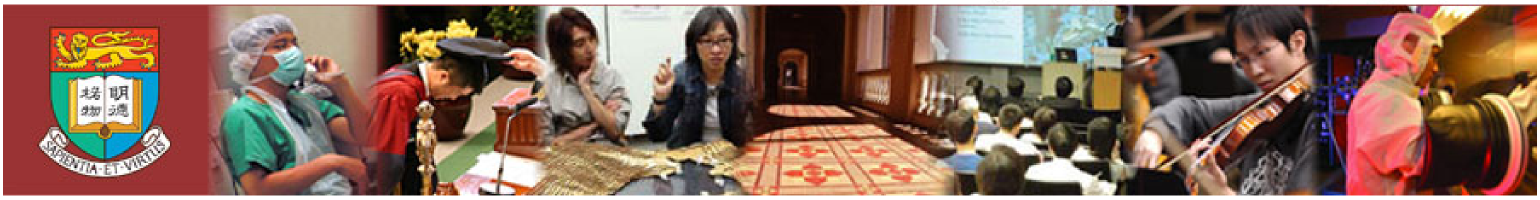


Title	A design spectrum model for flexible soil sites in regions of low-to-moderate seismicity
Author(s)	Tsang, HH; Wilson, JL; Lam, NTK; Su, RKL
Citation	Soil Dynamics and Earthquake Engineering, 2017, v. 92, p. 36-45
Issued Date	2017
URL	http://hdl.handle.net/10722/242795
Rights	This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License.

A Design Spectrum Model for Flexible Soil Sites in Regions of Low-to-Moderate Seismicity

H.H. Tsang[a,*], J.L. Wilson[a], N.T.K. Lam[b], R.K.L. Su[c]

[a] *Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, VIC 3122, Australia*
[b] *Department of Infrastructure Engineering, The University of Melbourne, Parkville, VIC 3010, Australia*
[c] *Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong*

ABSTRACT

Design spectrum (DS) models in major codes of practice for structural design of buildings typically stipulate empirical site factors for each of the five, or six, site classes. Although the phenomenon of resonant like amplification behaviour of the structure caused by multiple wave reflections is well known, the potentials for such periodic amplification behaviour are not explicitly considered in code models. This is partly because of expert opinion that such effects are very "localised" in the frequency domain and can be suppressed readily by damping. However, investigations into the risk of collapse of non-ductile, and irregular structural systems, common in regions of low-to-moderate seismicity, revealed the extensive influence of periodic base excitations on flexible soil sites (with initial small-strain natural period $T_i > 0.5$ s). In this paper, an alternative DS model which addresses the important phenomenon of soil resonance without the need of computational site response analysis of the subsurface model of the site is introduced.

Keywords: Design spectrum, code, site factor, soil amplification, resonance, displacement

* Corresponding author. Tel.: +61 3 9214 5009.
E-mail address: htsang@swin.edu.au (H.H. Tsang).

1. Introduction

Seismic action models in major codes of practice 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. As different site factors are applied to the two sections, the corner periods in the DS model can vary a great deal between site classes. The International Building Code (IBC) of the United States [1] also stipulates different sets of site factors for different intensities of ground shaking in order that different levels of seismicity are covered in one model.

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. The concept of "frame analogy" [2] can be used to explain the phenomena that certain wave components in a range of frequencies are amplified. 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 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.

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 [3]. 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 a preference for simplicity and 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.

It is noted that non-ductile, and irregular, structural systems are common in regions of low-to-moderate seismicity. The priority in design, and retrofitting, in such built environments is to safeguard these structural systems from total, or partial, collapse in a rare event for avoiding loss of lives and for minimizing casualties. Until recently, the post-elastic behaviour of these systems in ultimate conditions featuring significant strength degradation and P-delta effects could only be modelled by rigorous non-linear time-history analyses. Reliable predictions can now be made using simple hand calculation techniques which employ displacement-based principles [4]. Importantly, investigations into the risk of collapse (overturning) of this type of structure employing a kinematic-based calculation technique revealed significant influence by the peak displacement demand of the ground motions irrespective of the exact dominant frequency of the ground excitations [5]. Although the effects of resonance on elastically responding systems are very localised, the effects on structures approaching the state of collapse, or overturning, can be widespread. This peak displacement demand has been shown to be amplified to a very high value by periodic excitations on a flexible soil site. Central to the calculation technique is the use of response spectrum in the displacement (RSD) format or acceleration-displacement response spectrum (ADRS) format which shows more clearly the amplified displacement demand behaviour of the ground motion than a response spectrum in the conventional acceleration format.

Fig. 1(a–e) presents the results of a case study of a flexible soil site (T_i ~ 1.0 s) experiencing resonant-like amplification behaviour. Clearly, the frequency contents of ground motions have been dramatically modified by the flexible soil sediments as revealed by the displacement response spectrum (Fig. 1(d)) and ADRS diagram (Fig. 1(e)). In contrast, the phenomenon is not as clearly shown on response spectra presented in the conventional acceleration (RSA) format (e.g. Fig. 1(a)). Furthermore, it should be noted that the resonant phenomenon as illustrated in Fig. 1 can be easily masked by averaging response spectra from a suite of accelerogram records (except when all the recordings are from one soil site or from soil sites with very similar site natural period properties which is usually not the case). Resonant-like soil amplification behaviour is therefore not well represented in empirically developed codified models which were usually derived by statistical analyses of averaged response spectral values from accelerograms recorded on a diversity of soil sites.

A DS model in the displacement format which takes into account the described amplification phenomenon as depicted in Fig. 1(d) for flexible soil sites (T_i > 0.5 s) is introduced in this paper. Relationships for estimating the site factor and the site natural period (with considerations for a shift in the site natural period value) are presented in the form of algebraic expressions and design charts in order that a representative DS model can be constructed readily which can mimic results from computational dynamic analyses. The important effects of site natural period have been parameterised whereas the effects of damping in the soil and impedance ratio at the soil-bedrock interface have also been taken into account.

2. Appraisal of Existing Codified DS Models

DS models in five codes of practice as listed in below (in alphabetical order of the abbreviated names shown in bold fonts) have been included in the review to be presented in this section:

1. Australian Standard (**AS** 1170.4–2007) [6]
2. Eurocode 8 (**EC**) (EN 1998-1:2004) [7]: a. Type 1, b. Type 2
3. Chinese Code for Seismic Design of Buildings (**GB** 50011–2010) [8]
4. International Building Code (**IBC**–2012) [1]
5. New Zealand Standard (**NZS** 1170.5:2004) [9]

The inconsistencies between various codes of practice are illustrated in Fig. 2 using the DS of a flexible soil site in Hong Kong constructed in accordance with various code models. The uniform hazard spectrum (UHS) with a return period of 2,500 years for rock sites in Hong Kong [10,11] is also shown on the same figure for comparison. It is noted that all the acceleration spectra (in Fig. 2(a)) have been normalised with respect to the maximum response spectral acceleration (RSA_{max}) value on rock. The effects of site amplification are reflected in the differences between the DS stipulated for the soil site and the UHS for a rock site.

It is observed that the soil DS derived from different codes of practice vary substantially across the entire range of natural periods. To facilitate a systematic comparison between the code models, the implied spectral amplification ratios (i.e. Soil DS/Rock UHS) at natural periods of 0.2 s, 0.5 s, 1.0 s and 2.0 s are listed in Table 1. The values of the two corner periods, T_1 and T_2, of each DS are also listed for comparison. It is noted that EC has recommended two types of DS: one for the higher seismicity areas (Type 1, annotated as **EC1**) and the other for the less active areas (Type 2, annotated as **EC2**).

