Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

Recommended Site Classification Scheme and Design Spectrum Model for Regions of Lower Seismicity

H.-H. Tsang & J.L. Wilson

Centre for Sustainable Infrastructure, Swinburne University of Technology, Melbourne, Australia.

N.T.K. Lam

Department of Infrastructure Engineering, The University of Melbourne, Melbourne, Australia.

ABSTRACT: This paper proposes a site classification scheme and a design spectrum (DS) model for different ground conditions, with site natural period as the key parameter. The proposed model has a particular emphasis on the phenomenon of resonant-like amplification behaviour in soil sites, which have not been explicitly considered in existing code models. The need to address the effects of soil resonance is particularly justified in regions of lower seismicity, where structures are typically of limited ductility with low energy dissipation capability. Significantly, the mitigating effects of a very flexible soil site resulting in reduction in the level of seismic demand on low rise buildings is a distinctive feature of the proposed model which has been well validated by comparison with results obtained from computational site response analysis of soil columns derived from real borehole records, as well as from strong motion data recorded in the 1994 Northridge earthquake.

1 INTRODUCTION

Seismic action models in major codes of practice (e.g. International Building Code (IBC) 2012). for structural design of buildings typically stipulate empirical site factors for each of the five, or six, site classes. The value of the empirically derived site factor is expressed simply as a function of the site class each of which is identified with a range of shear wave velocity (SWV) values. These site factors are applied uniformly over the flat (constant acceleration) and the hyperbolic (constant velocity and constant displacement) sections of the spectrum.

This simple format for modelling site effects is widely accepted albeit that in reality the modification of seismic waves through soil sediments is well known to be highly frequency selective and under the influence of many factors. It has also been shown that the extent of the amplification can be very dependent on the energy absorption behaviour of both the soil sediments and the superstructure. Thus, the amount of shear strains (i.e. non-linearity) imposed on the soil material and (for cohesive soils) the plasticity index (PI) are amongst the controlling parameters.

Resonant-like amplification behaviour of the structure found on the soil surface can occur as a result of superposition of reflected waves. Thus, factors such as seismic impedance ratio at the soil-bedrock interface and thickness of the soil layers can also have important influences on the behaviour of ground motions on the soil surface, given that these factors control the reflections of shear waves within the soil medium (Tsang et al. 2006a; 2006b; 2012).

The wave modification mechanisms as described are well known and can be simulated by simple one-dimensional equivalent-linear dynamic analysis of the soil sediments. However, periodic amplification behaviours as described have not been well represented in code provisions for the modelling of site effects, given that factors such as soil depth and impedance contrast at the interface between soil and bedrock are usually not parameterised. The decision adopted by codes of practice not to model the effects of resonance is partly because of expert opinion that such effects are only “localised” in the frequency domain and can be suppressed readily by energy dissipation in the form of damping of the soil layers and ductile behaviour of the structure. However, non-ductile, and irregular, structural systems are common in regions of lower seismicity. It is therefore inappropriate to adapt current codified provisions for site effects for use in these regions although the practice is common.

A new design spectrum (DS) model in the displacement format which takes into account the described amplification phenomenon (Lam et al. 2001; Tsang et al. 2006a) is introduced in this paper in order that a representative DS model can be constructed readily without the need of undertaking computational dynamic analyses. The important effects of soil depth have been parameterised in order that effects of impedance contrasts at the soil-bedrock interface have been taken into account.

2 SITE CLASSIFICATION SCHEME

2.1 Current Scheme in AS1170.4–2007

Taking AS1170.4–2007 as example, sites are classified into five site classes. For rock sites, unconfined compressive strength or average shear wave velocity (SWV) over the top 30 m ($V_{S,30}$) is used. For soil sites consisting of layers of several types of material, the low-amplitude natural period T_S, depths of soils H_S, undrained shear strength and SPT–N values are used. As stated in the Commentary to AS1170.4–2007, the basic parameter for site classification in the standard is site natural period. The site-period approach recognises that deep deposits of stiff, or dense, soils exhibit high-period site response characteristics which are not found in deposits which have thickness of only tens of metres.

