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EVALUATION OF THE SHAPE OF IEEE-693 RESPONSE SPECTRA FOR SUBDUCTION AND CRUSTAL EARTHQUAKES

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Abstract

Electric equipment qualification is generally based on shake-table tests that use generic response spectra as the target intensity measure for the ground motions used. These response spectra are specified as part of IEEE-693 recommendations and intended to reasonably envelope anticipated earthquakes. The objective of this paper is to investigate the applicability of, and possible adjustments needed for, the IEEE-693 generic response spectra for subduction events. A parametric study of earthquake scenarios demonstrated that the enveloping spectral shapes are dependent on both the event type and the level of intensity of the scenarios. Crustal-event scenarios as well as intra-slab and interface event scenarios were evaluated. The main difference in spectral shape for these types of events was found at the short-period range below one second.

Keywords: Ground Motions; Response Spectra; Subduction

1. Introduction

The IEEE-693 Standards for seismic design of substations recommend a set of target spectra for equipment qualification for electric substations [1]. The objective of the qualification is to secure equipment that will be undamaged with continued operation after being subjected to the shaking.

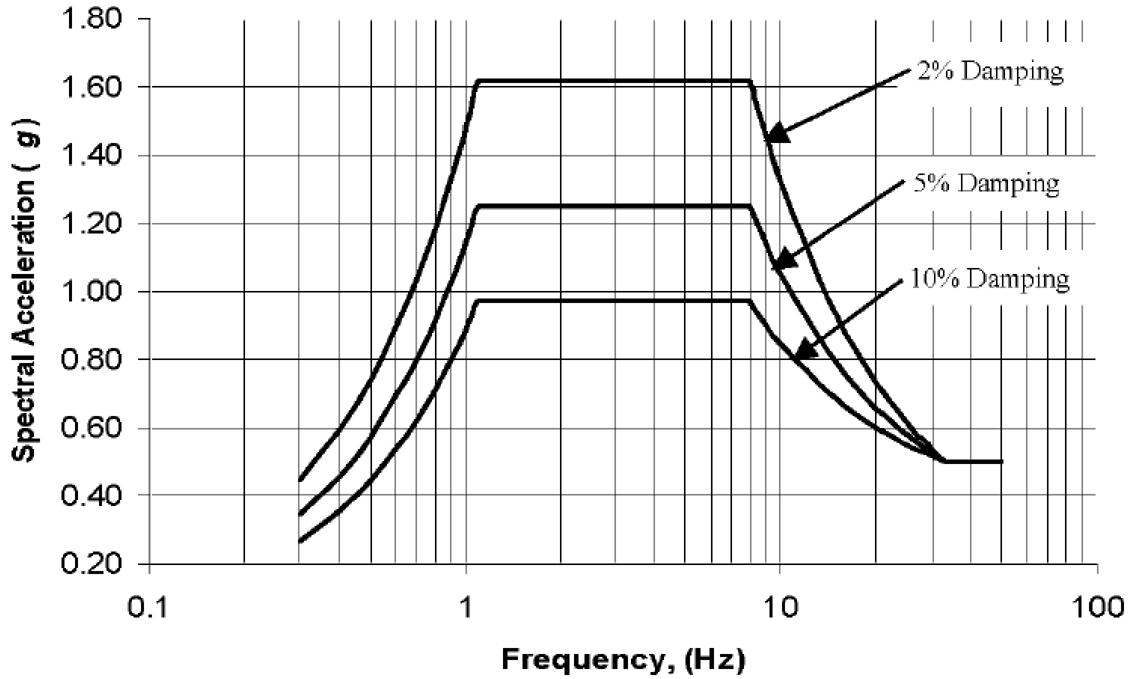
The IEEE-693 target spectra are used to determine the spectra for the ground motions to be used in shake-table testing or analysis of the equipment being qualified. There are two performance levels for qualification: RRS, the Required Response Spectrum, and PL, the Performance Level, which is twice the RRS. Within these two performance levels, there are three seismic qualification levels defined: low, moderate and high. The high and moderate levels are tied to a specified target spectrum for the input motions, while the low seismic qualification level does not require actual testing, but is tied to a set of prescribed requirements. Testing to the moderate level is acceptable only when testing to the high level is not possible, with provisions made in the acceptance criteria. Testing to the moderate level is intended to represent the desire to avoid the possible higher costs associated with designing to the absolute highest level. Which performance level is recommended will also depend on the seismicity of the site, according to Section 8.6.1 of the IEEE-693 document.

According to the IEEE document, the shape of the RRS spectrum is a “broadband response spectrum that attempts to account for the effects of earthquakes in different areas, encompassing magnitude/distance combinations, and considering conditions ranging from rock to soft soil….Although the RRS has taken the above effects into account, it has not been derived by enveloping response spectra from historical earthquakes included in the evaluation. Indeed, the response spectra of many earthquakes exceed the RRS at some frequencies….The RRS shapes bracket most substation site conditions and, in particular, provide longer-period coverage for soft sites.” In addition, “it is the intent of this practice that equipment qualified to one seismic qualification level would remain functional after a seismic event corresponding to a level of shaking twice that actually tested. This level is defined as the Performance Level….This projected performance must be sufficient that equipment qualified to a seismic qualification level would likely perform satisfactorily if it was to be tested to the performance level.”

