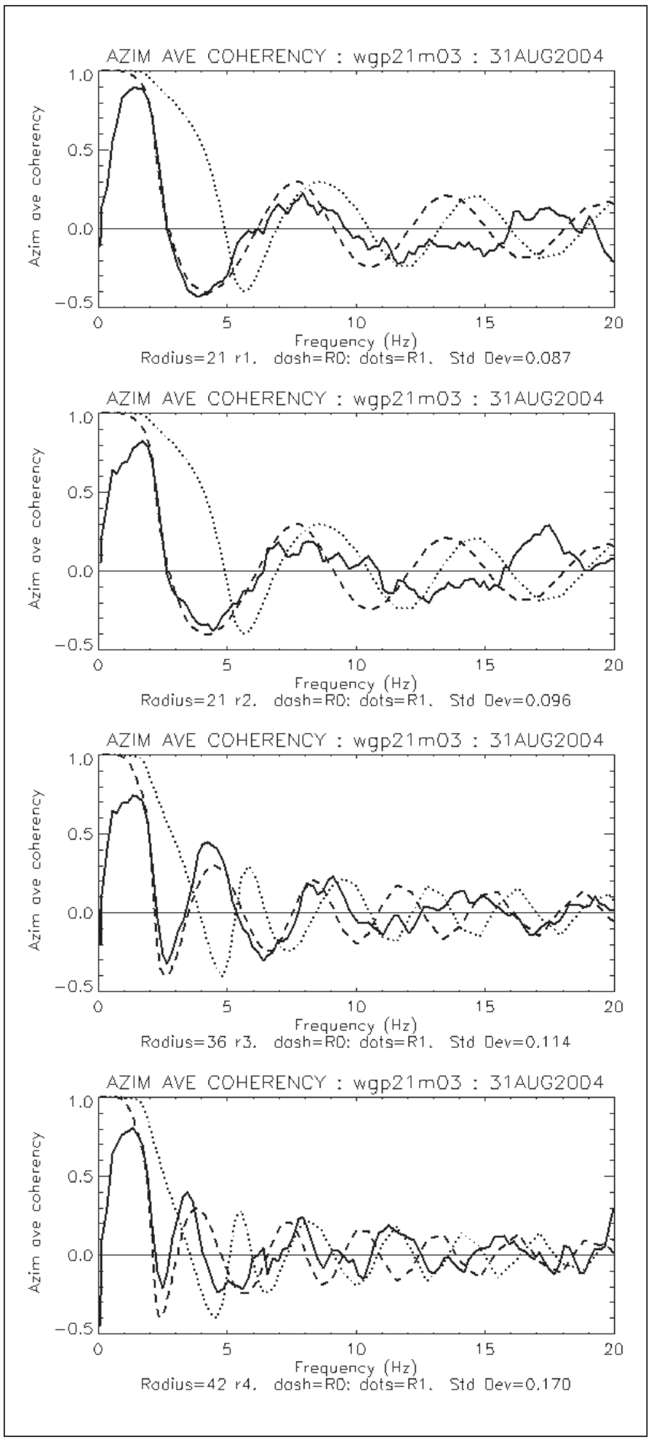

Fig. 5. Results of iterative interpretation procedure for Westgate Park 21 m radius array. Station separations are (a) 21 m, (b) 21 m, (c) 36 m, (d) 42 m. Line types as for Figure 3.

increase in shear velocity from 130 to 235 m/s between these two layers is justifiable and consistent with the geological section. Finally, the 'basement' resolved by the SPAC spectra most likely corresponds to the presence of the Moray Street Gravels, for which a shear velocity on the order of 650 m/s is physically reasonable.

Westgate Park Array

Field and modelled coherency spectra for the 21-m radius array located at Westgate Park are shown in Figure 5. It is noted that the fit between field and model coherencies is good only for frequencies between 2 and 10 Hz at this site. The shape of the coherency spectra above 10 Hz are consistent with a (relatively) high velocity layer in the near surface as evidenced by a relative increase in the spacing between successive crossovers (points of zero coherency) of the field data. Such a velocity structure can potentially favour the dominance of complex modes of Rayleigh wave propagation, complicating the interpretation procedure beyond the scope of discussion for this study. It is also possible that the coherency response in the higher frequencies may be affected by variations in the physical properties of the upper few metres within the array footprint. Between 2 and 10 Hz, the fit is much better, enabling good resolution of shear wave velocity over the corresponding depth range (approximately 5–50 m) based on the resulting Rayleigh wave dispersion curve.