The value of T_S can be estimated based on geophysical, or geotechnical, measurements with the use of Eq. (1). It can be computed based on four times the shear-wave travel-time through materials from the surface to underlying stiff sediments or bedrock, if the thickness (d_i) and initial SWV (V_i) of the individual soil layers are known.

$$T_S = \sum_{i=1}^{n} \frac{d_i}{V_i} \times 4 = \frac{4H_S}{V_S} \qquad (1)$$

Alternatively, this can be expressed in terms of the total thickness of the soil layers (H_S) and the weighted average initial SWV (V_S) using Eq. (1). Higher-tier methods for calculating the value of T_S can be found in Larkin and Van Houtte (2014).

2.2 Proposed Scheme

In the proposed scheme, a site shall be characterised by the weighted average initial SWV (V_S), depths of soils (H_S) and the initial low-amplitude natural period (T_S) of all the soil layers down to the depth of very stiff sedimentary materials or bedrock. It is recommended that sedimentary layers with SPT-N values greater than 100 be omitted in the calculation of the site natural period.

The current two rock site classes are proposed to be combined together, as (1) it is usually difficult to distinguish between the two rock types in practice, and (2) the differences in the spectral contents between the corresponding design spectra are not clearly known. A single spectral shape has also been adopted for all rock sites in New Zealand (NZS1170.5:2004), as the data used for deriving the rock spectra are dominated by records from Class B rock sites (NZS1170.5 Supp 1:2004).

For a site with $T_S < 0.15$ s, where the soil layers are very thin and/or stiff, the site could be classified as a rock site, as the soil amplification would mainly concern structures with a natural period lower than 0.2 s, whilst the amplification for a natural period higher than 0.2 s is minimal. It is noteworthy that the corresponding peak displacement demand for such low period structures is very small in regions of lower seismicity. Most structures which are not brittle would be capable of sustaining this very minor peak displacement demand without being subjected to any significant risks of collapse.

The proposed site classification scheme is presented in Table 1. There are minor changes in the description of the soil types, which become less ambiguous. For Class C, a site with natural period lower than 0.6 s can be composed of deep layers of dense materials, but not necessarily a shallow soil site, hence, the term “Stiff Soil” is considered more appropriate. Likewise, Class D (Deep or Soft Soil) and Class E (Very Soft Soil) can be renamed as “Flexible Soil” and “Very Flexible Soil” respectively.

The site Class E in the current edition of AS1170.4 has also considered those onerous conditions, for which the DS has been stipulated in a conservative way, or else site-specific dynamic site response analyses would be required. The proposed scheme describes such sites as “Special Soil” (Class S), which includes sites with $T_S > 1.2$ s, or deposits consisting of at least 10 m thick of clays/silts with a high plasticity index (PI > 50) or undrained shear-strength less than 12.5 kPa. A soil column with $T_S > 1.2$ s is considered extremely flexible, there could be significant higher modes effects in the site response behaviours. For such Special Soil sites, the envelope of DS models for all site classes (i.e. A to E) shall be taken, or site-specific dynamic site response analyses should be undertaken to justify a lower level of seismic demand.

Table 1. Proposed site classification scheme.

Site Class	Description	Site Period T_S (s)
A & B	Rock	$T_S < 0.15$
C	Stiff Soil	$0.15 \le T_S < 0.6$
D	Flexible Soil	$0.6 \le T_S < 0.9$
E	Very Flexible Soil	$0.9 \le T_S \le 1.2$
S	Special Soil	$T_S > 1.2$

3 DESIGN SPECTRUM MODEL

3.1 Design Spectrum (DS) Format

The DS model can be constructed using Eq. (2) in the displacement (RSD) format, as expressed in terms of three spectral parameters, RSD_{max}, T_1 and T_2. The emphasis on the prediction of the value of *RSD* is to align with displacement-based seismic design methodology.

$$\begin{aligned} T \le T_1: &\quad RSD(T) = RSD_{max}\left(\frac{T^2}{T_1 T_2}\right) \\ T_1 \le T \le T_2: &\quad RSD(T) = RSD_{max}\left(\frac{T}{T_2}\right) \\ T_2 \le T \le 5: &\quad RSD(T) = RSD_{max} \end{aligned} \tag{2}$$

The DS model in the conventional acceleration (RSA) format can be conveniently obtained by direct transformation from the displacement format using Eq. (3).

$$RSA(T) = RSD(T)\left(\frac{2\pi}{T}\right)^2 \tag{3}$$

This model is identical to that currently adopted in AS1170.4, and is similar in form to those adopted in various codes of practice worldwide. RSD_{max} is the maximum spectral displacement demand. T_1 is the first corner period at the upper limit of the constant spectral acceleration region of the DS model, whereas T_2 (the second corner period) characterises the constant spectral displacement region.