At the time the broadband RRS spectrum was developed most of the ground-motion modeling was on shallow crustal events. An increased awareness of the high seismic risk in subduction zones has raised the question of whether this broadband spectrum is applicable to subduction-type source. The above description of the RRS spectrum was used in making this assessment through a series of scenario-type of analyses using ground motion models to evaluate the IEEE against these scenarios. The first step in the process was to assess the range and type of crustal scenarios that are represented by the IEEE RRS spectrum. Rather than checking the envelope of the scenarios, the range of scenarios was validated by having the RRS spectrum envelope the 84 percentile of these scenarios (mean + 1 standard deviation). An equivalent set of subduction scenarios was selected, both interface and intraslab. By using ground motion models for subduction, the scenario spectra were compared against the IEEE RRS and PL spectra, both high and moderate levels. Based on the results of this evaluation, a set of period-dependent modification factors are being recommended to modify the RRS high spectrum to be useable for subduction areas. The other levers were validated without needing modification.

2. IEEE-693 Spectra

The IEEE High Required Response Spectrum, with a PGA of 0.5 is shown in Fig. 1. The PL spectrum is computed by doubling the RRS spectral values, with a PGA at 1.0g. The spectrum for the moderate level is half of the high spectrum, with a PGA at 0.25g.



Spectral Accelerations, $S_a(g)$, for Frequencies, f (Hz):

$S_a = 1.144\,\beta f$ for $0.0 \le f \le 1.1$

$S_a = 1.25\,\beta$ for $1.1 \le f \le 8.0$

$S_a = (13.2\,\beta - 5.28)/f - 0.4\,\beta + 0.66$ for $8.0 \le f \le 33$

$S_a = 0.5$ for $f > 33$

$\beta = (3.21 - 0.68\ln(d))/2.1156$, where d is the percent damping (2, 5, 10, etc.) and $d \le 20\%$.

Fig. 1 High Required Response Spectrum, 0.5g

3. Earthquake Scenarios Analyses

After a series of studies of ground-motion models and model-input variability, two sets of earthquakes scenarios were developed, one for the high and one for the moderate levels of the RRS for crustal events. Rather than using earthquake recordings, whose model space is not complete, the 2008 versions of the NGA-West ground-motion prediction equations (GMPEs) were used to compute the spectra for the scenarios [2]. This version of the ground-motion models was selected as it is closer in time to the development of the IEEE spectrum. The 84 percentile spectral accelerations were computed with these ground-motion models, to represent high enough spectral accelerations for the average horizontal component. The distance range for the crustal events, for both high and moderate levels, was set to 10km-30km. This distance range is expected to yield high enough spectral values without needing special near-fault considerations. The magnitude range for the high level for the crustal events was selected to be between 7 and 8.5, while that for the moderate level was selected to be between 5 and 6.5. Only the 5% damping case was considered in the first set of scenarios.

The other variable considered in the scenario study was the site class, represented by the shear-wave velocity, Vs_{30}, in the NGA-West GMPEs. While all site classes needed to be represented, a higher weight needed to assigned to softer sites because they are more common. To achieve this goal, the following set of Vs_{30} was used in the scenario study: 180, 210, 240, 270, 300, 330, 360, 560 and 760 m/sec. As a result, out of 9 scenarios, 7 are in Site Class D, one in Site Class C, and one in Site Class BC. To show the completeness of the selected schenarios, the model space represented by the scenarios is compared to that represented by the NGA-West2 ground-motion database in Fig. 2 [3].

