SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

Turkish Earthquake Foundation - Earthquake Engineering Committee
Prime Ministry, Disaster And Emergency Management Presidency

COMPARISON OF EUROCODE 8 SITE CLASS AMPLICATION FACTORS WITH NON-LINEAR SITE RESPONSE ANALYSIS

Rory MCCULLY[1], Ifigeneia KOULOURI[2], Zygmunt LUBKOWSKI[3], and Jack PAPPIN[4]

ABSTRACT

This paper presents a comparison of the Eurocode 8 (EN 1998) site class amplification factors with those calculated using non-linear site response analyses. In the current version of Eurocode 8 (EN 1998) it is inferred that the seismic demand for structures on soil is generally equal to or greater than that of structures founded on hard soil and rock. While this is true for longer period structures it is not always evident for structures with lower periods.

The paper will also examine the inconsistency in site amplification factors highlighted by both Lubkowski and Duan (2001) and Booth and Lubkowski (2012) between the factors proposed by Eurocode 8 (EN 1998) and NEHRP as indicated in Figures 1 and 2. Figure 1 shows that for soft soil conditions (shear wave velocity of less than 180m/s; i.e. EN 1998 Soil Type D) there are considerable differences in the amplification factors at short periods. Figure 2 shows that for stiff soil conditions (shear wave velocity of less than 360m/s; i.e. EN 1998 Soil Types C and D) there are considerable differences in the amplification factors at long periods. These differences seem similarly large for both lower and higher accelerations.

The 1D non-linear site response analysis has been undertaken using two different programs, SIREN, Arup's in-house site response package and DEEPSOIL (Hashash et al. 2011). In both programs, a 1D soil column is split into any number of layers; each of these layers can be assigned different soil properties such as shear wave velocity, density and a shear modulus reduction curve. A total of 1,120 analyses have been run for this study which allows the effect of various aspects of the analyses to be examined, such as the difference shear wave velocity profiles, different average VS30 values and different ground motion intensities.

INTRODUCTION

This paper is intended to examine further the inconsistency in site amplification factors highlighted by both Lubkowski and Duan (2001) and Booth and Lubkowski (2012) between the factors proposed by Eurocode 8 (EN 1998) and NEHRP, as shown in Figure 1 and Figure 2. Figure 1 shows that for soft soil conditions (shear wave velocity of less than 180m/s; i.e. EN 1998 Soil Type D) there are considerable differences in the amplification factors at short periods. Figure 2 shows that for stiff soil conditions (shear wave velocity of less than 360m/s; i.e. EN 1998 Soil Types C and D) there are considerable differences in the amplification factors at long periods. These differences seem similarly large for both lower and higher accelerations.

---

[1] Senior Engineer, Arup, London, United Kingdom, rory.mccully@arup.com
[2] Graduate Engineer, Arup, London, ifigeneia.koulouri@arup.com
[3] Associate Director, Arup, London, United Kingdom, ziggy.lubkowski@arup.com
[4] Arup Fellow, Arup, Hong Kong, jack.pappin@arup.com

To examine these issues, 1D site response analyses have been undertaken using the programs Oasys SIREN and DEEPSOIL, from which the resulting amplification factors are compared with the amplification factors for site class B, C, and D based on the Eurocode 8 (EN 1998) Type 1 spectrum. The computer program SIREN solves non-linear site response analyses in the time domain using the explicit finite difference method. Previous studies (Henderson et al., 1990 and Heidebrecht et al., 1990) indicate that SIREN gives similar results to those calculated by SHAKE (Schnabel et al., 1972) for moderate levels of ground motion. At higher levels, SIREN gives somewhat lower amplification than SHAKE due to the fact that it more correctly models the non-linear hysteretic behaviour of the soil. DEEPSOIL (Hashash et al., 2012) is a computer program that can solve 1D non-linear analysis in the time domain and also 1D equivalent linear analysis in the frequency domain.

