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COMPARISON OF APPROACHES FOR SELECTING AND ADJUSTING TIME HISTORIES TO BE USED IN SEISMIC FRAGILITY ANALYSES

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ABSTRACT

Modern probabilistic seismic fragility analyses used for probabilistic safety assessments of important or critical installations make use of multiple time histories for the structural response evaluation. Usually, the input for this evaluation is based on a site-specific Seismic Hazard Assessment (SHA) and the resulting hazard curves or the corresponding Uniform Hazard Spectra (UHS) for different annual return periods. The focus of this paper is to study the statistical stability of the structural response results when using different approaches for matching the statistical properties of the imposed response spectra, as defined by the hazard results. The case of the generation of artificial ground motions is not covered in this contribution. Today, usually around 30 time histories for the annual return period or UHS of interest are used for a probabilistic assessment. The selection process of the time histories is often based on picking time histories from databases of recorded ground motions. The time histories are supposed to be consistent with the hazard disaggregation, thus with magnitude, distance, soil conditions, duration, etc. Furthermore, the amplitude and frequency content are an important measure which needs sometimes to be adjusted to comply with the hazard and regulatory requirements. For this, various techniques (e.g. spectral matching) have been used and already discussed in the past. To study the statistical stability of the structural response results when using different approaches for matching the statistical properties of the imposed response spectra, three cases, for a representative structure, are investigated and compared among them and to a fourth base case. There is no unique solution to the problem of selecting or defining the time histories to be used for the structural simulation. Nevertheless, this contribution shall help to better understand the differences and consequences of some common approaches.

Keywords: PSHA, UHS, Fragility, Probabilistic, Time History, Soil-Structure Interaction

INTRODUCTION

Modern probabilistic seismic fragility analyses used for probabilistic safety assessments of important or critical installations make use of multiple time histories for the structural response evaluation (EPRI 1994, 2009). Usually, the input for this evaluation is based on a site-specific Seismic Hazard Assessment (SHA) and the resulting hazard curves or the corresponding Uniform Hazard Spectra (UHS) for different annual return periods. The definition or selection of the hazard consistent time histories is the natural hand over from seismology to the engineering community. More and more this transition is fluent as both groups have started to interact with and challenge each other in order to understand the nature of the provided information and the implicit assumptions or boundary conditions behind.

Today, usually around 30 time histories for the annual return period or UHS of interest are used for a probabilistic analysis. In case a soil-structure interaction (SSI) analysis is required - which is often the case for an important lifeline like a bridge or a critical installation like a nuclear power plant - strain

compatible soil profiles need to be considered. These strain-compatible soil profiles are dependent on the time history amplitude and frequency content. To perform a probabilistic analysis of a structure, the time histories are combined with a randomization of the soil profiles and soil material properties, as well as a randomization of the structural properties of the assessed structure. Practical implication issues of this process, like double counting of uncertainties, are discussed in the following. The selection process of the time histories is often based on picking time histories from databases of recorded ground motions. The time histories are supposed to be consistent with the hazard disaggregation. Thus, with magnitude, distance, soil conditions, duration, etc. Furthermore, the amplitude and frequency content are an important measure which needs sometimes to be adjusted to comply with the hazard and regulatory requirements. For this, various techniques (e.g. spectral matching) have been used and already discussed in the past.

To study the statistical stability of the structural response results when using different approaches for matching the statistical properties of the imposed response spectra, three cases, for a representative structure, are investigated and compared among them and to a fourth base case: 1) a set of time histories which spectral mean is consistent with and tightly matched to the mean UHS. The representation of the ground motion variability for different fractiles is introduced at the level of the structural response; 2) a set of time histories which spectral distribution covers the range of fractiles of the hazard based UHS, but still having a consistent mean corresponding to the mean UHS. In this case the ground motion variability is part of the input already; 3) a different set of selected time histories than the case 2). The results from the analyses with these three sets of time histories will be compared to the results of a base case. The base case time histories will be selected based on the conditional mean spectrum concept for which the UHS is divided in two or three realistic response spectra conditioned for different frequency ranges, but still reproducing approximately the original mean UHS.

This paper is a continuation of previous work (Renault & Kurmann, 2013 and Renault et al., 2015), which compared the UHS to the conditional mean spectrum and conditional spectra approach (Abrahamson, N. A., Al Atik, L., 2010).