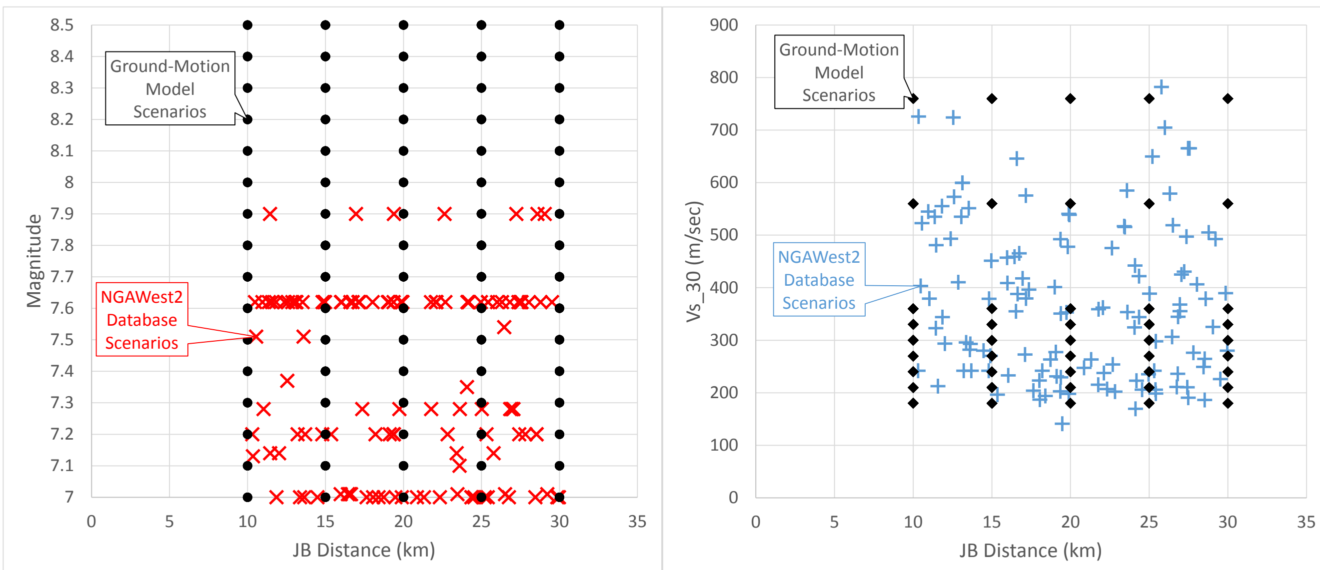


Fig. 2 Model Space for Scenario Analysis. Magnitude, Distance and Shear-Wave Velocity

The 2009 version of the BC-Hydro ground-motion model was used to develop the spectra for the subduction scenarios [4]. Two different source mechanisms, Interface and Intraslab, were considered separately and together in the scenarios. As was done for the crustal scenarios, the 84-percentile spectral accelerations for the average horizontal component were computed using the BC-Hydro ground motion model (mean plus one standard deviation). The horizontal-distance range for the Interface scenarios was set at between 20 and 60km, with a hypocentral depth of 30km. The horizontal-distance range for the Intraslab scenarios was set between 30 and 60km, with a hypocentral depth of 60km. The magnitude range for the high RRS for Interface was set between 8 and 9.3, and 5 to 7.5 for the moderate RRS. The magnitude range for the high RRS for Intraslab was set between 7 and 8, and between 5 and 6.5 for the moderate RRS. The same set of weighted site-classes as the crustal scenarios was used for the subduction events.

The 84-percentile spectra were computed for the entire model space of varying magnitude, distance, site class, and source mechanism (all other variables were kept constant). Statistics on these spectra were then performed to compute the mean and mean+- one standard deviation of these scenario spectra. These statistical values were then compared to the IEEE spectra. While magnitude and distance are expected to affect the overall amplitude of the spectra, the results from the different site classes were evaluated separately and together.

The effect on the spectral shape due to source type and site class is shown in Fig 3 and Fig. 4. Each figure has four graphs for the sets of scenarios for the High RRS. The first graph consists of the scenarios from the crustal events. The second graph in the first row consists of the scenarios from all subduction sources -- Interface and Intraslab combined. The graphs in the bottom row of each figure separate the two different types of subduction sources. The mean and mean +- one standard deviation of the scenarios are plotted on top of the scenarios lines, as are the high RRS and high PL. Limitations in the plotting program only allow to show 200 scenario lines. The statistics, however, are performed on all scenarios. A comparison of the two figures shows the effect of site class on the overall spectral shapes – softer soils sites have a higher energy content in the long-period range, as expected. A comparison of the spectra for the different sources in both figures show the effect of source model on the spectral shapes, and how these spectral shapes compare with the IEEE spectra. When looking at the crustal events, it is evident that the RRS spectrum envelopes the 84 percentile of the combination of different site classes. This is most evident in Fig. 5, where the weighted set of site classes was used. This result is as expected since the scenarios were chosen to achieve this, even though these scenarios are, indeed, representative of a high-seismicity area not in the near field.

As shown in the figures, the spectral shapes of the individual subduction sources and of the combination of these sources is significant enough that the IEEE High RRS falls below the mean of the scenario in all cases in the short-period range, as well as part of the moderate-period range. For the Moderate level of the RRS, on the other hand, the IEEE spectrum envelopes both crustal and subduction scenarios, as shown in Fig. 6.