The hump phenomenon and the characteristic decrease in *RSD* in the higher period range have been featured in the model of Newmark and Hall (1982). Eurocode 8 stipulates an additional corner period T_E of 5.0 s or 6.0 s for the onset of the decrease in *RSD* for soil sites. Amirsardari et al. (2014) also proposed a DS model in which such phenomenon is featured. However, the hump phenomenon as described has not been incorporated into the proposed model in view of the huge uncertainties in the estimates of the soil parameters, as well as the varying extents of shear modulus reduction and period lengthening (Tsang et al. 2006b). *RSD* might peak at a higher period than predicted for certain sites.

3.2 Proposed Spectral Parameters

For rock sites (Class A & B), the highest response spectral displacement demand (RSD_{max}) is equal to $SD_R(1.5)$ which is the location-specific spectral displacement demand on rock at T = 1.5 s. The existing set of corner period (T_1 and T_2) values is considered appropriate. Taking Melbourne as example, a Z-factor (or hazard factor) of 0.08 g corresponds to $SD_R(1.5)$ of 26.2 mm for a notional return period of 500 years.

A DS model that takes into account resonant-like amplification phenomenon in soil sites (i.e. Classes

C, D, E and S) is proposed. Figure 1 is a schematic diagram illustrating the proposal. Parameter values for $RSD_{\max}$, T_1 and T_2, can be obtained using Eqs. (4)-(6):

$$RSD_{\max} = SD_R(\beta T_S) \times S \tag{4}$$

$$T_1 = \alpha T_S \tag{5}$$

$$T_2 = \beta T_S \tag{6}$$

where $SD_R(\beta T_S)$ is the response spectral displacement (*RSD*) on rock (Class A & B) at $T = \beta T_S$, whilst S is the site amplification factor, which is applied at the constant-velocity range. α and β are recommended to be 1.2 and 1.5, respectively, as response spectral velocity (*RSV*) of a soil spectrum typically peaks between $1.2T_S$ and $1.5T_S$, with respect to the level of ground shakings in regions of lower seismicity (Tsang et al. 2006b). The effects of plasticity (PI) has not been parameterised in view of their much weaker influence on dynamic soil properties than was previously believed as revealed recently (Darendeli 2001; Zhang et al. 2005; Vardanega and Bolton 2011).

The S-factor is principally a function of V_S (Tsang et al. 2006a). Site response analysis also reveals the value of the S-factor increasing with the site natural period T_S. Moreover, resonant style amplification behaviour is highly selective in view of a very narrow half-power bandwidth (i.e. frequency ratio = 2ζ = 0.1, where $\zeta = 0.05$ is the assumed structural damping ratio). With DS which peaks at $T = 0.4$ s, the half-power bandwidth (i.e. zone of influence by resonance) is in the narrow range of 0.38 s – 0.42 s; whereas with DS which peaks at $T = 1.0$ s, the slightly wider zone of influence is 0.95 s – 1.05 s. An S-factor of 2.5 has been stipulated for stiff soil sites; whereas a higher value of 3.5 for all flexible, and very flexible, soil sites which feature a wider zone of influence.