Seismic Hazard Assessment

The PEGASOS Project, a new state-of-the-art probabilistic seismic hazard assessment (PSHA) for the nuclear power plant sites in Switzerland, was carried out from 2000 to 2004. The quantification of the epistemic uncertainty and aleatory variability in seismic hazard at the four Swiss nuclear power plant sites was the key aspect of the PEGASOS Project. After the completion of the project, the Swiss utilities decided to perform a refinement of the study by collecting additional data and using new advances in earthquake science, especially in the field of ground motion modelling, to further reduce the identified epistemic uncertainties by their more realistic quantification. The PEGASOS Refinement Project (PRP) started in 2008 and was completed in 2013. An overview of the different components of the project and the approaches used are documented in the project reports (swissnuclear, 2013). An important aspect of the ground motion characterization that had a significant impact on the PSHA results and associated uncertainties is the adjustment of ground motion prediction equations to make them applicable to the site conditions in the study region.

Seismic Risk Assessment

A Seismic Probabilistic Risk Assessment (S-PRA) (EPRI, 2003) is a multi-disciplinary activity combining the inputs and experience of different specialized domain disciplines, such as seismic hazard analysis, seismic fragility evaluation and system analysis, under the umbrella of risk or safety analysis, respectively. Thus, there are a lot of interfaces and it is important to translate the various boundary conditions and assumptions between the experts. A Nuclear Power Plant (NPP) S-PRA aims at estimating the probability of occurrence of different sizes of earthquakes that may affect an NPP and assesses the NPP response due to those earthquakes. The results of the assessment are presented in terms of seismically induced Core Damage Frequency (CDF) and Large Early Release Frequency (LERF).

All the analyses carried out in S-PRA are affected by uncertainties: in general, these can be categorized as either aleatory variability or epistemic uncertainty (e.g. EPRI, 2004). Aleatory variability covers the randomness of observable events and thus, is implicitly irreducible. Epistemic uncertainty represents our lack of knowledge to specify parameters or the right models to reproduce the real world. The latter uncertainties can theoretically be reduced by data collection and improvement of the models.

The American Nuclear Society has developed a national standard (AMSE/ANS, 2007, 2009) which provides requirements of three capability categories for conducting S-PRA: Capability Category I can rely on generic or regional mean seismic hazard estimates and only a calculation of the mean CDF. Capability Category II requires a more thorough seismic hazard analysis and a full uncertainty analysis of the risk quantification. This means the seismic hazard is considered by using the median and fractile hazard curves. Capability Category III follows along the lines of the Seismic Safety Margin Research Program. In most practical cases, a calculation of the mean CDF (Capability Category I) is accepted to determine any changes in risk or in addressing generic safety issues in the US regulatory framework (NRC, 2009). For example, only a mean CDF estimate is required in IPEEE (Individual Plant Examinations of External Events) and, therefore, almost all of the IPEEE S-PRA submittals only comply with this requirement.

SOIL AND STRUCTURAL MODEL

The study has been performed on a nuclear building of an existing NPP. The structural model as well as the soil model, part of the SSI, are described in the next sections.

Soil Model

The strain compatible median soil profile used for this building is listed in Table 1. These soil properties are maintained constant for all analyses.

Table 1. Strain Compatible Median Soil Profile. The layer 1* and 2* are representing the embedment.

Layer	Thickness [m]	Density		Damp. Ratio	G	Vs	Vp	Vp/Vs
		[mN/m^3]	[kg/m^3]		[kN/m^2]	[m/s]	[m/s]	
1*	2.5750	22.05	2250.00	0.052	176,551,232	280.12	1260.55	4.50
2*	2.8000	22.05	2250.00	0.084	154,555,128	262.09	1179.40	4.50
3	1.3600	21.07	2150.00	0.079	199,571,189	304.67	1096.79	3.60
4	2.0000	24.50	2500.00	0.037	244,234,384	312.56	1187.75	3.80
5	3.0000	24.50	2500.00	0.038	257,490,162	320.93	1219.52	3.80
6	3.0000	24.50	2500.00	0.039	312,971,481	353.82	1344.50	3.80
7	3.0000	24.50	2500.00	0.039	652,598,116	510.92	1941.50	3.80
8	3.0000	24.50	2500.00	0.033	735,955,512	542.57	2061.77	3.80
9	4.0000	24.50	2500.00	0.032	773,062,416	556.08	2113.09	3.80
10	4.0000	24.50	2500.00	0.033	810,227,760	569.29	2163.29	3.80
11	4.0000	24.50	2500.00	0.033	851,676,672	583.67	2217.96	3.80
12	5.0000	24.50	2500.00	0.034	902,011,122	600.67	2282.53	3.80
13	5.0000	24.50	2500.00	0.034	952,926,030	617.39	2346.07	3.80
14	5.0000	24.50	2500.00	0.034	1,005,714,369	634.26	2410.20	3.80
15	6.0000	24.50	2500.00	0.034	1,063,901,306	652.35	2478.92	3.80