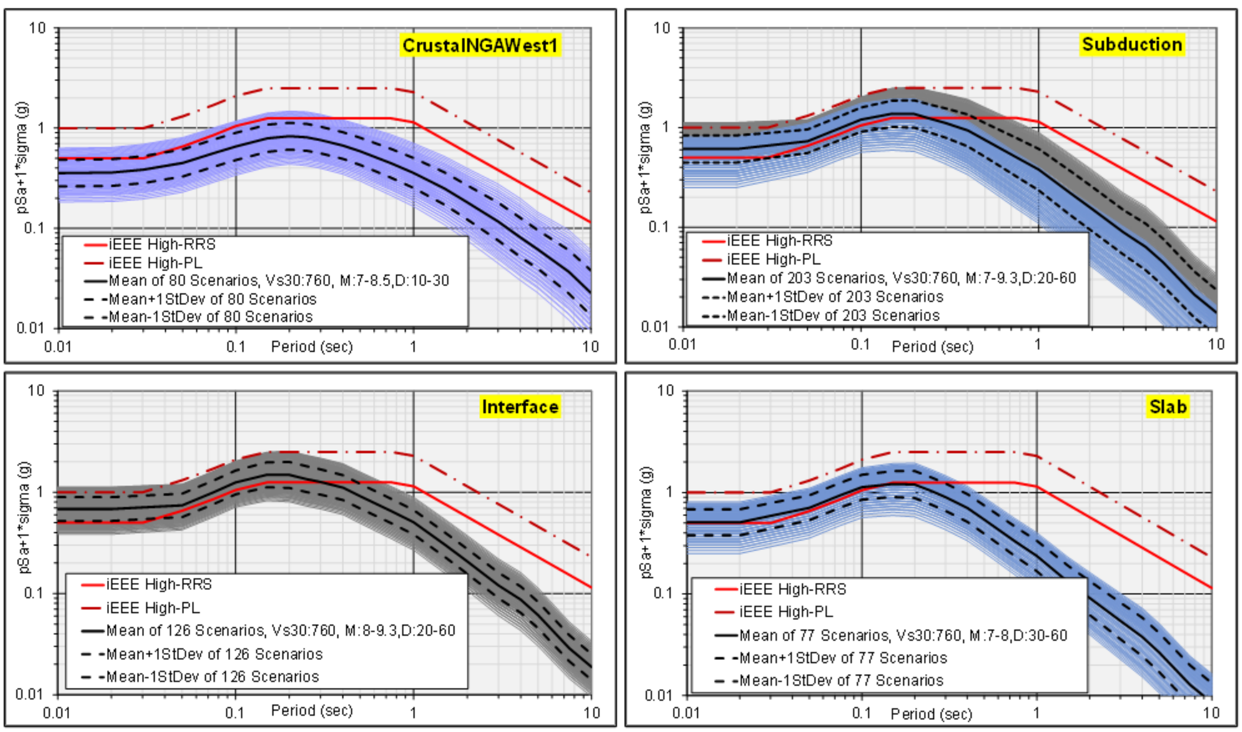


Fig 3. Scenario Spectra for Vs_{30}=760 m/sec, High RRS (only 200 scenarios are plotted)

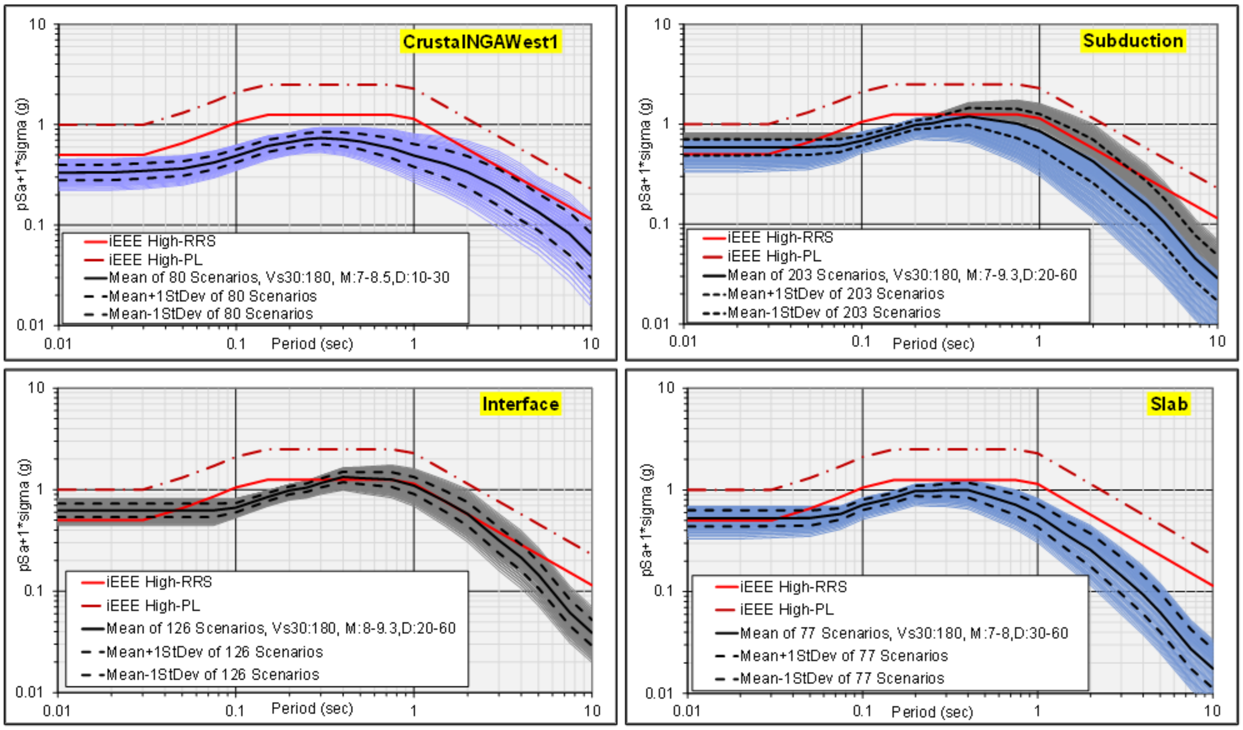


Fig. 4 Scenario Spectra, Vs_{30}=180m/sec, High RRS (only 200 scenarios are plotted)

