Effects of Vertical Heterogeneity of Soil Sediments on Seismic Soil Response

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Abstract

Site effects are resulted from the non-linear filtering mechanisms within the soil sedimentary layers overlying bedrock. In contemporary design codes, site effects are taken into account by introducing different site factors for different site classes. The prescribed site classification systems are based on averaging shear wave velocity in the soil sediments. However, significant amplification of the seismic displacement demand may be developed from mechanisms which can result in resonance behaviour. In such situations, soil amplification cannot be determined accurately by considering the average shear wave velocity of the sediments alone. The effects of vertical heterogeneity in the soil sediments have not been explicitly parameterised in the conventional code provisions.

This paper presents results from parametric studies showing the influence of vertical heterogeneity in the soil sediments on the soil amplification behaviour. A methodology for modelling soil heterogeneity is described. Importantly, the presented results quantify the influence of vertical heterogeneity on the seismic soil response behaviour. It is found that variations in the sub-soil layer properties can accentuate soil amplification by up to 1.6 times. Comparisons with previous research results revealed consistencies in the findings. It is expected that information presented in this paper would be useful for engineering design applications.

Keywords: site response, shear wave velocity (SWV), vertical heterogeneity, Response Spectral Velocity (RSV), soil SWV profile factor.

1. INTRODUCTION

The amplitude and frequency content of seismic shear waves reaching the earth's surface is greatly modified by the local soil sediments. The mechanisms responsible for this local soil effects can be explained by the principles of conservation of energy in that the amplitude of seismic waves will increase when entering from a medium of high impedance (rock or stiff soil sediments) to that of a lower impedance (softer soils with lower density) . This modelling approach on its own, however, has not taken into account the dissipation of energy by reflection, scattering and anelastic attenuation.

Soil amplification is also dependent on other parameters such as the thickness of the soil layers, hysteretic properties of the soil and the variation of the shear stiffness (or Shear Wave Velocity, SWV) of the soil with depth (i.e. vertical heterogeneity in the soil), and finally, the impedance contrasts at the rock-soil interface. Site effects have long been recognised in major earthquake codes of practice. The International Building Code (IBC, 2006), the (old) Australian Earthquake Loading Standards (AS 1170.4: 1993), and the new Australian Standard (draft DR 04304, 2004) have all recommended that site factors be functions of the site class and the level of hazard at a given site. The site classification is based on weighted averaging of the SWV over the upper 30 m of the soil layers as shown in equation (1).

$$V_s = \frac{\sum_i h_i}{\sum_i \frac{h_i}{V_{si}}} \qquad (1)$$

where V_s = is the weighted average SWV
i = layer number,
h_i = thickness of layer i and
V_{si} = SWV of layer i

It is noted that equation (1) does not take into account of the vertical heterogeneity of the soil medium. Besides, the recommended factors in IBC (2006) have been derived from regression analyses of the strong motion data. During this process, a wide range of site conditions have been averaged and this procedure has effectively smeared the effects of soil resonance (Lam et al., 2001, 2002). The factors so derived may be directly applicable to high seismicity regions like California where the majority of structures are ductile and the energy imparted during resonant conditions could be easily dissipated by the structure. However, low and moderate seismicity regions like Australia that possess a majority of non-ductile structures (and hence low energy dissipation characteristics) are more likely to experience resonance behaviour. The implication of the above statement is significant displacement demand may be imposed on the structures at resonant conditions. In addition, it is noted that the paucity of recorded strong motion data in Australia has resulted in the codes adopting provisions from data-rich regions like Western North America. Thus the recommended factors are open to further research. It is noted that the Peak Ground Velocity (PGV) is considered as a more appropriate parameter for the characterisation of earthquake ground motions particularly in low and moderate seismicity regions (Gaull et al., 1990) as opposed to the Peak Ground Acceleration (PGA) parameter which is commonly adopted in high seismicity regions. Consequently the site factor (or the soil amplification factor) adopted in this study is defined as the ratio between the Response Spectral Velocity RSV_{max} of the soil at conditions of resonance divided by the corresponding RSV of the rock outcrop at the natural period of the site (as shown in Figure 1).