16	6.0000	24.50	2500.00	0.035	1,482,635,025	770.10	2926.36	3.80
17	6.0000	24.50	2500.00	0.033	4,887,967,396	1398.28	2796.56	2.00
18	4.0000	24.50	2500.00	0.025	5,604,693,360	1497.29	2994.58	2.00
19	6.0000	25.97	2650.00	0.025	6,772,302,647	1598.62	3197.23	2.00
20	10.0000	25.97	2650.00	0.010	4,470,786,524	1298.88	2597.75	2.00
21	10.0000	25.97	2650.00	0.010	3,809,388,466	1198.96	2397.93	2.00
Halfspace		25.97	2650.00	.0100	10,600,000,000	2000.00	3600.00	1.80

Structural Model

The building foundation is embedded (elevation 321.200 m to 326.575 m). The 5.375 m embedment was considered for the SASSI analysis. The number of interaction nodes (structural nodes in contact with the soil) is 376. The main structural properties of this are:

Concrete Young's Modulus E = 3.5x107 KN/m^2,
Poisson's Ratio = 0.17,
Damping Ratio = 0.07.

These structural properties are maintained constant for all the analyses.

The main frequencies are 14.21 Hz in the X-direction and 10.66 Hz in the Y-direction and greater than 29.79 Hz in the Z-Direction.

Its system of coordinates is oriented as follows:

X = East-West direction (X positive in the East direction),
Y = North-South direction (Y positive in the North direction),
Z = Vertical direction (Z positive upward).

Figure 1 shows a general view of the emergency (Notstand) building. The building was already assessed in the past (Tinic et al., 2007) and used for other comparative hazard studies (Renault & Kurmann (2013), Renault et al. (2015).

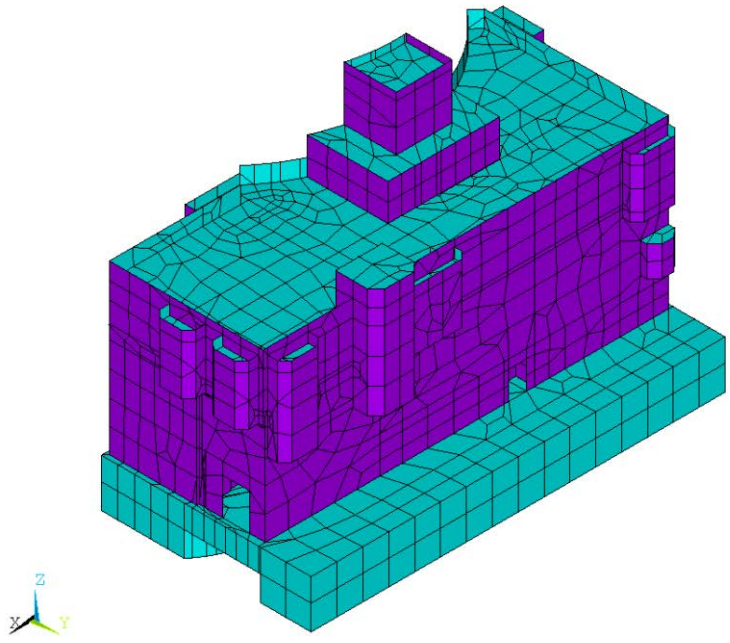

Figure 1. General view of the FEM model of the NOTSTAND building.