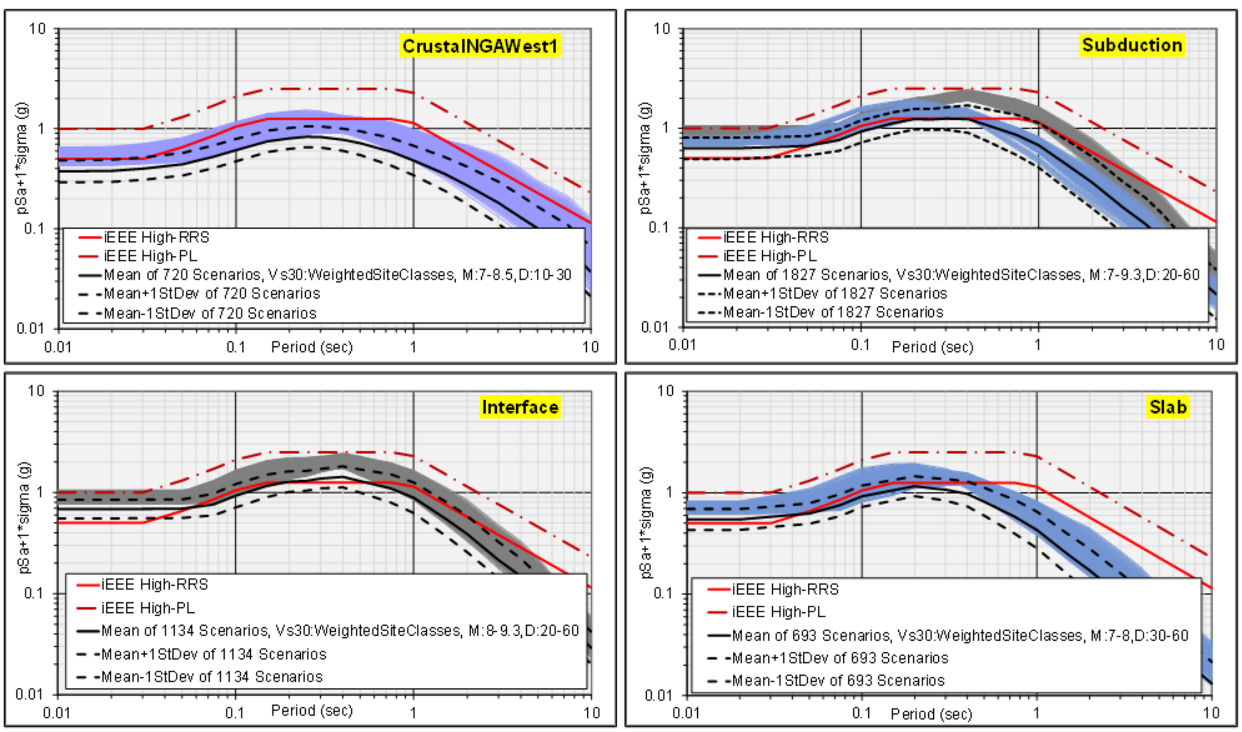


Fig. 5. Scenario Spectra, Weighted Vs_{30}, High RRS (only 200 scenarios are plotted)

