6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch, New Zealand

Site-Specific Response Analysis in Australia and Comparison with AS1170.4 and Geoscience Australia 2012 Seismic Hazard Maps

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ABSTRACT

The current Australian Standard for Earthquake Loading (AS1170.4-2007) includes response spectrum for design guidance. The spectrum is constructed in the form of ADRS (Acceleration-displacement response spectra). In 2012 Geoscience Australia (GA) published updated seismic hazard maps for which the response spectrum is calculated directly from Ground Motion Prediction Equation (GMPEs) for different structural periods for different return period. Although AS1170.4 currently governs design, the discrepancies between the two spectra can be significant, with potentially costly implications to construction in Australia. For example, in Sydney the spectral values for a short building with a structural period of 0.3s is between 50% to 100% higher in AS1170.4 for return periods of 500, 1000, and 2500 years. The large discrepancy between AS1170.4 and GA spectra for rock directly influence the basis for site response analysis. This paper summarises a site specific response analysis undertaken in Perth using response spectra from AS1170.4 and GA. As the availability of ground motions in low to moderate seismicity and intra-plate regions such as Australia is limited, input motions were selected from world events considered to be appropriate based on geological setting. The resultant surface response spectra were compared between AS1170.4 and the GA, and also compared with the soil response spectra defined in AS1170.4.

Introduction

Seismic design in Australia follows AS1170.4 "Structural design actions, Part 4: Earthquake actions in Australia" published in 2007 (Standards Australia, 2007a). In AS1170.4, the design response spectra was constructed in the form of an ADRS plot (acceleration-displacement response spectrum which simultaneously indicates the acceleration (force and displacement (drift) demand) for a Hazard Factor (Z). Z is equivalent to the peak ground acceleration (PGA) with a return period of 500 years. The estimation of Z is primarily based on Peak Ground Velocity (PGV) by Z=0.1 g equivalent to PGV=75mm/s. The PGV map was first generated by Gaull et al., (1990) using a Probabilistic Seismic Hazard Analysis (PSHA) and subsequently refined and smoothed. In major cities of southeastern Australia including Sydney, Melbourne and Canberra, a Z of 0.08 is applied instead of using the PGV map. The response spectra in AS1170.4 are associated with different return periods by applying a Probability Factor (k_p). (Wilson et al, 2006; Wilson et al, 2008, Standards Australia, 2007b). Also, the response spectral shape using ADRS plots considered the ground motion from a magnitude 7 earthquake (Standards Australia, 2007b), which is considered the largest earthquake event that could be expected in Australia. Hence, the response spectral shape of AS1170.4 is effectively the maximum credible earthquake (MCE) (Standards Australia, 2007b, Somerville et al., 1998).

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Although PSHA was undertaken to create PGV maps for correlation to hazard maps in AS1170.4 (both 1993 and 2007 version use the same map), the Ground Motion Prediction Equation (GMPE, also known as attenuation equation) of PGV used in the PSHA was indirectly derived using the seismic intensity (*I*) relationships based on iso-seismal maps for Australian earthquakes available in the early 1990s. Also, the other spectral coordinates were indirectly estimated using the form of ADRS plots with MCE events, which is not considered to represent the most probable ground motion that is likely to occur in the length of time under consideration (i.e. probability of exceedance which can be in terms of return period). This potentially leads to an exaggeration of the velocity and displacement response for long periods when using AS1170.4.

In 2012 (approximately 20 years since the hazard map of AS1170.4 was published), Geoscience Australia (GA) published the seismic hazard of major cities in Australia (Burbidge et al, 2011; Leonard et al, 2013). Since the early 1990s, there has been significant advancement of GMPEs in Australia (Somerville et al. (2009), Allen (2012)) and worldwide (e.g. Atkinson and Boore (2006), NGA, etc.) including developed GMPEs for other spectral periods. Hence, the PSHA used in GA has adopted the GMPEs not only for PGA but also for different spectral periods. The resultant response spectral shape better exemplifies the ground motion response at longer structure periods, partly due to the specific seismic source to site distances in different cities. Also, the response spectrum represents the hazard at particular return periods, which allows the use of a specified level of ground motion for performance base seismic design.