INPUT MOTIONS

All time history sets used for this study are based on the latest Swiss seismic hazard curves (ENSI, 2015) and were developed by swissnuclear in the framework of the post-PRP phase. The purpose of this study is to compare the effects of possible different engineering choices on how to use hazard consistent ground motions for the risk assessment of a structure. The target UHS used here is the spectrum for an annual probability of exceedance (APE) of 1E-4 and as the spectral shape is very similar, it is assumed that it is representative also for the other relevant APE levels. For the sake of inter-comparability, the time histories and associated response spectra are all targeted to represent the mean UHS. This would also be the choice for a Capability Category I S-PRA. Furthermore, in the framework of deterministic assessments and for design purposes, usually also the mean is the target. Nevertheless, if a full S-PRA is required the median UHS should be the target and all associated fractiles will be used.

The sets are defined as follows:

- Set 1: time histories which spectral mean is consistent with and tightly matched to the mean UHS.
- Set 2.1: time histories which spectral distribution covers the range of fractiles of the hazard based UHS, but still having a consistent mean corresponding to the mean UHS.
- Set 2.2: a different set of selected 30 time histories than the Set 2.1.
- Set 3: time histories based on the conditional mean spectrum (CMS) concept for which the UHS is divided in two realistic response spectra conditioned for different frequency ranges, but still reproducing approximately the original mean UHS.
- Set 4: same set of time histories as for Set 3, based on the conditional mean spectrum concept, but with the two time history sets tightly matched to the two CMS.

In this study, only real, recorded earthquake ground motions have been used. The magnitude and distance distribution of the seed time history sets is shown in Figure 2. Depending on the set, unmodified in spectral content or for the other cases modified in spectral content by applying spectral matching according to Abrahamson (1992). Other studies have been using synthetic records as input motion (e.g. Zentner, 2014), but the discussion if recorded or synthetic motions are better is beyond the scope of this paper.

From a seismological point of view all those time histories are appropriate, as they are consistent with the hazard and their statistics represent the requested mean (or median) and associated fractiles of the UHS. But from the engineering point of view the robustness of the structural response is important and the statistical stability of the end result might be influenced on the choice of the input motions – which is usually based on expert judgement.

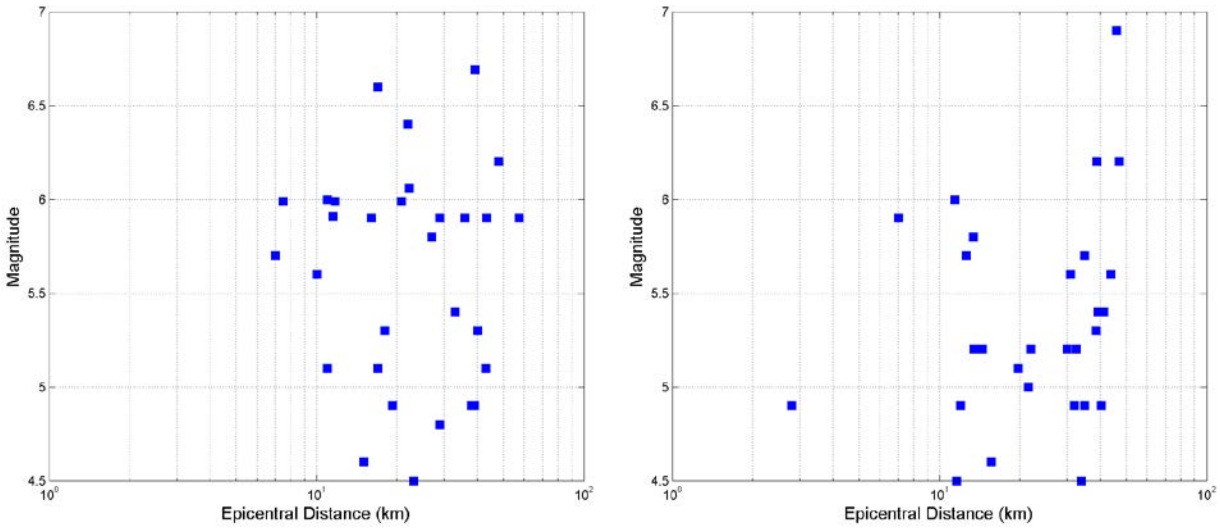

Figure 2. Magnitude and distance distribution of selected time histories. For Set 1, 2.1, 3@5 Hz (left) and Set 2.2, 3@20 Hz (right).

