Site Classification and Elastic Response Spectrum Model for Soil Sites

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(Photos and details of authors on page 44.)

This paper introduces the elastic response spectrum models for different ground conditions, with a particular emphasis on the phenomenon of periodic ground shaking in flexible soil sites. The natural period of the site, which is closely correlated with the depth of the soil sediments, has been incorporated as a parameter in the construction of the soil response spectrum.

This model, to be introduced in the draft National Annex (NA) to Eurocode 8 (EC8) for Malaysia, resembles real behaviour much better than the response spectrum models stipulated by EC8 itself. The need to address the effects of site periodicity is particularly justified in regions of low-to-moderate seismicity such as Malaysia, where structures are typically of limited ductility and so, are vulnerable to the elastic amplification phenomenon as described in the paper.

INTRODUCTION

Soil modification of seismic waves within soil sedimentary layers overlying bedrock can have significant effects on both their amplitude and frequency properties. Multiple reflected seismic waves that are trapped within the soil layers are periodic in nature as a result of filtering and wave super position. The deeper the soil layers, the longer it takes for the reflected wave front to travel through the soil medium. Thus, the natural period of the site is controlled by the thickness of the soil layers.

The extent of soil amplification also depends on the level of shaking, the properties of the soil materials (including its shear modulus and plasticity) and the shear modulus of the underlying bedrock materials. Amplification of the response of structures to periodic excitation is very selective in nature, in that the effects are only pronounced in structures of a certain period range. In conditions of severe ground shaking, site amplification associated with the periodic motions can be suppressed by energy dissipation in an in elastically responding ductile structure and in the soil medium itself. Thus, its effects have not been explicitly parameterised in major codes of practices that were derived from research and experiences in regions of high seismicity. The issue of periodicity has much greater design implications in regions of low-to-moderate seismicity such as Malaysia, where structures are typically of limited ductility and motions in the soil are not as intensive, as the amount of energy dissipation is much less than that in regions of high seismicity.

Site effects can be conveniently observed on response spectra. In situations where a distinct soil-rock interface exists, the amplification ratio usually has a maximum value close to the natural period of the soil layer (T_S). Figure 1 is a good example of amplification driven by soil site periodicity; it shows the acceleration response spectrum recorded on rock and soil sites at Oakland Outer Harbour in the 1989 earthquake at Loma Prieta, California, United States (Dickenson *et al.*, 1991). In the draft NA to EC8 for Malaysia, the site natural period (T_S) is incorporated as a parameter in the construction of the response spectrum for structures.

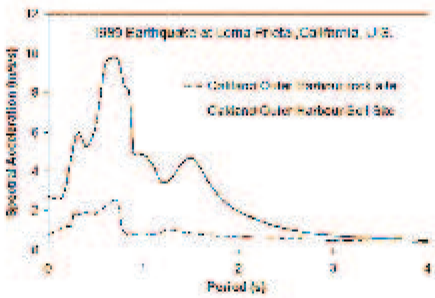

Figure 1: Acceleration response spectrum recorded on rock and soil sites at Oakland Outer Harbour in the 1989 earthquake at Loma Prieta, California, United States.

The spectral acceleration values are a few times larger on a soil site in comparison with a rock site, while the amplification ratio is in the order of four times for the peaks at 0.7s. Such significant and selective amplification phenomenon has to be taken into account in the construction of the response spectrum as per design code of practices

BRIEF REVIEW OF EXISTING EC8 MODEL

EC8 recommends two types of elastic response spectrum: Type 1 for high seismicity areas and Type 2 for less active areas. The spectral shapes mimick the spectral shapes of large (M = 7~7.5) and small (M = 5.5) magnitude events occurring at a site-source distance of 10km, which will in effect, result in different sets of corner periods. However, it is stated clearly in EC8, Part 1: Clause 3.2.2.2 (2)P that suitable values of corner periods could be investigated and specified in the NA of a country and that it is not necessary to stick to the use of either Type 1 or Type 2 response spectrum.

Although the importance of the total thickness of soil layer is well recognised, site classification nowadays is based solely on the properties to a certain fixed depth of near-surface materials. In EC8, a site shall be classified according to the value of the average shear wave velocity (SWV) ($V_{s,30}$), or the value of Standard Penetration Resistance Test (SPT) – N (for cohesion-less soil), or the value of undrained shear strength c_u (for cohesive soil), over the upper 30m.