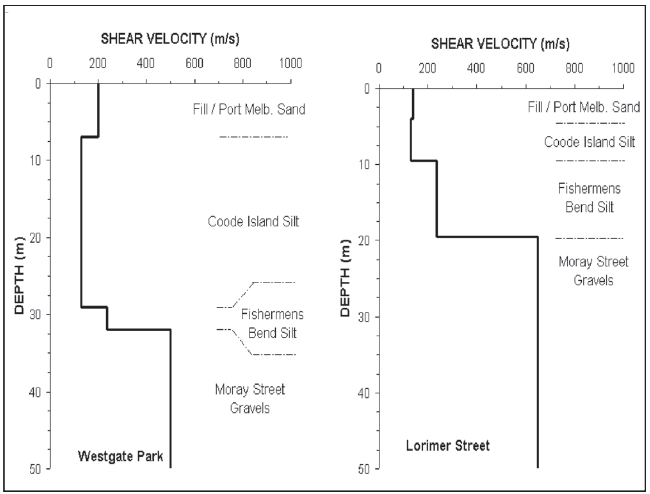

Fig. 6. Best-fit shear-wave velocity profiles corresponding to the interpreted coherency spectra shown in Figures 3 and 4 (Lorimer Street) and Figure 5 (Westgate Park).

The SWV profile for the resulting layered-earth model is shown in Figure 6. At the top of this profile lies a 7-m thick layer with a shear velocity of 200 m/s. The velocity here is not well resolved (to do so would require use of a smaller array), although it is clearly higher than that of the underlying layer. Inspection of the geological section of Figure 2 shows that the surface material is likely to be Port Melbourne Sand, with a greater thickness (on the order of 8 metres thick) than that seen at the Lorimer Street site. The shear velocity of this layer at the Westgate Park site (V_s = 200 m/s) is also higher than for the surface layer at Lorimer Street (V_s = 140 m/s). However, Westgate Park bears evidence of significant earthworks in the construction of ponds and hills as landscaping features, which may have altered the physical properties (density and stiffness) of the natural soils.

Beneath the surface layer lies a 22-m thickness of low-velocity material, with a well-constrained shear velocity of 130 m/s (±5%). The thickness of this layer is also relatively well constrained by the match between observed and model coherency spectra. Owing to the very low velocity in this layer, which corresponds to the velocity observed at Lorimer Street, this layer is interpreted to be representative of Coode Island Silt. The geological section (Figure 2) published by Cupper et al. (2003) supports the notion of an increase in thickness of Coode Island Silt between Lorimer Street and Westgate Park. The same section also suggests a thinning of the Fishermans Bend Silt (nominal velocity of 235 m/s based on Lorimer Street results), which is evidenced in the interpreted SWV profile. The presence of a 3 m thick layer of shear velocity 235 m/s used in this model is too thin to be resolved by the data, but is included only for consistency with the geological sequence.

Beneath the well-resolved thickness of very low shear velocity (Coode Island Silt) lies a stiffer layer with an approximate shear velocity of 500 m/s. This velocity is not well resolved by the smaller array used at this site, and is interpreted to be associated with a "basement" representing the Moray Street Gravels (equivalent to the 650 m/s layer observed at the bottom of the profile for the Lorimer Street array).

Horizontal to vertical spectral ratio measurements

Three-component recordings (for HSVR analysis) were made at a range of locations on the vacant land at Lorimer Street, along the edges of Lorimer Street itself, within the boundaries of Westgate Park and along bicycle paths passing beneath the Westgate Bridge. Three-component recordings were also recorded at the centre of

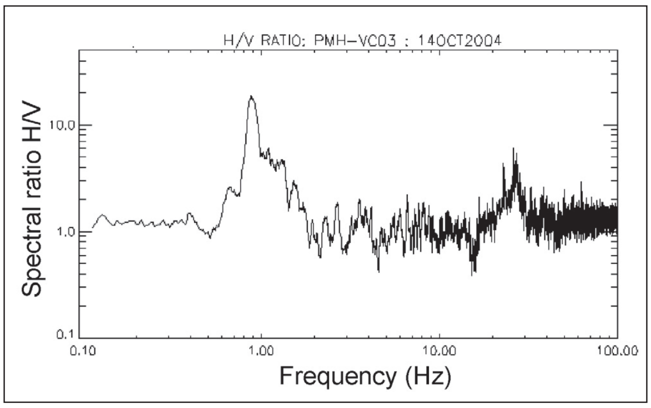

Fig. 7. Sample H/V spectral ratio. Note the distinct peak at a frequency of approximately 0.9 Hz. Similar records (at locations shown in Figure 1) were used to construct the contour map shown in Figure 8.