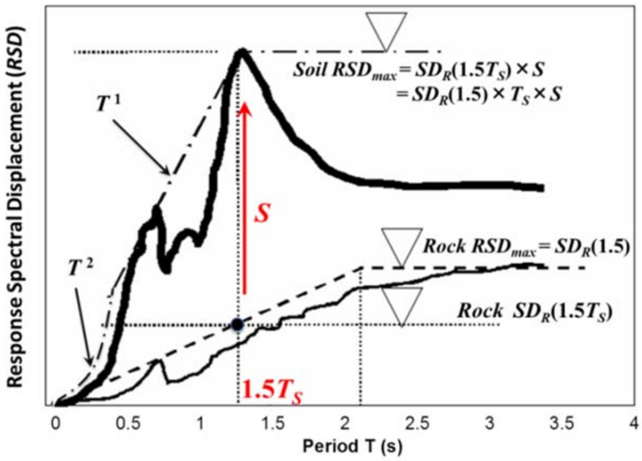


Fig. 1. Schematic diagram of the proposed model for soil sites (Class C, D, E & S) (in RSD format).

4 COMPARISON WITH AS1170.4–2007

The DS model proposed for use in Australia can be adapted into the format of the current edition of AS1170.4 with a simpler site classification scheme as described in Section 2.2. Parameter values for all site classes have been listed in Table 2 for Melbourne (Z = 0.08 g). The proposed DS models are compared with those stipulated in AS1170.4–2007 in Figs. 2 – 6 in both the RSA, and RSD, formats.

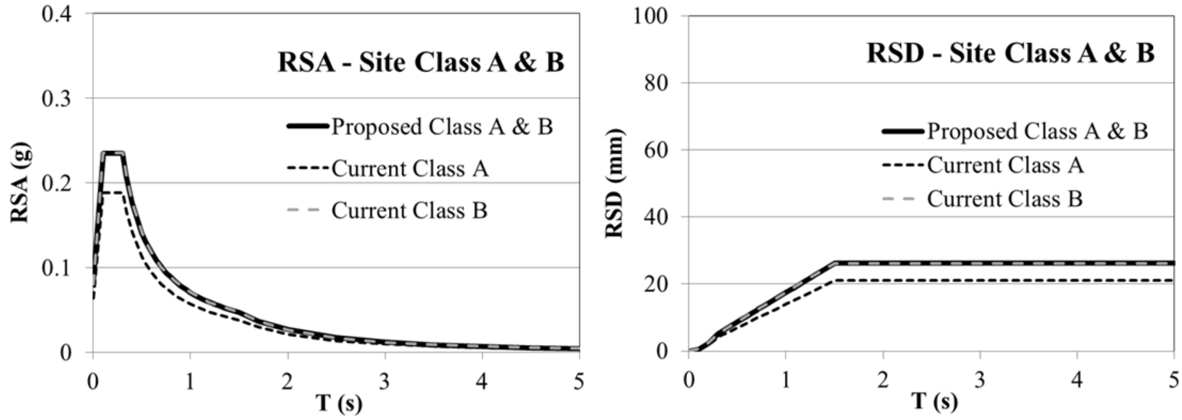
In the proposed DS model for site Class C, an amplification ratio of 1.25 is stipulated for the low period range, which is consistent with stipulation by the current standard. The model is shown to be more conservative than the spectrum model of AS1170.4 in the intermediate period range (between 0.3 and 1.2 s) but the value of *RSA* is consistently lower than the maximum limit of 0.294 g. Also, there is a reduction in the value of the peak displacement demand from 37 mm to 34 mm.

In the proposed model for site Class D, the amplification ratio is 1.3 and 2.3 for the low, and high, period range respectively, which are very close to stipulations by the current standard for the same site class. The higher demand in the intermediate period range for site Class C and D compared to the AS1170.4 model can mimic resonant-like amplification behaviour around the site natural period.

Table 2. Proposed spectral parameters, $RSD_{\max}$, T_1 and T_2.