Amongst the six codified DS, only the GB model does not show any spectral amplification at the constant acceleration "plateau" (up to T = 0.5 s), whereas an amplification ratio of up to 1.8 is stipulated by the EC2 model in that part of the response spectrum. The amount of spectral amplification stipulated by the GB model is also consistently lower at the low-to-intermediate period range, as a result of an un-amplified constant acceleration "plateau" and a low first corner period (T_1) value. However, the amplification factor becomes much higher in the period range exceeding 2.5 s ($5T_1$), because of the abnormal shape of this part of the DS model of GB. This leads to disproportionately high displacement demand in the high period range.

In the DS models of AS, EC1 and NZS, the spectral amplification ratios in the intermediate-to-high period range are relatively large as a result of the high first corner period (T_1) values. The amplification ratio of the AS model becomes smaller at high natural period beyond 2.0 s, because of the smaller second corner period (T_2) value of 1.5 s. The function of $1/T^{0.75}$ between T_1 and 1.5 s adopted in NZS contributes further to the exceptionally high displacement demand. As EC1 and NZS are applied to regions of moderate-to-high seismicity, with design peak ground acceleration (PGA) ≥ 0.13 g for return period of 500 years [9], the resulted higher displacement demand is deemed appropriate.

In view of the high level of inconsistencies (*i.e. several hundred per cent differences*) between the soil DS models stipulated by various codes of practice, and their deficiencies in capturing site-specific characteristics, an alternative DS model is proposed in this paper to provide more realistic predictions for soil sites.

It is well known that the shape of an earthquake response spectrum is typically controlled by the fundamental natural period of the soil layers, and particularly so in situations where there is a distinct soil-rock interface [Luzi et al., 2011; Héloïse et al., 2012; Casterllaro and Mulargia, 2014]. The amplification ratio usually has a maximum value at the large-strain natural period of the soil layer (T_S), which has however not been explicitly taken into account by any existing codes of practice. The proposed site-specific DS model is in a format that can be used conveniently in a hand calculation procedure, as for most contemporary codified DS models. The DS model proposed herein has been demonstrated to produce soil DS which match reasonably well with those generated from site response analyses. The proposed *S-Factor* in the order of 4 is reflected in the proposed model. Similarly, the phenomenon of shift in the site natural period resulting from reduction of the shear modulus of the soil is also modelled.

3. Proposed Soil DS Model

3.1. General

Significant amplification of ground shaking on flexible soil sites is evident in many past earthquakes. The effects of such amplification behaviour are particularly significant in regions of low-to-moderate seismicity, given the very limited mitigating effects of damping that are associated with the non-linear response behaviours of both the soil layers and the structure which is found on the soil surface. In situations where there is a distinct soil-rock interface, the resonant phenomena that are associated with multiple reflections of seismic waves may occur, and this could result in much higher amplification of the structural responses.

This period selective amplification phenomenon, which is highly dependent on the total thickness of the soil layers, has not been factored into any contemporary code models and can only be captured by dynamic analysis of a soil column model involving the use of accelerograms recorded, or simulated, on rock outcrops (or bedrock). The analysis requires expert knowledge and experience, given that the generated results could be sensitive to the choice of input parameter values and the nature of the input excitations. From the perspective of a practicing engineer, it is preferable to have a simple and convenient hand calculation model, which can save efforts for undertaking dynamic analyses.

The key feature of the proposed site-specific DS model, as shown in Fig. 3, has been developed mainly for estimating the value of response spectral displacement (*RSD*) at the natural period of the site (T_S) (which is the peak displacement demand, RSD_{max}). The emphasis on the prediction of the value of *RSD* is to align the modelling of site effects with displacement-based seismic design methodology. As illustrated in Fig. 3, the proposed model involves estimating (i) the large-strain natural period of the site, T_S, and (ii) the site amplification *S-Factor* which is defined as the ratio between the maximum spectral displacement of the soil spectrum and the spectral displacement of the rock spectrum at T_S. Both variables are functions of the dynamic properties of the soil materials and the impedance contrast between the soil layers and the underlying bedrock.

A theoretical model involving a large number of input parameters was initially developed by the authors [12,13] to model the aforementioned site-specific amplification behaviour for idealised soil column models of homogenous materials. The model was developed based on the fundamental principles of wave propagation and designed to yield more conservative estimates than results from a higher-tier, and more rigorous, approach of computational site response analysis. It is noted that the model proposed herein does not intend to account for the complexity of the SWV profile in relation to the change in the SWV values with depth which could have significant influence on site amplification behaviour [Régnier et al. 2014].

The rest of this section presents the adaptation of the original theoretical model to the analysis of realistic soil column models (showing changes in the SWV values with depth) along with newly developed, more simplified, expressions. Importantly, the modified model has been verified by comparison with results of dynamic analyses of a number of soil column models derived from real borehole records in order that the model has become amenable to practical applications (Section 4).

3.2. Characterisation of Soil Sites

In the proposed calculation procedure, a soil site shall be characterised by the weighted average initial SWV ($V_{S,i}$) and the initial natural period (T_i) of all the soil layers down to the depth of very stiff sedimentary materials or bedrock.

The value of T_i 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.

$$T_i = \sum_{i=1}^{n} \frac{d_i}{V_i} \times 4 = \frac{4H_S}{V_{S,i}} \quad (1)$$

Alternatively, this can be expressed in terms of the total thickness of the soil layers (H_S) and the weighted average initial SWV ($V_{S,i}$).

For a site with $T_i \leq 0.15$ s, where the soil layers are relatively 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. It is noteworthy that the corresponding peak displacement demand for such low period structures is very small in regions of low-to-moderate 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, or overturning.

The values of initial SWV of soil layers (V_i) (in m/s) can also be calculated from the SPT-*N* values, as recorded in borehole logs. There are various available correlating relationships between SPT-*N* values and V_i, as comprehensively reviewed in the recent PEER Report 2012/08 [Wair, DeJong and Shantz (2012)]. It was shown that significant variabilities exist amongst those relationships. The popularly-used conversion formula of Eq. (2) [14] is selected for demonstration purpose, because it was developed from analyses of the largest dataset, and it gives median predictions by all the models that have been reviewed in the PEER Report.

$$V_i = 97 \times N^{0.314} \qquad (2)$$

There is typically an upper limit for the number of blows per foot (or 300 mm) in practice. If the limit is 100, equivalent *N* values greater than 100 can be calculated pro rata when the penetration depth is less than a foot (or 300 mm) (e.g. 100 blows per 250 mm is equivalent to 120 blows per 300 mm, i.e. equivalent *N* value of 120). It is noted that data showing SPT-*N* values of around 400 can be found in the original publication by Imai and Tonouchi [14]. Also, it is recommended that sedimentary layers with SPT-*N* values greater than 250 be omitted in the calculation of the site natural period.

In analysing the seismic response behaviour of the soil layers, the value of the shear modulus (and hence SWV) of the soil materials would decrease with increasing intensity of ground shaking due to material non-linearity. The ratio between the shifted (large-strain) site natural period (T_S) and the initial (small-strain) site natural period (T_i) has to be estimated as per the intensity of shaking. The modelling of this phenomenon will be addressed in the next section.

3.3. Shifted (Large-Strain) Site Natural Period (T_S)

The values of T_S and the reduced weighted average SWV of soil layers have to be estimated according to the intensity of shaking, which can be represented by the value of *RSD* or response spectral velocity (*RSV*) at T_i, i.e. RSD_{Ti} or RSV_{Ti}, of the rock DS.

