

A SOIL RESPONSE SPECTRUM MODEL FOR MELBOURNE

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ABSTRACT:

A new model used in constructing response spectra representing conditions pertaining to resonance on soft soil sites is presented in this paper. Factors controlling the extent of soil amplifications including the shape of the soil shear wave velocity profile, hysteretic damping properties of the soil and impedance contrast between soil and bedrock have been taken into account in the model. The last of these factors controls the extent of radiation damping which is highly dependent on the shear wave velocity of the bedrock close to its interface with soil sediments. The prediction for this radiation damping factor has been filled with uncertainty since information related directly to the strength and stiffness of the bedrock is not included in a typical borehole record. The shear wave profiling in Silurian mudstone in the Melbourne area using the SPAC (Spatial Auto-Correlation) method as reported in a companion paper fills this important gap. This shear wave velocity information newly obtained for the Melbourne area has been incorporated into the seismic soil amplification model presented in this paper.

1. INTRODUCTION

Engineering codes of practice typically classify local soil conditions into discrete site classes based on the average shear wave velocity (SWV) of the soil in the upper layers. The International Building Code IBC(2000) for example, recommends amplification factors that are functions of the site class and the level of seismic hazard. Soil amplification is highly dependent on the impedance contrast at the rock-soil interface (which controls the amount of radiation damping), the soil shear wave velocity gradient and the soil hysteretic properties. Code provisions for high seismic regions such as IBC(2000) do not explicitly parameterise these effects individually. Such code provisions have been based on regression analyses of instrumented strong-motion data that has been augmented by analytical results (Dobry, 2000). Regions like Australia that do not have sufficient strong motion data would typically adopt provisions developed originally in well studied data-rich regions like Western North America. Note, the majority of structures in Australia are non-ductile and hence have relatively little energy dissipation capacity. Consequently, structures experiencing earthquake excitations in these regions will be particularly sensitive to the soil response behavior pertaining to resonance conditions. Importantly, the extent of soil amplification is controlled by the SWV of the bedrock governing the impedance. In practice, bedrock SWV is not measured in normal engineering site investigations. Thus there are great uncertainties in the modeling of the soil amplification effects in practice. The companion papers presented in this conference, [Roberts et al., 2004 and Lam et al., 2004] describes the application of a new technique known as SPAC (a passive seismological monitoring technique based on the analyses of surface waves), in measuring and modelling the SWV profile in bedrock. Of particular interest in this paper is the incorporation of such information in quantifying the effects of radiation damping, which in turn controls the overall level of soil amplification.

This paper introduces a new model for estimating the extent of soil amplification based on the aforementioned modelling considerations. The soil amplification factor defined in Figure 1, is represented by its component factors and is expressed in the form

$$S = S_{\psi} S_{\xi} S_{\lambda} \quad (1)$$

The definition of amplification factor in Figure 1 was first introduced in Lam et al., (2001). The first factor S_{ψ} represents the effects of the shape of the soil shear wave velocity profile. S_{ξ} represents the effects of hysteretic damping and S_{λ} represents the effects of radiation damping. Both S_{ψ} and S_{λ} have been normalized to unity. Each of these factors is addressed in sections 2 – 4. The developed model as a whole is then summarized in Section 5 with concluding remarks in Section 6.

Nine soil profiles from Melbourne having natural periods in the range 0.35 - 0.95 s have been analysed. These sites fall in the category of Site class C or D according to IBC 2000 & AS 1170.4 (2004). Program SHAKE-91 [Schnabel et-al, 1972] computes quasi non-linear response of soil profiles based on one-dimensional shear wave analyses of soil columns is adopted in this study. The use of this methodology for soil response analyses is well supported in the literature [Dickenson 1991, Seed 1994, Dobry 2000]. Bedrock accelerograms for magnitude 7 have been simulated using program GENQKE [Lam, 2000].