When comparing AS1170.4 with GA, the PGA from AS1170.4 of some major cities such as Sydney, Brisbane and Melbourne is generally higher than the PGA calculated from GA for the 500 year return period. The PGA becomes quite similar when the return period is 2500 (see an example of Sydney in Figure 1). In Perth, the PGA for all return periods from AS1170.4 is higher than GA (Figure 1). For the long structural periods, the GA spectra are significantly lower than AS1170.4 for all the cities. The reduction of spectral acceleration would significantly reduce spectral velocity and spectral displacement for the design, in particular, for many of the buildings in the structural period range from 0.5 to 1s

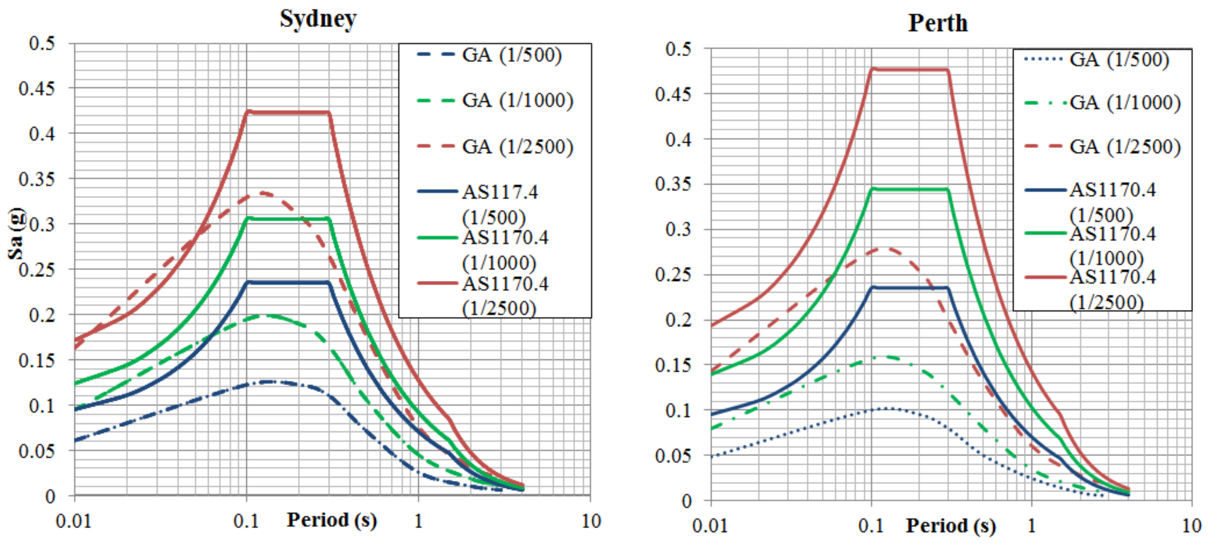

Figure 1: Response spectra comparison between GA and AS1170.4.

For buildings founded on soil (i.e. not directly on bedrock), the surface response spectra is more critical for the design. In this study, a site response analysis has been carried out using the bedrock response spectrum from AS1170.4 and GA to compare the effect of the surface response using different bedrock spectrum. The result was compared with the soil response spectrum defined in 1170.4, which was developed using soil factors (Fa and Fv) (Wilson et al., 2003). A site in Perth is selected for this case study.

Site Response Analysis

Methodology

Oasys SIREN is a finite difference program that analyses the response of a 1-dimensional soil column subjected to an earthquake bedrock motion at its base. The earthquake motion is modelled as vertically propagating shear-waves. The soil column is specified as a series of horizontal layers, each layer being modelled as a non-linear material with hysteretic damping. The soil damping is derived as a function of the shear modulus degradation curve. Detailed calibration analyses undertaken using *Oasys* SIREN are described by Henderson et al. (1990) and Heidebrecht et al. (1990).

Input ground motions

The propagation of ground motions through the soil profile requires input motions at the bedrock-soil interface in the form of acceleration time histories. A design bedrock response spectrum is used to match selected time histories to represent the bedrock motion.

As noted before, the deviation of PGA between AS1170.4 and GA becomes closer when return period becomes higher. Hence, a 1000 year return period is selected as a "middle" scenario for the case study.

Following AS1170.4, a bedrock design spectra is calculated for different periods from the product of the Z (Hazard Factor), multiplied by a k_p (Probability Factor) corresponding to the different return period. Z in Perth is 0.09g and the k_p for 1/1000 is 1.3. As such, the design PGA for Perth with an annual probability of exceedance equal to 1/1000 is 0.12 g.