The shifted site natural period T_S can be estimated using Eq. (3), which has been simplified from the original expressions developed in [13]. The term in the original expression representing the effects of plasticity has been removed in view of recent research findings that showed less dependency of dynamic soil properties on the value of the plasticity index than previously believed [15–17].

$$\frac{T_S}{T_i} = 1 + \frac{\pi}{4}\frac{RSD_{Ti}}{H_S} \tag{3}$$

Given Eq. (1) and $RSD_{Ti} = RSV_{Ti}\frac{T_i}{2\pi}$, the period-shift ratio can be expressed in terms of RSV_{Ti} and $V_{S,i}$ as shown by the following alternative relationship:

$$\frac{T_S}{T_i} = 1 + \frac{RSV_{Ti}}{2V_{S,i}} \tag{4}$$

In the equations shown above, RSD_{Ti} is in units of mm, RSV_{Ti} in mm/s, $V_{S,i}$ in m/s and H_S in m.

The initial natural period T_i of soil sites typically ranges from 0.3 s to 1.2 s, whilst RSV_{Ti} on rock sites for this period range may be taken as constant (i.e. constant-velocity range). In view of this, a specific value of RSV_{Ti} can be identified for each location depending on the design hazard level, in order that the period-shift ratio can be estimated conveniently as function of only one variable, $V_{S,i}$. The correlating relationships are presented in Fig. 4 for four levels of earthquake ground shaking intensities: i.e. RSV_{Ti} = 50, 100, 200 and 400 mm/s. The period-shift ratios corresponding to the intensity levels can be identified using the design chart of Fig. 4 (in lieu of using Eq. (3) or (4)). The selected values of RSV_{Ti} cover the whole range of shaking levels in regions of low-to-moderate seismicity.

3.4. Non-linear Site Amplification Factor (S)

An estimate for the *S-Factor* can also be obtained through the use of the design charts of Fig. 5. It was revealed from a sensitivity study that the non-linear site amplification *S-Factor* is most sensitive to the SWV of both soil and bedrock materials [Tsang et al., 2006a]. Hence, design curves as functions of initial soil SWV ($V_{S,i}$) have been created for four bedrock SWV (V_R), namely, 760, 1100, 1800, 3000 m/s, as shown in Fig. 5(a). In developing the design charts, a typical value of 1.3 is assumed for the rock-to-soil density ratio ρ_R / ρ_S and a moderate shaking level characterised by RSV_{Ti} = 200 mm/s is used. The proposed model is consistent with the notion recommended by McVerry [20] that the site factor be expressed as a continuous function of one or two soil parameters that can readily be measured.

The value of V_R = 760 m/s was selected as it has been used as a time-averaged SWV in the top 30 m (V_{S30}) in defining the reference site condition (i.e. B/C boundary) for developing the site coefficients included in the National Earthquake Hazards Reduction Program (NEHRP) provisions (Building Seismic Safety Council, 2015). A consistent NEHRP B/C crustal profile has recently been developed (Boore, 2016) which is regarded as the new generic rock profile as an update of the well-known generic rock profile (Boore and Joyner, 1997). V_{S30} = 1100 m/s (or 1130 m/s) is the most common value for defining the reference rock condition in the NGA-West models (Abrahamson et al., 2008) and the updated NGA-West2 models (Gregor et al., 2014). SWV value of 3000 m/s was recently recommended for defining the reference (hard) rock site condition in Central and Eastern North America (CENA) and also adopted in the NGA-East models [Hashash et al., 2014]. An intermediate value of 1800 m/s between the two extremes has also been selected as the bedrock SWV (V_R) for regions of massive granitic rock, such as the region near Anza in Southern California (Silva et al., 1999) and Hong Kong and surrounding region in Southern China [18,19].

The *S*-factor curves for various shaking levels based on the reference rock site condition in CENA (i.e. V_R = 3000 m/s) are shown in Fig. 5(b) as an illustration. It is observed that the *S*-factor for stiffer soil ($V_{S,i}$ > 400 m/s) does not vary significantly with the level of ground shaking when the value of RSV_{Ti} is greater than 100 mm/s. In fact, changes in the value of *S* with the level of ground shaking becomes smaller for softer (and more prevailing) bedrock conditions. It is noted that the non-linear (shaking level dependent) behaviour of site response is the combined effects of period-shift (due to shear modulus reduction of soils as evidenced in Figure 4), soil damping and impedance contrast. When the shaking level is high, the spectral contents of the ground motions are shifted to a higher period (lower frequency). Thus, there are lower amplification at a lower period and higher amplification at a higher period, which is consistent with field observations as reflected in the NEHRP site coefficients.

3.5. Design Spectrum (DS) Model for Soil Sites

The DS model for soil sites can be constructed using Eq. (5), as expressed in terms of three parameters, $RSD_{\max}$, T_1 and T_2, which can be computed using Eqs. (7)-(9).

$$T \le T_1: \qquad RSD_T = RSD_{\max}\left(\frac{T^2}{T_1 T_2}\right)$$

$$T_1 \le T \le T_2: \qquad RSD_T = RSD_{\max}\left(\frac{T}{T_2}\right) \tag{5}$$

$$T_2 \le T \le 5: \qquad RSD_T = RSD_{\max}$$

The DS model in the acceleration format can be conveniently obtained by direct transformation from the displacement format using Eq. (6).

$$RSA_T = RSD_T\left(\frac{2\pi}{T}\right)^2 \quad (6)$$

The proposed DS model is similar in form to those adopted in various codes of practice worldwide. T_1 is the first corner period at the upper limit of the constant spectral acceleration region of the DS model, whilst T_2 is the second corner period at the beginning (lower limit) of the constant spectral displacement region of the DS model. The three parameters, $RSD_{\max}$, T_1 and T_2, shall be computed using Eqs. (7)-(9).

$$RSD_{\max} = RSD_{Ts} \times S \quad (7)$$

where RSD_{T_S} is the *RSD* on rock at $T = T_S$.

$$T_1 = k \times T_i \quad (8)$$

$$T_2 = T_S \quad (9)$$

where k is recommended to be 1.2, as *RSV* of a soil spectrum typically peaks between $1.2 \times T_i$ and T_S, with respect to the level of ground shakings in regions of moderate seismicity. A different value of k can be derived based on the seismicity of the region.

4. Applications of the Proposed Model

The site-specific DS model proposed in this paper was essentially further developed, and simplified, from the theoretical model that was first presented in [12,13]. The original theoretical model was based on considering the propagation, and reflection, of shear waves in idealised soil profiles. Thus, an important objective of this paper is to demonstrate that site specific response spectra calculated from the dynamic analysis of subsoil profiles of real flexible soil sites (as described in authentic borehole records) are reasonably, and conservatively, represented by the (further developed) DS model presented in this paper.

Five flexible soil sites (T_i > 0.5 s) with different characteristics and distinctive site natural periods have been employed to evaluate the accuracy of the proposed model. Details of the borehole records for the five soil sites are provided in Appendix A. The key parameters that are involved in the process of calculating the response spectral parameters as per the proposed procedure have also been summarised in Table 2.

The DS as derived from the proposed procedure for the five sites are shown in Fig. 6–10 along with the DS stipulated by various major codes of practice in both the RSD and ADRS formats. The response spectrum (STRATA RS) for each site was obtained by multiplying the rock UHS by the response spectral ratio curves computed by computational site response analysis using program STRATA [21] (which has a computational algorithm similar to program SHAKE [3]). Three sets of input bedrock ground motions, with a probability of exceedance of 2% in 50 years (or a return period of 2,500 years), each of them representing near-field (NF), medium-field (MF) and far-field (FF) earthquake scenarios, have been simulated using program GENQKE [22,23]. It was found that the three sets of simulations give very consistent response spectral ratio curves.

Very good consistencies can also be seen between the DS derived from the proposed procedure and the response spectra obtained from dynamic analysis of the soil profiles using program STRATA. In contrast, displacement demand in the high natural period range (exceeding the respective site natural period) is grossly exceeded by all the code models (except EC2) (and to different extents depending on the value of T_2 that has been stipulated). Such over-conservatism with the code models would hinder the use of the displacement-based seismic design principle in regions of low-to-moderate seismicity.

