Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)

Integration of invasive and non-invasive techniques in ground characterisation

S. D. Ekanayake
Coffey Corporate Services, Chatswood, NSW, Australia.

C. J. Leo & D. S. Liyanapathirana
School of Computing, Engineering and Mathematics, Western Sydney University, Penrith, NSW, Australia.

P. Harutoonian
Citilink Piling, Quantum Corporate Park, Rydalmere, NSW, Australia.

ABSTRACT: This paper presents a case study, where non-invasive Horizontal-to-Vertical Spectral Ratio (HVSR) of microtremors was used to assess the compaction of a large site located in Western Sydney area in NSW. The integration of measurements of non-invasive microtremors, with invasive CPT and PS-logging techniques were investigated aiming to optimise the characterisation of the compacted ground. The invasive CPT and PS-logging tests were carried out sparsely at the compacted site due to the cost and they would only give spot-wise soil information at the test location. Hence there were many areas at the compacted site, where the quality of the compaction cannot be ascertained based on the invasive techniques. On the other hand, the low cost non-invasive HVSR technique is well suited for areal-wise site characterization in terms of the shear wave velocity, although not with the same reliability, detail and accuracy as the invasive methods. Integrating the two forms of techniques can thus help to exploit the respective strengths of invasive and non-invasive methods and optimize site characterization in terms of resources, cost and reliability. The study presented in this paper measured vertical and horizontal components of microtremors at regularly spaced stations across the site. The measured HVSR curves were then interpreted to obtain the shear wave velocity profile of the ground. Results show that the non-invasive HVSR technique can be successfully integrated with invasive techniques such as CPT and PS-logging to characterise large compacted areas.

1 INTRODUCTION

The invasive site investigation methods such as boreholes, standard penetration tests (SPTs), cone penetration tests (CPTs), flat plate dilatometer tests (DMTs), P-S well logging and density tests are well known techniques for site characterization, which are widely accepted by practicing geotechnical engineers. These techniques generally provide accurate and detailed characterisation of the soil but the results are localised to the points being tested. Hence, in order to provide a reasonable assessment of the site, a sufficient number of invasive tests must be conducted, which can be a costly and time consuming exercise for a large site.

Alternatively, the non-invasive site characterisation techniques incorporating seismic surface waves such as Multichannel Analysis of Surface Waves (MASW), Spectral Analysis of Surface Waves (SASW), Multichannel Simulation with One Receiver (MSOR) and Horizontal-to-Vertical Spectral Ratio (HVSR) have gained popularity among geotechnical practitioners due to the reduced costs and simplicity of the testing methods (Harutoonian et al., 2010; Tokeshi et al., 2013). In these methods, the shear wave velocity (V_s) of the soil profile is determined. V_s is influenced by the density of the soil medium (Kim et al., 2001); it can be appropriately used to estimate the properties of the soil layers underneath. Theoretically, V_s is defined as

$$V_S = \sqrt{\frac{G}{\rho_b}} \tag{1}$$

where G is the shear modulus and ρ_b is the bulk density of the soil. This shows that V_s is a geotechnical property and it supports the concept of using V_s to investigate the stiffness of soil.

These non-invasive techniques can survey deep soil profiles over large areas more expeditiously when compared to traditional invasive site investigation techniques. The HVSR technique uses ambient vibrations in soil to determine the Vs profile while the other active techniques require an artificial excitation to infer the *Vs* profile of the soil domain. Empirical experimental evidence and theoretical modelling results reveal that the shape and peaks of the HVSR curves are mainly governed by the geology of the site (Fah et al. 2003, Nakamura 1989).

Understandably, the shortcoming of these techniques is that the results may not be as reliable when compared to invasive site investigation techniques as they rely on inversion of the theoretical model to infer the V_s profile. Hence if the more reliable invasive techniques can be used to calibrate and validate the inversion, then the integration of the invasive and non-invasive techniques will provide an efficient and cost effective means of assessing large sites. However, caution is necessary because invasive techniques such as CPT are large strain measurements while the V_s is obtained from small strain dynamic tests. Moreover the CPT measures the cone resistance and not the *Vs* of the ground, though some investigators have established empirical relationships between the two (e.g. Robertson, 2009). For this reason an attempt was made to use a second invasive technique, the PS logging as an additional tool to directly validate the HVSR inversion.