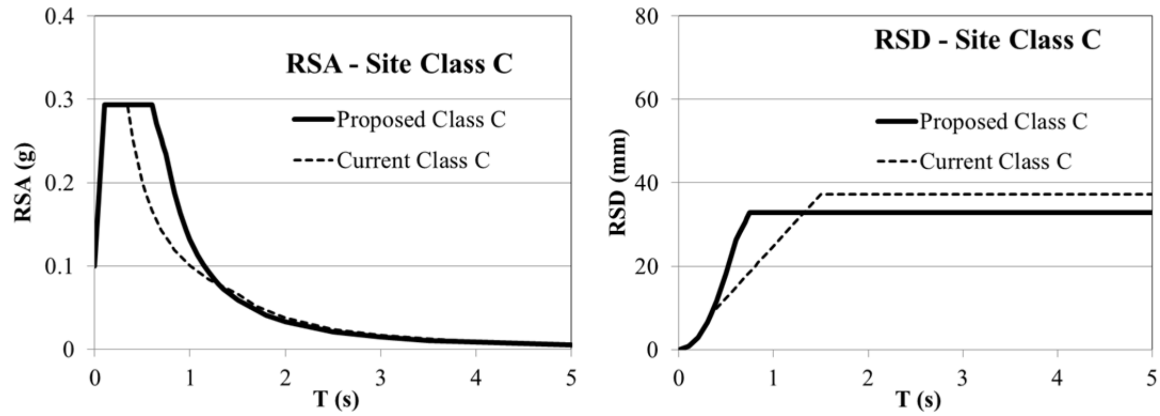
Site Class	Description	T_S (s)	$RSD_{\max}$ (mm)	T_1 (s)	T_2 (s)
A & B	Rock	$T_S < 0.15$	26.2	0.3	1.5
C	Stiff Soil	$0.15 \leq T_S < 0.6$	13.1 × 2.5 = 33	0.6	0.75
D	Flexible Soil	$0.6 \leq T_S < 0.9$	17.5 × 3.5 = 61	0.8	1.0
E	Very Flexible Soil	$0.9 \leq T_S \leq 1.2$	26.2 × 3.5 = 92	1.2	1.5
S*	Special Soil	$T_S > 1.2$	26.2 × 3.5 = 92	0.8	1.5

* For Class S sites, site-specific dynamic site response analysis is allowed to justify lower demand.



(a) (b)

Fig. 2. The proposed design spectrum for Rock Sites (Class A & B) in (a) RSA and (b) RSD formats, in comparison with AS1170.4–2007.

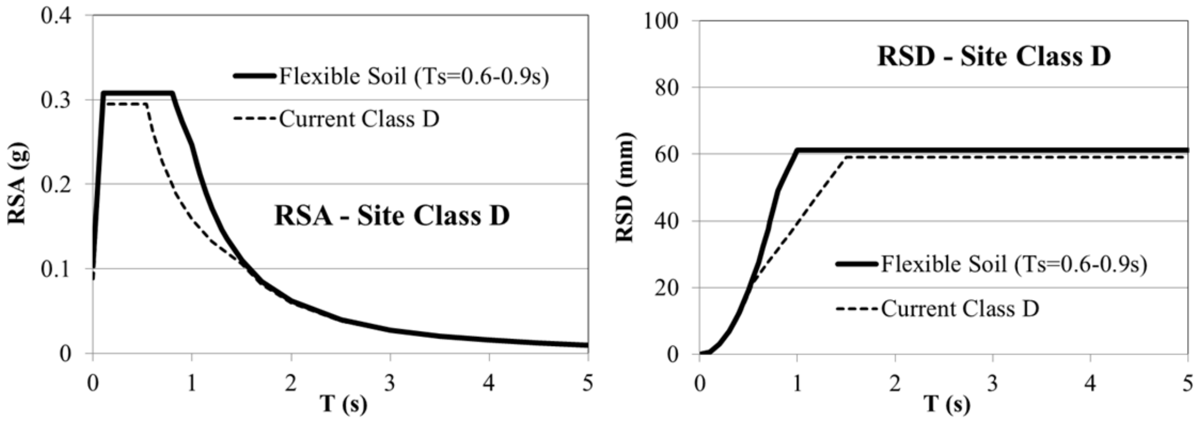


(a) (b)

Fig. 3. The proposed design spectrum for Stiff Soil Sites (Class C) in (a) RSA and (b) RSD formats, in comparison with AS1170.4–2007.