In summary, the proposed DS model provides much better predictions of the displacement demand than code models in the intermediate and long period range (but spectral values at certain period range may exceed estimates from program STRATA because of the simple idealised shape of the DS). The proposed DS model is particularly suitable to be used for predicting displacement demand on structural systems that are found on the surface of flexible soil sites for assessing the risk of collapse and overturning.

5. Summary and Closing Remarks

A heuristic site-specific design spectrum (DS) model for flexible soil sites (T_i > 0.5 s) which takes into account resonant-like amplification behaviour of soil sediments is presented in this paper. The construction of the soil DS involves estimations of the large-strain site natural period (T_S) and site factor (S). The model has been well validated by comparison with results obtained from dynamic analyses of soil column models derived from real borehole records, as well as strong motion data recorded in the 1994 Northridge earthquake [12,13].

In the proposed hand calculation procedure, the initial small-strain site natural period (T_i) is first calculated from information of the shear wave velocity (SWV) values (inferred from SPT-*N* values) and thicknesses of the individual soil layers. The effects of period-shift resulting from shear straining (non-linearity) of the soil materials are then taken into account in the estimation of the (shifted/final) large-strain site natural period (T_S). The process of finding the values of T_S and S can be simplified further in a codified procedure through the introduction of design charts.

Finally, values of response spectral displacement $RSD_{\max}$ and corner periods T_1 and T_2 are to be identified for construction of the soil DS in different formats. In this paper, the accuracies of DS derived from the proposed procedure have been verified by comparative analyses involving program STRATA for benchmarking purposes and five soil profiles as per information derived from authentic borehole logs. The proposed DS model provides much better predictions of the response spectral demand than code models and particularly so in the intermediate and long period range.

In closing, it is acknowledged that the complex influences of the SWV profile of the site in relation to the change in the velocity values with depth could not be taken into account in the proposed procedure. In spite of this limitation, it is desirable and preferred by most practicing engineers to have a simple and convenient means of providing realistic predictions of site response behaviour and to ensure safe design, without the need to undertake dynamic (time-history) analyses of the sub-surface model of the site. In situations where dynamic analyses are employed, results generated by the analyses could be compared against estimates provided by the proposed simplified model as sanity check (thereby avoiding the dynamic analyses to become open ended).

References

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

[2] Lam NTK, Wilson JL, Chandler AM. Seismic displacement response spectrum estimated from the frame analogy soil amplification model. Engineering Structures 2001;23:1437-1452.

[3] Schnabel PB, Lysmer J, Seed HB. 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; 1972.

[4] Lumantarna E, Lam NTK, Wilson JL, Griffith MC. Inelastic displacement demand of strength degraded structures. Journal of Earthquake Engineering 2010;14:487-511.

[5] Kafle B, Lam NTK, Gad EF, Wilson JL. Displacement controlled rocking behaviour of rigid objects. Earthquake Engineering and Structural Dynamics 2011;40:1653-1669.

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

[7] 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.

[8] GB 50011-2010, Code for Seismic Design of Buildings. Beijing, China: The Ministry of Housing and Urban-Rural Development of the People’s Republic of China, China Architecture & Building Press; 2010.

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

[10] Tsang HH, Chandler AM. Site-specific probabilistic seismic-hazard assessment: direct amplitude-based approach. Bulletin of the Seismological Society of America 2006;96(2):392-403.

[11] Tsang HH, Su RKL, Lam NTK, Lo SH. Rapid assessment of seismic demand in existing building structures. The Structural Design of Tall and Special Buildings 2009;18(4):427-439.

Luzi L, Puglia R, Pacor F, Gallipoli MR, Bindi D, Mucciarelli M. Proposal for a soil classification based on parameters alternative or complementary to $V_{S,30}$. Bulletin of Earthquake Engineering 2011;9(6):1877–1898.

Héloïse C, Bard P-Y, Duval A-M, Bertrand E. Site effect assessment using KiK-net data: part 2—Site amplification prediction equation based on f_0 and V_{SZ}. Bulletin of Earthquake Engineering 2012;10(2):451–489.

Castellaro S, Mulargia F. Simplified seismic soil classification: the V_{fz} matrix. Bulletin of Earthquake Engineering 2014;12(2):735–754.

[12] Tsang HH, Chandler AM, Lam NTK. Estimating non-linear site response by single period approximation. Earthquake Engineering and Structural Dynamics 2006;35(9):1053-1076.

[13] Tsang HH, Chandler AM, Lam NTK. Simple models for estimating period-shift and damping in soil. Earthquake Engineering and Structural Dynamics 2006;35(15):1925-1947.

Régnier J, Bonilla LF, Bertrand E, Semblat J-F. Influence of the V_S profiles beyond 30 m depth on linear site effects: assessment from the KiK-net data. Bulletin of the Seismological Society of America 2014;104(5):2337-2348.

Wair BR, DeJong JT, Shantz T. Guidelines for estimation of shear wave velocity profiles. Pacific Earthquake Engineering Research Center (PEER) Report: 2012/08. USA: University of California; 2012.

[14] Imai T, Tonouchi K. Correlation of N-value with S-wave velocity and shear modulus. In: Proceedings of the 2nd European Symposium on Penetration Testing. Amsterdam, The Netherlands; 1982, p. 57-72.

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

[16] Zhang J, Andrus RD, Juang CH. Normalized shear modulus and material damping ratio relationships. Journal of Geotechnical and Geoenvironmental Engineering 2005;131(4):453-464.

[17] Vardanega PJ, Bolton MD. 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; 2011, p. 372-379.

[20] McVerry GH. Site-effect terms as continuous functions of site period and Vs30. In: Proceedings of the 9th Pacific Conference on Earthquake Engineering. Auckland, New Zealand; 2011, paper no. 010.

Building Seismic Safety Council. NEHRP Recommended Seismic Provisions for New Buildings and Other Structures, Part 1 Provisions, Part 2 Commentary, FEMA Report No. P-1050-1, 2015 Edition, Vol. 1, National Institute of Building Sciences, Washington, D.C.

Boore DM. Determining generic velocity and density models for crustal amplification calculations, with an update of the Boore and Joyner (1997) generic site amplification for $\overline{V}_S(Z)$ = 760 m/s. Bulletin of the Seismological Society of America 2016;106(1):316-320.

Boore DM, Joyner WB. Site amplifications for generic rock sites. Bulletin of the Seismological Society of America 1997;87(2):327–341.

Abrahamson N, Atkinson G, Boore D, Bozorgnia Y, Campbell K, Chiou B, Idriss IM, Silva W, Youngs R. Comparisons of the NGA Ground-Motion Relations. Earthquake Spectra 2008;24(1):45–66,

Gregor N, Abrahamson NA, Atkinson GM, Boore DM, Bozorgnia Y, Campbell KW, Chiou BSJ, Idriss IM, Kamai R, Seyhan E, Silva W, Stewart JP, Youngs R. Comparison of NGA-West2 GMPEs. Earthquake Spectra 2014;30(3):1179-1197.

Hashash YMA, Kottke AR, Stewart JP, Campbell KW, Kim B, Moss C, Nikolaou S, Rathje EM, Silva WJ. Reference rock site condition for central and eastern North America. Bulletin of the Seismological Society of America 2014;104(2):684-701.

Silva WJ, Darragh RB, Gregor NN, Martin G, Abrahamson NA, Kircher C. Reassessment of Site Coefficients and Near-Fault Factors for Building Code Provisions, NEHRP External Research Program, Final Technical Report, U.S. Geological Survey Award No. 98HQGR1010, Pacific Engineering & Analysis. El Cerrito, CA, 1999.