Following the PGA of 0.12g, three target response spectra have been developed for comparison.

The three response spectra are:

1) Using the rock spectrum (Class B) defined by AS1170.4, with PGA = 0.12 g. The rock definition of AS1170.4 Site Class B assumes Vs = 360 m/s.

2) GA response spectrum of 1/1000 year return period. The V_S of the GMPEs adopted for GA spectra is between 760 to 865 m/s.

3) The GA response spectra was scaled to be equivalent to the design PGA of 0.12 g if considering PGA defined in AS1170.4 as a basis of seismic hazard. This also provides the similar situation where the PGA of GA and AS1170.4 are very similar (e.g. In Sydney, the PGA at 1/2500 is the same as AS1170.4). The authors have undertaken a PSHA of Perth. The PSHA shows the scaled spectrum to be approximately equivalent to a 3000 year return period response spectrum. The bedrock spectrum was obtained for

bedrock with average shear-wave velocity over the top 30 m of about 760 m/s, which differs from AS1170.4.

These three response spectra are shown in Figure 2.

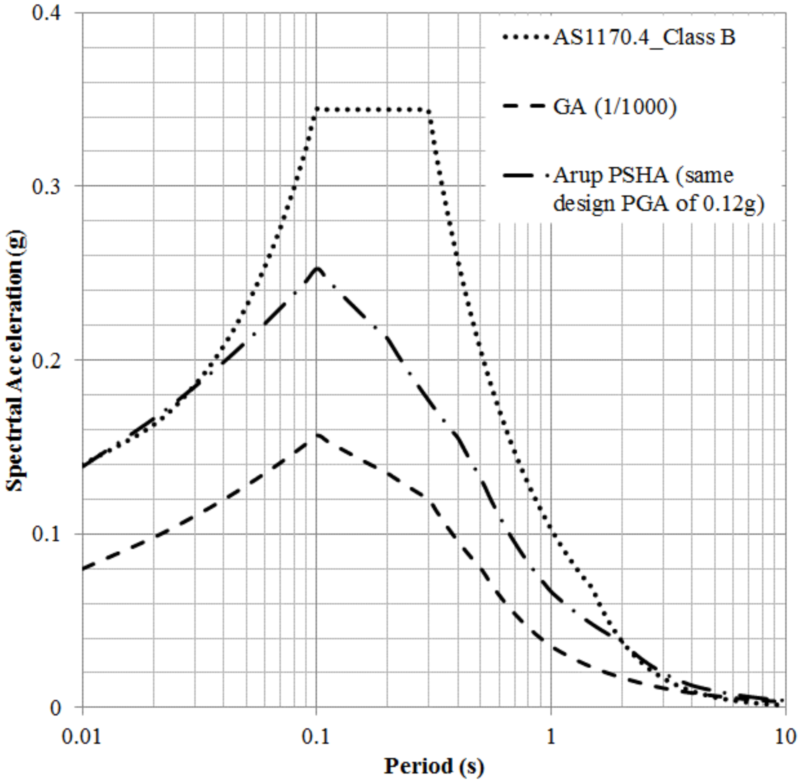

Figure 2: Target bedrock response spectrum for site response analysis.

Analysis of the variation in propagation of ground motion through different soil profiles requires different input motions for the bedrock in the form of earthquake acceleration time histories. Time histories were selected to match the possible earthquake occurrences generating the target bedrock spectra. The basis for the target ground motion hazard spectra is the magnitude-distance de-aggregation from the case study PSHA.

Seven time histories were selected for a range of earthquakes of different magnitudes (amplitudes and duration) and distances from the site to account for uncertainty in knowledge of future seismicity in Perth (Figure 3). To capture the wide range of controlling distance and magnitude, a total of 7 pairs of ground motion recordings were selected from the international Pacific Earthquake Engineering Research (PEER) strong motion database. The seven selected time histories were modified using the computer program RSPMatch2005 (Hancock et al., 2006) to match the target bedrock response spectrum.

