Seismic site response analysis for Australia

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ABSTRACT:

The aim of this study was to investigate the effects of local site conditions on ground shaking and the validity of the current site classification system in the Australian earthquake loading standard, AS1170.4:2007. Numerical analysis was conducted by using an equivalent linear program to explore the effects of shear wave velocity and the depth of soil/rock to bedrock on the site amplification factors for sand and clay with a plasticity index of 30%. Particular attention has been given to the displacement response spectra when evaluating the site response of the various sub-soil classes. Ground motions selected for the analysis are based on providing a good overall match to the target spectra, as well as being representative of real earthquakes which could take place in Australia. Due to the paucity of records in regions of low-to-moderate seismicity, this study has been conducted by using a combination of historical records and stochastically generated earthquakes.

Keywords: Seismic site response analysis, site classification system, low-to-moderate seismicity, displacement response spectra, site amplification factors

1. INTRODUCTION

It has been well established that local site conditions have a significant effect on the ground's response to seismic excitation. Many of the standards and codes account for the difference in site response by categorising the various types of soil conditions into numerous classes. These are based on qualitative descriptions (such as hard rock, shallow stiff sites, deep or soft sites), and quantitative measurements, predominantly the site's weighted average shear wave velocity and depth of soil to bedrock. Such a method is incorporated in the Australian earthquake loading standard, AS1170.4 (Standards Australia, 2007). As mentioned in the commentary of AS1170.4 (Wilson & Lam, 2007) the purpose of site classification is to allow determination of site response without the need for detailed site investigations, since these are not necessarily always carried out. It is also useful for assessment of existing buildings where the site class can only be determined from local geology.

For each of the site classes, a generalised response spectra is provided, from which the acceleration, velocity and displacement response of a site under a specific level of hazard can be determined. Traditionally the focus has primarily been on acceleration response spectra. However, over the last few decades there have been significant advancements in the earthquake resistant design of structures, which has lead into a change from traditional force-based design to displacement-based design, thus requiring displacement response spectra (RSD) as well as acceleration response spectra (RSA).

A generalised response spectrum for rock is usually produced for a region, such as a country. This is commonly in the form of uniform hazard spectra (UHS) which is based on a probabilistic seismic hazard analysis (PSHA) for various events, namely 500 and 2500 year return period. It is then multiplied by the hazard level which is specific for a site. Hazard level and generalised spectra for rock are very debatable and prone to change (after an earthquake), especially in areas of low-to-moderate seismicity such as Australia. However, the ratios between the response of the ground surface and outcrop bedrock, known as amplification factors, are more robust and consistent for a particular intensity of earthquake. Thus this study has investigated the effects of local rock/soil conditions on site response via amplification factors, for a hazard level of 0.1g, which is referred to as the *Z* factor in AS1170.4 (Standards Australia, 2007). The hazard level of 0.1g approximately corresponds to a 500 year return period event in some cities within Australia (see Table 3.2 in AS1170.4). The aim of the study was to establish a method which allows the application of amplification factors to any target spectra on hard rock, and to thus obtain the ground response for various site conditions.

2. LITERATURE REVIEW

Site classifications utilised in many codes are predominantly based on the stiffness of the ground conditions. American and European based codes (Building Seismic Safety Council, 2003; European Standard, 2004) define all sites according to the average shear wave velocity at a depth of 30 m (V_{s30}). However, studies have shown that the combination of both depth to bedrock and shear wave velocity is required to accurately categorise sites (Rodríguez-Marek, Bray & Abrahamson, 1999). This is why AS1170.4 (Standards Australia, 2007) defines the non-rock classes according to the site period. Despite this, it should be noted that in AS1170.4 (Standards Australia, 2007) the site class B which refers to rock site conditions, is based on V_{s30} within the range of 360-1500 m/s. This range is much greater than the other codes, which usually restrict the rock class to a minimum V_{s30} of 760 m/s or 800 m/s (Building Seismic Safety Council, 2003; European Standard, 2004) to exclude weathered rock conditions which can in fact behave significantly different to competent rock (Rodríguez-Marek, Bray & Abrahamson, 2001).