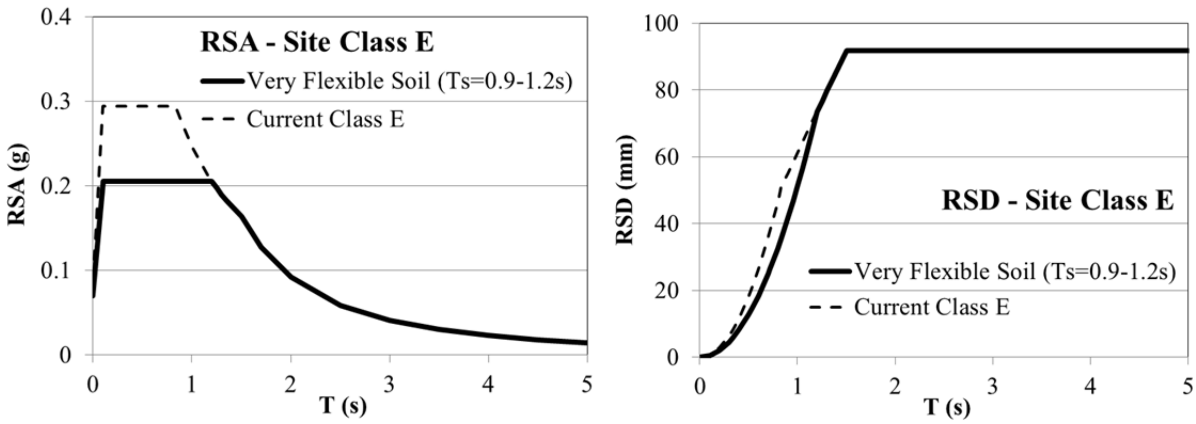
In the proposed site Class E, the high-period amplification factor is 3.5 which is consistent with the current standard. Significantly, the mitigating effects of a very flexible soil site resulting in a much lower acceleration demand on low rise buildings is a distinctive feature of the proposed DS model. Site Class E in AS1170.4 also refers to some of those rare, and onerous, site conditions, and are dealt with separately by a new site Class S (for Special Soil) for which the envelope of DS models for all site classes is adopted, which is consistent with the DS model stipulated by AS1170.4 for site Class E.

In summary, the newly proposed site factor model offers design engineers the option of designing to a lower level of seismic actions for certain structures found on very flexible soil sites provided that reliable, and relevant, information on the site subsoil conditions has been obtained. Similar, yet more accurate, response spectra would have been obtained from site-specific dynamic analysis of a soil column model (using programs such as SHAKE). Thus, the proposed site DS model serves to achieve a similar objective as a site-specific response spectrum without requiring the engineer in undertaking computational dynamic analysis of soil column models which requires accelerograms to be selected from a strong motion database, or synthesized by the computer, as information for input into the analysis. This distinctive feature of the proposed DS model is mainly attributed to including the site natural period as a parameter in the newly proposed site classification scheme.



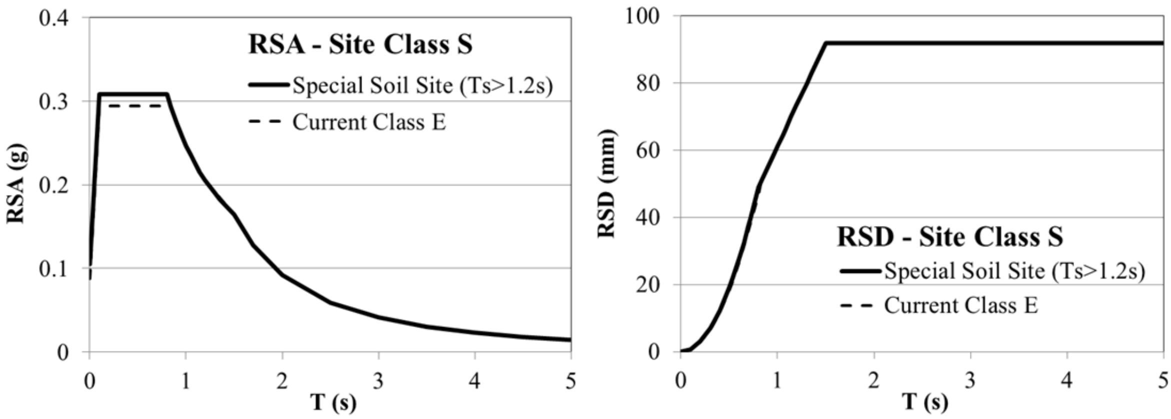
(a) (b)

Fig. 4. The proposed design spectrum for Flexible Soil Sites (Class D) in (a) RSA and (b) RSD formats, in comparison with AS1170.4–2007.