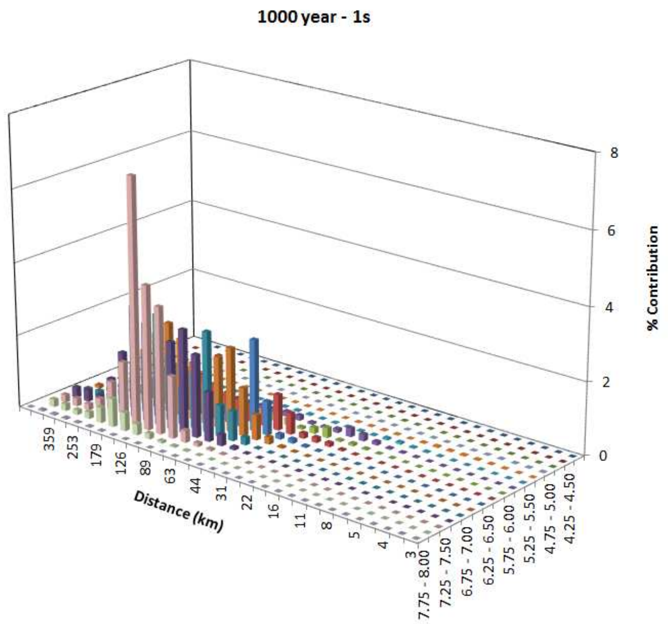

Figure 3 Magnitude-distance de-aggregation for bedrock spectra

Site Ground Conditions

The site is currently located next to a river channel and it is underlain by two paleochannel deposits. The upper most few metres of the ground is fill, followed by 7 to 15 m of a paleochannel deposit, Swan River Alluvium (SRA), underlain by another older paleochannel deposit, Sandy Channel Deposit (SCD). King Park Formation (KPF), recovered as sand, was encountered underneath SCD. It is note that SRA comprises generally very soil clay and silt of up to 24 m thickness. The stiffness and thickness of SRA is dependent on the paleochannel location. SDC comprises much stiffer sandy material compared with SRA. Similar to SRA, the thickness of SDC varies with the paleochannel location.

Seismic Cone Penetration Tests (SCT) were carried out to measure the V_S of the site. They show that the V_S of SRA is generally less than 150 m/s. As such, a portion of the site where consisting SRA greater than 15 m of soil is classified as Site Sub-Soil Class E (Very soft soil site) in accordance with AS1170.4 site classification system. While portions of the site remained with Site Sub-Soil Class D (Deep or soft soil site) where SRA is less than 15 m. Subsequently, two soil profiles, Profile 1 (Class E) and Profile 2 (Class D) were developed for this study and they are shown in Figure 4.

To obtain the small strain shear modulus (G_0) for the site response analysis, V_S measured from SCT was a primary used to develop a V_S profile. To supplement the SCT, different material parameters have been assessed from available and relevant in- situ ground investigation data (notably SPTs, CPTs). A number of published empirical relationships has been used to derive shear wave velocity (V_S) and G_0 from the existing data. Rix & Stokoe (1991), Mayne & Rix (1993) have been used for CPT, Imai & Tonouchi (1982) for SPT. The V_S profile was estimated for two soil profiles are also shown in Figure 4.