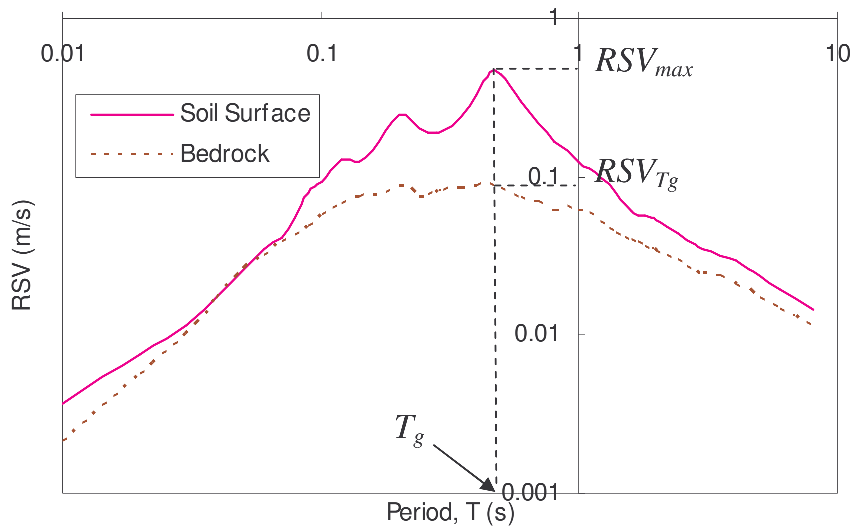


Figure 1.Definition of soil amplification factor.

Since the focus of this paper is on ascertaining the influence of vertical heterogeneity in the soil medium, parametric studies have been carried out using the well-known computer program SHAKE (Schnabel et al., 1972). SHAKE computes the quasi non-linear response of soil profiles based on one-dimensional shear wave analyses of the soil column. The use of this methodology for soil response analyses is well reported in the literature (Dickenson, 1991; Seed, 1994; Dobry, 2000). Bedrock accelerograms for earthquake magnitudes varying between 5 and 7 and site-source distances varying between 30 km to 100 km have been simulated using program GENQKE (Lam et al., 2000). GENQKE simulations have been verified against recorded earthquake motions (Wilson, 2000; Venkatesan, 2006).

The next section of the paper describes research efforts that have been undertaken by the authors in quantifying the effects of vertical heterogeneity in the soil. Furthermore, parametric analysis has been presented in Section 3. The final section of this paper summarises the presented findings and identifies future research directions.

2. MODELLING THE EFFECTS OF VERTICAL HETEROGENEITY

The effects of vertical heterogeneity in the soil have been addressed by Venkatesan et al. (2004, 2006). A series of component factors (reproduced in Appendix -A) have been proposed to categorise SWV profiles into three distinct groups: SWV varying linearly with depth, SWV varying as a power function (i.e. polynomial variation) and the most general case of irregular variation of SWV with depth. Soil plasticity properties have been broadly classified into sandy soils (Plasticity Index, PI ≤ 15%) or clayey soils (PI ≥

30% and up to 100%). Figure 2 presents an example of the calibration of the soil SWV profile factor developed by Venkatesan et al. (2006) for the case of linear variation in the soil SWV. This analysis was based on magnitude 6 earthquakes with a site-source distance of 30 km and bedrock SWV of 1000 m/s. Weighted averaged SWV of between 120 m/s and 400 m/s has been considered. The factors so derived have been checked for variations in the earthquake magnitude, site-source distances and shear stiffness (SWV) of the bedrock. The results were supportive of the recommended factors. However the developed model has not taken into account variations of the PI between the soil layers or variation of the soil SWV. Therefore, the recommendations were classified into two categories: SWV varying within ±20% and SWV varying by ±50%. Also, note that the profile factor of 1.4 is in fact the average value for a suite of soil sites. Thus, there is a need to quantify the influences of the SWV within the sub-soil layers.