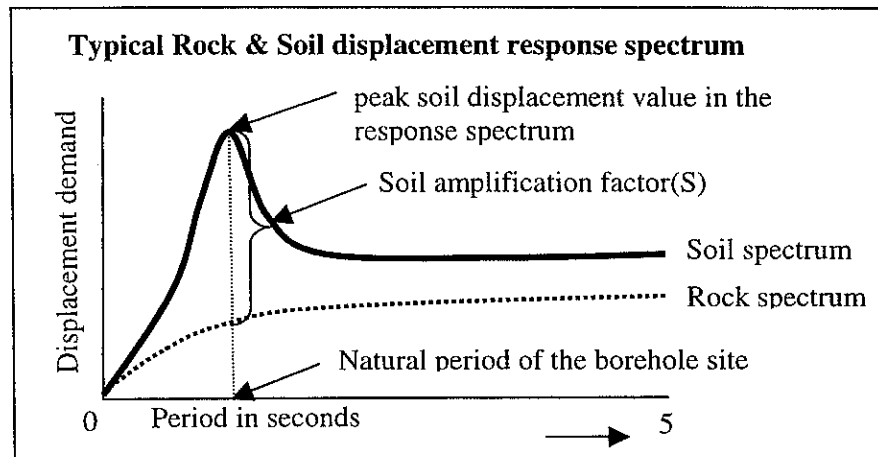


Figure 1. Definition of Soil Amplification factor

2. Soil SWV Profile factor S_{ψ}

To investigate the effects of the soil shear wave velocity profile, the selected sites were grouped into irregular, linear and polynomial profiles as shown in Figure 2 (depth range 15 - 55m). The factors listed for each profile type were obtained from comparative analysis using SHAKE-91. It is recognized that not all soil profiles can be distinctly classified as linear or polynomial profiles and soil profiles may exhibit a complex combination of different profiles. Studies are continuing to determine the extent in which these factors can be applied in practice. Notwithstanding this, Figure 2 provides very useful indications on the sensitivity of soil amplification to the shape of soil SWV profile.

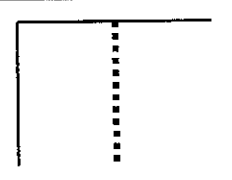
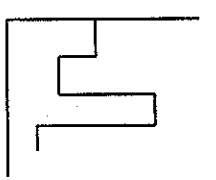
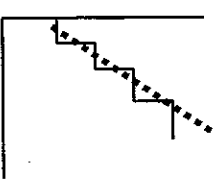
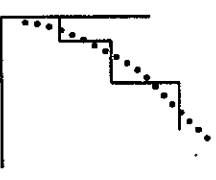
Soil SWV Profile				
S_{ψ}	1	1.3	1.4	1.5

Figure 2. Effects of Soil Shear wave velocity profiles on Soil Amplification factors

3. Hysteretic Damping factor S_{ξ}

Trends related to the effects hysteretic damping were studied by varying the intensity of the input motion at bedrock level with Peak Ground Velocity (PGV) varying between 20 and 100 mm/sec. Soil sites have been idealized to possess constant Plasticity Index (PI). It is noted that a real soil profile typically contains a combination of materials with different PI. Notwithstanding this, Figure 3 provides useful indications on the sensitivity of soil amplification behavior on the hysteretic properties of the soil.