Based on the site classifications, many of the current codes have produced response spectra for each class by taking the average response of either empirical records or numerical analyses of various soil profiles. This includes the study performed by Crouse and McGuire (1996), which has formed the basis of the amplification factors included in the International Building Code and AS1170.4 (Wilson & Lam, 2007), even though the true ground response behaviour is lost in the averaging process (Lam & Wilson, 2004; Tsang, Chandler & Lam, 2006). Tsang, Lam and Wilson (2013) explain that this limitation is usually accepted on the basis that resonance effects can be suppressed by the damping of structures, however, this is not the case for non-ductile buildings which are very common in regions of low-to-moderate seismicity.

The averaging process discussed above has also been shown to have an impact on the estimation of the second corner period (T_2), which defines the period at which maximum displacement occurs (Lumantarna, Wilson & Lam, 2012). For rock conditions, T_2 is based on the maximum considered earthquake magnitude and has been determined as 1.5 seconds for Australia based on the extensive study conducted by Lam, Wilson, Chandler and Hutchinson (2000a; 2000b). Interestingly, the same value of T_2 has also been extended to all other site classes in AS1170.4 (Standards Australia, 2007) even though it is well recognised that there is a significant difference between seismic response of rock and soil sites.

Furthermore, an improved idealisation of the RSD in the longer period range is necessary to account for the reduction in response after the degraded period for some soil sites. The European code (European Standard, 2004) accounts for this behaviour in the Annex, by providing an alternative RSD for regions of high seismicity in which the displacement gradually reduces up to the peak ground displacement at a period of 10 seconds. This type of spectra is preferred in dynamic modal analysis of structures as it allows better approximation of the contribution of the displacement response from the higher modes.

The purpose of this study was to provide generalised response spectra for various site classes through a conservative and systematic approach, and using suitable ground motion records currently available for Australia. In addition a method has been established to allow RSD and RSA to be obtained from any target spectra for hard rock. This was achieved by analysing the key site parameters which effect site response, i.e. shear wave velocity and depth to bedrock, for sand, and for clay with a plasticity index of 30%.

3. METHODOLOGY

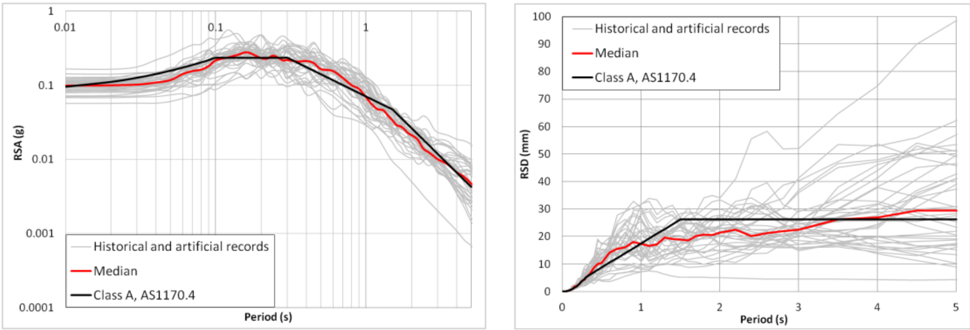
Numerical analysis was conducted to obtain the site amplification factors of various site profiles. This was achieved by using the equivalent-linear, one-dimensional site-specific response program, SHAKE2000 (Ordonez, 2014). The three key steps in the analysis are described below.

3.1 Selection of seismic input motion

Ground motions were selected such that their median matched the RSA and RSD of Class A (hard rock) in AS1170.4 (Standards Australia, 2007) for a hazard level of 0.1g. While there are no stringent rules, ground motions have been selected according to best practice (Kramer, 1996, p. 340): (i) using historical records which are representative of earthquakes within the region of interest, and (ii) using artificial earthquakes, as sufficient suitable historical records are not available.