In this paper, a case study is presented where HVSR of microtremors was used to obtain the V_s profile of a large compacted site in order to assess the compaction. A methodology was developed to calibrate and verify the V_s profile against the data obtained from CPTs. The results are later also compared with the V_s profile obtained from P-S logging technique. This will improve the reliability of incorporating HVSR technique to conduct site characterisation, without significantly increasing the operational costs as well as the time.

2 SITE CONDITIONS AND TEST PROCEDURES

The test site is located in a sand and gravel quarry on the Hawkesbury-Nepean River flood plain west of Sydney at the edge of the Blue Mountains region. The site consists of Bringelly shale of the Wianamatta group. The subject area of this study, Dynamic Compaction Prototype Trial Area 7 (DCPT-7), has been dynamically compacted with a 20 tonne weight free falling about 20 m, providing approximately 400 tonne-m energy with each drop. Each dynamic compaction station, 4.2 m apart from each other, was compacted using 32 drops. The craters created by the compaction were then backfilled and re-levelled with ground surface. The fill consists of a mixture of clayey, silty and sandy soil, which extends over an area of 9,500 m^2. The bedrock can be found approximately 12 – 13 m below the surface and the ground water level is approximately 10 m below the surface. The stratification of the ground was examined by the following methods: HVSR technique, Cone Penetration Test (CPT) and P-S logging.

2.1 *Determining V_s using HVSR technique*

The HVSR technique relies on the measurement of the horizontal and vertical spectra of the ambient vibrations (the microtremors and microseisms) which are ubiquitous in the Earth surface. Microseisms and microtremors, strictly speaking, refer to ambient vibrations attributed to the natural atmospheric phenomena (e.g. ocean current, wind, strong meteorological conditions) and cultural sources (e.g. anthropic activities such as traffic, construction and plant operations) respectively. However, both have been loosely lumped as 'microtremor' to the extent that the distinction between the two terms 'microtremors' and 'microseisms' have often become blurred in the literature. The components of ambient vibrations linked to natural atmospheric sources generally occur in the low frequency range (less than 1 Hz) while the cultural noises (traffic, machinery etc) will generally include components of higher frequencies (greater than 1 Hz). HVSR technique has been widely used in the past to identify the fundamental resonance frequency of a site at the observation point (e.g. Nakamura, 2008). The horizontal to vertical ratio (H/V) of the Fourier amplitude spectra of the microtremors is defined as:

$$HVSR(\omega) = \frac{|F_H(\omega)|}{|F_V(\omega)|} \tag{2}$$

where $|F_H(\omega)|$ and $|F_V(\omega)|$ are horizontal and vertical Fourier amplitude spectra, respectively. The HVSR curve is thought to be mainly constituted of fundamental and higher modes of surface waves (both Rayleigh and Love waves, and the proportion varies with frequency and location of sensor). HVSR curves are derived in this study by analysing data recorded using a single station with three sensor components (North-South, East-West and Vertical). Since the time and effort required in setting up a single station for HVSR technique is much less than that for setting up other types of surface wave techniques, the HVSR technique is much preferred for its ease of use in site investigations. Figure 1 shows the velocimeter (Tromino^{TM}) used by the authors to record the surface waves generated by microtremors.

HVSR was measured using a regularly spaced grid of observation points, as described in Figure 2. The squares represent the HVSR observation points spread across an area of 95 x 100 m while the circles represent the locations of invasive tests (CPT and P-S logging). A commercially available software Grilla, was used to transfer the recorded data from the velocimeter to a computer.

Adequate statistical sampling for the frequency range used in this investigation: 1-50 Hz; was achieved by sampling the ground vibrations at a rate of 512 Hz. Vibrations were sampled for 16 minutes at each station. An in-house program developed using MATLAB language was utilised to analyse the recorded data and optimize the misfit between the measured and theoretical HVSR curves.

Figure 1. Tromino[TM] velocimeter used for HVSR technique.