A site shall be classified as either *Site Class* A, B, C, D, E, S_1 or S_2 based on site soil properties. Profiles containing distinctly different soil and/or rock layers shall be subdivided into those layers designated by a number from 1 to n at the bottom where there are a total of n distinct layers in the upper 30m. The symbol i then refers to any one of the layers between 1 and n. The average shear wave velocity V_{s30} can be computed by Equation (1). The same equation also applies to the computation of the values of *SPT–N* and undrained shear strength.

$$V_{s,30} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{s,i}}} \qquad (1)$$

where $V_{s,i}$ = The shear wave velocity in m/s;
d_i = The thickness of any layer between 0 and 30m.

A uniform soil factor, *S*, shall be applied across the whole response spectrum for each site class (ground type), which is up to 1.4 (for Type 1) and 1.8 (for Type 2). The first corner period T_C varies between 0.4 s to 0.8s (for Type 1) and between 0.25s to 0.3s (for Type 2) elastic response spectrum. Larger values of T_C essentially translate to a higher demand at the intermediate-to-long-period range. T_D is fixed at 2.0s (for Type 1) or 1.2s (for Type 2). Noted that T_C is the first corner period at the upper limit of the constant spectral acceleration region of the elastic response spectrum model, whilst T_D is the second corner period at the beginning (lower limit) of the constant spectral displacement region.

PROPOSED SITE CLASSIFICATION 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. This site-period approach recognises that deep deposits of stiff or dense soils exhibit high-period site response characteristics not shown by deposits of only a few 10s of metres of the same material.

The value of T_s can be estimated based on geophysical (or geotechnical) measurements, with the use of Equation (2). 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* ($V_{s}i$) of the individual soil layers are known. Alternatively, the value of T_s can be expressed in terms of the total thickness of the soil layers (H_s) and its weighted average *SWV* (V_s).

$$T_S = \sum_{i=1}^{n} \frac{d_i}{V_{s,i}} \times 4 = \frac{4H_S}{V_S} \qquad (2)$$

In the proposed site classification scheme, a site with T_s < 0.15s, where the soil layers are very thin and/or stiff, the site can be classified as a rock site (equivalent to the original ground type A in EC8). The elastic response spectra for rock sites for the three regions have already been fully discussed in a companion article (Lam *et al.,* 2016a).

The site amplification for such very thin and/or stiff ground would mainly concern structures with a natural period lower than 0.2s, while the amplification for a natural period higher than 0.2s is minimal. It is note worthy that the corresponding peak displacement demand for such low period structures is very small in regions of low-to-moderate seismicity. Most structures that are not brittle, would be capable of sustaining this very minor peak displacement demand without being subjected to any significant risks of collapse.

A site with T_s between 0.15s and 0.5s is classified as a stiff soil site (which combines the original ground type B and C in EC8, for simplicity and practicality). When the site natural period T_s is greater than 0.5s, the site can be considered as flexible soil site. However, for T_s > 1.0s, or deposits consisting of at least 10m thick of clays/silts with a high plasticity index (PI > 50), dynamic site response analyses shall be performed or Type 1 elastic response spectrum for ground type D shall be adopted. A soil column with T_s > 1.0s is considered very flexible and there may be significant higher modes effects in the site response behaviours. For deposits of 10m thick (or more) of clays/silts with a high plasticity index (PI > 50), special consideration should be taken, as exceptionally high amplification can happen.

The proposed site classification scheme is presented in Table 1. This scheme was designed for simplicity, which is more suitable for application in regions of low-to-moderate seismicity, and for using site natural period as the sole parameter for site classification. More features of the response spectrum model for each site will be discussed in a later section.