Historical records have been obtained from the Pacific Earthquake Engineering Research Center (PEER, 2014) and Internet Site for European Strong-Motion Database, (ISESD, 2014). Accelerograms on rock (V_s > 800 m/s) were selected with characteristics typical of Australian earthquakes: shallow earthquakes with reverse fault mechanisms (Brown & Gibson, 2004), and realistic magnitude and distance (M-R) combinations based on attenuation models of Gaull, Michael-Leiba and Rynn (1990) and Lam et al. (2000a) for a hazard level of 0.1g. Despite this, some leniency was allowed with the M-R combinations, as priority was given to matching the target spectra Class A in AS1170.4 (Standards Australia, 2007)

Furthermore, to avoid problems associated with simple amplitude scaling, stochastically generated earthquakes were obtained using the program GENQKE (Lam, 1999) which is capable of producing ground motions that are representative of Australian earthquakes. This was to ensure that sufficient records were used in order to obtain statistical stability of median and standard deviation of results. Although the study presented here is for median responses, it could be extended to provide 84^{th} and 98^{th} percentile responses. In total, 11 pairs of unscaled historical records and 23 artificial earthquakes were obtained (total of 45 horizontal ground motions). Figure 1 shows the RSA and RSD of ground motions selected and their median compared to the target spectra.



a) RSA b) RSD

Figure 1: Acceleration and displacement response spectra of input ground motions and target spectra

3.2 Defining site properties

Numerous soil profiles (with constant shear wave velocity) within each of the five site classes, as classified in AS1170.4 (Standards Australia, 2007), were considered for average sand conditions and clay with a plasticity index (PI) of 30%, and bedrock with a constant shear wave velocity of 1800 m/s. The aim was to consider soil profiles which ranged between the maximum and minimum possible shear wave velocities or site periods allowed within each class, for four different depth to bedrock profiles: 30, 60, 90 and 150 m. In total about 80 soil profiles amongst the five classes were analysed with particular attention to Classes B, C and D.

3.3 Analysis of site response

To obtain the response spectra of an individual soil profile, the geometric mean of each pair of historical responses was obtained, and then the median of the resulting 34 responses was calculated. The amplification factors were obtained from amplification spectra. These were calculated by dividing the response spectra for each individual record by the response spectra for the outcrop bedrock motion (i.e. Class A) corresponding to that record. This was done to minimise the effect of input ground motion variability on the amplification factor.

4. RESULTS AND DISCUSSION

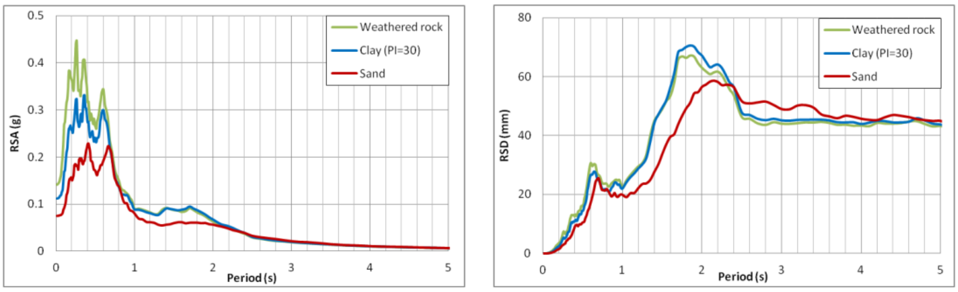
The following section includes the key results and observations obtained from the numerical analysis.