[18] Chandler AM, Lam NTK, Tsang HH. Regional and local factors in attenuation modelling: Hong Kong case study. Journal of Asian Earth Sciences 2006;27(6):892-906.

[19] Tsang HH, Sheikh MN, Lam NTK. Modeling shear rigidity of stratified bedrock in site response analysis. Soil Dynamics and Earthquake Engineering 2012;34(1):89-98.

[21] Kottke AR, Wang X, Rathje EM. Technical Manual for Strata. Austin, Texas, USA: Geotechnical Engineering Center, Department of Civil, Architectural, and Environmental Engineering, University of Texas; 2013.

[22] Lam NTK, Wilson JL, Hutchinson GL. Generation of synthetic earthquake accelerograms using seismological modelling: a review. Journal of Earthquake Engineering 2000;4(3):321-354.

[23] Lam N, Wilson J, Tsang HH. Modelling earthquake ground motions by stochastic method. In: Stochastic Control, Chris Myers (Ed.), ISBN: 978-953-307-121-3, InTech; 2010. p. 475-492.

Appendix A

Table A.1

Summary of the borehole records of Site 1.

Type	*Thickness* d_i (m)	*SPT-N*	V_i (m/s) = $97 \times N^{0.314}$	$4d_i / V_i$
Alluvium (Sand)	6.0	9	193	0.124
Alluvium (Silt)	9.0	13	216	0.167
Residual Soil (Clay)	6.0	16	232	0.103
Karst Deposit (Clay)	9.4	19	245	0.153
	H_S = 30.4 m		$V_{S,i}$ = 222 m/s	T_i = 0.55 s

Table A.2

Summary of the borehole records of Site 2.

Type	*Thickness* d_i (m)	*SPT-N*	V_i (m/s) = $97 \times N^{0.314}$	$4d_i / V_i$
Fill (Gravel, Cobble)	2.0	10	200	0.040
Fill (Cobble, Sand)	6.5	11	206	0.126
Fill (Gravel, Sand)	4.0	27	273	0.059
Fill (Sand)	2.7	23	260	0.042
Fill (Cobble, Silt)	2.8	13	217	0.052
Marine Deposit (Clay)	2.5	16	232	0.043
Marine Deposit (Clay)	2.5	20	248	0.040
Marine Deposit (Clay)	2.5	19	245	0.041
Marine Deposit (Clay)	2.5	25	267	0.038
Marine Deposit (Sand)	2.5	33	291	0.034
Marine Deposit (Sand)	2.7	35	296	0.036
Alluvium (Gravel)	2.5	38	304	0.033
	H_S = 35.7 m		$V_{S,i}$ = 245 m/s	T_i = 0.58 s

Table A.3

Summary of the borehole records of Site 3.

Type	*Thickness* d_i (m)	*SPT-N*	V_i (m/s) = $97 \times N^{0.314}$	$4d_i / V_i$
Fill (Sand, Gravel)	4.0	6	170	0.094
Fill (Sand, Gravel)	5.0	18	240	0.083
Fill (Sand)	2.0	11	206	0.039
Marine Deposit (Clay)	2.0	2	121	0.066

Marine Deposit (Clay)	2.0	8	186	0.043
Alluvium (Sand)	2.0	18	240	0.033
Alluvium (Sand)	2.0	16	232	0.035
Granite (Silt)	2.0	16	232	0.035
Granite (Silt)	2.0	26	270	0.030
Granite (Sand)	2.0	45	321	0.025
Granite (Sand)	2.0	50	331	0.024
Granite (Sand)	2.0	51	333	0.024
Granite (Sand)	2.0	63	356	0.022
Granite (Sand)	2.0	90	398	0.020
Granite (Sand)	2.0	121	437	0.018
Granite (Sand)	2.0	207	518	0.015
Granite (Sand)	2.0	93	403	0.020
Granite (Sand)	2.0	193	506	0.016
	H_S = 41.0 m		$V_{S,i}$ = 255 m/s	T_i = 0.64 s

Table A.4

Summary of the borehole records of Site 4.

Type	*Thickness* d_i (m)	*SPT-N*	V_i (m/s) = $97 \times N^{0.314}$	$4d_i / V_i$
Fill (Sand)	11.1	36	299	0.148
Marine Deposit (Clay)	24.6	21	254	0.387
Alluvium (Silt/Clay)	5.9	15	225	0.105
Tuff (Silt)	5.2	21	252	0.083
	H_S = 46.8 m		$V_{S,i}$ = 259 m/s	T_i = 0.72 s

Table A.5

Summary of the borehole records of Site 5.

Type	*Thickness* d_i (m)	*SPT-N*	V_i (m/s) = $97 \times N^{0.314}$	$4d_i / V_i$
Fill (Sand)	7.5	16	232	0.128
Marine Deposit (Clay)	6.0	0.4	73	0.329
Alluvium (Sand)	4.0	9	193	0.083
Alluvium (Dense Sand)	8.0	18	242	0.132
Granite (Sand)	24.0	52	335	0.287
Granite (Sand)	8.0	105	418	0.077
	H_S = 57.5 m		$V_{S,i}$ = 222 m/s	T_i = 1.04 s

Table 1

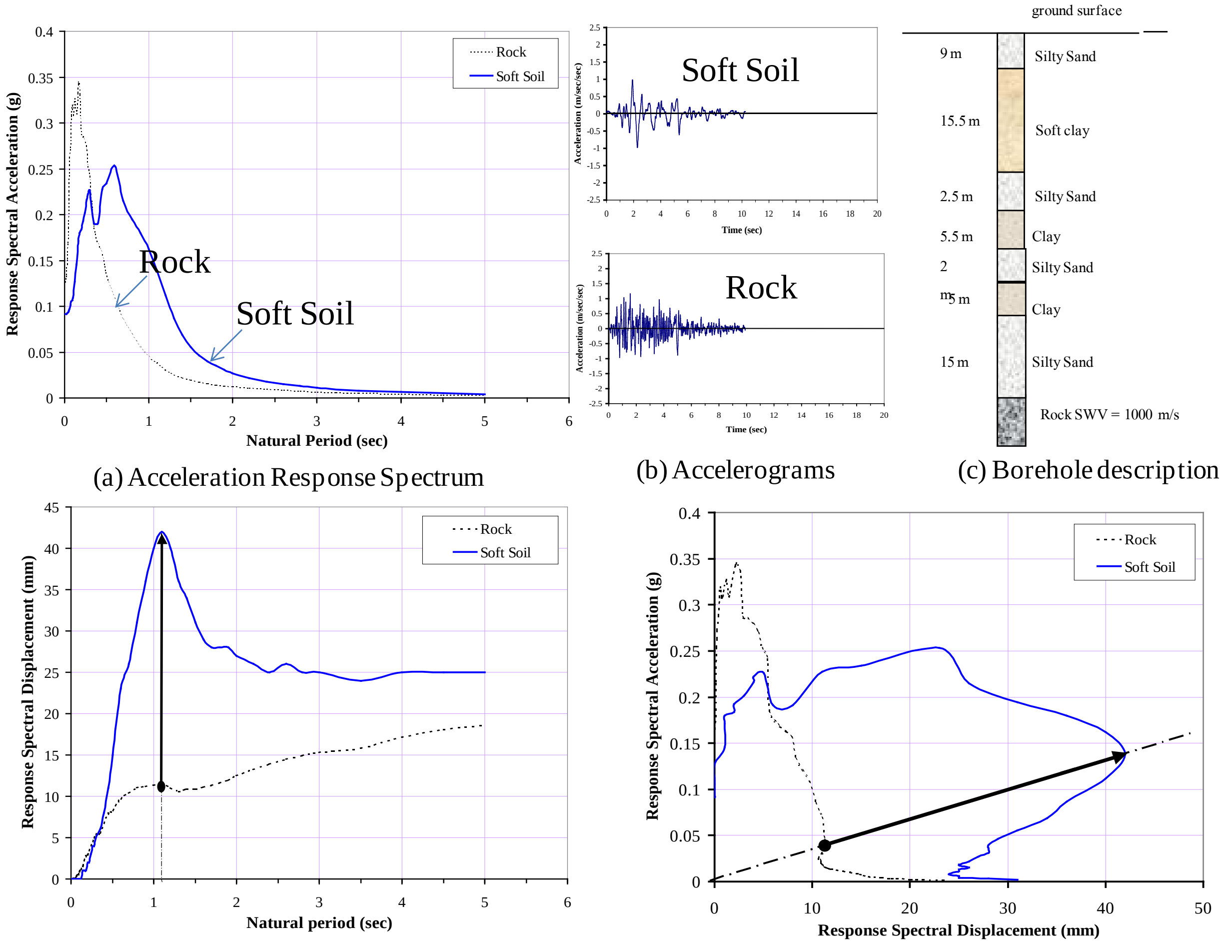
Implied spectral amplification ratios (i.e. Soil DS/Rock UHS) at 0.2 s, 0.5 s, 1.0 s and 2.0 s of the DS constructed based on various codes of practice, and the corner periods T_1 and T_2.