Table 1: Proposed site classification scheme

Description	Site Period T_s (s)
Rock (R)	$T_s < 0.15$
Stiff Soil (SS)	$0.15 \leq T_s < 0.5$
Flexible Soil (FS)	$0.5 \leq T_s \leq 1.0$ *

** For T_s > 1.0 s, or deposits of at least 10m thick of clays/silts with a high plasticity index (PI > 50), dynamic site response analyses shall be performed or Type 1 elastic response spectrum for ground type D shall be adopted.*

ELASTIC RESPONSE SPECTRUM FORMAT

The Elastic Response Spectrum model can be constructed using Equation (3) in the displacement (RSD) format, as expressed in terms of four spectral parameters, $S_D(T_D)$, T_C, T_D and *m*. The emphasis on the prediction of the value of RSD is to align with displacement-based seismic design methodology.

$$\begin{aligned} T \leq T_C: &\quad S_{De}(T) - S_D(T_D)\left(\frac{T^2}{T_C T_D}\right) \\ T_C \leq T \leq T_D: &\quad S_{De}(T) - S_D(T_D)\left(\frac{T}{T_D}\right) \qquad (3) \\ T_D \leq T \leq 4: &\quad S_{De}(T) - S_D(T_D) + m \times (T \quad T_D) \end{aligned}$$

The elastic response spectrum model in the acceleration (RSA) format can be conveniently obtained by direct transformation from the displacement format using Equation (4).

$$S_e(T) - S_{De}(T) \times \left(\frac{2\rho}{T}\right)^2 \qquad (4)$$

This response spectrum format is nearly identical to that currently adopted in EC8 and is similar in form to those adopted in various codes of practice worldwide. The only difference is at the constant-displacement range, where a linear function has been proposed for reflecting the unique seismicity pattern of the region.

PROPOSED SPECTRAL PARAMETERS

For rock (R) sites, $S_D(T_D)$ is the region-specific spectral displacement on rock $S_{DR}(T\ )$ at T = 1.25s. This value is 16mm (24mm) for Peninsular Malaysia and Sarawak, and 28mm (42mm) for Sabah, for a notional return period of 475 years (values in parenthesis for return period of 2,475 years).

For stiff soil (SS) sites, a uniform S-factor of 1.5 shall be applied across the whole response spectrum on rock. This recommendation is consistent with that for ground type D of EC8 Type 2 spectrum (for regions of low-to-moderate seismicity). The values of the two corner periods T_C and T_D are taken as the same as that for rock sites, which are equal to 0.3s and 1.25s respectively. T_B is fixed as 0.1s for all ground types in the proposed scheme. However, it is noted that the form of the response spectrum in the NA has not explicitly indicated T_B as it is undesirable in practice, given uncertainties in the value of the natural period of vibration of the structure.

For flexible soil (FS) sites, a response spectrum model that takes into account resonant-like amplification phenomenon is proposed (Lam *et al.*, 2001; Tsang *et al.*, 2006a; Tsang *et al.*, 2006b; Tsang *et al.*, 2013; Tsang *et al.*, 2015). $S_D(T_D)$, T_C and T_D, shall be computed using Equations (5)-(7):

where $S_{DR}(1.5T_S)$ is the response spectral displacement (*RSD*) on rock at $T = 1.5T_S$.

$$S_D(T_D) \quad S_{DR}(1.5T_S) \times S \qquad (5)$$

$$T_C \quad 1.2T_S \qquad (6)$$

$$T_D \quad 1.5T_S \qquad (7)$$

Response spectral velocity (RSV) of a soil spectrum typically peaks between $1.2T_S$ and $1.5T_S$ (Tsang *et al.*, 2006b), with respect to the level of ground shakings in regions of low-to-moderate seismicity. S is the site amplification factor of 3.6 (Tsang *et al.*, 2006a), which is applied at the constant-velocity range (intermediate period range). For example, the equivalent amplification ratio at T = 1.0s ranges from 2.5 to 5.9 in other major codes of practice (including EC8, International Building Code, Australian Standard and New Zealand Standard). In fact, the largest amplification ratio at the low-period range would be 1.8, which is consistent with that for ground type D of EC8 Type 2 spectrum.

Table 2 shows a summary of the proposed models for all site classes. Table 3 summarises the key regional-dependent hazard parameters. Importance factor γ_I should be referred to another companion paper (i.e. Lam *et al.* 2016b). The parameters slope m_R and m_F are aimed at capturing the long period spectral shape of distant events. Figure 2 shows a schematic diagram of the proposed response spectrum models for the three ground types (in *RSD* format). The model has been well validated through 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 Northridge earthquake, 1994.