SSI time history Set 1 – ASCE 4-16, Method 1

The first set of 30 time histories has been selected and developed so that the geometric mean of the two horizontal components and the vertical component tightly match the horizontal and vertical mean UHS, respectively. For the two horizontal components a specific directional variability is enforced. When using those time histories, the representation of the ground motion variability for different fractiles must be introduced at the level of the risk assessment, as it is not part of the variability represented by the used time history records. Thus, here only the mean structural response is going to be compared to the other approaches and it is assumed that the distribution of the ground motion variability around the mean UHS is added later on. ASCE 4-16 is calling this approach "Method 1" (see ASCE 4-16, Section 5.5.4.1 a): "*In Method 1, the N acceleration time series sets are conditioned such that they closely match the target control motion (FIRS or free surface motion) as an ensemble (Reed and Kennedy 1993). The horizontal motions are conditioned to minimize the peak-and-valley random variability, because that variability is already considered in the development of the seismic hazard.*"
Figure 3 shows the three individual input motions and Figure 4 shows their comparison to the target UHS.

It should be noted that even if the geometrical mean of the two horizontal components is tightly matched to the mean UHS, the response spectra of the individual two horizontal components have a variability comparable with the range of the 16% to 84% fractile and also similar to the time histories developed for Set 2, as each component includes the component-to-component (directionality) variability.

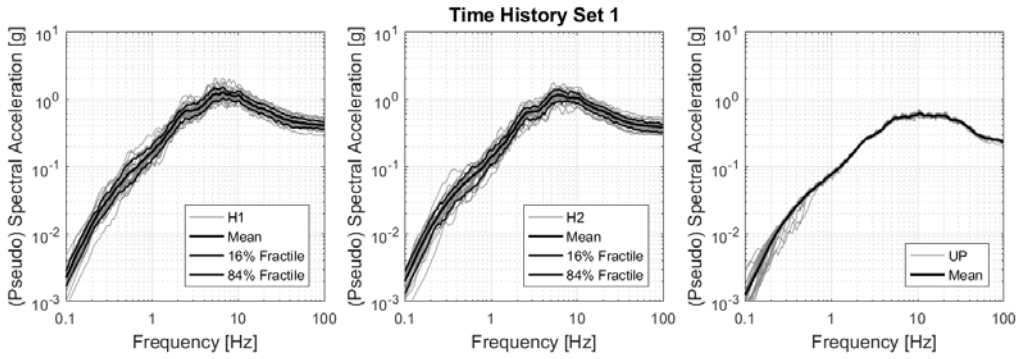

Figure 3. All three components of the time history Set 1 and their mean and fractiles for each component.

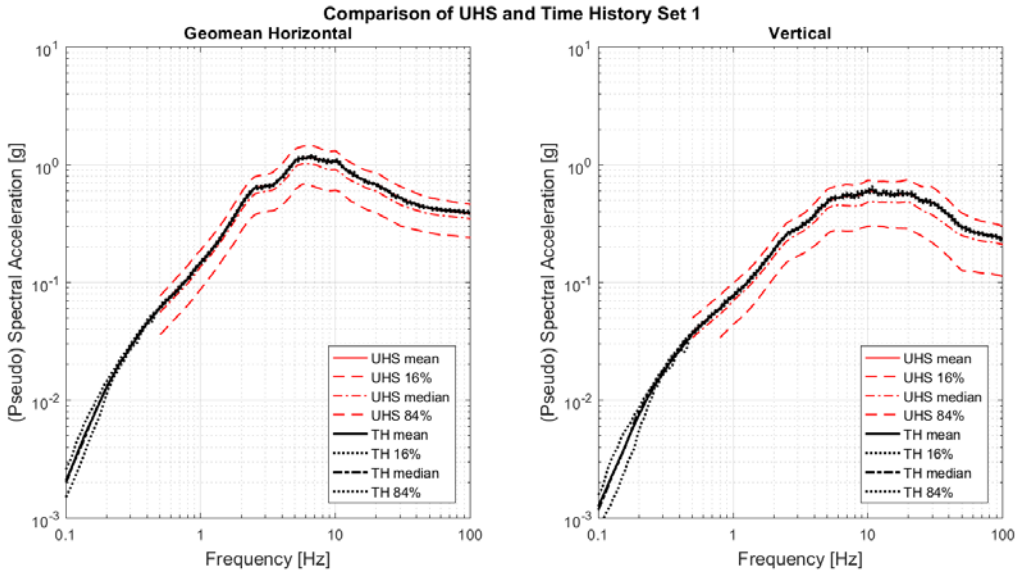

Figure 4. Comparison of target UHS for an APE of 1E-4 and time history Set 1.