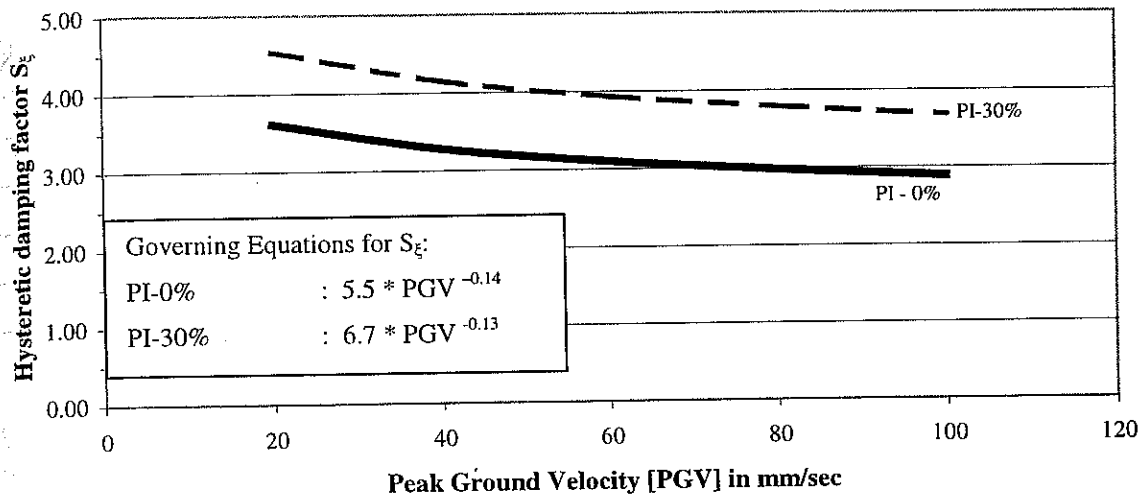


Figure 3. Influence of soil material type and PGV on hysteretic damping

It is shown in Figure 3 that the sensitivity of the S_{ξ} factor on PGV is variable. For any given site with a random combination of different material types, the actual S_{ξ} curve would be some weighed average of the idealized curves shown in the figure. (Since the soil profiles considered in this study were composed of PI-0 & PI-30, only these curves have been presented) The soil dynamic properties pertinent to the analyses are presented in Appendix A. Governing equations for S_{ξ} presented in Figure 3 have been evaluated by residual analyses the results of which are presented in Figure 4.

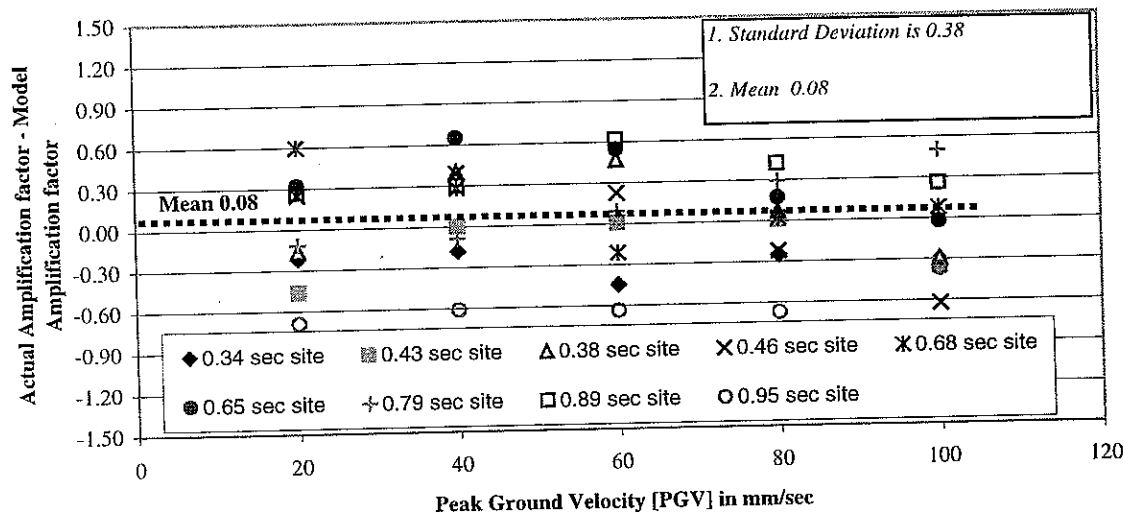


Figure 4. Residual analyses of hysteretic damping factor S_{ξ} [based on equations in Figure 3]

It is noted from Figure 4 that the residual analysis shows no significant bias in the model in view of the closeness of the mean of the residuals to zero.

4. Radiation Damping factor S_λ

As noted earlier, the radiation damping factor has been normalized to unity at reference bedrock SWV of 1000 m/sec. Factors associated with other half-space SWV values are presented in Table 1.

Bedrock SWV in m/sec	Radiation damping factor S_λ
1000 m/sec	1
1500 m/sec	1.125
2000 m/sec	1.25

Table 1. Radiation Damping factor S_λ

The above factors are based on rock SWV values representing a half-space. It is noted that in reality the bedrock is far from being a half-space with uniform SWV profile. An equivalent bedrock half-space that would have similar amplification properties as that of actual bedrock would need to be identified. A 1 sec soil site was analysed with the rock SWV profiles represented down to a depth of 500 m. The corresponding input motions at 500 m depth and that at rock outcrop were generated using program GENQKE. The SWV value of the idealised half-space was calibrated to achieve a match in the computed values for RSV_{max} as shown in Figure 5. The half-space SWV was found to correspond to an effective depth of 100 m into bedrock. Sheikh (2003) conducted a similar calibration for Hong Kong conditions and identified an effective depth of only 30 m.