Code Abbreviation	AS	EC1	EC2	GB	IBC	NZS
Principal Applicable Region	Australia	Europe (higher seismicity)	Europe (lower seismicity)	China	USA	New Zealand
Ratio at 0.2 s	1.25	1.35	1.80	1.00	1.60	1.28
Ratio at 0.5 s	2.76	2.98	2.39	2.21	3.27	2.82
Ratio at 1.0 s	4.84	4.99	2.49	2.48	3.41	5.90
Ratio at 2.0 s	4.66	6.40	1.92	3.40	4.38	8.37
T_1	0.8	0.8	0.3	0.5	0.46	1.0
T_2	1.5	2.0	1.2	-	-	3.0

Table 2

Summary of input parameters, period-shift ratio T_S / T_i, site amplification factor (*S-Factor*), and peak response spectral displacement ($RSD_{\max}$) for the five example soil sites.

Site	H (m)	$V_{S,i}$ (m/s)	T_i (s)	RSD_{Ti} (mm)	T_S / T_i	T_S (s)	RSD_{Ts} (mm)	S	$RSD_{\max}$ (mm)
1	30.4	222	0.55	17.5	1.45	0.80	25.4	4.03	102
2	35.7	245	0.58	18.7	1.41	0.82	26.3	3.86	102
3	41.0	255	0.64	20.5	1.39	0.89	29.0	3.78	110
4	46.8	259	0.72	23.1	1.39	1.00	32.0	3.76	120
5	57.5	222	1.04	32.5	1.45	1.50	39.0	4.03	157



(a) Acceleration Response Spectrum (b) Accelerograms (c) Borehole description

(d) Displacement Response Spectrum (e) Acceleration-Displacement Response Spectrum

Fig. 1. Response spectra showing the effects of resonant-like soil-amplification behaviour.

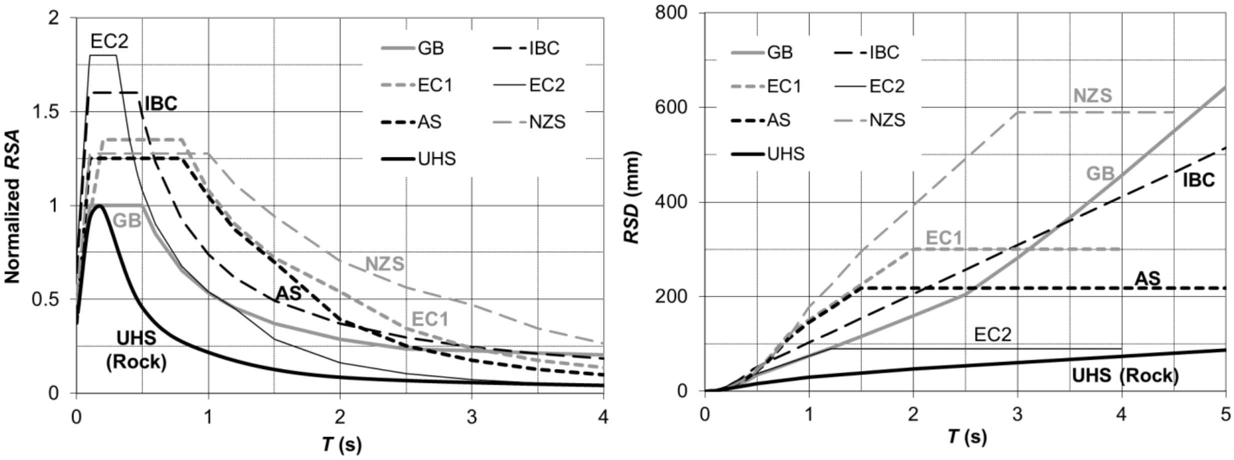


Fig. 2. DS for a flexible soil site in Hong Kong constructed based on various codes of practice. (a) RSA format, normalised to the peak of the UHS (i.e. RSA_{max}) for rock sites in Hong Kong. (b) RSD format.

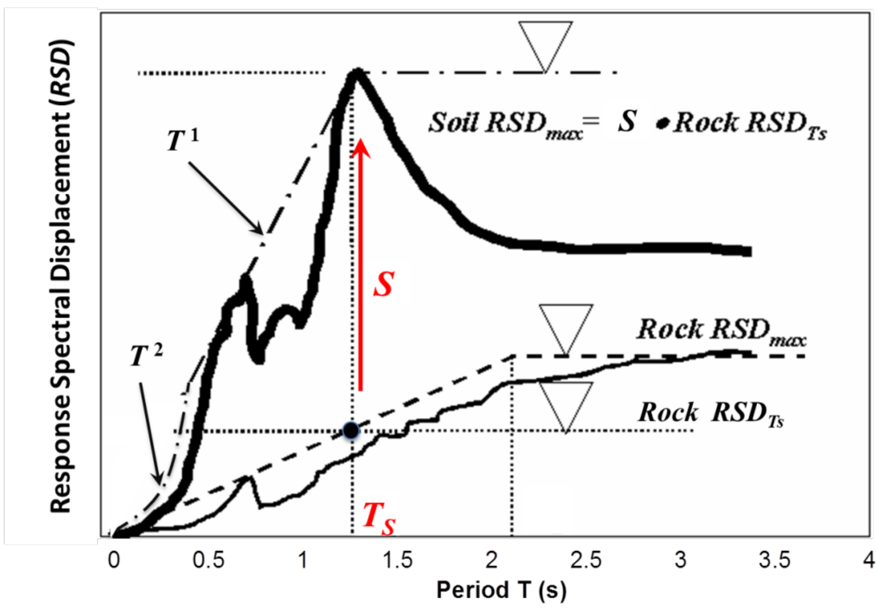


Fig. 3. Schematic diagram of the proposed site-specific DS model (in RSD format).