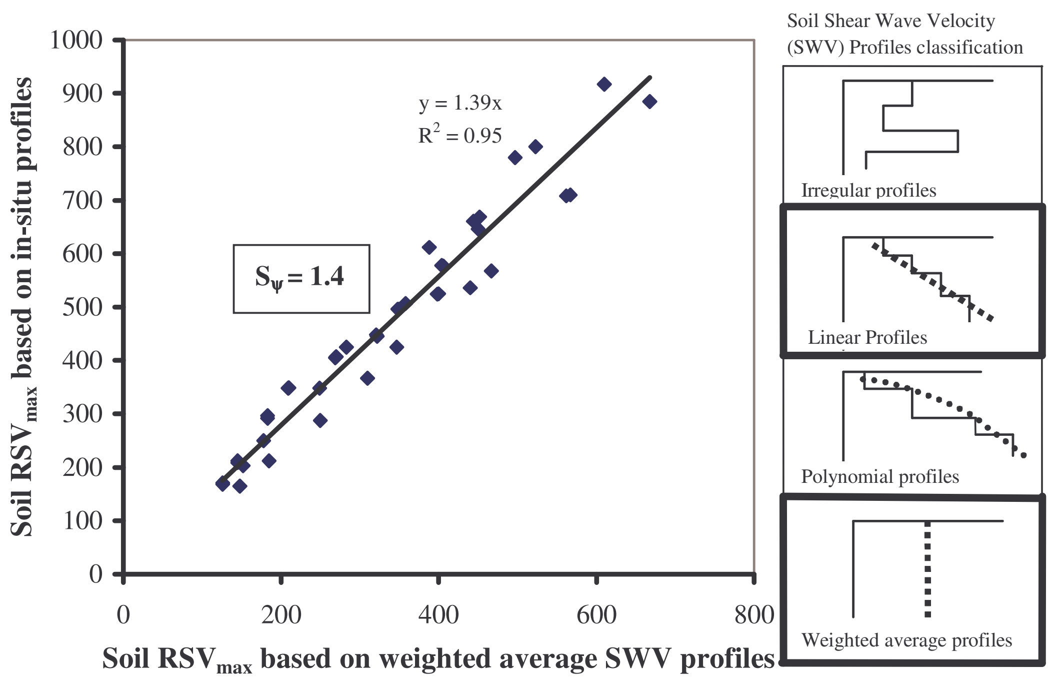


Figure 2. Calibration of Soil Shear Wave Velocity Profile factor (S_ψ) – Linear profile.

It is noted that the model presented in Venkatesan et al. (2006) was based on the parametric variation of the soil SWV. An important feature of this model is the comparison of the response behaviour of an idealised soil column model which has a constant (weighted average) SWV profile with a model based on the actual in-situ SWV profile. The natural period of the idealised model has been calibrated to match with the actual site natural period. In essence, only the SWV profile was left to vary.

Tsang et al. (2006a, 2006b) proposed a simple, heuristic manual calculation procedure for estimating the soil amplification factor, based on the Single Period Approximation (SPA) approach, with appropriate considerations for the level of shaking, impedance contrasts between the soil-bedrock interface and the plasticity of the soil layers. As the SPA model was developed based on a homogeneous soil medium, its capability can be enhanced by incorporating vertical heterogeneity in the soil. The applicability of the component factors proposed by Venkatesan et al (2006) and results from the parametric studies undertaken by Tsang and Yu (2006) are reviewed in this paper.