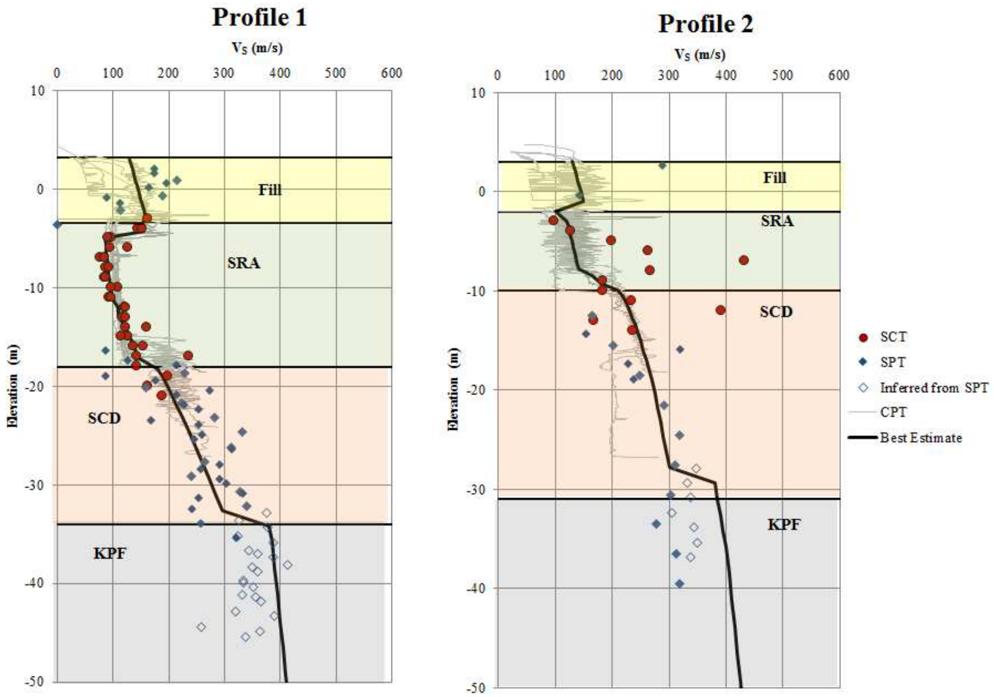

Figure 4: Vs for the two ground profiles. Profile 1 is Class E and Profile 2 is Class D.

It is also noted that the bedrock underlying KPF was not revealed from Geotechnical Investigation data. For the case study, two different depths of bedrock with V_S=760m/s were assumed: (30m below SCD (shallow bedrock) and 80m below SCD (deep bedrock)

Published shear modulus degradation curves were applied for site response analysis. Seed & Idriss (1970) - Upper Bound was used for Fill and SCD and Vucetic & Dobry (1991) was used for SRA.

Results

The results of the three sets of input bedrock motions are shown in Figure 5.

When using AS1170.4 input ground motion (Figure 5i), the surface response of Class D (Profile 2) is higher than AS1170.4 Class D, and AS1170.4 Class E can envelope the surface response of Class E soil. This is largely due to the original bedrock having Vs = 360 m/s, much lower than the 760 m/s input for the site response analysis. The conservatism of the long return period bedrock gives an unrealistic input motion for site response analysis.

When using GA bedrock input motion (Figure 5ii), the surface responses for both Class D and E are significantly lower than AS1170.4 Class D and Class E design spectra.

When using the scaled bedrock spectra (PGA anchored at 0.12 g, Figure 5iii), AS1170.4 Class D can bound Class D soil response at 0.6 to 0.8.s but is higher for lower structural periods which are less than the natural site period. The AS1170.4 Class E soil response is much higher than the site specific results.