4.1 Site classifications

Based on the results of the analysis, amendments to the current site classification in AS1170.4 (Standards Australia, 2007) are recommended, see Table 1. It was observed that the behaviour of soft/weathered rock with shear wave velocity (V_s) less than 760 m/s behaved similarly to stiff deep soil conditions (particularly clay with PI of 30%), as shown in Figure 2. As such it is recommended that weathered rock be classified based on site period (T_s), similar to Class C and D, to ensure that the displacement response is not underestimated. Furthermore it is suggested that Class D is categorised into two sub-classes based on site period; Class D1: soft shallow sites or deep stiff sites and Class D2: soft deep sites, as described in Table 1. Class D2 is limited to an initial site period of 3 seconds, as it was observed higher site periods behaved similarly to Class E, with significant increase in displacement response and as such should be treated with care.

Table 1: AS1170.4 and suggested site classification based on V_s and T_s

	AS1170.4 site classification	Suggested site classification
Class A	V_s > 1500 m/s	V_s > 1500 m/s
Class B	360 m/s ≤ V_s ≤ 1500 m/s	760 m/s ≤ V_s ≤ 1500 m/s
Class C	T_s ≤ 0.6 s	T_s ≤ 0.6 s (including weathered rock)
Class D1	T_s > 0.6 s (Class D)	0.6 s < T_s < 1.6 s (including weathered rock)
Class D2		1.6 ≤ T_s < 3.0 s
Class E	V_s ≤ 150 m/s	V_s ≤ 150 m/s or T_s ≥ 3.0 s



a) RSA b) RSD

Figure 2: Comparison between weathered rock, clay (PI=30), and sand for depth of 150 m and V_s of 360 m/s

4.2 Amplification factors

Originally maximum amplification factors were obtained within the acceleration, velocity and displacement controlled regions as they are usually presented in such a format in codes and guidelines. The results showed that there was no real trend with depth or shear wave velocity of the site when the amplification factors were obtained in such a manner. This is because while the magnitude of the amplification factor is highly dependent on the shear wave velocity, the location of the amplification is highly dependent on the site's period. The only true trend which was observed from the results was between the maximum amplification factor (referred to as site amplification factor, F_{site}) and the site's degraded period. Thus a relationship between the site amplification factor and the site's shear wave velocity exists when there is no restriction on the period range (see Figure 3**)**.

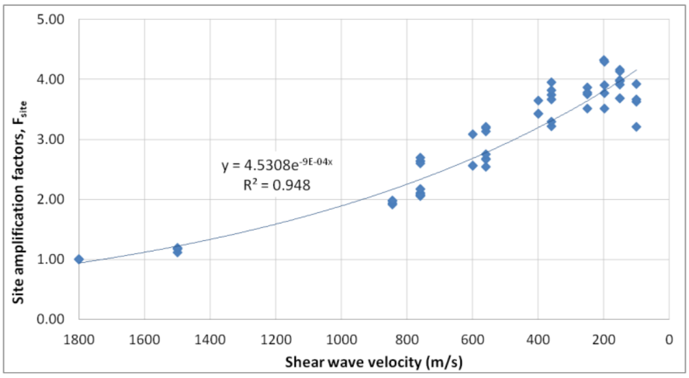


Figure 3: Site amplification factors versus site shear wave velocity for clay (PI=30), depth range: 30-150 m

It was also observed that a relationship exists between the site's initial ($T_{initial}$) period and degraded period (or final period, T_{final}) which is dependent on the depth to bedrock (d), as shown in Figure 4. This allows for a systematic approach of approximating the second corner period for each class, as discussed in Section 4.3.