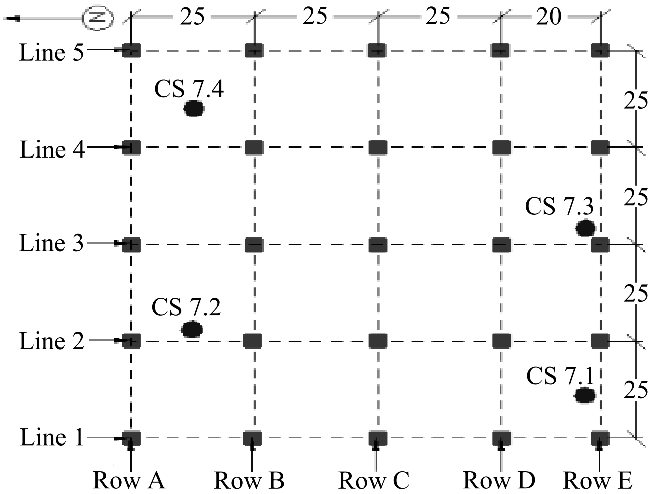

Figure 2. Observation stations of the compacted area (dimensions are in metres).

The H/V curves were calculated by averaging the H/V data obtained by dividing the recorded signal into non-overlapping time windows. The geometric average was used to combine the North-South (H_{NS}) and East-West (H_{EW}) components in the single horizontal spectrum. It was then divided by the vertical component (V) to obtain the measured HVSR curves. Equation 3 shows the calculation of measured HVSR curves.

$$HVSR_m = \frac{\sqrt{H_{NS} \times H_{EW}}}{V} \quad (3)$$

Once the measured HVSR curve is obtained for a given location, a theoretical HVSR curve is derived by forward modelling (Lunedei & Albarello 2009) of the measured data. This incorporates a layered soil model (Figure 3) with assumed soil parameters: shear wave velocity (V_s), primary wave velocity (V_p), soil layer thickness (y), bulk density (ρ) and quality factors (Q_s, Q_p). The inversion is a process to minimise the misfit between the theoretical and the measured HVSR curves. The errors between the measured and theoretical HVSR curves are minimised with each iteration using optimisation techniques based on the Covariance Matrix Adaptation - Evolutionary Strategy (CMA-ES) (Young et al. 2013). The final values of the soil model used in the forward modelling are considered as the estimated soil properties. Care should be taken not to result in unrealistic soil properties when the errors are being minimized by modifying the initial soil properties. Figure 4 presents the process of forward modelling in a flow chart.

Layer 1	$\boldsymbol{V_{s1}}, V_{p1}, \boldsymbol{y_1}, \rho_1, Q_{s1}, Q_{p1}$
Layer 2	$\boldsymbol{V_{s2}}, V_{p2}, \boldsymbol{y_2}, \rho_2, Q_{s2}, Q_{p2}$
Layer 3	$\boldsymbol{V_{s3}}, V_{p3}, \boldsymbol{y_3}, \rho_3, Q_{s3}, Q_{p3}$
Layer 4	$\boldsymbol{V_{s4}}, V_{p4}, \boldsymbol{y_4}, \rho_4, Q_{s4}, Q_{p4}$
⋮	⋮
Layer *n*	$\boldsymbol{V_{sn}}, V_{pn}, \boldsymbol{y_\infty}, \rho_n, Q_{sn}, Q_{pn}$

Figure 3. Layered soil model for forward modelling.

2.2 *Determining the soil layering using CPT*

CPT involves continuously pushing a cone tip to the soil medium at a constant rate, reflecting soil properties at large strains. Interconnected cylindrical steel rods are used to push the cone tip deep in to soil, enabling investigation of soil layers at greater depths. As the cone is pushed to the ground, the resistance at the tip and the surface friction along the outer sleeve of the rod are measured.