(a) (b)

Fig. 5. The proposed design spectrum for Very Flexible Soil Sites (Class E) in (a) RSA and (b) RSD formats, in comparison with AS1170.4–2007.



(a) (b)

Fig. 6. The proposed design spectrum for Special Soil Sites (Class S) in (a) RSA and (b) RSD formats, in comparison with the Class E spectrum in AS1170.4–2007.

5 PROPOSED SPECTRAL SHAPE FACTOR

A table of spectral shape factor ($C_h(T)$), that is of consistent format as Table 6.4 in AS1170.4–2007, is given in Table 3 and illustrated in Fig. 7.

Table 3. Proposed spectral shape factor ($C_h(T)$).

Period T (seconds)	Site Class				
	A & B Rock	C Stiff Soil	D Flexible Soil	E Very Flexible Soil	S Special Soil
	$T_S < 0.15$	$0.15 \le T_S < 0.6$	$0.6 \le T_S < 0.9$	$0.9 \le T_S \le 1.2$	$T_S > 1.2$
0.0	1.00	1.25	1.31	0.88	1.31
0.1	2.94	3.68	3.86	2.57	3.86
0.2	2.94	3.68	3.86	2.57	3.86
0.3	2.94	3.68	3.86	2.57	3.86
0.4	2.21	3.68	3.86	2.57	3.86
0.5	1.76	3.68	3.86	2.57	3.86
0.6	1.47	3.68	3.86	2.57	3.86
0.7	1.26	3.15	3.86	2.57	3.86
0.8	1.10	2.58	3.86	2.57	3.86
0.9	0.98	2.04	3.43	2.57	3.43
1.0	0.88	1.65	3.09	2.57	3.09
1.1	0.80	1.37	2.55	2.57	2.81
1.2	0.74	1.15	2.14	2.57	2.57
1.3	0.68	0.98	1.83	2.37	2.37
1.4	0.63	0.84	1.58	2.21	2.21
1.5	0.59	0.74	1.37	2.06	2.06
1.7	0.46	0.57	1.07	1.60	1.60
2.0	0.33	0.41	0.77	1.16	1.16
2.5	0.21	0.26	0.49	0.74	0.74
3.0	0.15	0.18	0.34	0.51	0.51
3.5	0.11	0.14	0.25	0.38	0.38
4.0	0.083	0.10	0.19	0.29	0.29
4.5	0.065	0.08	0.15	0.23	0.23
5.0	0.053	0.07	0.12	0.19	0.19
Equations for Spectra					
$0 \le T \le 0.1$ $0.1 \le T \le T_2$ $T \ge T_2$	$1.0 + 19.4T$ $0.88/T$ (≤ 2.94) $1.32/T^2$	$1.25 + 24.3T$ $2.21/T$ (≤ 3.68) $1.65/T^2$	$1.31 + 25.4T$ $3.09/T$ (≤ 3.86) $3.09/T^2$	$0.875 + 17.0T$ $3.09/T$ (≤ 2.57) $4.63/T^2$	$1.31 + 25.4T$ $3.09/T$ (≤ 3.86) $4.63/T^2$
T_2 (s)	1.5	0.75	1.0	1.5	1.5

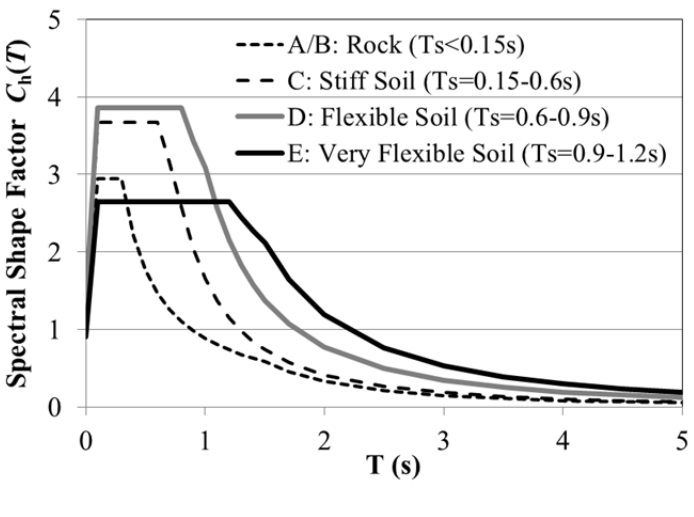


Fig. 7. Proposed spectral shape factor ($C_h(T)$) (Class A & B: Rock; Class C: Stiff Soil; Class D: Flexible Soil; Class E: Very Flexible Soil). The envelope of DS models for all site classes is taken as the model for Class S: Special Soil.