3. RESULTS FROM PARAMETRIC STUDIES

Parametric studies using SHAKE were carried out on soil sites with weighted average SWV of 150, 300 and 500 m/s. Total thickness of the soil was fixed at 30 m with 12 sub-layers of 2.5 m thick each. Ground motions were generated using program GENQKE based on the Response Spectral Velocity (RSV) on rock in the range of (i)15 – 25 mm/s, (ii) 70 – 110 m/s and (iii) 320 – 360 mm/s. Earthquake magnitudes in the range of 5 – 7 were considered in this study. In total, nine groups of analyses have been carried out (note: a RSV of 70 – 100 m/s corresponds to PGV of around 35 – 55 m/s and this represents Australian seismic hazard for a return period of 500 years). Within the soil layers, the gradient of SWV, denoted mathematically by dV_s/d_z, varies between 0 (the reference case) and 30, as illustrated in the example of Figure 3.

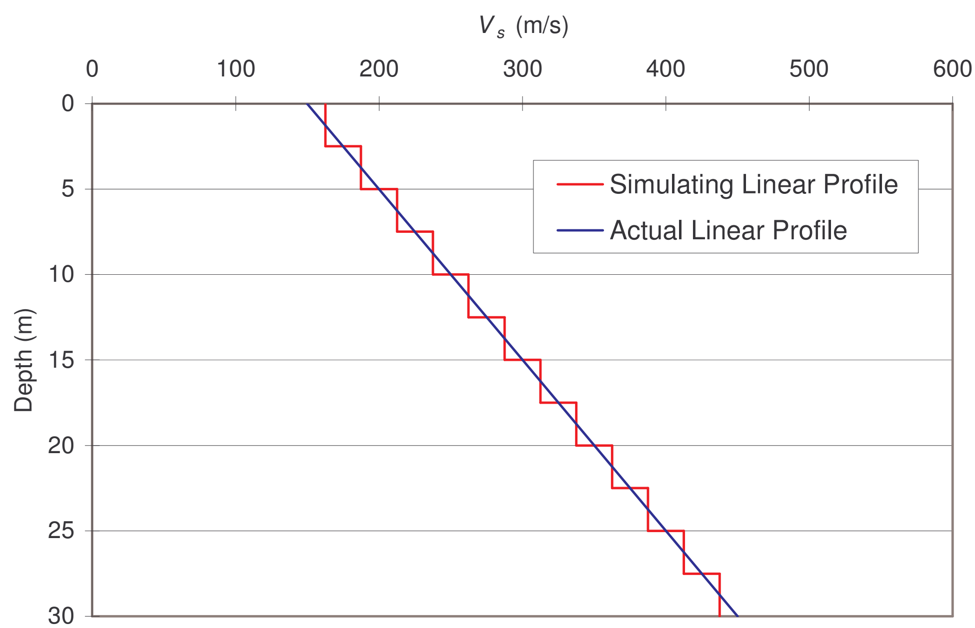


Figure 3. Linear SWV Profile of the soil with mean SWV = 300 m/s for $dV_s/d_z = 10$.

Figures 4 to 6 show the results of analysis for the three levels of shaking. It is observed that the *profile factor*, in general, is higher for sites with lower SWV. This is expected as the lower SWV profile has a higher impedance contrast. It can be observed from Figure 4 that for $dVs/d_z = 10$, the ratio of the *profile factors* (S_ψ) is 1.22 / 1.04 = 1.17. Note that the range of variation of the *profile factors* (in the vertical axis) is between 1 – 1.6 and this is consistent with the values observed in Figure 2.

It is also observed that the profile factors (S_ψ) generally increases with increasing rate of change in V_s. Also, when dV_s/d_z is high (such that the values of V_s in the soil surface falls below 70-110 m/s), the profile factors (S_ψ) drops off rapidly. However, given that soil profiles with V_s lower than 100m/s is rare, these cases have been excluded from the study and hence not shown in the figures.

It is observed that the slope of the lines decreases with increasing average SWV in the soil. This means that, given the same level of earthquake shaking, the profile factors (S_ψ) increases by a lesser extent when the average SWV of the soil stratum becomes higher. Such observation can be explained by the simple number theory: for cases with the same rate of change of V_s, a soil profile with higher averaged SWV will have smaller impedance ratio α between the individual soil sub-layers, and hence, lower soil amplification.