Table 2: Proposed spectral parameters, S_D (T_D), T_C and T_D

Ground Type	T_s (s)	S_D (T_D) (mm)	Slope m	T_C (s)	T_D (s)
Rock (R)	T_s < 0.15	$\gamma_I \times S_{DR}$ (1.25)	$\gamma_I \times m_R$	0.3	1.25
Stiff Soil (SS)	0.15 ≤ T_s < 0.5	$\gamma_I \times S_{DR}$ (1.25) x 1.5	$\gamma_I \times m_R$		
Flexible Soil (FS)	0.5 ≤ T_s ≤ 1.0 *	$\gamma_I \times S_{DR}$ (1.5 T_s) x 3.6	$\gamma_I \times m_F$	1.2 T_s	1.5 T_s

** For T_S > 1.0 s, or deposits consisting of at least 10m thick of clays/silts with a high plasticity index (PI > 50), dynamic site response analyses shall be performed or Type 1 elastic response spectrum for ground type D shall be adopted.*

Table 3: Proposed regional-dependent hazard parameters, a_{gR}, S_{DR} (1.25), m_R and m_F for notional 475 years return period.

Region	a_{gR} (g)	S_{DR} (1.25)(mm)	m_R	m_F
Peninsular Malaysia	0.07	16	6.7	0
Sarawak	0.07	16	0	0
Sabah	0.12	28	40	26.7

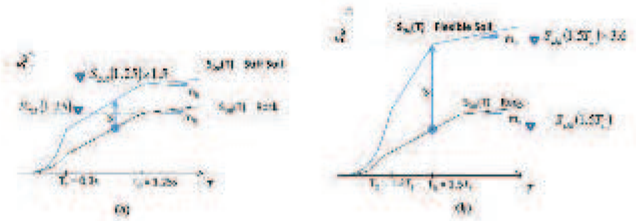

Figure 2: Schematic diagram of the proposed model for (a) rock and stiff soil sites, as well as (b) flexible soil sites (in RSD format).

WORKED EXAMPLE

In order to demonstrate the proposed model for incorporation into the draft NA for flexible soil (FS) sites, a typical engineering borehole record was taken from a soil site in Peninsular Malaysia as example (See Figure 3). For clarity, Table 4 shows the SPT-N values for individual soil layers. It is noted that the computation of equivalent values of N > 50 for certain soil layers is above the normally considered "saturated limit" of 50 (e.g. at depth of 33m, N = 50 with a penetration depth P = 270mm; the equivalent N should be calculated as 50x300/270 = 55.6).

In view of the lack of local studies, empirical formulas that are applicable to all types of soils as summarised in Wair *et al.* 2012 were referenced. Table 4 also shows computations of *SWV* values and the corresponding SPT–N values based on two empirical formulas that are applicable to all types of soils (i.e., Imai and Tonouchi, 1982 and Sisman, 1995). The individual soil layers thickness (d_i) over initial *SWV* (V_{Si}) ratio were calculated to obtain the weighted average *SWV* (V_S) by the use of Eq. (1). In this case, V_S = 42/0.19 = 221 m/s. The value of T_S can be expressed in terms of the total thickness of the soil layers (H_S) and its weighted average *SWV* (V_S) via the use of Eq. (2), T_S = 4 x 42/221 ≈ 0.7s, which falls in between 0.5s and 1.0s, and is categorised as FS (as in Table 2).

Based on the spectral parameters in Tables 2 and 3, the following calculations show steps for construction of the response spectrum for this FS site in Peninsular Malaysia for a notional 475 years return period (γ_I = 1):