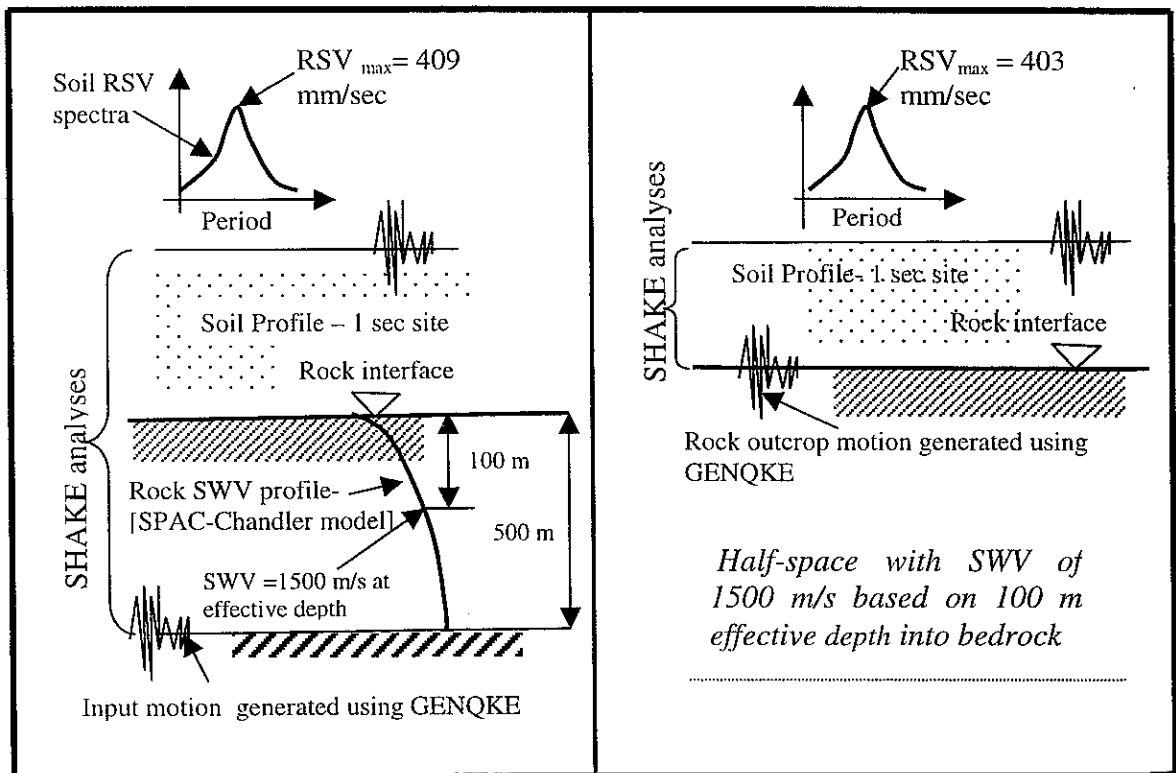


Figure 5. Equivalent bedrock half-space SWV value for Melbourne conditions

5. SUMMARY OF THE PROPOSED MODEL

The component soil amplification factors introduced and developed in this paper are summarized herein in the form of simple algebraic relationships:

- $S_{\psi} = 1$ for soils possessing a uniform shear wave velocity profile (reference case)
- = 1.3 for soils possessing an irregular shear wave velocity profile (typical soil profile in practice)
- = 1.4 for soils possessing a distinct linear shear wave velocity profile
- = 1.5 for soils possessing a distinct polynomial shear wave velocity profile