SSI time history Set 2 – ASCE 4-16, Method 2

The time histories of the second set have a distribution that covers the range of the fractiles (16-84%) of the hazard based UHS at 1E-4, but still having a consistent mean corresponding to the mean UHS. In this case the ground motion variability is part of the input motion already and does not need to be included in the SSI analysis or risk assessment.

ASCE 4-16 is calling this approach "Method 2" (see ASCE 4-16, Section 5.5.4.1 b): "*Method 2 is based on the idealization* of the probabilistic input response spectrum by an ensemble of randomized variable shape spectrum realizations (Ghiocel and Ghanem 2002; Ghiocel 1998). This implies that the statistical correlation between the spectral amplitudes at different frequencies is included. Method 2 is applicable when information on the randomized spectral shape variation is available either from a set of acceleration records or from a set of randomized realizations of variable shape spectra computed during the probabilistic site response analysis."

The description of Method 2 in ASCE 4-16 implies that synthetic motions are used, as it requires randomized spectral shapes which achieve rigorous statistical correlation between amplitudes at different frequencies. Nevertheless, the authors believe that recorded ground motions ought to be permitted as well for developing a larger ensemble of ground motions.

As for the sake of simplicity the same SSI input files were used, the soil model as already used for the Set 1 evaluation was considered. As the UHS at soil surface inherently includes the variability of the soil on top of the variability of the rock ground motion, the range of UHS fractiles to be covered can be reduced to remove the portion due to the soil variability. In order to avoid double counting the range of fractiles for the target spectra were reduced by the values provided in Table 2. The spectral range reduction to avoid double counting of the soil uncertainties is based on the ratios of the rock and soil surface UHS fractiles at 1E-4. The negative values, leading to an increased distribution compared to the original for the horizontal high frequency range were kept, as the soil amplification lead to these results and were used in the probabilistic hazard assessment.

Table 2. Reduction factors for range of response spectra and modified spectral ordinates for the 16th and 84th fractile to avoid double counting of variability.

	Horizontal				Vertical			
Freq [Hz]	Lower Reduction	Upper Reduction	Reduced 16%-Fractile [g]	Reduced 84%-Fractile [g]	Lower Reduction	Upper Reduction	Reduced 16%-Fractile [g]	Reduced 84%-Fractile [g]
0.5	3.7%	1.5%	0.0373	0.0758	n.a.	3.5%	n.a.	0.0483
1	7.3%	7.6%	0.0944	0.1745	-0.1%	6.1%	0.0440	0.0930
2.5	7.5%	8.1%	0.4011	0.7247	0.1%	6.8%	0.1491	0.2982
5	4.8%	7.9%	0.6463	1.2479	11.1%	8.1%	0.2877	0.5679
10	-0.3%	4.3%	0.6052	1.2579	7.1%	6.3%	0.3213	0.6922
20	-2.1%	2.1%	0.3829	0.8404	3.7%	2.7%	0.2976	0.7314
33	-5.0%	0.7%	0.2794	0.6233	8.9%	15.6%	0.2177	0.5029
50	2.1%	-2.1%	0.2686	0.5350	32.7%	9.5%	0.1672	0.3503
100	0.9%	-0.5%	0.2432	0.4633	21.3%	3.9%	0.1371	0.2894

The 30 time histories are based the same seed time histories as Set 1, but were modified to fit the ground motion distribution defined by the hazard curves. The Fourier's amplitude of each of the time histories is modified using an iterative process such that, at each frequency, the mean (or median) and the standard deviation (or 84% fractile) of the acceleration response spectra of the ensemble of time histories matches the mean (or median) and the standard deviation (or 84% fractile) of the target UHS.

In order to assess the dependency of the choice of 30 time histories and the modification to fit a distribution, a second set of 30 time histories has been selected and modified in the same way as the first. This leads to two sets labelled Set 2.1 and 2.2 in the following.