CPT tests were conducted at 4 locations at the DCPT-7 site (denoted by "CS" symbol in Figure 2). The CPT data were used to assist in providing an initial guess of the material layering information including the stiffness contrast between layers. One set of CPT data (CS 7.2) was also used to "calibrate" the soil model during the forward modelling procedure in HVSR technique. The "calibration" methodology is a process, where the peaks in the HVSR curve were studied from right to left, from high to low frequency (i.e. from shallow to deep soil). The amplitude and frequency of the predominant and secondary peaks of the HVSR curves were thus identified. These features represent possible impedance contrasts identifying significant material changes picked up by the ambient vibration recordings, as well as giving an indication of the number and the likely depth of the soil layering. The thicknesses of the soil layers revealed by the CPT were used to

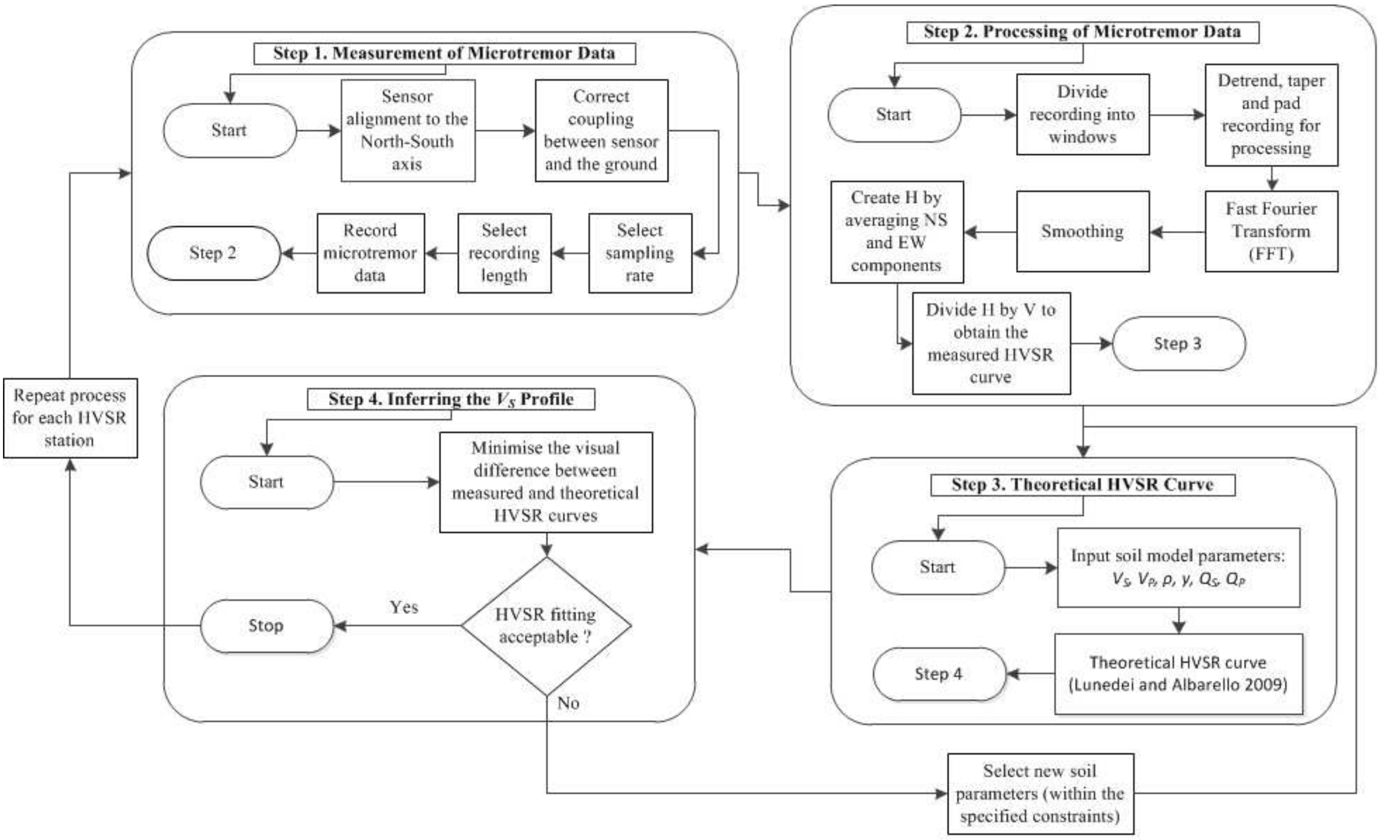

Figure 4. Flow chart for the forward modelling of HVSR technique (Harutoonian et al. 2012)