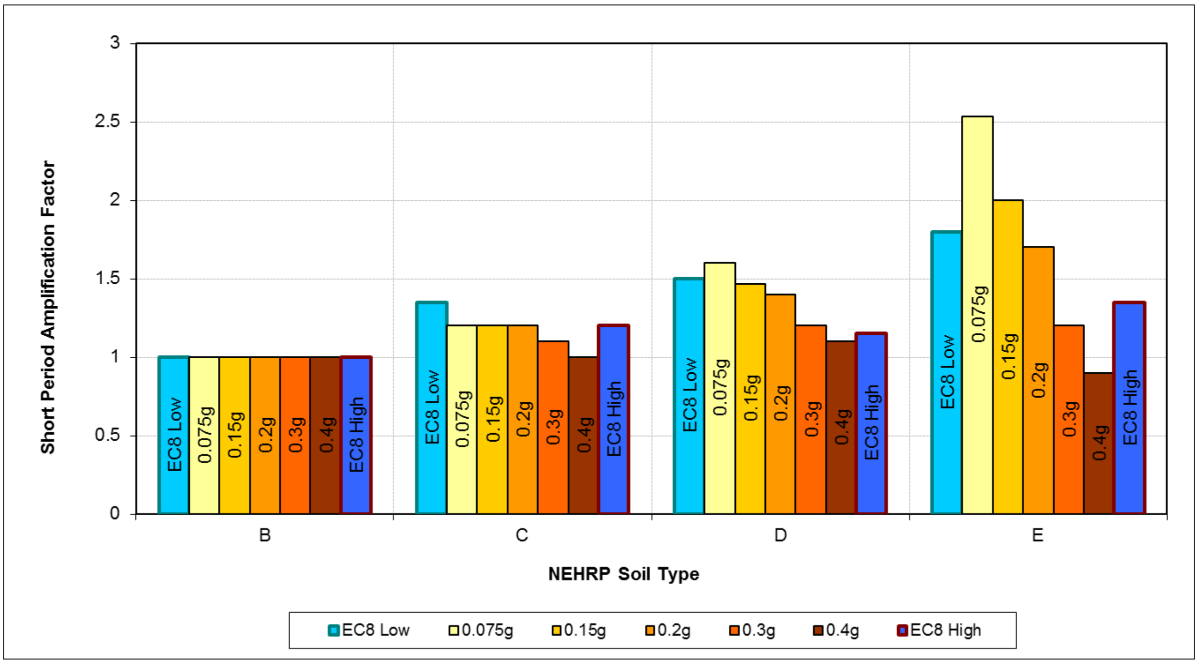


Figure 1. Comparison of NEHRP with Eurocode 8 amplification factors at short periods

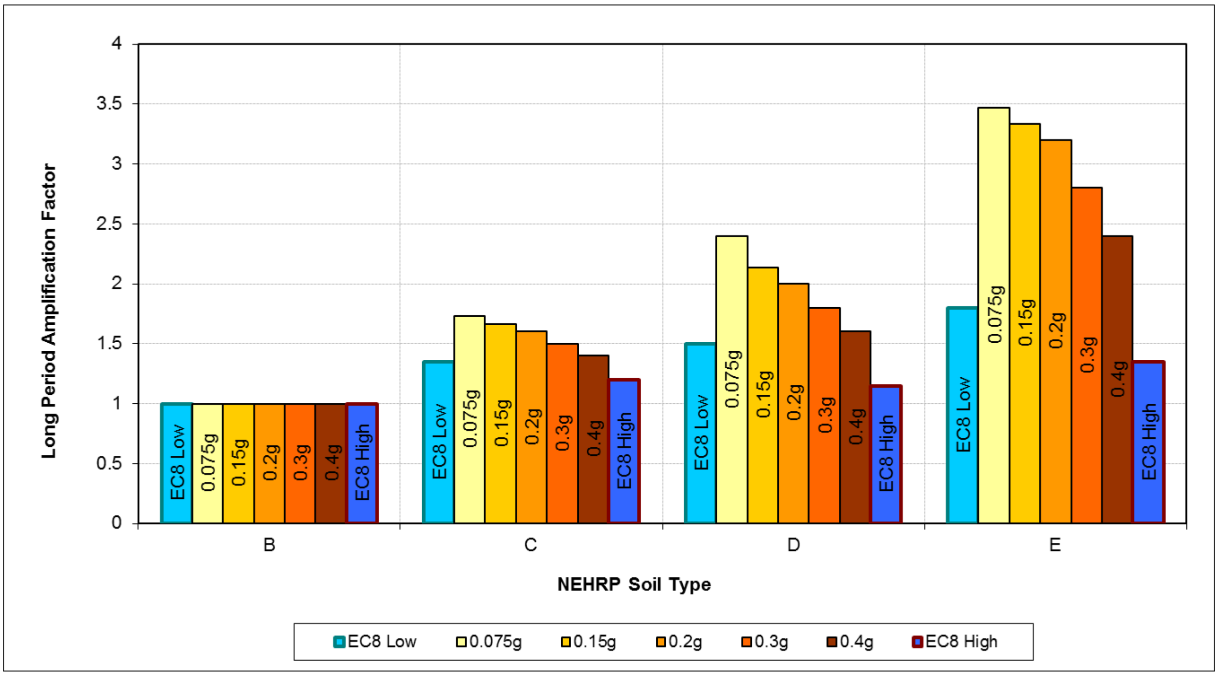


Figure 2. Comparison of NEHRP with Eurocode 8 Amplification Factors at long periods

In EN 1998 Part 1, the seismic actions are represented by two types of elastic response spectrum, classified as Type 1 and Type 2 spectra. Each country's National Annex details which type of spectra shall be used and the spectral shape can be taken as the same in each horizontal direction for both the no-collapse and damage-limitation requirements. In cases where the site could be affected by multiple source of seismicity it is considered appropriate to consider both types of response spectra.

The elastic response spectra of EN 1998 are defined as a piecewise function, divided into four segments. The segments are divided between the peak ground acceleration (T = 0.0s) and the start of the plateau of the response spectra (denoted T_B) (Eqn. 1), the plateau of the spectra (between T_B and T_C) (Eqn. 2), a phase of constant spectral velocity (between T_C and T_D) (Eqn. 3) and finally a phase of constant displacement (T_D to 4.0s) (Eqn. 4). The values of T_B, T_C and T_D are defined by the type of spectra and the site class. For the purposes of this paper, only Type 1 spectra are considered.