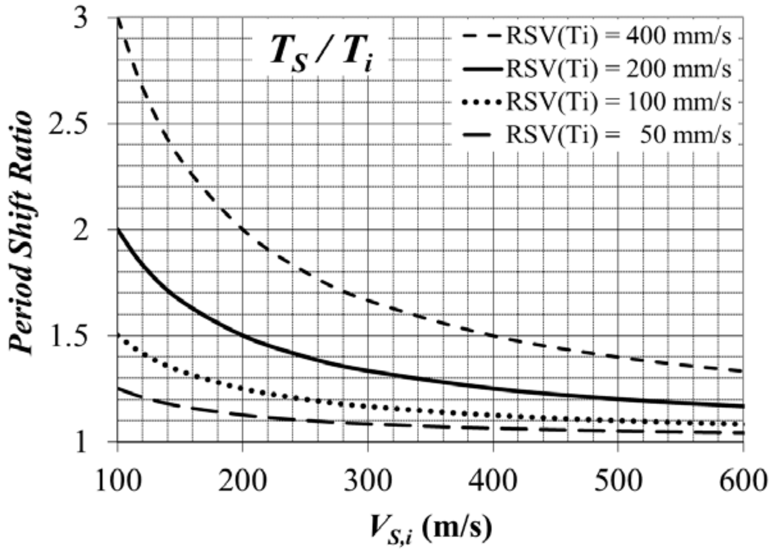
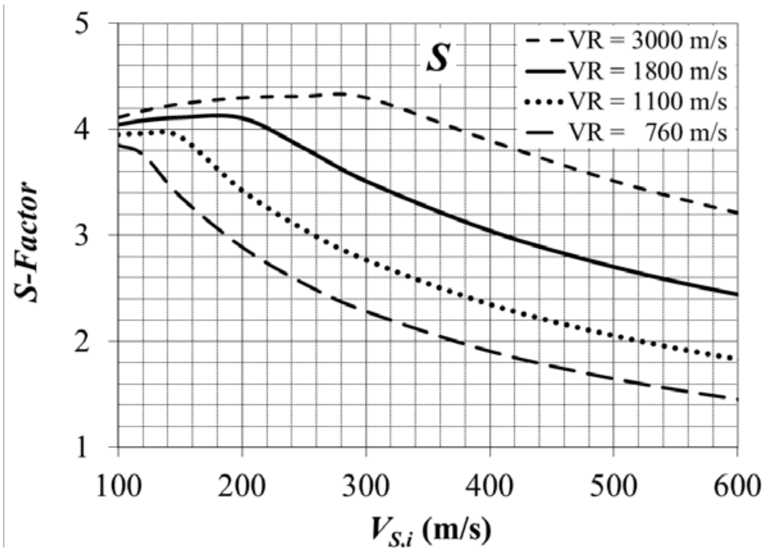
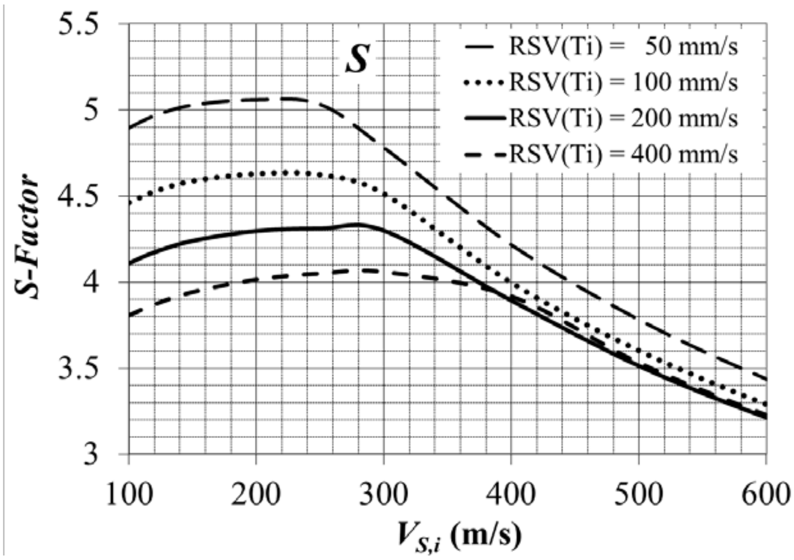


Fig. 4. Design chart for the period-shift ratio T_S / T_i as functions of shaking level (in terms of RSV_{Ti}) and initial soil SWV ($V_{S,i}$).

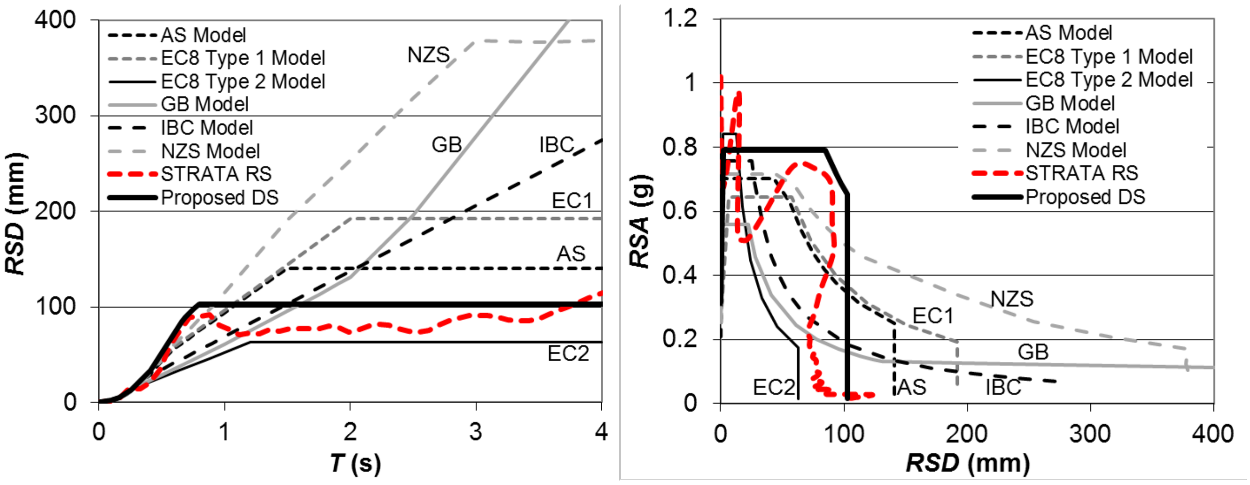


(a)



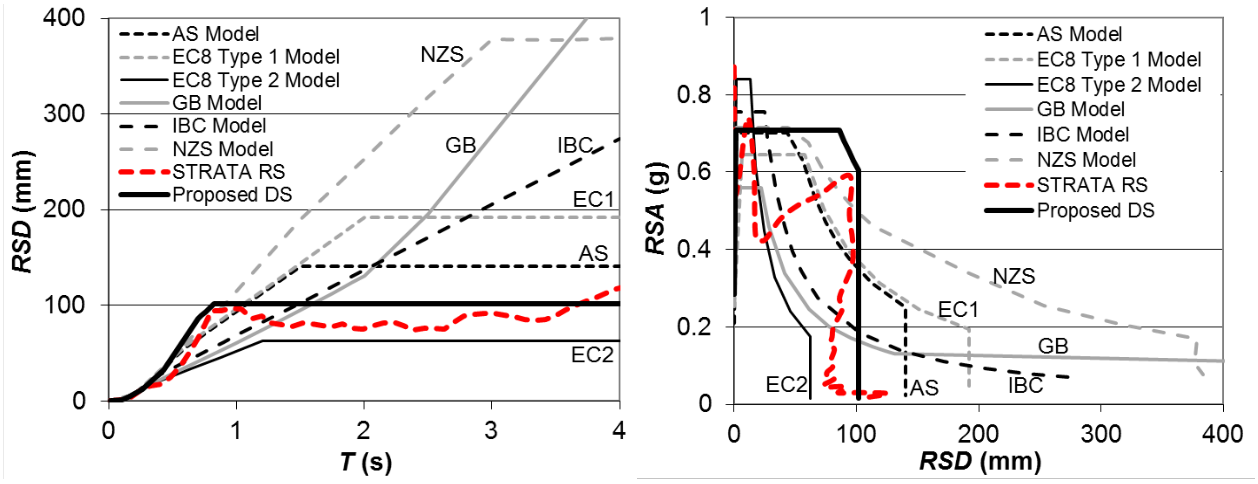
(b)

Fig. 5. Design chart for the site amplification factor (*S-Factor*) at T_S as functions of (a) bedrock SWV (V_R) and initial soil SWV ($V_{S,i}$) (with fixed RSV_{Ti} = 200 mm/s), and (b) shaking level (in terms of RSV_{Ti}) and initial soil SWV ($V_{S,i}$) (with fixed V_R = 3000 m/s).