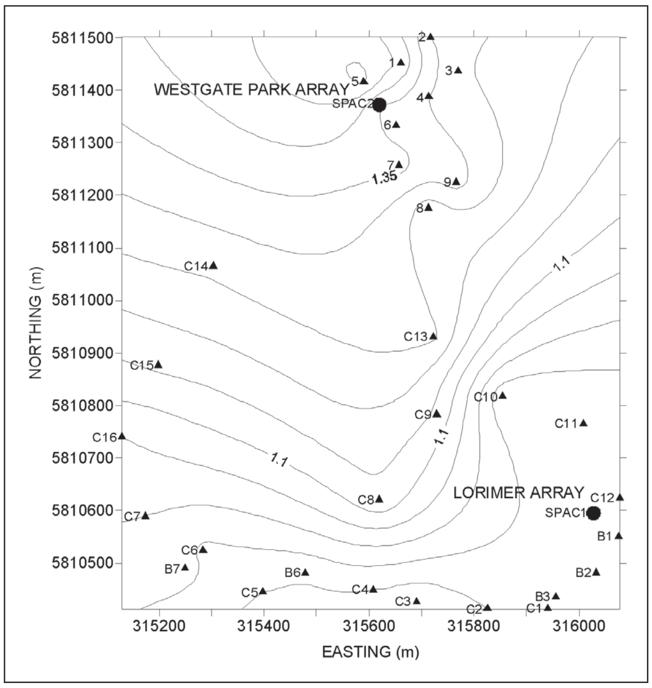

Fig. 8. Contour map showing trends in H/V spectral ratio (HVSR) peaks (in Hz), based on three-component ground motion recordings. Higher values correspond to zones where silt is thinner, firmer, or both. Triangles with station labels show site positions for HVSR data. Circles show position of arrays used for SPAC analysis. Contour interval is 0.05 Hz.

each of the two array locations at Lorimer Street and Westgate Park. The location of all recordings is shown in Figure 1.

For each of the three-component measurements, ground motion was recorded in the vertical and two orthogonal horizontal directions for 220 seconds at a sampling rate of 200 Hz. A vector sum of the horizontal components for each sample was calculated, in order to produce the Fourier spectrum of horizontal ground motion for each location. The Fourier spectrum was also calculated for the vertical component and the ratio of horizontal to vertical spectral amplitude calculated to produce an H/V spectrum for each location. An example of an H/V curve showing a significant peak at about 0.9 Hz is included in Figure 7.

Each spectrum was examined to pick the peak ("resonant") frequency for that location, with recording sites spaced approximately 50 to 200 m apart, as shown in Figure 1. The frequency at which the H/V ratio is maximum is indicative of (among other parameters) the thickness of soft sediment overlying stiffer materials. Figure 8 is a contour plot showing variations in the frequency of peak H/V ratio across the survey area. There is a clear trend in this data for an increase in the frequency of "resonance" from the south of the section (around Westgate Park) to the north around Lorimer Street. This increase in peak H/V frequency is equivalent to a thinning or stiffening of "soft" material overlying a harder "basement" layer. Given the relative consistency of the shear velocities between sites obtained from the SPAC measurements, it is more likely to be representative of variations in thickness of Coode Islands silt. This interpretation of Figure 8 is also consistent with trends seen in the geological section (Figure 2).

Many of the HVSR curves contained a complex series of peaks indicative of a complex system of resonances caused by multiple interfaces of significant velocity contrast in the subsurface. Given the relatively complex nature of the geology underlying the Port Melbourne area (multiple layers of distinctly varying shear velocities), this is not a surprising result.

The HVSR can also be theoretically computed for the layered-earth models derived for each of the two SPAC locations. This was done for each of the SPAC survey locations, and the results were consistent with the resonant frequencies observed in the field (i.e., each model maximum frequency coincided with that observed in the field, and the peak HVSR frequency predicted for Lorimer Street was higher than for the layered-earth model at Westgate Park).

DISCUSSION

The results presented in this paper demonstrate that microtremors carry significant information about the structure of the subsurface, principally the shear velocity which is a proxy for low-strain shear modulus. The data presented here illustrates how measurement of 'natural' ground vibrations in an urban environment can allow determination of SWV profiles with relatively high precision from non-intrusive surface observations without an active seismic source. In comparison with other studies using similar array sizes (e.g., Roberts and Asten, 2003), the 'depth of penetration' or, more accurately in the microtremor context, the depth of sensitivity, is dependent upon the velocity structure beneath the array. The depth of sensitivity is a function of wavelength, and hence for a fixed band of (microtremor) frequencies, the depth of investigation using the SPAC techniques is dependant on Rayleigh wave phase velocities. The 48-m array used at Burnley by Roberts and Asten (2003) resolved velocities to a depth of approximately 75 to 100 m. The Lorimer Street array of similar size in this paper begins to lose resolution at a much shallower depth (approximately 30 m depth). This is a large difference, but entirely attributable to the notable contrast in the shear velocity structures for each site.