The piecewise linear function used to define the spectra is as follows:

$$0 \le T \le T_B : S_e(T) = a_g \cdot S \cdot \left[1 + \frac{T}{T_B} \cdot (\eta \cdot 2.5 - 1) \right] \qquad (1)$$

$$T_B \le T \le T_C : S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \qquad (2)$$

$$T_C \le T \le T_D : S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \cdot \left[\frac{T_C}{T} \right] \qquad (3)$$

$$T_D \le T \le 4.0 : S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \cdot \left[\frac{T_C \cdot T_D}{T^2} \right] \qquad (4)$$

Where a_g is the design peak ground acceleration for type A ground, S is the soil type factor, η is a damping correction factor and T is the vibration period. The soil factor S is used to account for the amplifacation of the underlying bedrock ground motion at the ground surface. This phenomenon has been observed in many earthquakes including the 1985 Mexico City event (Dobry and Vucetic, 1987), the 1989 Loma Prieta event (Seed et al., 1990) and the 2011 Christchurch event (Bradley and Cubrinovski, 2011). Figure 3 demonstrates the effect of different soil types on the elastic response spectra as defined by EN 1998. Here it can be seen that the amplification of ground motion and the length of the constant spectral acceleration plateau increases as the soil stiffness decreases, these traits are the same regardless of the amplitude of ground shaking at bedrock and the period considered.

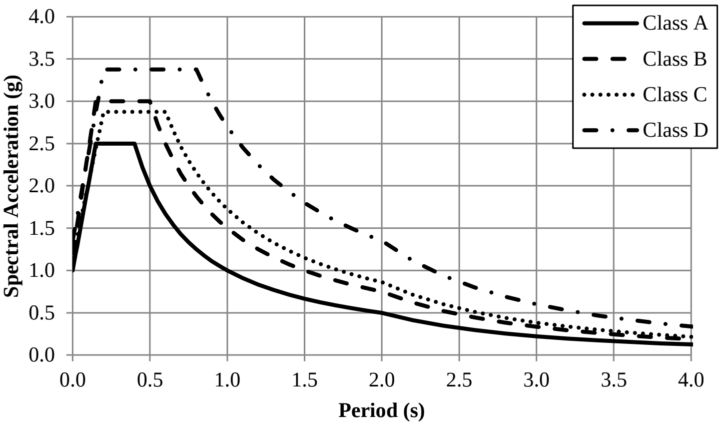


Figure 3. Spectral shapes for Type 1 spectra and site classes A to D as per EN 1998 with $a_g = 1.0$

Evidence from previous earthquake events where very strong ground motions have been experienced suggests that at short periods the spectral accelerations may be significantly different for the rock than they are for soft soils. Evidence also shows that amplification of the ground motion at long periods may be greater than those suggested by design standards. Such evidence was reported by Seed et al (1976) using 147 records that were from the USA. A more recent and extreme example of this behaviour was observed in the 2011 Christchurch earthquake (Bradley and Cubrinovski, 2011) and is presented in Figure 4, where one site on rock (LPCC) and one site on soil (LPOC) in the area of Lyttelton showed very large differences in the surface response spectra.

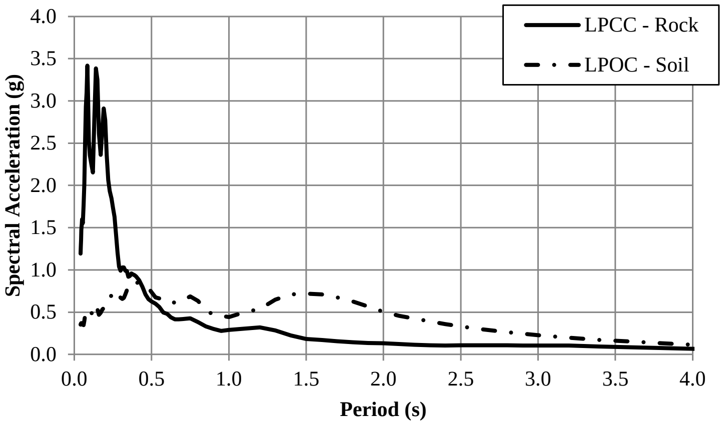


Figure 4. Comparison of response spectra for the 2011 Christchurch earthquake at rock and soil sites in Lyttelton (Bradley and Cubrinovski, 2011)

This paper considers the effect of non-linear site response for a range of soil profiles and strong ground motions in order to assess whether the current method of accounting for site effects on ground motion in EN 1998 are appropriate.

1D SITE RESPONSE ANALYSIS INPUTS

In order to assess the range of responses that can occur at the ground surface due to the propogation of shear waves a series of 1D non-linear site response analyses have been considered for a range of soil profiles and ground motion intensities. To undertake this assessment a total of 10 soil profiles have been analysed to represent site classes B, C and D. These profiles are based on both linearly and parabolically increasing shear wave velocity with depth, such that the average shear wave velocity, V_{S30}, is equal to either 150, 180, 270, 360 and 580m/s. The reason for considering different shear wave velocity profiles that result in the same V_{S30} values is so the effect of this can be considered as it is recognised that a variety of shear wave velocity profiles can exist on real sites. V_{S30} has been calculated in accordance with Clause 3.1.2 (3) of EN 1998 and the variation of the shear wave velocity with depth for each profile is presented in Figure 5 below. The bedrock has been assumed to be 30m below ground level for all soil profiles. The shear wave velocity of the bedrock is taken to be 800m/s.