6 CONCLUSIONS

A new design spectrum (DS) model which encapsulates displacement principles in the modelling of site effects on seismic actions is proposed in this paper. Central to the construction of the DS model is the adoption of the site natural period (T_S) as parameter in the proposed site classification scheme. The selective nature of response spectral amplification on a soil site is well reflected in the shape of the proposed soil spectrum which resembles real behaviour (as observed from results generated by computational dynamic analysis of soil column models and from recordings in the field) much better than the response spectrum models stipulated in existing codes of practice. The newly proposed site DS model offers design engineers the option of designing to a lower seismic action for low rise (stiff) structures that are found on very flexible soil sites (i.e. new Class E sites) provided that reliable, and relevant, information on the site subsoil conditions has been obtained.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contribution of the Bushfire and Natural Hazards CRC grant.

REFERENCES

Amirsardari A., Lumantarna E., Goldsworthy H.M. 2014. Seismic site response analysis for Australia. In: *Proceedings of the Australian Earthquake Engineering Society 2014 Conference*, Nov 21-23, Lorne, Victoria.

Australian Standard: AS 1170.4-2007, *Structural Design Actions, Part 4: Earthquake Actions in Australia*. Sydney, Australia: Standards Australia; 2007.

Australian Earthquake Engineering Society (AEES) 2007. *AS 1170.4–2007 Commentary*. Supplement to the Australian Standard AS 1170.4 Structural Design Actions – Part 4: Earthquake Actions in Australia. Editors: J. Wilson and N. Lam. Australian Earthquake Engineering Society, Australia.

Darendeli M.B. 2001. *Development of a new family of normalized modulus reduction and material damping curves* [Ph.D. thesis]. USA: University of Texas at Austin.

EN 1998-1:2004, *Eurocode 8: Design of Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings*. United Kingdom: European Committee for Standardisation; 2004.

International Building Code (IBC). Country Club Hill, Illinois, USA: International Code Council; 2012.

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

Larkin T., Van Houtte C. 2014. Determination of site period for NZS1170. 5: 2004. Bulletin of the New Zealand Society for Earthquake Engineering. 47 (1).

Newmark N.M., Hall W.J. 1982. *Earthquake Spectra and Design*. Earthquake Engineering Research Institute, Berkeley, California.

New Zealand Standard: NZS 1170.5:2004, *Structural Design Actions Part 5: Earthquake Actions – New Zealand*. Wellington, New Zealand: Standards New Zealand; 2004.

Schnabel P.B., Lysmer J., Seed H.B. 1972. SHAKE: a computer program for earthquake response analysis of horizontally layered sites. Earthquake Engineering Research Center Report: EERC 72-12. USA: University of California at Berkeley.

Supplement to New Zealand Standard: NZS 1170.5 Supp 1:2004, *Structural Design Actions Part 5: Earthquake Actions – New Zealand – Commentary*. Standards New Zealand, Wellington, New Zealand.

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

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

Tsang H.H., Sheikh M.N., Lam N.T.K. 2012. Modeling shear rigidity of stratified bedrock in site response analysis. *Soil Dynamics and Earthquake Engineering*. 34. 89-98.

Vardanega P.J., Bolton M.D. 2011. Practical methods to estimate the non-linear stiffness of fine grained soils. In: *Proceedings of the 5th International Symposium on Deformation Characteristics of Geomaterials*. Seoul, South Korea; p. 372-379.

Zhang J., Andrus R.D., Juang C.H. 2005. Normalized shear modulus and material damping ratio relationships. *Journal of Geotechnical and Geoenvironmental Engineering*. 131 (4). 453-464.