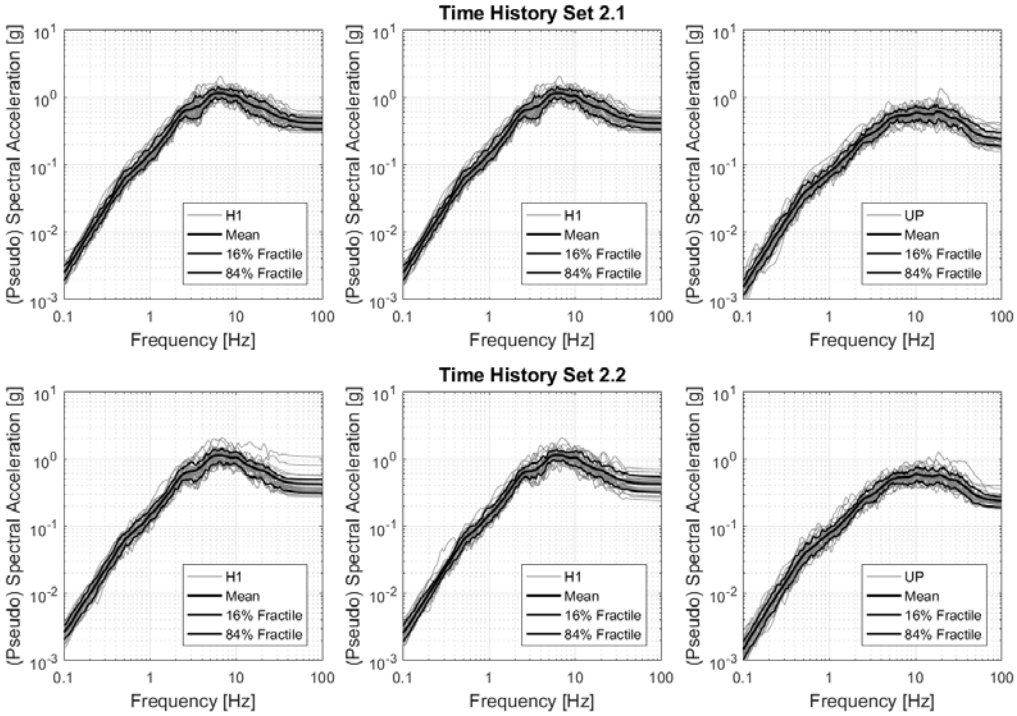

Figure 5. All three components of the time history Set 2 and their mean and fractiles for each component.