Four different levels of ground motion have been considered for this study; these are defined by the EN 1998 Type 1 response spectrum for ground type A and anchored to PGA of 0.05, 0.15, 0.25 and 0.4g. Fourteen pairs of time history records with a spread of magnitude values and distances from the recording sites have been selected from the PEER database such that the average geometric mean closely matches that of each response spectra. Only records with a magnitude greater than 5.5 have been selected in line with the notion that the Type 1 spectrum is for larger magnitude events. The selected records are scaled no more than 0.8 to 1.2 times the original record. A comparison of the elastic response spectra with the spectra of the time history records is presented in Figure 6 below, where the blue line is the EN 1998 response spectra and the black line is the average of all 14 geometric means.

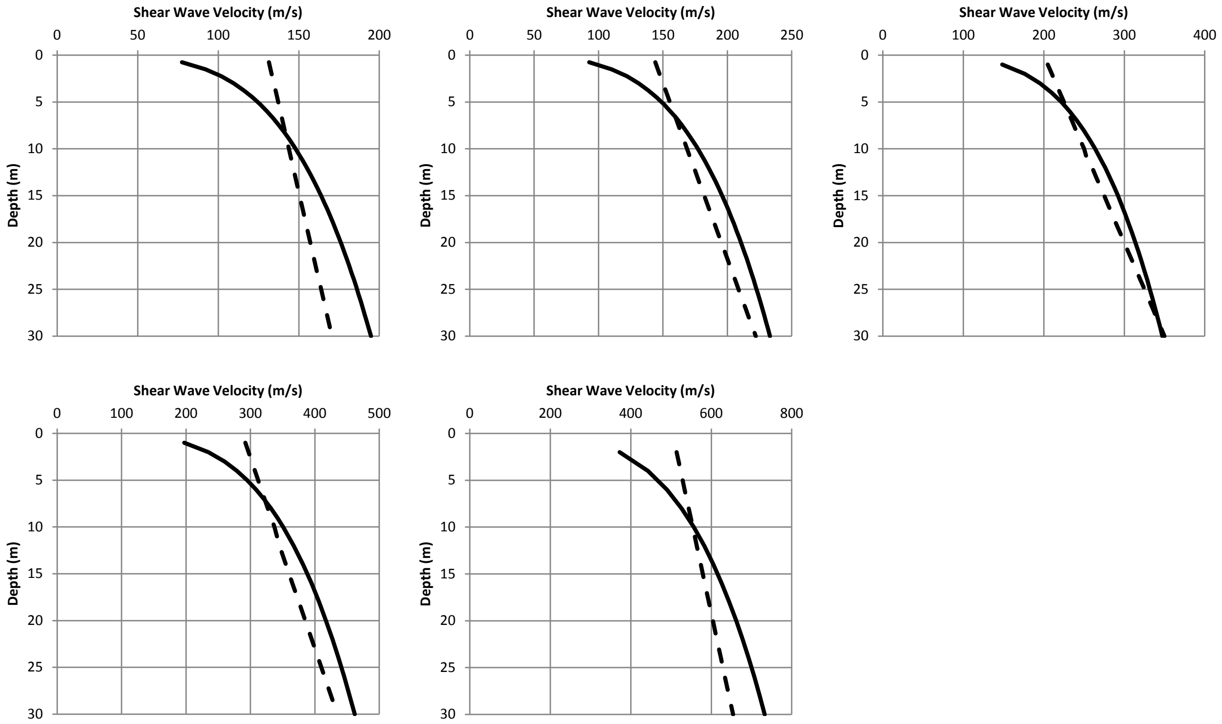


Figure 5. Shear wave velocity profiles for V_{S30} = 150, 180, 270, 360 and 580m/s (left to right, top to bottom).