provide a reliable guide to constrain the layering thickness of the soil model applied in the forward modelling. The soil type, the CPT data and depth of the water table moreover provide feasible constraining ranges for the V_s and V_p values of the soil layers. These constraining data were used to formulate an "initial guess" of the soil model while taking cognizance of the identified features from the HVSR curve. After this, iteration of the layered soil properties of the soil model was undertaken with due regard for the constraints and the identified features of the HVSR curve to seek an improved fit between measured and theoretical curves at each successive iteration, until the best possible fit was achieved. It is noted that during this process, some of the secondary peaks could be fitted (i.e. the theoretical and measured HVSR curves are in agreement at those points in the curves). These secondary peaks are kept while the ones that did not fit were ruled out as reflecting the impedance contrasts within the surface layers. After a satisfactory calibration had been achieved, the "calibrated" soil model was used as an initial guess to derive the Vs profiles for the rest of the site. Independent validations of the HVSR inversions were also made against CPT data at the remaining locations where CPT data are available (CS 7.1, 7.3 and 7.4). This is done by confirming that the impedance contrasts of the inferred Vs profiles produced by the HVSR techniques were consistent with those obtained from the CPT data. Figure 5 shows the validated profile for HVSR 'V_s' against CPT data for borehole CS 7.2).

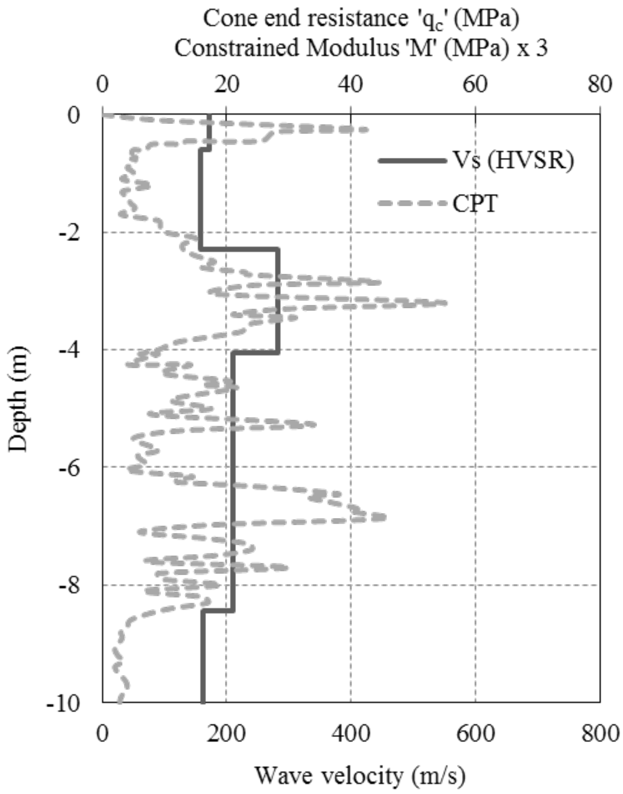

Figure 5. Validated HVSR 'V_s' profile for borehole CS 7.2.

2.3 *Determining V_s using P-S logging*

One of the limitations in using the CPT data for calibration and validation of the HVSR results is that it can only confirm the relative impedance contrasts of the V_s profiles but not the absolute values of the V_s. The P-S logging on the other hand is considered to be the gold standard for measuring the in-situ V_s of the ground. However, conducting a P-S logging test is an invasive, expensive and time consuming task. Nevertheless, for a large site, integration of an invasive technique such as P-S logging with a non-invasive technique such as HVSR technique would facilitate determining the stratification with higher accuracy when compared to the use of surface wave techniques alone. Moreover, with integration a lesser number of invasive tests is required, thus it is less expensive to investigate large sites using this method.