It is also observed that when the intensity of the earthquake shaking is increased, the linear relationships shown in Figure 6 tend to come closer to each other. This is basically the result of the increase in energy dissipation with higher intensity of shaking.

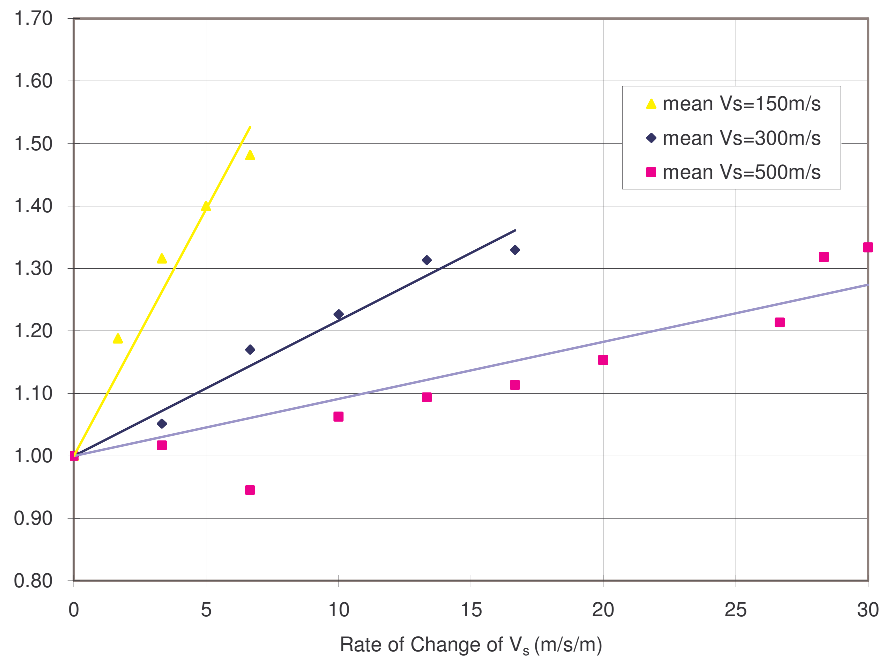


Figure 4. Variation of SWV profile factor (S_ψ) for RSV (rock) = 15 – 25 mm/s.

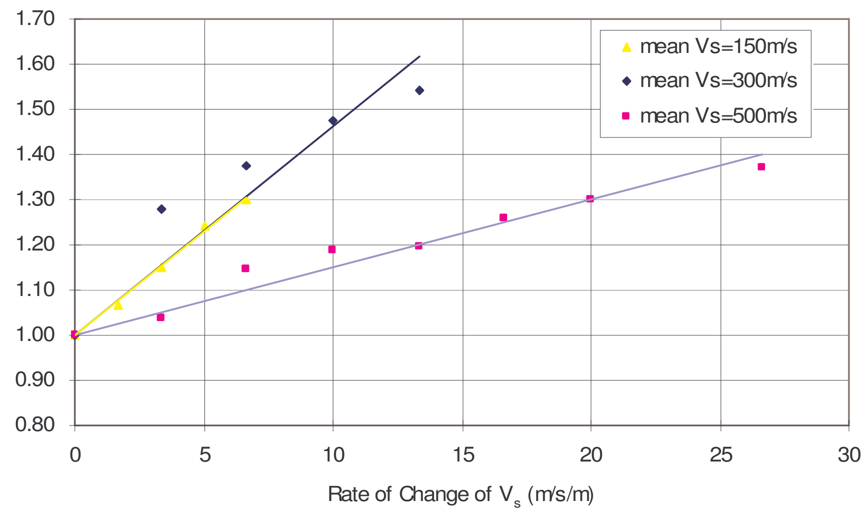


Figure 5. Variation of SWV profile factor (S_ψ) for RSV (rock) = 70 – 110 mm/s.