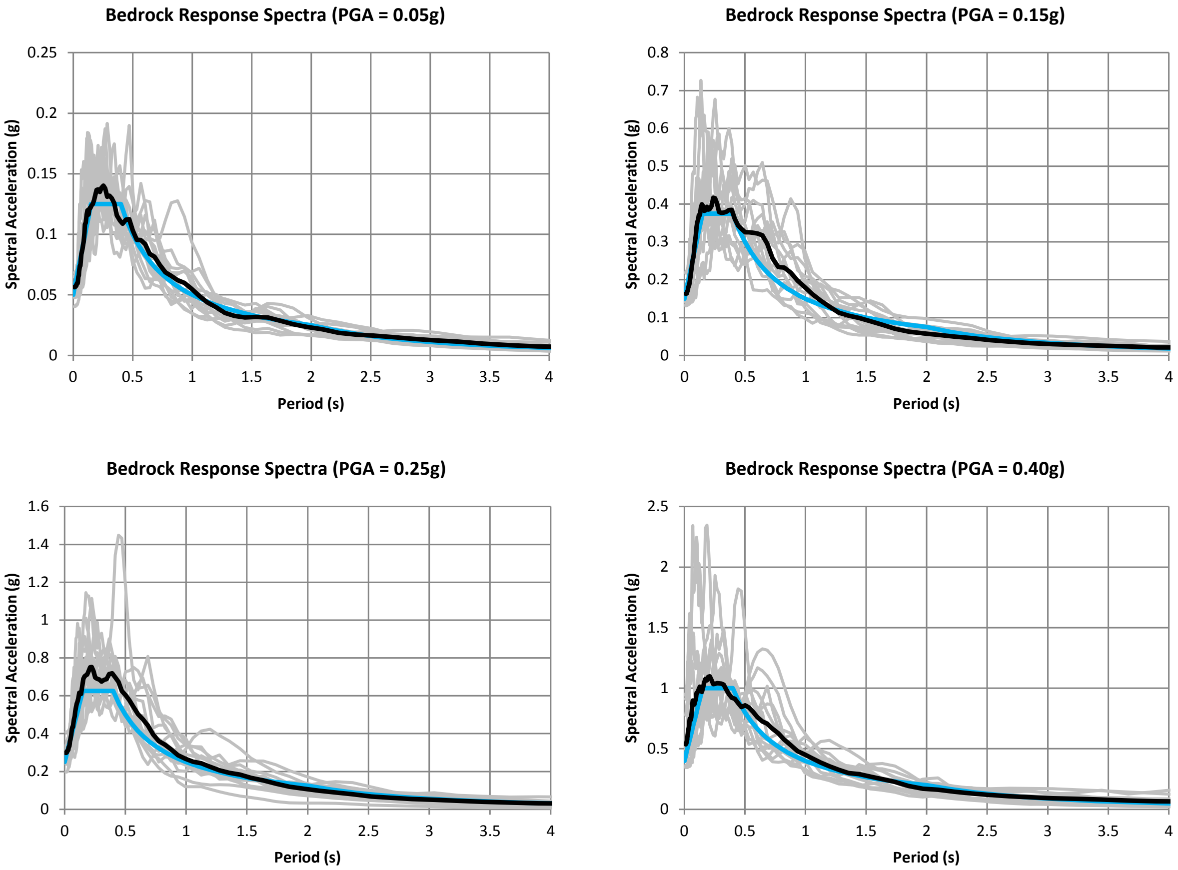


Figure 6. Comparison of geometric mean spectra vs. site class A elastic response spectrum

RESULTS OF PARAMETRIC ANALYSES

To compare the results of the two different site response programs analyses have been undertaken for the same three soil profiles, with V_{S30} values of 180, 270 and 360m/s, in each program for all bedrock ground motions anchored to 0.25g. The results of these analyses are presented below in terms of surface response spectra in Figure 7, where each line is the average of the geometric mean for all 14 pairs of time history records. From this figure it is clear to see that the results are very similar between the two programs; however, for periods equal to or less than 0.1s the results computed by DEEPSOIL are all lower than those from SIREN. For periods greater than 0.1s, the DEEPSOIL results are approximately 5% less than the SIREN results for the 180m/s profile but this difference diminishes as the soil profile stiffness is increased.