The borehole CS7.1 was used to conduct a P-S logging test to determine the stratification of the site. The P-S logging probe, with geophone receivers inside, is suspended inside the borehole by pneumatic clamping. A vibration source is stationed at the surface and generates excitations as necessary. In this test, the time it takes for a wave to travel from the source to the receiver suspended in the borehole is used to determine the wave velocity of the soil medium. The P-S logging equipment used in this test was a single receiver system with two horizontal geophones and one vertical geophone placed inside. The horizontal geophones record the arrival of the shear wave while the vertical geophone records the arrival of the primary wave. Figure 6 shows the Geotomographie™ borehole equipment used for the P-S logging during this study.

Figure 6. Geotomographie™ borehole geophone and other equipment used for P-S logging in DCPT-7.

The probe is 50 mm in diameter and the borehole used for P-S logging was 90 mm in diameter. The drum, which holds the cable of the probe, has a control unit for the operator to supply air to clamp the probe pneumatically and also to record the readings by connecting a personal computer to the drum.

The source was located 2.5 m away from the borehole. The travel times of the ground waves from the source to the receiver were recorded at each 1 m depth down to 10 m. Commercially available software SoilSpy Rosina™ was used to record the travel times for shear (V_s) and primary (V_p) waves. The system has one channel recording movements at the impact source and another three channels recording the readings from three geophones in the borehole probe. Once the system senses the impact at the source, rest of the channels connected to the probe start recording data from the geophones. This allows the operator to measure the travel times correctly as the ground waves arrive at the probe. Recordings from the horizontal geophones are considered to calculate the arrival of shear waves. The velocity was calculated considering soil layers with a 1 m depth.

3 RESULTS AND DATA INTEPRETATION

The results obtained from each technique for the location CS 7.1 are plotted in Figure 7. The estimated V_s values in this study are normalised to avoid the influence of the confining pressure using the equation

$$V_{sn} = V_{sm}\left(\frac{P_a}{\sigma'_v}\right)^{0.25} \quad (4)$$

where V_{sn} is the normalised shear wave velocity, V_{sm} is the measured shear wave velocity, P_a is the atmospheric pressure and σ'_v is the vertical effective stress (Robertson et al 1992). The unit weight of soil obtained from borehole logs was used to determine the effective stress.

The mechanical data obtained from CPTs have also been normalised to eliminate the influence of confining pressure as

$$q_{cn} = q_{cm}\left(\frac{P_a}{\sigma'_v}\right)^{0.5} \quad (5)$$

where q_{cn} is the normalised end resistance of the cone and q_{cm} is the measured end resistance of the cone (Robertson et al 1992).

The V_s profile derived from inversion of the HVSR curves, as described in Section 2.2, shows a good agreement with the CPT data in Figure 7. Hence, the methodology described may also be applied with some confidence to the rest of the HVSR measurements which are not adjacent to invasive test locations. However, as mentioned before, the CPT data can only be used to confirm the relative stiffness contrast between layers but not the absolute values of the V_s.

An attempt was therefore made here to compare the V_s profile from P-S logging with that of the HVSR technique. According to Figure 5, a reasonable match between the two profiles can be surmised. However, a slight discrepancy in the two profiles closer to the surface of the soil medium is apparent. This can be attributed to the smaller travel times between the source and the receiver at those levels.

Since the travel time is quite small closer to the surface, even a slight error in picking the travel time will result in significant changes to the V_s profile. Perhaps this can be eliminated by placing the wave source sufficiently away from the borehole. Further studies will be conducted to eliminate these issues and to integrate P-S logging with HVSR technique, providing reliable and cost effective technique of investigating large sites.