S_{ξ} for different soil material types (categorized by PI value) is given by

$$S_{\xi} = 3.9 * PGV^{-0.14}, \text{ (for PI-0\%)} \\ S_{\xi} = 4.8 * PGV^{-0.13}, \text{ (for PI-30\%)}$$

$$S_{\lambda} = 1 + 0.00025 (V_{\text{bedrock}} - 1000) \text{ and } 0.9 \leq S_{\lambda} \leq 1.25 \text{ (where } V_{\text{bedrock}} \text{ is bedrock SWV in m/sec)}$$

6. CLOSING REMARKS

A new model for estimating the soil amplification factor in intra-plate conditions pertaining to resonance on soft soil conditions has been presented. The model is based on component factors representing various observed phenomenon in soil amplification. Simple expressions have been developed to represent the effects of the soil shear wave velocity profiles, hysteretic and radiation damping properties. Importantly, radiation damping is highly dependant on the SWV properties in bedrock governing the impedance. In principle this crucial information is available with the newly developed SPAC technique, although limitations in array sizes used to date yield inadequate resolution of the basement SWV [Roberts et al., 2004, this volume]. Standard deviation and mean of the residual amplification factors have been computed to evaluate the developed model. It is recognized that the amplification factors derived from the proposed model would generally be higher by about 1.5 times, than the code provisions of IBC 2000 and AS 1170.4 (1993 & 2004), since code provisions are based on averaging across a range of soil conditions.

7. REFERENCES

- Australian Standard - AS 1170.4, (1993) Minimum design loads on structures, Part 4: Earthquake loads, Standards Association of Australia, North Sydney, NSW, Australia
- Australian Standard - AS 1170.4, (2004) Structural Design Actions : Earthquake Actions in Australia, Pre-Public comment draft, 5212-PDR-311, Feb, 2004.
- 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.
- Hardin, B.O., and Drnevich, V.P., (1972) Shear modulus and damping in soils: Measurement and parameter effects, Journal of Soil Mechanics and Foundations, American Society of Civil Engineers, Vol 98 (SM6), pp 603-624.
- International Building Code - IBC 2000, (2000) International Code Council (ICC), USA.

- Lam, N.T.K., Wilson, J.L., (1999) Estimation of the site natural period from borehole records, Australian Journal of Structural Engineering, Vol SE1 (3) pp 179-199
- 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, Journal of Engineering Structures, Vol 23 (11), pp 1437-1452.
- Lam, N.T.K., Asten, M., Chandler, A.M., Tsang, H., Venkatesan, S. and Wilson, J., (2004) Seismic attenuation modelling for Melbourne based on the SPAC-CAM procedure, Proceedings of the Conference of Australian Earthquake Engineering Soc., Mount Gambier, [this volume].
- Roberts, J., Asten, M., Tsang, H., Venkatesan, S. and Lam, N.T.K., (2004) Shear wave velocity profiling in Silurian mud stone using the SPAC method, Proceedings of the Conference of Australian Earthquake Engineering Soc., Mount Gambier, [this volume].
- 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.
- Seed, R.B., Dickenson, S.E., Rau, G.A., White, R.K., and Mok, C.M., (1994) Observations regarding seismic response analyses for soft and deep clay sites, Proceedings of the 1992 NCEER/SEAOC/BSSC Workshop on site response during earthquakes and seismic code provisions, National Centre for Earthquake Engineering Research Special Publication NCEER-94-SP 01, Buffalo, New York.
- Sheikh, M.N., (2003) Effect of bedrock rigidity on site response study for typical Hong Kong rock classes, Internal report, Department of Civil Engineering, University of Hong Kong., Hong Kong.
- Vuectic, M., and Dobry, R., (1991) Effect of soil plasticity on cyclic soil response, Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol 117, pp 89-109
- Vuectic, M., Lanzo, G., and Doroudian, M., (1998) Damping at small strains in cyclic simple shear test, Journal of Geotechnical and Environmental Engineering, Vol 124, pp 585-594

8. APPENDIX - A

Summary of Soil Dynamic Properties

Stiffness Degradation [Hardin & Drnevich model, 1972]

$$\frac{G}{G_{\max}} = \frac{1}{\left(1 + \frac{\gamma}{\gamma_{ref}}\right)} \quad \text{Eqn (2)}$$