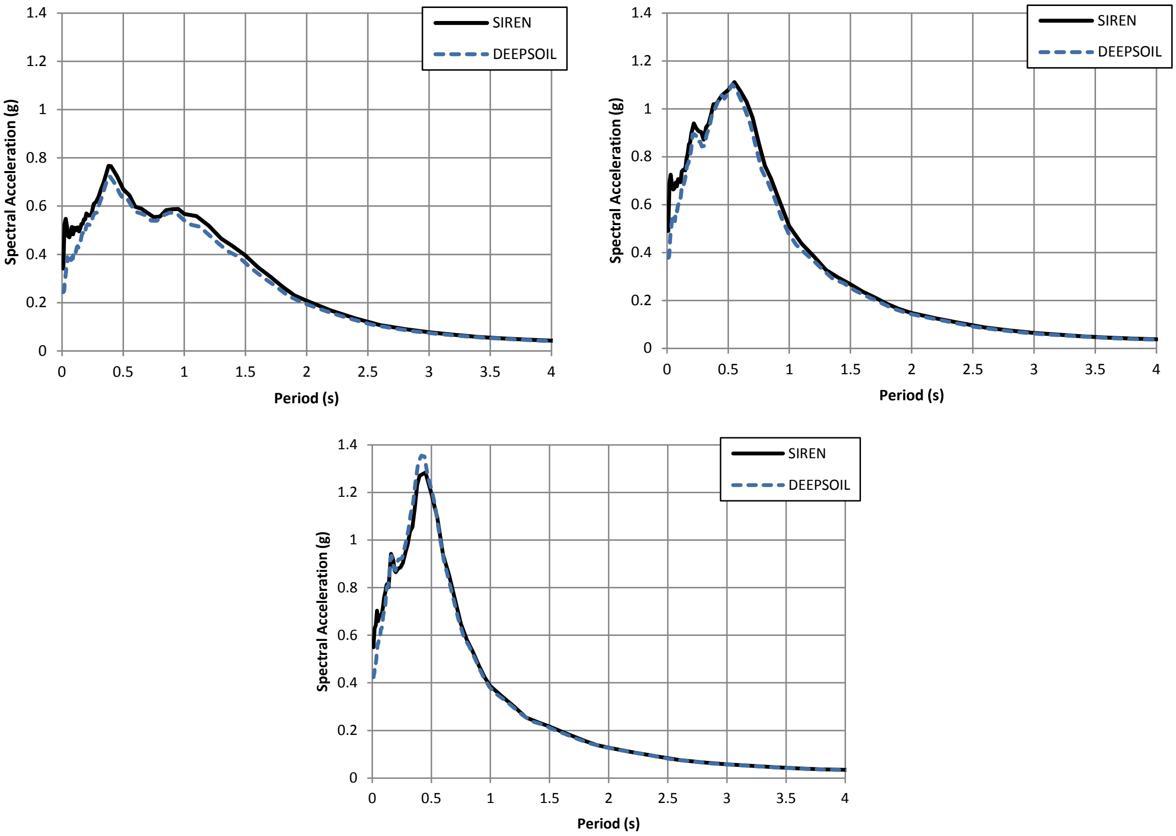


Figure 7. Comparison of DEEPSOIL and SIREN results for V_{S30} = 180, 270 and 360m/s (top left to bottom) and a_g = 0.25g.

As discussed in the previous sections, it is known that the soil stiffness has an effect on the amplification of strong ground motions as the shear waves travel from bedrock to the ground surface. Figure 8 presents a comparison of different soil profiles which have the same V_{S30} value. As demonstrated in Figure 8 the soil profile with a linearly increasing shear wave velocity results in less amplification of ground motion than its parabolic counterpart. This is a consistent trend for profiles with different V_{S30} values and also for varying ground motion intensities, though similarly to the difference between DEEPSOIL and SIREN, the difference in the response spectra between the different profiles diminishes at longer periods. The reason for observing higher accelerations in the short period range for the parabolic shear wave profile is attributed to having stiffer soil between bedrock and approximately 10m below ground level. This stiffer soil enables greater amplification of the ground motion in the high frequency range through behaving in a more linear fashion when compared with its softer counterpart which behaves in a more non-linear fashion, in turn increasing the overall damping of the soil column.

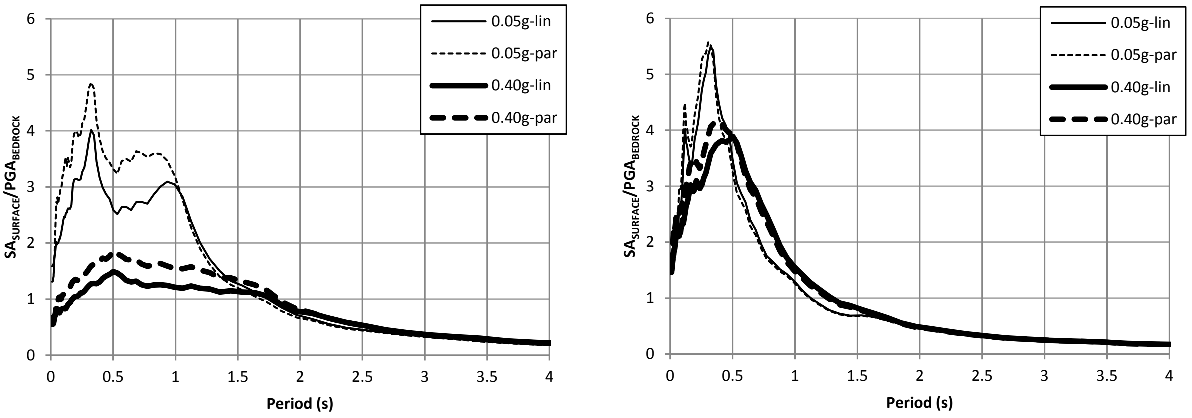
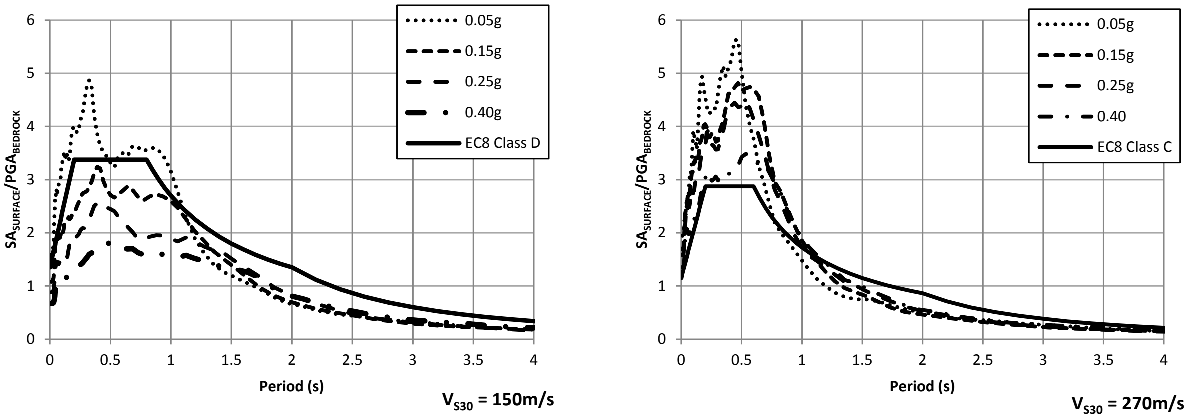


Figure 8. Comparison of ground motion amplification between linear and parabolic shear wave velocity profiles for V_{S30} = 150m/s (left) and 360m/s (right).