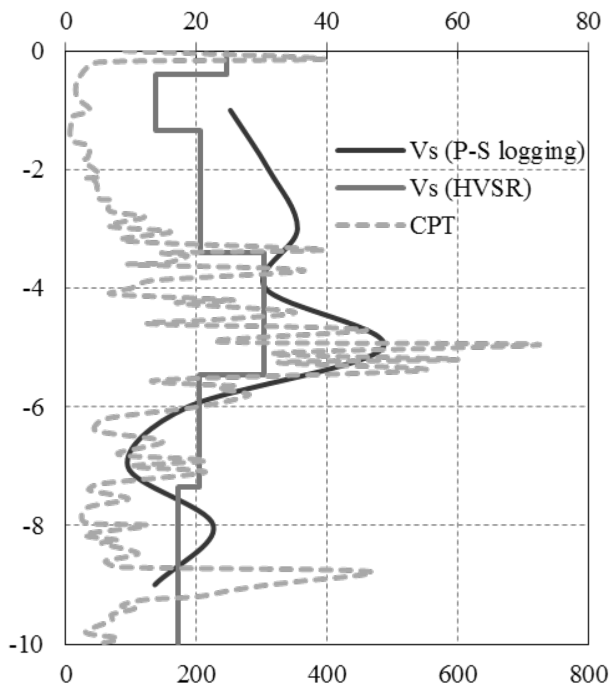

Figure 7. Normalised HVSR V_s versus normalised CPT q_c versus normalised P-S logging V_s.

4 CONCLUSION

A case study on integration of invasive and non-invasive techniques for geotechnical site investigations is presented. Non-invasive HVSR technique is integrated with invasive CPT to determine the shear wave velocity profile of the site. The V_s profiles obtained by inversion of the HVSR curves are found to be in agreement with the CPT data extracted at the same location, in terms of the relative impedance contrasts of the soil layers. Hence, it can be concluded that the HVSR technique can successfully be used for site investigation by integrating with an invasive testing procedure such as CPT. This provides a significantly better coverage in determining the stratification of soil, without restricting the judgement to few control stations of mechanical tests.

These data are then compared with the V_s profile obtained from another invasive technique: P-S logging. The two V_s profiles are a reasonable match, however, discrepancies in picking the travel times closer to the surface challenges the validity of the system. However, once improved, P-S logging technique will offer a better calibration and validation of the measured HVSR data, providing enhanced insight to the stratification of the soil medium. This will be the direction of this study in future.

5 ACKNOWLEDGEMENTS

The authors would like to acknowledge the Western Sydney University, Australian Research Council, Penrith Lakes Development Corporation and Coffey Geotechnics for facilitating this research.

6 REFERENCES

Harutoonian, P., Chapman, B., Yong, C. N., Leo, C. J. and Zou, J. J. (2010) “Near surface soil characterisation by passive ambient noise HVSR method.” GeoShanghai, GSP 201, eds M. Huang, X. Yu & Y. Huang, ASCE, Shanghai, China. 288-293.

Harutoonian, P., Leo, C. J., Liyanapathirana, S. and Wong, H. (2012) “Site characterisation by the HVSR technique.” Australian Geomechanics, 47(3):101-110.

Fah D, Kind F, Giardini D. (2003) “Inversion of local S-wave velocity structures from average H/V ratios, and their use for the estimation of site-effects.” Journal of Seismology, 7: 449–67.

Kim, D. S., Shin, M. K., and Park, H. C. (2001) “Evaluation of density in layer compaction using SASW method.” Soil Dynamics and Earthquake Engineering, 21(1): 39-46.

Lunedei, E. & Albarello, D. (2009) “On the seismic noise wavefield in a weakly dissipative layered earth.” Geophysical Journal International, 177(3): 1001 - 1014.

Nakamura, Y (1989). A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. Quarterly Report of Railway Technical Research Institute (RTRI), 30 (1989): 25–33.

Nakamura, Y. (2008). 'On the H/V spectrum', paper presented to the The 14th World Conference on Earthquake Engineering, Beijing, China. Paper ID: 07-0033, 12 - 17 October 2008.

Robertson, P.K., Woeller, D.J. & Finn, W.D.L. (1992) “Seismic cone penetration test for evaluating liquefaction potential under cyclic loading.” Canadian Geotechnical Journal, 29(4): 686-695.

Robertson, P.K. (2009), Interpretation of cone penetration tests – a unified approach. Canadian Geotechnical Journal, 46: 1337-1355.

Tokeshi, K., Harutoonian, P., Leo, C. J. and Liyanapathirana, . (2013) “Use of surface waves for geotechnical engineering applications in Western Sydney.” Advances in Geosciences, 35: 37-44.

Young, C., Le Brese, C., Zou, J. and Leo, C.J. (2013) A Robust Search Paradigm with Enhanced Vine Creeping Optimisation, Engineering Optimisation. 45(2),pp225-244. ISSN: 0305-215X (Print), 1029-0273.