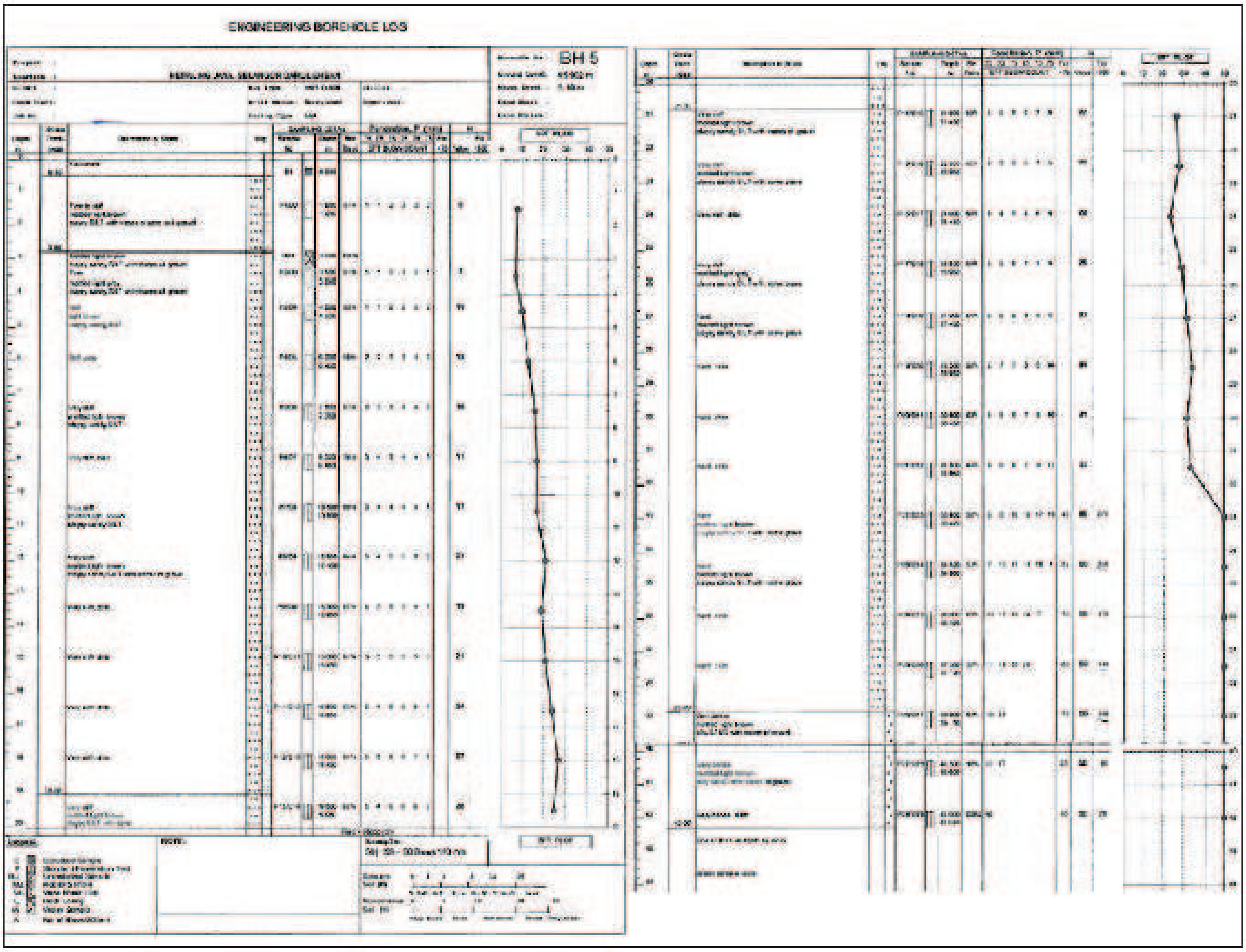

Figure 3: Sample engineering borehole log record in Peninsular Malaysia

Table 4: Computation of site natural period T_S

depth (m)	d_i (m)	SPT-N	Imai & Tonouchi (1982)	Sisman (1995)	V_s (m/s)	d_i/V_s (s)
0	0	0	0	0	0	0.000
1.5	1.5	6	170	82	126	0.012
3.5	2	7	179	88	134	0.015
4.5	1	10	200	106	153	0.007
6	1.5	10	200	106	153	0.010
7.5	1.5	16	232	135	183	0.008
9	1.5	17	236	139	188	0.008
10.5	1.5	17	236	139	188	0.008
12	1.5	21	252	155	204	0.007
13.5	1.5	19	245	147	196	0.008
15	1.5	21	252	155	204	0.007
16.5	1.5	24	263	166	214	0.007
18	1.5	27	273	176	225	0.007
19.5	1.5	25	267	169	218	0.007
21	1.5	27	273	176	225	0.007
22.5	1.5	28	276	179	228	0.007
24	1.5	24	263	166	214	0.007
25.5	1.5	29	279	183	231	0.006
27	1.5	31	285	189	237	0.006
28.5	1.5	34	294	198	246	0.006
30	1.5	31	285	189	237	0.006
31.5	1.5	33	291	195	243	0.006
33	1.5	55.6	343	255	299	0.005
34.5	1.5	60	351	265	308	0.005
36	1.5	88.2	396	322	359	0.004
37.5	1.5	107	421	356	388	0.004
39	1.5	100	412	343	378	0.004
40.5	1.5	150	468	422	445	0.003
42	1.5	214	523	506	515	0.003
	Σ = 42.0					Σ = 0.190

NOTE: the Malaysia EC8 NA suggested that sedimentary layers with SPT-N value greater than 100 can be omitted in the computations of site natural period and weighted average SWV; nonetheless more layers of soil after SPT-N 100 can be included for calculation as shown in Table 4.

Step 1: Calculate T_C and T_D for flexible soil site according to Equations (6)-(7):

$T_C = 1.2 \times T_S = 1.2 \times 0.7 = 0.84s$

$T_D = 1.5 \times T_S = 1.5 \times 0.7 = 1.05s$

Step 2: Calculate $S_{DR}(T_D)$ on rock according to Equation (3) and Table 3:

For rock site, $T_C = 0.3$s and $T_D = 1.25$s, hence