The effect of bedrock motion intensity on the amplification of the ground motion is demonstrated in Figure 9, along with a comparison of the EN 1998 spectral shapes. It is clear to see that as the bedrock ground motion intensity increases there is a decrease in the amplification of the ground motion, particularly in the short period range. The difference in the amplification of the ground motion between different shaking intensities is less prononuced with an increase in soil stiffness, this is clearly demonstrated by comparing the range of results for the soil profile with a V_{S30} of 150m/s with the results for the 580m/s profile.

Figure 10 is perhaps the most telling figure when comparing the results with the EN 1998 spectral shapes presented previously in Figure 3. Here it can be seen that the spectral shapes defined in EN 1998 have some similarities but also a number of differences with the spectral shapes assessed from the site response analyses. Firstly it appears that the amplification in the short period range is underestimated, particularly for site classes C and B where the peak of the spectra can exceed 5 times the PGA at bedrock compared with a maximum of 3 times for site class B and 3.375 for site class D. Secondly, the results show that amplification of the ground motion at short periods is not greater for softer soils as the current EN 1998 site class factors would suggest. Figure 10 clearly shows that the soil profile with a V_{S30} value of 150m/s (site class D) produces lower amplification than all of the stiffer soil profiles regardless of the intensity of the ground shaking.

However the results in Figure 10 do show agreement with the EN 1998 spectral shapes where the softer soil profiles result in larger amplification at long periods and this can be observed for all ground shaking intensities.



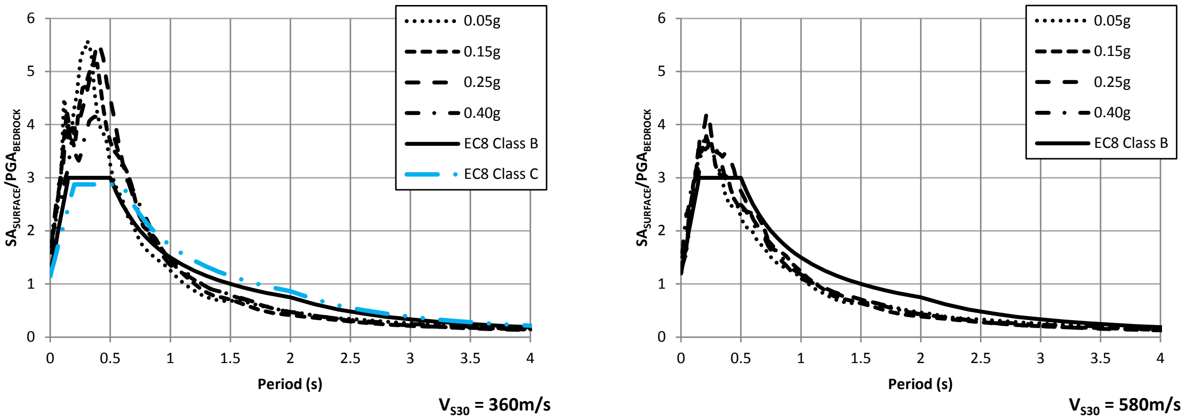


Figure 9. Comparison of spectral shapes defined by EN1998 with those derived from site response analysis for soil profiles with V_{S30} equal to 150, 270, 360 and 580m/s