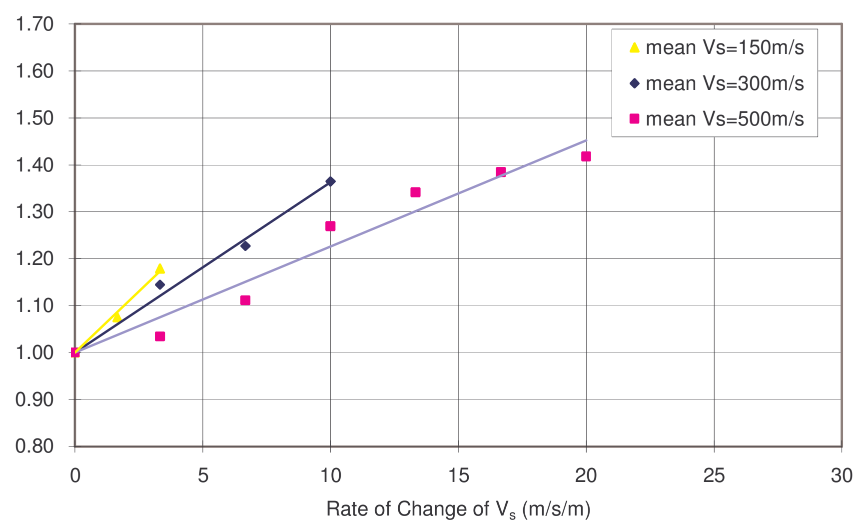


Figure 6. Variation of SWV profile factor (S_ψ) for RSV (rock) = 320 – 360 mm/s.

4. DISCUSSIONS AND CLOSING REMARKS

It is evident from the parametric studies presented in this paper that the profile factor (S_ψ) which accounts for vertical heterogeneity in the soil increases with increasing gradient of the soil SWV profile.

The rate of increase of the profile factors (S_ψ) decreases with increasing averaged SWV in the soil. This can be attributed to the stiffness of the soil layers. Stiffer soils undergo less cyclic shear strains and hence their behaviour is governed by elastic deformation. However at a higher level of ground shaking, the shear strains sustained by the soils would be of greater magnitude and hence variations in the soil SWV will have less effects on the soil response behaviour. Thus the possibility of using 'effective impedance' as a measure of variations in the soil SWV can be explored. Results show that S_ψ varies typically between 1 and 1.6 (1 being the reference case of weighted average SWV profile) for sites with a linear variation in the soil SWV.

The results obtained in the parametric study are in agreement with the range of profile factors specified in Venkatesan et al (2006). Refer Appendix – A: Profile factor (S_ψ) = 1.55 for linear SWV variation – spread of SWV within soil layers is within ± 20%.

It is important to note that the study has not covered the wide spectrum of SWV variation in real soil sites. (for example, soil layers of varying thicknesses or adjacent soil layers having constant SWV values together with layers having a linear variation in the SWV). Considering the random nature of real soil sites, results presented in this study should be adopted with careful judgement. On-going research is undertaken by the authors to tackle the random nature of real soil sites.

6. REFERENCES

AS1170.4 – 1993. (1993) Standards Association of Australia. *Minimum design loads on structures: Part 4: Earthquake Loads - AS1170.4 and Commentary*.

Dickenson, S.E., Seed, R.B., Lysmer, J., and Cok, C.M. (1991) Response of soft soils during the 1989 Loma Preita earthquake and implications for seismic design criteria. *Proceedings of the Pacific conference on earthquake engineering, New Zealand*, pp 191-203.

Dobry, R., Borcherdt, R.D., Crouse, C.B., Idriss, I.M., Joyner, W.B., Martin, G.R., Power, M.S., Rinne, E.E., and Seed, R.B. (2000) New site coefficients and site classification system used in recent building seismic code provisions, *Earthquake Spectra*, Vol 16, No 1, pp 41-67.