The geological section indicates that the basement rock (Silurian mudstone) is at an approximate depth of 80 metres under much of the Port Melbourne area. In order to measure a SWV profile down to this depth, a much larger array is required in order to 'see through' the very low velocity layers, such as the 130 m/s of the Coode Island Silt. Deployment of a larger array (e.g., 100–200 metre radius) is possible, although logistically more difficult as an array of this size would need to straddle roads, buildings and other infrastructure. The trade-off for limited penetration results in a high degree of resolution of the Coode Island Silt's shear wave velocity. The data collected in this survey at Lorimer St closely constrains the layer velocity (interpreted to be Coode Island Silt) to be 130 m/s ±5%. The Fishermans Bend Silt, which dominates the section at Westgate Park, is clearly resolved to be of higher shear velocity 235 m/sec.

The contour map of HVSR maxima for the survey locality shows that such single-station methods correctly map variations in silt thickness in a qualitative sense but do not give guidance on the important parameter of silt stiffness differences between the two silt strata.

CONCLUSIONS

Based on the results presented here and in other studies (e.g., Roberts and Asten, 2003), there is significant potential for further utilization of microtremor measurements in appropriate geotechnical engineering projects. Although the microtremor technique for estimates of shear velocity cannot provide the level of precision given by boreholes, the technique can complement information from geotechnical borehole logs. SWV profiles obtained using SPAC processing of array measurements can be obtained at sites coincident with borehole locations and then performed elsewhere in order to provide 'in-filling' information between borehole locations. Single station HVSR measurements can also be used to provide either reconnaissance or subsidiary information, particularly where there is insufficient space to deploy an array of geophones.

This approach would be most appropriate in areas where a large area must be investigated and the geology consists of predominantly near-horizontal layering. The effectiveness of the technique is also dependant upon sufficient microtremor energy being available, which is not usually a problem in urban environments where other forms of geophysical investigation suffer from noise, etc. Since microtremor measurements are relatively rapid (1–2 hours for an array measurement and 3–5 minutes for a single station HSVR record), the field cost of implementing these techniques is low.

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SPAC 微動アレイを使った第四紀シルト層の S 波速度断面の推定

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要　旨： 直径 96 m 以下のアレイを使って微動探査法を実施し、未固結の第四紀 Yarra デルタ堆積物の S 波速度断面を深さ 30〜50 m 程度まで非破壊で推定することができた。その結果を解釈し、この地域の地質は 2 種類のシルト層 (Coode 島シルトと Fishermans Bend シルト)に大別されることがわかった。微動探査法により、これらのシルト層の S 波速度を 5%の精度で推定し、軟弱な前者(Vs=130 m/s)と堅硬な後者(Vs=235 m/s)を識別した。この手法により、これらのシルトの下に既知の礫層に相当する堅い層(Vs=500〜650 m/s)を検出した。単一ステーションによる水平成分対垂直成分比のスペクトル分析法を測線に沿って適用すると、軟弱なシルト層の厚さの変化を速かに求めることができるが、それは定性的に求められるに過ぎない。地質断面が複雑な場合や S 波速度値自体が定量的に必要な場合にはアレイを用いた微動探査が不可欠となる。

Microtremor 배열 (SPAC) 측정을 이용한 제 4 기 실트층의 S 파 속도구조 추정

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요　약： 직경 96 m 까지의 배열을 이용하는 microtremor 방법을 통해 호주의 미고결 제 4 기 Yarra Delta 퇴적물의 30-50 m 심도까지의 S 파 속도구조를 비파괴적으로 추정할 수 있었다. 두 실트층(Coode Island silt 와 Fishermans Bend silt)이 주 해석대상인데, 5 %의 정밀도로 이 층들의 S 파 속도를 얻을 수 있었으며, 상부의 좀 더 연약한 층(Vs: 130 m/sec) 및 하부의 약간 단단한 층(Vs: 235 m/sec)으로 구별된다. 이 층들 하부에 이미 역층으로 알려진 단단한 층(Vs: 500 - 650 m/sec)도 구별해내었다. 단일 수진기 별로 수평/수직 성분 스펙트럼비를 이용한 지표 횡단 결과로 연약한 실트층 두께의 변화를 빠르게 파악할 수 있으나 단지 정성적이며, 복잡한 지질단면의 경우에 정량적인 S 파 분포를 알기 위해서는 배열방법이 사용되어야 할 것이다.

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