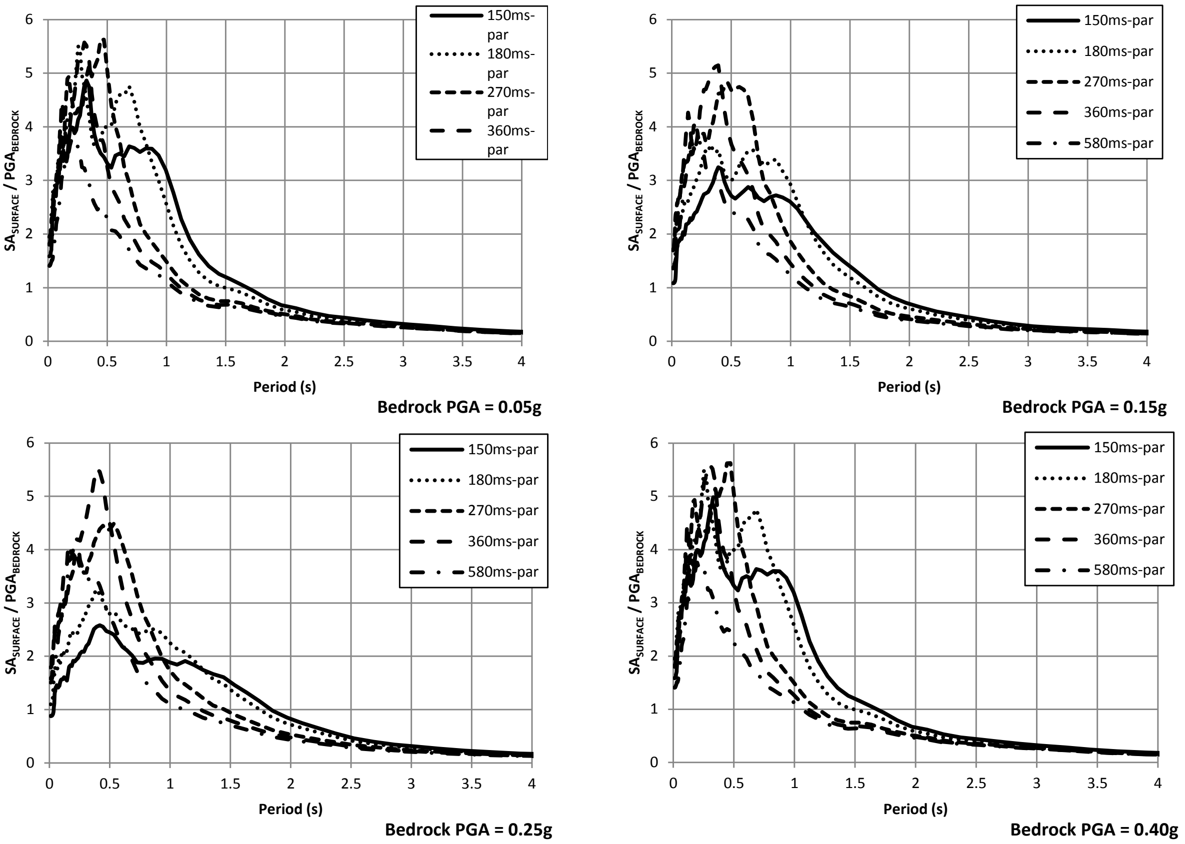


Figure 10. Comparison of spectral shapes defined by EN1998 with those derived from site response analysis for bedrock PGA of 0.05, 0.15, 0.25 and 0.4g

CONCLUSIONS

This paper has looked at the two different methods of numerical site response analyses (DEEPSOIL and SIREN) and shown consistency between the analysis methods.

It has also been demonstrated by utilising 1D non-linear site response that the current approach adopted in EN 1998 to account for site amplification effects is insufficient for a range of peak ground accelerations at bedrock, due to fairly significant under and over estimation of the ground motion amplification at short periods for a range of soil profiles and ground motion intensities. The 1D site response analysis has shown that the amplification of strong ground motion at a site is highly dependent on the stiffness of the soils and the intensity of ground motion at bedrock level. Conversely, there is reasonable agreement of the EN1998 site class B spectral shape with that of the site response results for soil with V_{s30} of 580 m/s.

It is recognised by the authors that not all sites have bedrock at 30 metres below ground level. To address this issues further analysis could be undertaken to consider the effect of different soil profiles

Papers should not be longer than 12 pages.

REFERENCES

Bradley BA and Cubrinovski M (2011) "Near-source strong ground motions observed in the 22 February 2011 Christchurch earthquake", *Seismological Research Letters*, 82, 853–865.

Booth, E.D. and Lubkowski, Z.A. (2012) "Creating a vision for the future of Eurocode 8," *15th World Conference on Earthquake Engineering*, Paper 3501, Lisbon.

Dobry, R. and Vucetic, M. (1987) "State-of-the-art report: Dynamic properties and response of soft clay deposits". *Proceedings, International Symposium on Geotechnical Engineering of Soft Soils, Mexico City* 2: 51-87.

EN 1998 (2004) Eurocode 8: Design of structures for earthquake resistance, Comité Européen de Normalisation.

Federal Emergency Management Agency (FEMA) 273, NEHRP Guidelines for the Seismic Rehabilitation of Buildings, Federal Emergency Management Agency, Washington DC, October 1997.

Hashash, Y.M.A, Groholski, D.R., Phillips, C. A., Park, D, Musgrove, M. (2012) "DEEPSOIL 5.1, User Manual and Tutorial." 107 p.

Heidebrecht, A.C., Henderson, P., Naumoski, N. and Pappin, J.W. (1990) "Site response effects for structures located in sand sites," *Canadian Geotechnical Journal*, Vol. 27 pp 342-354.

Henderson, P. Heidebrecht, A.C., Naumoski, N. and Pappin, J.W. (1990) "Seismic response and design for structures located on soft clay sites," *Canadian Geotechnical Journal*, Vol. 27, pp 330-341.

Lubkowski, Z.A. and Duan, X. (2001) "EN1998 Eurocode 8: Design of structures for earthquake resistance," *Proceedings of the Institution of Civil Engineers - Civil Engineering*, Vol 144, November, pp55-60.

Schnabel, P.B. (1972) "SHAKE: a computer program for earthquake response analysis of horizontally layered sites," UCB/EERC-72/12, Berkeley: Earthquake Engineering Research Center, Univ. of California.

Seed, R.B., Dickenson, S.E., Reimer, M.F., Bray, J.D., Sitar, N., Mitchell, J.K., Idriss, I.M., Kayen, R.E., Kropp, A., Harder, L.F., and Power, M.S. (1990). "Preliminary report on the principal geotechnical aspects of the October 17, 1989 Loma Prieta earthquake". *Report UCB/EERC-90/05,* Earthquake Engineering Research Center, University of California, Berkeley, 137 pp.

Seed, R.B., Ugas, C., and Lysmer, J. (1976). "Site-dependent spectra for earthquake-resistant design". *Bulletin of the Seismological Society of America,* Vol. 66, No. 4, pp. 221-243.