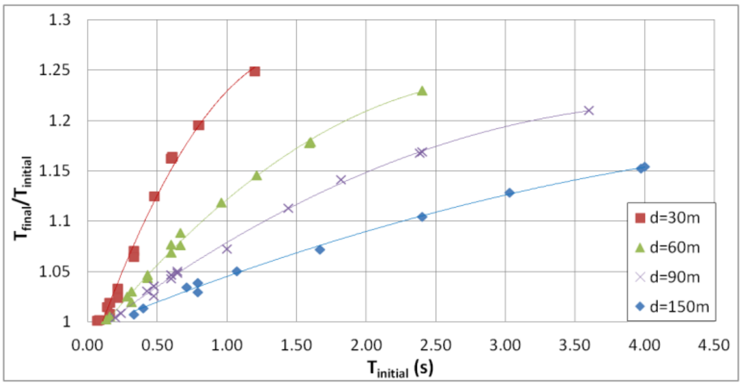


Figure 4: Ratio of T_{final} to T_{inital} versus $T_{initial}$ for various depths to bedrock

4.3 Response spectra from amplification factors

Through the relationships presented in the previous section, a systematic approach is suggested to obtain the RSA and RSD by using F_{site}. In addition, the maximum amplification factor at 5 seconds (F_E) is utilised to account for the significant reduction in displacement response which is observed for Classes C and D1. The amplification factors presented in Table 2 are for rock and clay with a PI of 30%. It is noted that maximum site amplification factors within each class have been suggested (and not median) as it is the authors' recommendation that for a general spectra conservatism should be a priority.

The critical periods and the method required to construct the RSA and RSD are described in the next sub-sections. For the most accurate results, amplification factors should be applied to uniform hazard spectra for hard rock conditions.

4.3.1 First corner period, T_1

The suggested T_1 values in Table 2 are based on the observed RSA for each class.

4.3.2 Second corner period, T_{2ampl} and T_{2spec}

Two definitions of second corner period are necessary:

$T_{2amplification} = T_{2ampl}$

- Required for calculating the magnitude of RSD_{max}.
- Obtained by considering the longest degraded site period possible for a particular class from Figure 4.

$T_{2spectra} = T_{2spec}$

- Required for defining the period at which RSD_{max} occurs and calculating all other critical values.
- Obtained graphically, when the stiffest ground condition peaks first.

4.3.3 Longer period limits, T_3 and T_4 (only for Class C and Class D1)

For an improved idealisation of RSD for Class C and D1 two more period limits are defined:

T_3: the period for which the maximum displacement response ends

$$T_3 = 1.5 \times T_{2ampl} \quad (1)$$

T_4: the period for which a constant value of RSD is reached in the long period range

$$T_4 = 2.5 \times T_{2ampl} \quad (2)$$

Table 2: Suggested amplification factors and critical periods

	Class B	Class C	Class D1	Class D2	Class E
Amplification factors					
F_{site}	2.2	4.3	4.3	4.0	4.0
F_E	-	1.5	1.8	-	-
Critical periods					
T_1	0.35	0.45	0.6	0.8	0.8
T_{2spec}	0.8	0.8	1	1.5	1.5
T_{2ampl}	1	1	1.8	3.3	5
T_3	-	1.5	2.7	-	-
T_4	-	2.5	4.5	-	-

4.3.4 Calculations required to obtain RSD and RSA

The formulae required to obtain the RSA and RSD are provided below. Graphical representation of the key parameters for the RSD is shown in Figure 5.

Displacement response spectra for Class B, D2 and E:

$$RSD_{max} = RSD_{bedrock\ at\ T_{2ampl}} \times F_{site} \qquad for: T \geq T_{2spec} \qquad (3a)$$

$$RSD = RSD_{max} \times \left(\frac{T^2}{T_{2spec}T_1}\right) \qquad for: 0 \leq T \leq T_1 \qquad (3b)$$

$$RSD = \frac{RSD_{max}}{T_{2spec}} \times T \qquad for:\ T_1 < T < T_{2spec} \qquad (3c)$$

Displacement response spectra for Class C and D1:

Equation 3b and 3c applies for $0 \leq T \leq T_1$ and $T_1 < T < T_{2spec}$

$$RSD_{max} = RSD_{bedrock\ at\ T_{2ampl}} \times F_{site} \qquad for: T_{2spec} \leq T \leq T_3 \qquad (4a)$$

$$RSD = \left(\frac{F_E \times RSD_{bedrock\ at\ 5sec} - RSD_{max}}{T_4 - T_3}\right) \times (T - T_3) + RSD_{max} \qquad for: T_3 < T \leq T_4 \qquad (4b)$$