$$S_{DR}(T_D) = S_{DR}(1.5T_S) = S_{DR}(1.05) = S_D(T_D)\left(\frac{T}{T_D}\right) = (16 \times 1.05 / 1.25) = 13.44 \text{ mm}$$

Step 3: Calculate $S_D(T_D)$ on soil according to Equation (5)

$S_D(T_D) = S_{DR}(1.5\,T_S) \times S = 13.44 \times 3.6 = 48.38$mm

Step 4: Calculate the whole range of $S_{De}(T)$ on soil according to Equation (3); corner periods are shown in detail and summarised in Table 5

$T \leq 0.84$s: $S_{De}(T) = 48.38\ [T^2 / (0.84 \times 1.05)]$

$0.84\text{s} \leq T \leq 1.05$s: $S_{De}(T) = 48.38\ (T / 1.05)$

$1.05\text{s} \leq T \leq 4$s: $S_{De}(T) = 48.38 + 0\ (T - 1.05)$, where $m = m_F = 0$

Step 5: Transformation into acceleration (*RSA*) format in unit of g from the displacement (RSD) format using Equation (4), both of which are shown in detail and summarised in Table 5

$T \leq 0.84$s: $S_e(T) = 48.38\ [T^2 / (0.84 \times 1.05)] \times (2\pi / T)^2 / 9810$

$0.84\text{s} \leq T \leq 1.05$s: $S_e(T) = 48.38\ (T / 1.05) \times (2\pi / T)^2 / 9810$

$1.05\text{s} \leq T \leq 4$s: $S_e(T) = [48.38 + 0\ (T - 1.05)] \times (2\pi / T)^2 / 9810$

Table 5. Summary of response spectral ordinates for an example FS site with $T_S = 0.7$s for notional 475 years return period ($\gamma_I = 1$).

Period (T), s	$T_S = 0.7$s	
	S_{De} (mm)	S_e (g)
0.00	0.00	0.22
0.10	0.55	0.22
0.20	2.19	0.22
0.30	4.94	0.22
0.40	8.78	0.22
0.50	13.71	0.22
0.60	19.75	0.22
0.70	26.88	0.22
0.80	35.11	0.22
0.84 (T_C)	38.70	0.22
0.90	41.47	0.21
1.00	46.08	0.19
1.05 (T_D)	48.38	0.18
1.10	48.38	0.16
1.20	48.38	0.14
1.30	48.38	0.12
1.40	48.38	0.10
1.50	48.38	0.09
1.60	48.38	0.08
1.80	48.38	0.06
2.00	48.38	0.05
2.20	48.38	0.04
2.40	48.38	0.03
2.60	48.38	0.03
2.80	48.38	0.02
3.00	48.38	0.02
3.20	48.38	0.02
3.40	48.38	0.02
3.60	48.38	0.02
3.80	48.38	0.01
4.00	48.38	0.01