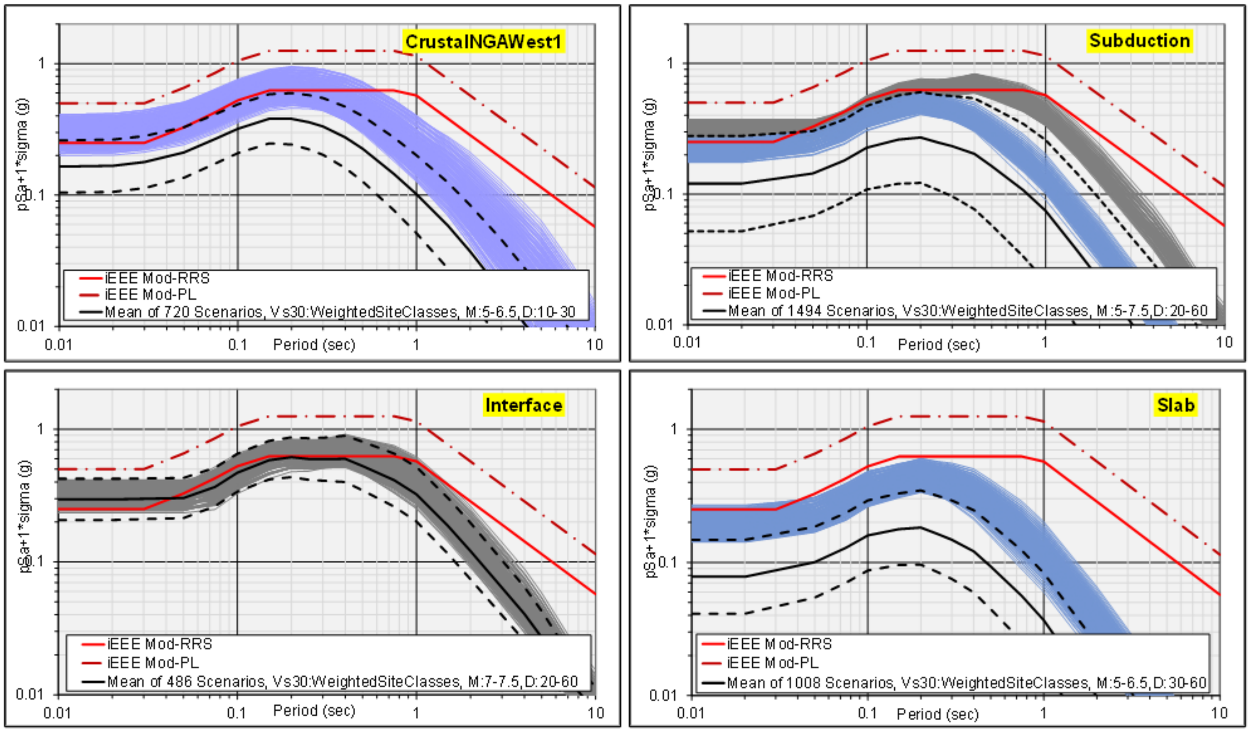


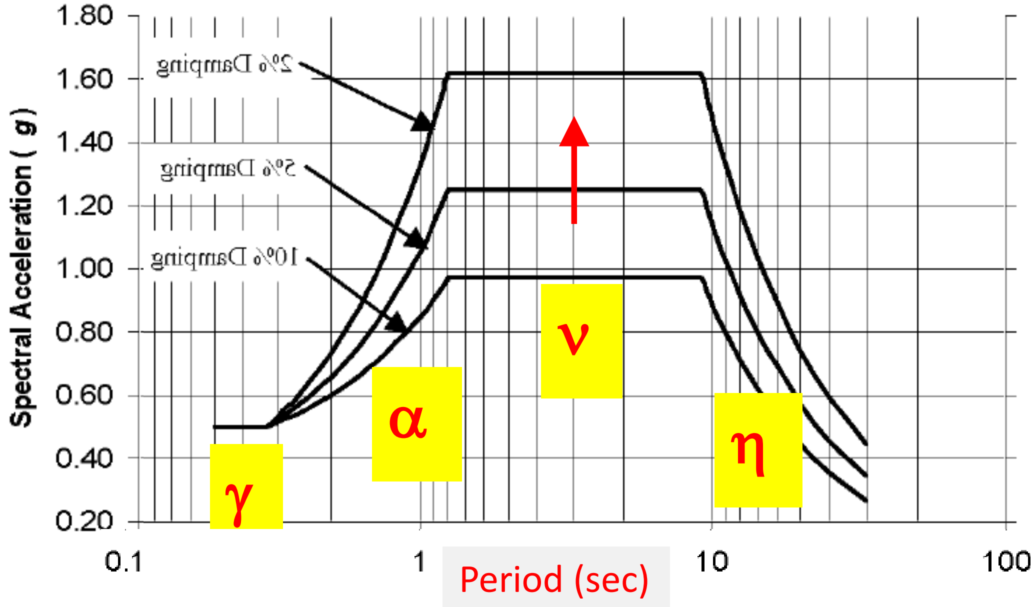
Fig. 6. Scenario Spectra, Weighted Vs_{30}, Moderate RRS (only 200 scenarios are plotted)

4. Proposed Modification to High RRS

To maintain the same margin between the IEEE spectrum and the scenario spectra, enveloping the 84 percentile of the scenarios, the data indicate a need to modify the IEEE spectrum in the short/moderate period range to account for subduction sources. Because the IEEE spectrum is defined by four segments in different period ranges, changing the spectral shape of the IEEE spectrum can be done effectively by applying different amplification factors to these regions in the IEEE equations, as shown in Fig. 7. The amplification factors are given in Table 1. As is shown in the table, even though it is not by the same margin, the IEEE High PL and moderate RRS and PL, spectra envelope the scenarios with an acceptable margin.

Table 1 Recommended IEEE Spectrum Modification Factors

Source	Perf Level	γ	α	ν	η
Subduction	High-RRS	1.65	1.65	1.5	1.25
Subduction	High-PL	1	1	1	1
Subduction	Mod-RRS	1	1	1	1
Subduction	Mod-PL	1	1	1	1
Crustal	all	1	1	1	1



Spectral Accelerations, $S_a(g)$, for Frequencies, f (Hz):

$S_a = 1.144\,\beta f *\eta$	for $0.0 \le f \le 1.1$
$S_a = 1.25\,\beta *\nu$	for $1.1 \le f \le 8.0$
$S_a = [(13.2\,\beta - 5.28)/f - 0.4\,\beta + 0.66]*\alpha$	for $8.0 \le f \le 33$
$S_a = 0.5*\gamma$	for $f > 33$

$\beta = (3.21 - 0.68\ln(d))/2.1156$, where d is the percent damping (2, 5, 10, etc.) and $d \le 20\%$.