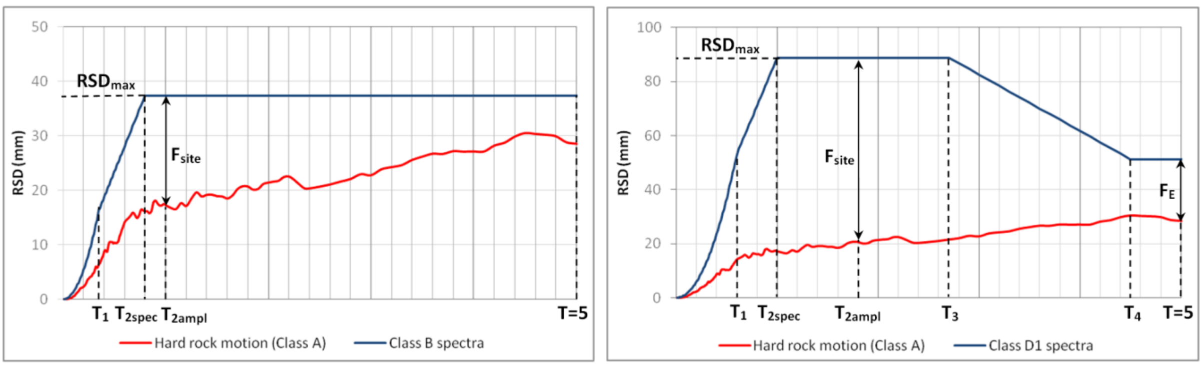
$$RSD = F_E \times RSD_{bedrock\ at\ 5sec} \qquad for: T > T_4 \qquad (4c)$$

Acceleration response spectra (for all classes):

$$RSA = RSD \times \left(\frac{2\pi}{T}\right)^2 \qquad for: 0 \leq T \leq 5 \qquad (5)$$

Note: $RSA_{max} = RSV_{max} \times \left(\frac{2\pi}{T_1}\right)$ (6)

where: $RSV_{max} = RSD_{max} \times \left(\frac{2\pi}{T_{2spec}}\right)$ (7)



a) Class B spectra b) Class D1 spectra

Figure 5: Graphical representation of proposed method for obtaining RSD

4.3.5 RSD and RSA obtained using the proposed method

The charts in Figure 6 show the RSA and RSD spectra obtained using the proposed method for clay with a PI of 30%, and are compared with the current spectra in AS1170.4 (Standards Australia, 2007) and the envelope of median sub-class responses obtained from the numerical analysis. It is clear that the proposed method provides a better approximation of acceleration and displacement response for stiffer classes; Class B, C and D1.