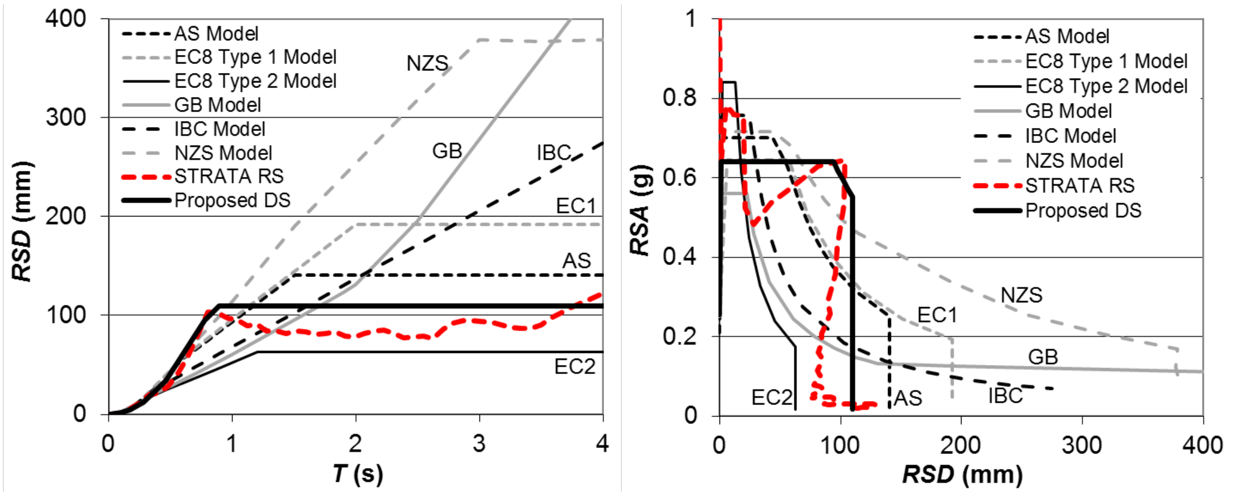
(a) (b)

Fig. 6. Site 1: Comparison of the proposed DS model with those constructed based on major codes of practice, and superimposed with the results from STRATA. (a) RSD format. (b) ADRS format.



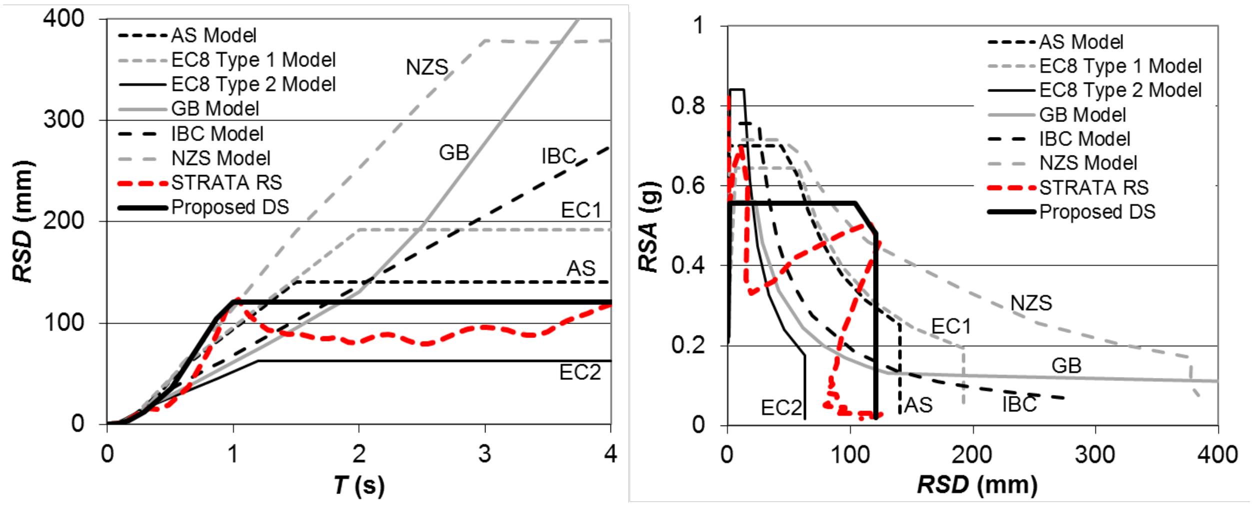
(a) (b)

Fig. 7. Site 2: Comparison of the proposed DS model with those constructed based on major codes of practice, and superimposed with the results from STRATA. (a) RSD format. (b) ADRS format.



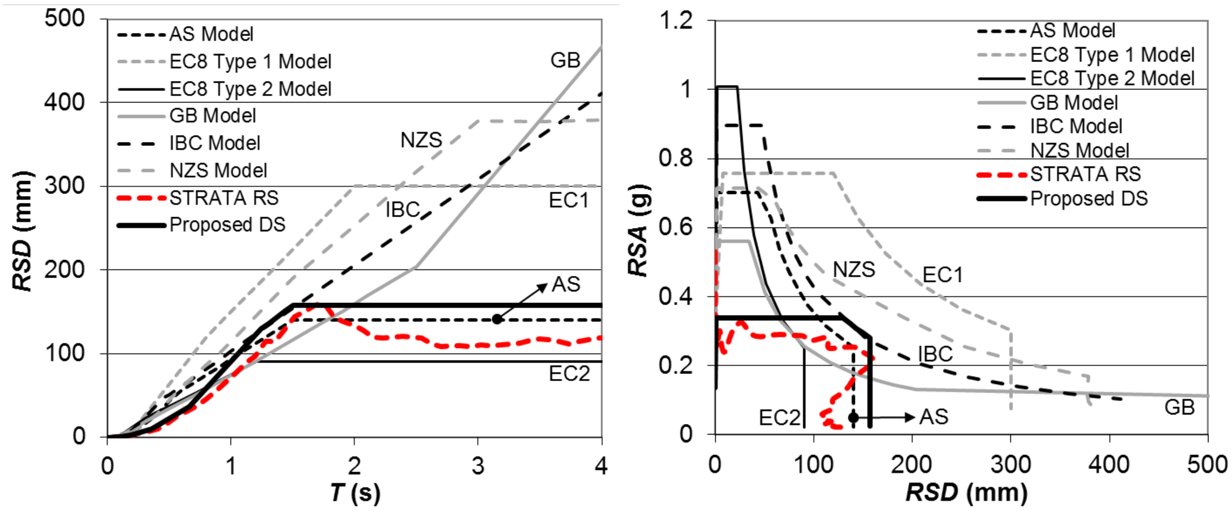
(a) (b)

Fig. 8. Site 3: Comparison of the proposed DS model with those constructed based on major codes of practice, and superimposed with the results from STRATA. (a) RSD format. (b) ADRS format.



(a) (b)

Fig. 9. Site 4: Comparison of the proposed DS model with those constructed based on major codes of practice, and superimposed with the results from STRATA. (a) RSD format. (b) ADRS format.



(a) (b)

Fig. 10. Site 5: Comparison of the proposed DS model with those constructed based on major codes of practice, and superimposed with the results from STRATA. (a) RSD format. (b) ADRS format.