Fig. 7. Modification of IEEE High RRS Spectrum

The recommended IEEE spectra, which implement the recommended amplification factors, are compared to the scenario spectra in Fig. 8 for both crustal and subduction sources, as well as for the High and Moderate levels, separately. This comparison is for the 5%-damped case.

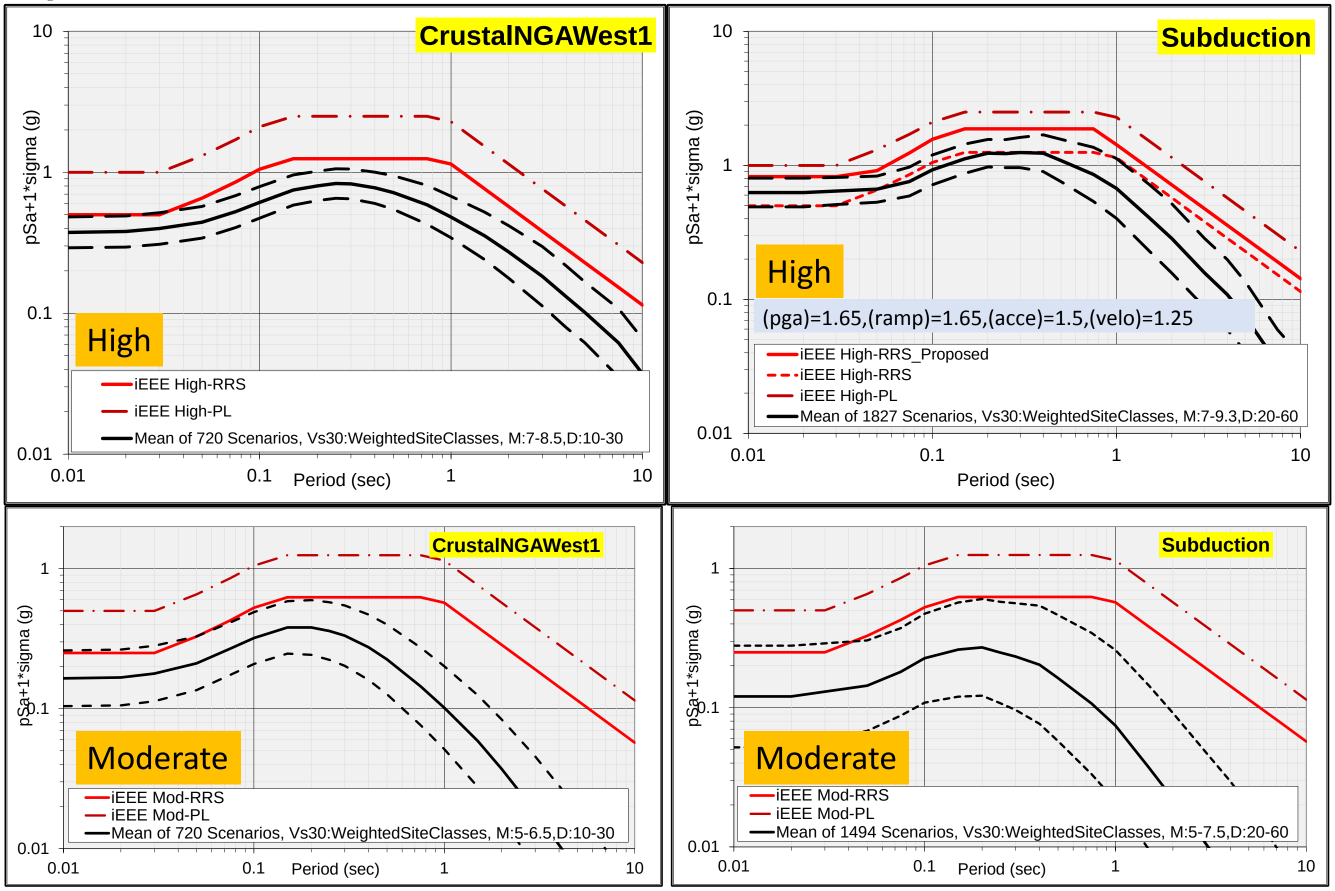


Fig. 8. Recommended IEEE Spectra for Crustal and Subduction Sources, Weighted Site Classes

5. Damping other than 5%

As shown in Fig. 1, the IEEE spectrum has an additional factor, β, to account for damping. This factor is equal to one for 5% damping. The damping to be used with the ground-motion model is based on a study by Razeian, et al. in 2012 [5]. This damping model is both magnitude and distance dependent, and, thus, needs to be implemented at the computation of the individual scenario spectra. This damping model was used for both crustal and subduction scenarios. The damping ratios of interest, other than 5%, are 2%, 10% and 20% -- the limit of applicability of the IEEE model.

To validate the proposed model for all damping ratios, the scenarios spectra were recomputed for these damping ratios and the mean and 16/84 percentile of the spectra were computed for all seismic sources and scenarios and were compared to the corresponding IEEE spectra, including the proposed amplification of the High RRS spectrum. The recommended IEEE and scenario spectra for the additional damping ratios are shown in Fig. 9. As the figures demonstrate, no additional damping-depended modification to the IEEE spectrum is required. The proposed modification to only the High RRS is sufficient for all damping ratios. Results similar to those for the High level were found, but not shown here, for the Moderate level.