Viscous Damping

$$\zeta = \zeta_i + \zeta_{\max} \frac{\left(\frac{\gamma}{\gamma_{ref}}\right)}{\left(1 + \frac{\gamma}{\gamma_{ref}}\right)} \quad \text{Eqn (3)}$$

$$\zeta_i = 0.015 + 0.0003 \times PI(\%) \leq 0.058$$

$$\zeta_{\max} = 0.16 - 0.001 \times PI(\%) \geq 0.0$$

where,

G is the dynamic shear modulus

G_{max} is the initial dynamic shear modulus at very low shear strain

γ is the shear strain level in soils typically in the order of 0.0001% to 0.1%

γ_{ref} is the reference strain level identified to match the equations presented in Appendix-A [Lam and Wilson, 1999]

ζ_i is the initial damping at very low shear strain

ζ_{max} is the maximum damping at shear failure.

Table A1. Soil Parameters Summary

Soil Type	PI %	γ_{ref}	ζ_i	ζ_{max}
Sand	0	0.00025	0.015	0.16
Clay	15	0.00045	0.0195	0.145
Clay	30	0.001	0.024	0.13
Clay	50	0.002	0.030	0.11
Clay	100	0.004	0.045	0.06

Note : Higher damping values at initial strain levels may be predicted by the above equations for soil PI-100%, which accommodate the findings of Vucetic et-al.(1998)

Figure A1 presents a comparison of Modulus reduction curves developed using equations (2) & (3) with the modulus reduction curves recommended by Vucetic and Dobry (1991).

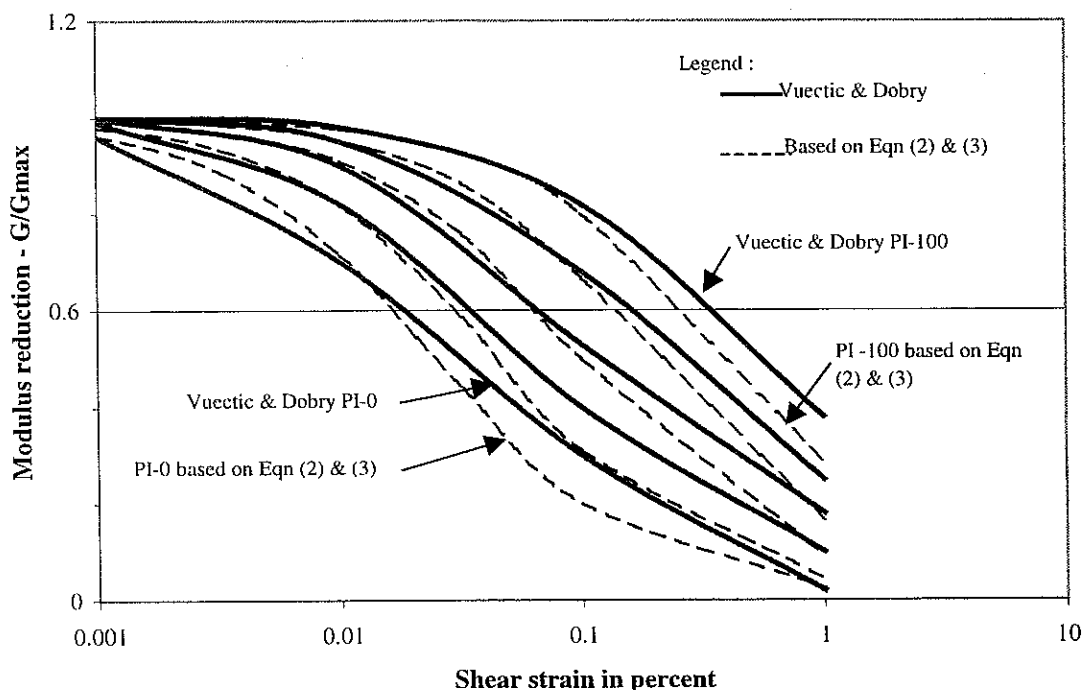


Figure A1. Shear modulus reduction curves – Comparison based on curves calibrated using Eqn (2) & (3) with Vucetic and Dobry (1991) recommendations.