COMPARISON OF RESPONSE SPECTRUM MODEL FOR FLEXIBLE SOIL SITE WITH EC8 MODEL

The elastic response spectrum constructed in accordance with the proposed model as per the draft NA for a flexible soil (FS) site with $T_S = 0.7$s (in the range of 0.5 s to 1.0 s) is shown in Figure 4, along with that stipulated by EC8 for Class D and E sites of Type 1 and Type 2 spectra. Both soil spectra are based on a common spectrum for rock, which is based on notional peak ground acceleration of 0.1g (2,475 years return period) in Peninsular Malaysia. The selective nature of response spectral amplification on a flexible soil layer is well reflected in the shape of the proposed soil spectrum. Whilst the amount of amplification of the proposed RS in the higher period range falls in between Type 1 and Type 2 model of EC8, the proposed model is not as conservative in the short period range. In summary, the proposed RS model resembles real behaviour of elastically responding structures much better than that of the existing EC8 model.

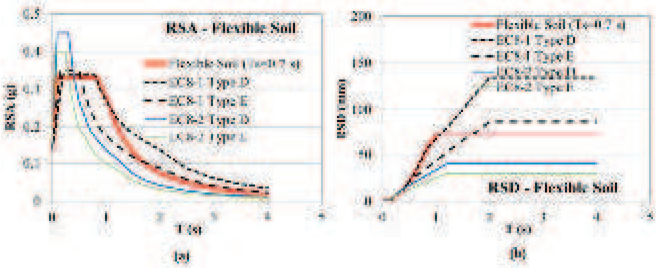

Figure 4. Comparison of proposed response spectrum model for flexible soil (a) RSA format (b) RSD format, for 2,475 years return period in Peninsular Malaysia.

COMMENTS ON VERTICAL EARTHQUAKE ACTIONS

Vertical action is particularly important for near fault ground motion which is the design earthquake scenarios in higher seismicity regions. Nonetheless, provisions for vertical earthquake actions as per recommendations by EC8 are introduced, whilst the ratio of a_{vg}/a_g is taken as 0.7 based on the recent research findings reported by Elgamal and He (2004). Given that the design horizontal action in Malaysia is generally low it is of the opinion of the NA drafting team that vertical action would not be the controlling factor in the design of most building structures. It is also noted that horizontal ground motion is amplified much more than vertical ground motion on soil sites.

CONCLUSIONS

A set of elastic response spectrum models for various ground conditions is to be incorporated into the NA to EC8 for Malaysia to replace the original provisions in EC8. Central to the construction of the response spectrum is the site natural period (T_S) which is to be estimated using relationships presented in the paper. The selective nature of response spectral amplification on a flexible soil layer is well reflected in the shape of the proposed soil spectrum which resembles real behaviour much better than the response spectrum models stipulated by EC8 itself.

Notations

H_S depths of soils

N SPT values

S soil factor
$S_D(T_D)$ region-specific spectral displacement on rock
$S_{De}(T)$ elastic displacement response spectrum
$S_{DR}(T)$ elastic displacement response spectrum on rock
$S_e(T)$ elastic horizontal ground acceleration response
T vibration period of a linear single degree of freedom system
T_B lower limit of the period of the constant spectral acceleration branch
T_C first corner period
T_D second corner period
T_S initial low-amplitude site natural period (note: this symbol is different from EC8 where Ts is referred as the duration of the stationary part of the seismic motion)
V_S weighted average initial shear wave velocity
V_{Si} shear wave velocity of individual soil layer
V_{S30} average value of propagation velocity of *S* waves in the upper 30 m of the soil profile
a_g notional design peak ground acceleration on rock
a_{vg} design ground acceleration in the vertical direction
d_i thickness of any layer between 0 and 30 m
m slope parameter to capture long period spectral shape of distant events
m_F slope parameter on flexible soil
m_R slope parameter on rock
q behaviour factor
γ_I importance factor

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