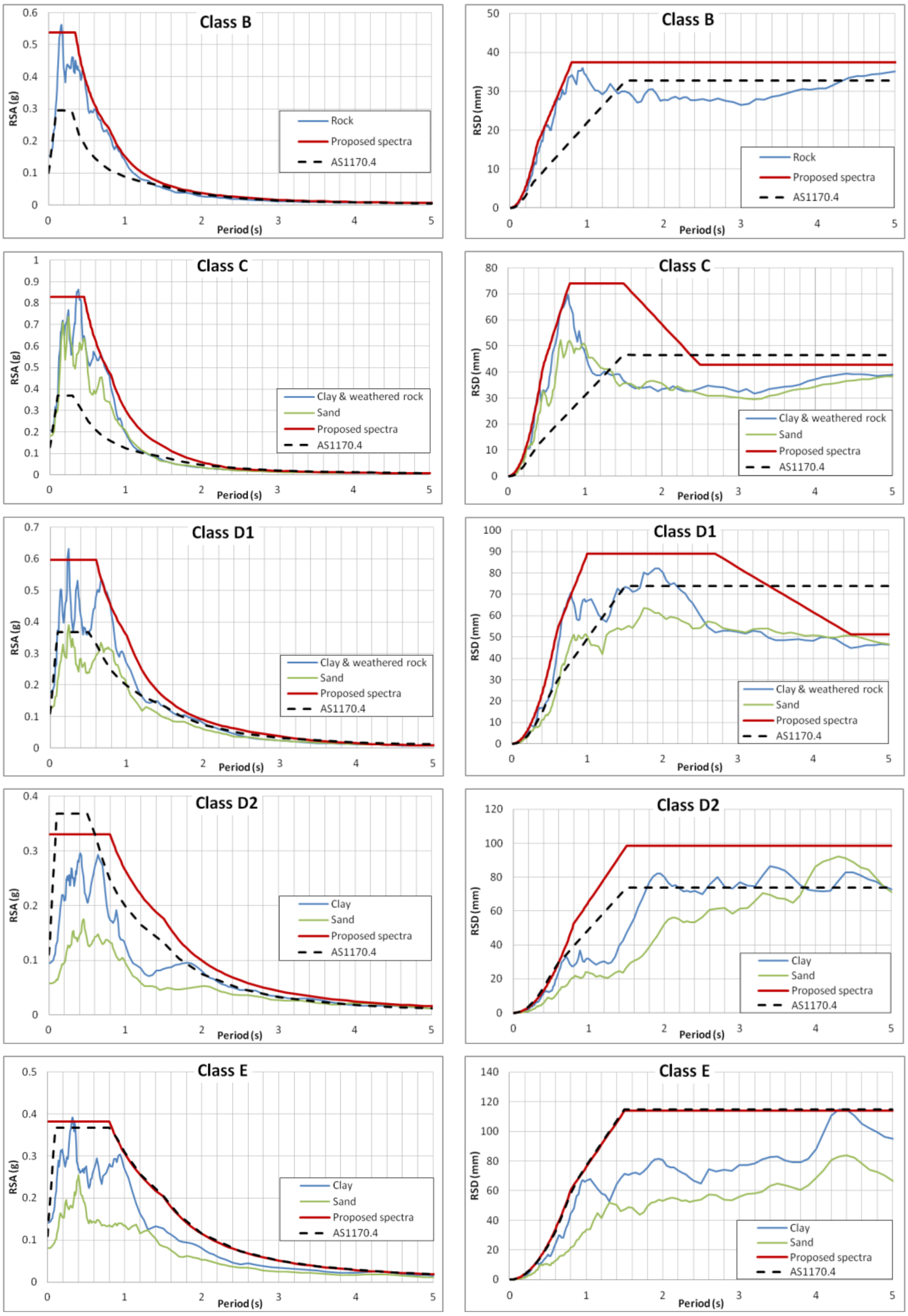


Figure 6: RSA and RSD of proposed method, results from numerical analysis and AS1170.4 spectra

5. CONCLUSION

The main aim of this study was to investigate the seismic site response for various soil conditions via site amplification factors. This process also led to the re-classification of some site classes. A systematic and conservative approach has been suggested to obtain response spectra of various classes, based on clay sites with a plasticity index of 30%. Furthermore, a more representative displacement response spectra shape has been suggested for Classes C and D1. The purpose of this is to not only overcome excessive conservatism in the long period range, but also to allow more accurate dynamic modal analysis of buildings via the use of response spectra.

The generalised spectra derived in this study broadly represent the response of all of the sites within each class and hence are able to cater for uncertainty about the site characteristics; namely the shear wave velocity and depth to bedrock. The same method used to find the amplification factors in this study for clay of plasticity index of 30% could be utilised to obtain the response spectra of other soil types, i.e. sand and clays with various plasticity indices, and this is the subject of further research.

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