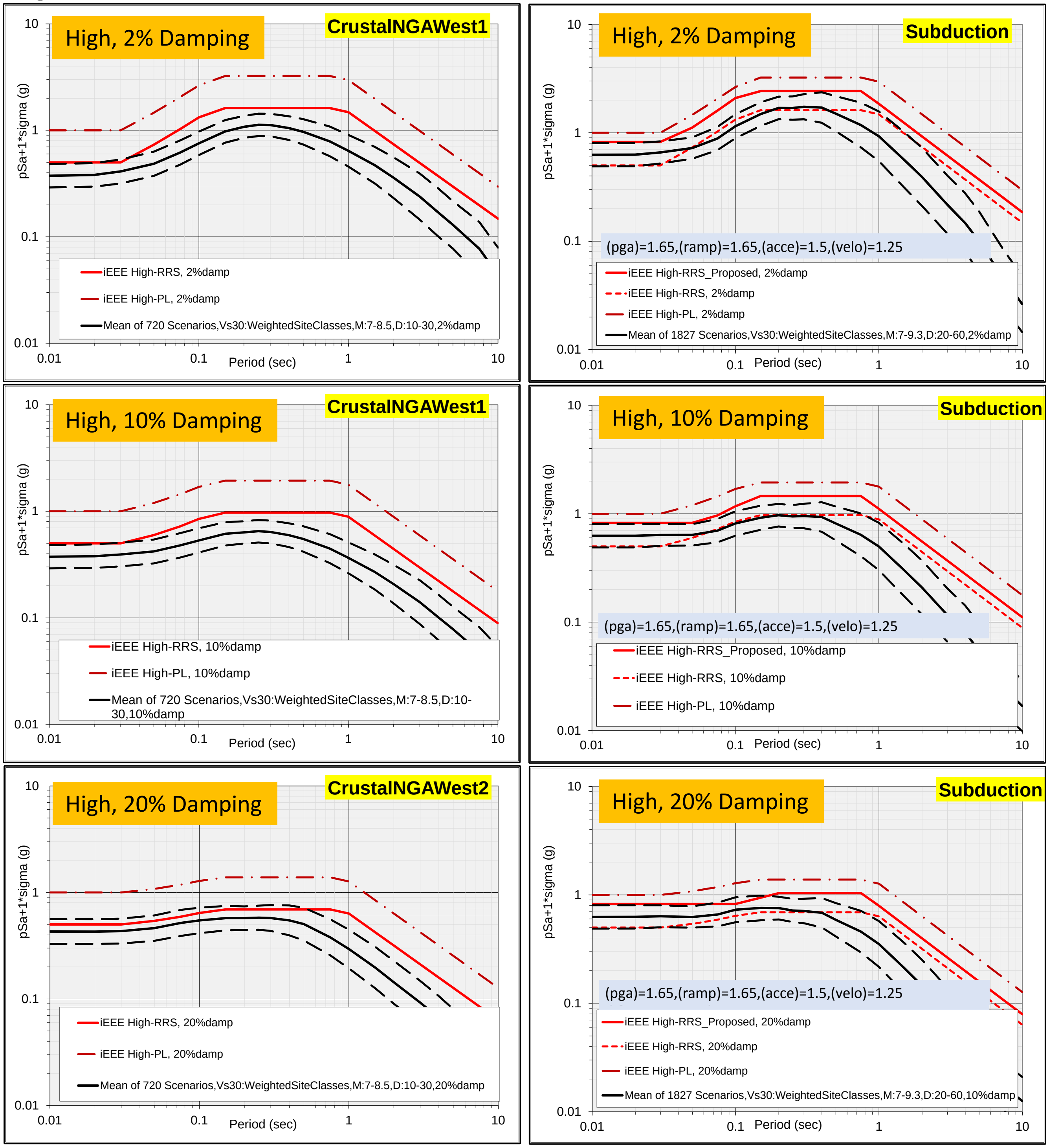


Fig. 9. Scenario Spectra for Damping Other than 5%, Weighted Site Classes, High Level

7. Summary and Conclusions

Even though they are broadband spectra, the IEEE required response spectra for equipment qualification were originally developed for crustal event. Through a rigorous parametric scenarios study of magnitude, distance, site class, and source mechanism, the study presented in this paper validated the IEEE spectra for crustal events and developed a proposed modification to the IEEE spectra to account for the different spectrum shape of subduction events. The study demonstrated that this modification is only necessary for the High level of the RRS, with no modification necessary for the Performance Level, high or moderate, and the moderate RRS.

The proposed modification consists of applying additional factors to the IEEE equations for computing the spectra. The amplification factors are 1.65 for the frequencies above 8 Hz, 1.5 for frequencies between 1.1 and 8 Hz and 1.25 for frequencies below 1.1 Hz. The highest amplification is in the short-period/high-frequency range, as predicted by the ground motion models.

The study presented in this paper has validated the proposed model for damping ratios other than 5%, such as 2%, 10% and 20%. No additional modification is required to account for the variation in damping.

8. References

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