DR 04304. (2004) Draft Australian Standard for Structural Design Actions, Part 4: Earthquake Actions in Australia, *Document No. D5212-5.1, PDR-311, Feb, 2004, Standards Australia, Homebush, Sydney.*

Gaull, B.A., Michael-Leiba, M.O. and Rynn, J.M.W. (1990) Probabilistic earthquake risk maps of Australia, *Australian Journal of Earth Sciences* Vol 37:169-187.

IBC. (2006) International Building Code. *International Code Council. U.S.A*.

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

Lam, N.T.K., Wilson, J.L., and Chandler, A.M. (2001) Seismic displacement response spectrum estimated from the frame analogy soil amplification model, *Engineering Structures*, Vol 23 (11), pp 1437-1452.

Lam N.T.K., Wilson J.L., Chandler A.M. and Hutchinson G.L. (2002) Response Spectrum Predictions for Potential Near-Field and Far-Field Earthquakes Affecting Hong Kong : Rock Sites, *Soil Dynamics and Earthquake Engineering*, Vol.22 pp. 47-72.

Schnabel, P.B., Lysmer, J., and Seed, H.B. (1972) A computer program for earthquake response analysis of horizontally layered sites, *Earthquake Engineering Research Centre EERC report 72-12. Berkeley (CA): University of California at Berkeley*.

Tsang, H.H., Chandler, A.M., and Lam, N.T.K. (2006a) Estimating non-linear site response by single period approximation, *Earthquake Engineering and Structural Dynamics*, Vol 35(9):1053-1076.

Tsang, H.H., Chandler, A.M., and Lam, N.T.K. (2006b) Simple models for estimating period-shift and damping in soil, *Earthquake Engineering and Structural Dynamics*, Vol 35(15):1925-1947.

Tsang, H.H., and Yu, H.C. (2006) Effects of vertical heterogeneity of soil shear stiffness and plasticity on seismic site response, *Internal Research Report, Department of Civil Engineering, The University of Hong Kong.*

Venkatesan, S., Lam, N.T.K., Wilson, J.L. and Asten, M. (2004) A soil response spectrum model for Melbourne, *Proceedings of the Conference of Australian Earthquake Engineering Society, Mt. Gambier, 2004*.

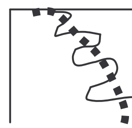
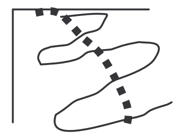
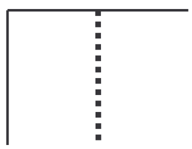
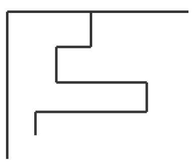
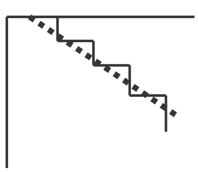
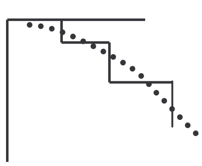
Venkatesan, S. (2006) A soil amplification model for intra-plate seismic regions, *PhD thesis, Department of Civil & Environmental Engineering, University of Melbourne.*

Venkatesan, S., Lam, N.T.K. and Wilson, J.L. (2006) A simple model accounting for the soil resonance phenomenon, *Proceedings of the Conference of Australian Earthquake Engineering Society, Canberra, 2006*.

Wilson, J. (2000) Earthquake design and analysis of tall reinforced concrete chimneys, *Doctor of Philosophy thesis, University of Melbourne, Australia*.

APPENDIX A

Soil SWV Profile factor S_{ψ} as presented in Venkatesan et al. (2006).

Lateral spread of SWV → / Generic classification of Soil SWV Profile ↓	S_{ψ} Lower Bound (consistent with the generic profile within ± 20%). Example: 	S_{ψ} Upper Bound (variation in SWV is greater than ± 50%). Example: 
 Weighted average uniform profile (reference profile)	1	1
 Irregular profile	1.45	1.7
 Linear profile	1.55	1.8
 Polynomial profile	1.65	1.95