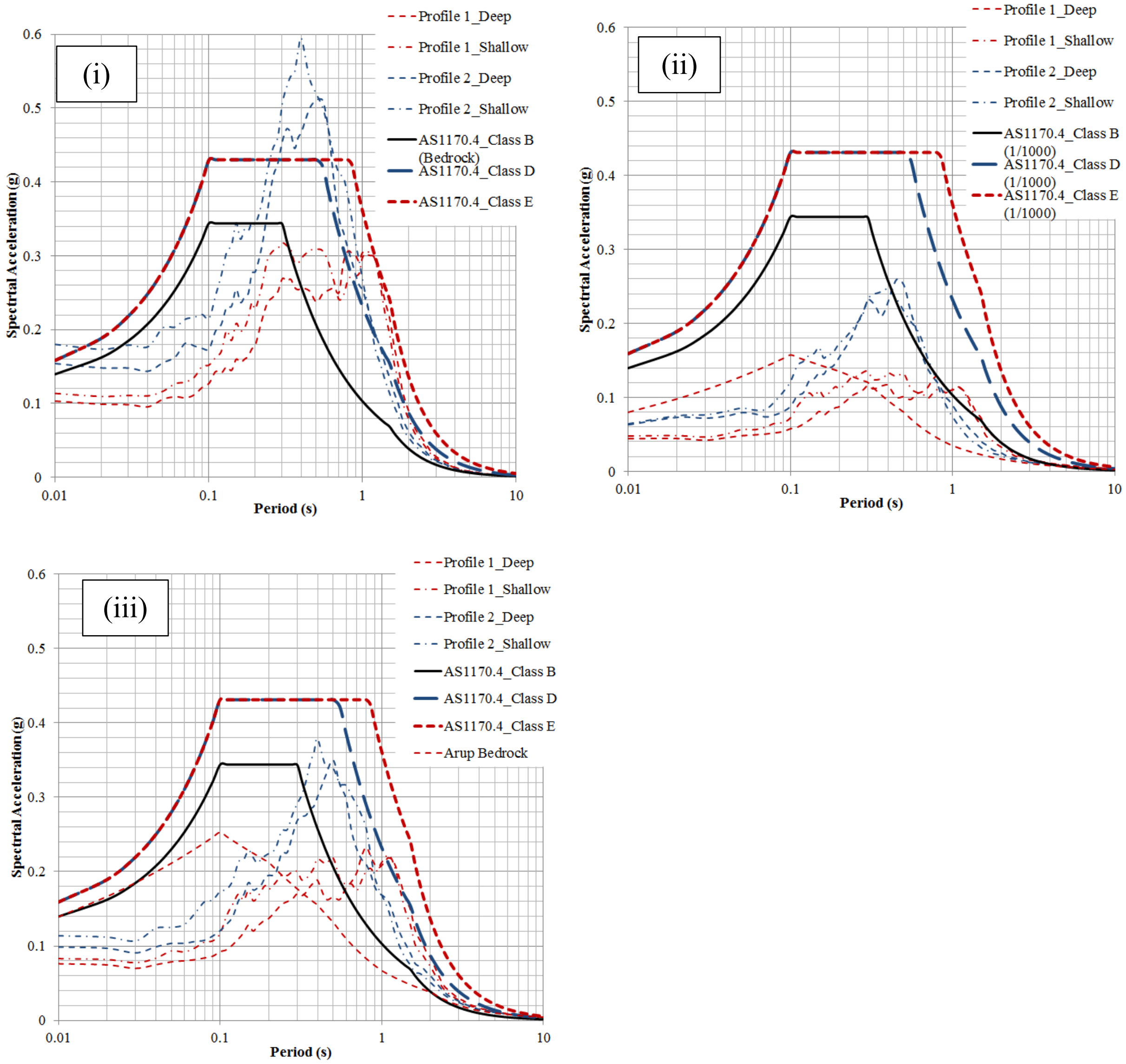

Figure 5: Surface response spectrum of the three sets of input bedrock motion, i) based on the AS1170.4 Class B input spectrum, ii) based on the GA rock spectra and iii) based on the Arup PSHA response spectra having return period of ~3000 years.

Summary and Discussion

When using the rock spectrum (Class B) shown in AS1170.4 to perform site response analysis, the surface response is likely to be overestimated, in particular, for the long structural period. This is because the Class B rock defined as $V_S = 360$ m/s or above, which is much lower than generally defined rock spectrum of 760 m/s in other international and national code (e.g. IBC, ASCE, etc). However, Class A (Hard rock) defined in AS1170 is set to $V_S = 1500$ m/s, which is too high for many types of bedrock for site response analysis. Also, the other spectral periods, in particular for long return periods, defined in AS1170.4 are likely to be over-conservative because they are derived using the ADRS format considering MCE events to construct the response spectral shape.

When using GA rock response spectrum for site response analysis, the surface response is much lower than the spectrum defined in AS1170.4 because the GA bedrock response spectra is generally much lower than AS1170.4 Class B.

It is considered that the response spectrum from GA developed from the PSHA generally provides a better bedrock response spectrum for site response analysis. The major reason is that spectral ordinates of the response spectra were developed by GMPE's directly in the PSHA which gives a more realistic response shape. The response spectrum developed from GA also represents the hazard for a particular ground level (i.e. in terms of different return period). The spectral shape of GA shows that the spectral acceleration attenuates more for the longer structural period than that in AS1170.4. The reduction of spectral acceleration at longer structural periods consequently reduces much of the seismic load applied for the design.

Even when the PGA of AS1170.4 and GA of the bedrock response spectrum are the same (i.e. scaled GA response spectrum), the spectral acceleration of the surface at the higher structural periods is still lower than that in the AS1170.4 spectra due to differences of response spectra shape. As explained above, the spectral shape of GA is more realistic and avoids over-conservatism for a particular ground motion level. When using this scaled response spectra as bedrock motion for site response analysis, the surface response of Class E soil is still lower than Class E spectrum defined in AS1170.4. For Class D soil, the spectral acceleration of surface response spectra can be lower than the AS1170.4 Class D depending on the period of interest.

Given the implication to seismic design in Australia it is considered that further investigation into the differences between the assumptions of AS1170.4 and the 2012 GA model should be undertaken for all capital cities.

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