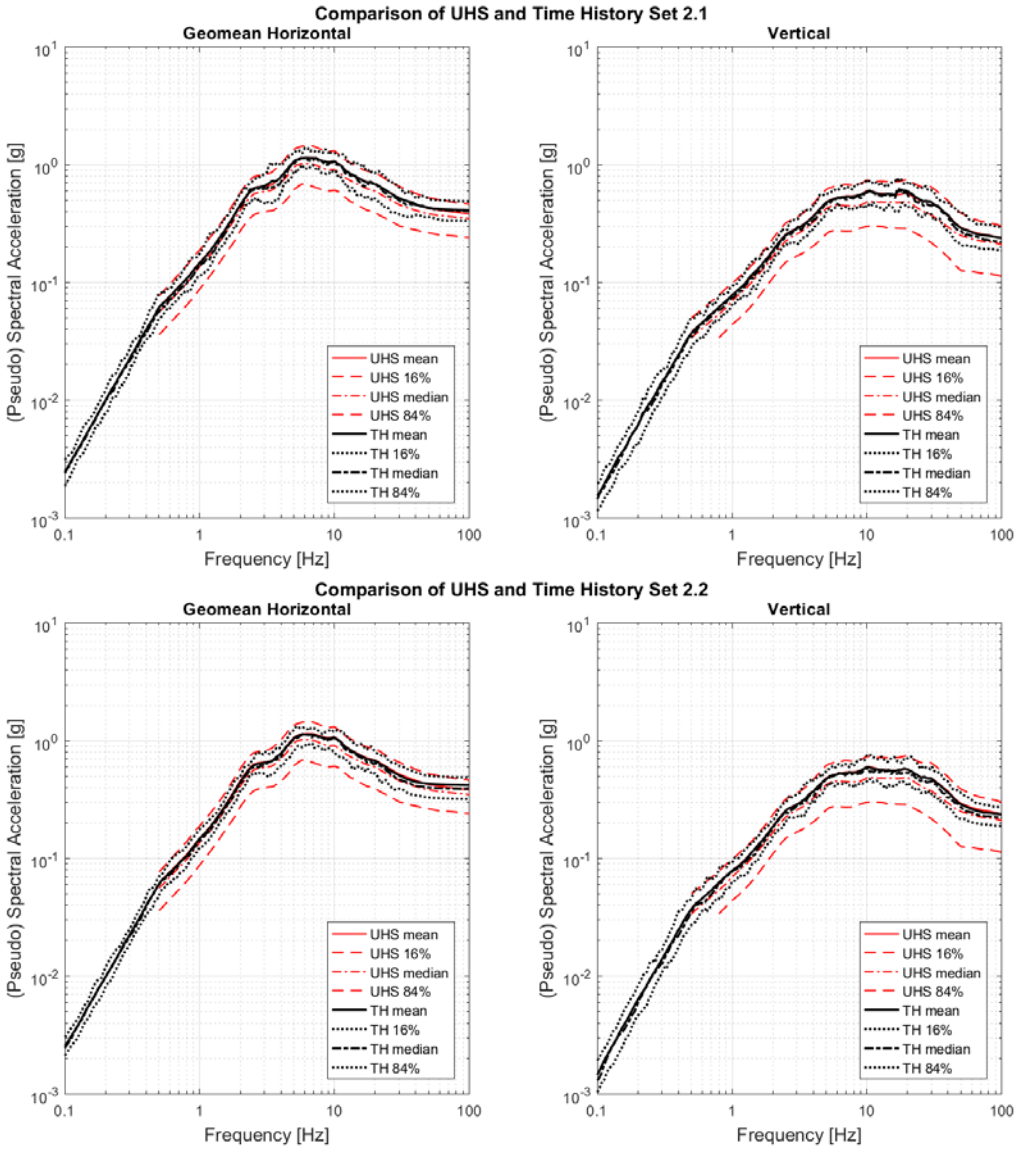

Figure 6. Comparison of target UHS for an APE of 1E-4 and time history Set 2.

As can be seen from the comparison to the target UHS, the mean and the 84%-fractile of the modified time histories fit well, as both are defined as criteria for the matching process. The 16%-fractile of the time histories is not matching well with the 16%-fractile of the target UHS, and is at the level of the median target UHS. This is due to the fact that the matching process is assuming a log-normal distribution of the ground motions around the mean, which is apparently not the case for the target UHS.

In order to consider also the alternative to perform a full probabilistic risk assessment, an alternative Set 2.1 and 2.2 was developed, where the median is consistent with the median UHS.

SSI time history Set 3 – CMS (Baker, 2011)

The third case consists of time histories which were developed based on the conditional mean spectrum (CMS) concept (see ASCE 4-16, Chapter C2): "*Currently, alternate definitions of the hazard spectrum, such as the conditional mean spectrum (Baker 2011), are being produced. Although these alternate*

definitions are not the current state of practice for analysis of nuclear facilities, they may be considerations in the future."

Here, the mean UHS is divided in two realistic response spectra conditioned for different frequency ranges, but still reproducing approximately the original mean UHS. For this case 5 and 20 Hz were selected as representative anchoring frequencies. This leads to the need to run two times 30 three component time histories to be applied for the SSI. For the sake of simplicity, the two CMS were developed based only on the most contributing GMPE and not all PRP GMPEs and expert weights were included. The two sets of time histories are based on two independent seeds and are the same as for Set 2.1 and 2.2, but scaled to the conditioning frequencies. The representation of the ground motion variability for different fractiles is introduced at the level of the risk assessment, as it is not part of the variability represented by the provided records.

One guideline regarding use of CMS can be found in the NEHRP/NIST report GCR 11-917-15 (2011) (see also Haselton et al., 2012). The application of the CMS approach has some practical questions which need to be addressed. First there is the development of the CMS in a consistent way with the hazard which requires some additional effort and in practice it is recommended that the envelope of the CMS does not fall 10% below the target UHS which requires some manual adjustments. Furthermore, the number of SSI analyses increases by the number of CMS which are used to sample the target UHS. One thing which is not obvious, as there is no guideline for this, is if the selected time histories should be used unmodified or if they should be adjusted in their spectral content to fit within some empirical bounds. Another alternative would also be to do a tight spectral matching to the target CMS (see next set). For the Set 3, the spectral content was not modified. The time histories were only scaled in amplitude to match for each set the two conditioning frequencies. This can be seen in Figure 8 when looking at the 16% and 84% fractiles which are pinched at 5 and 20 Hz respectively.

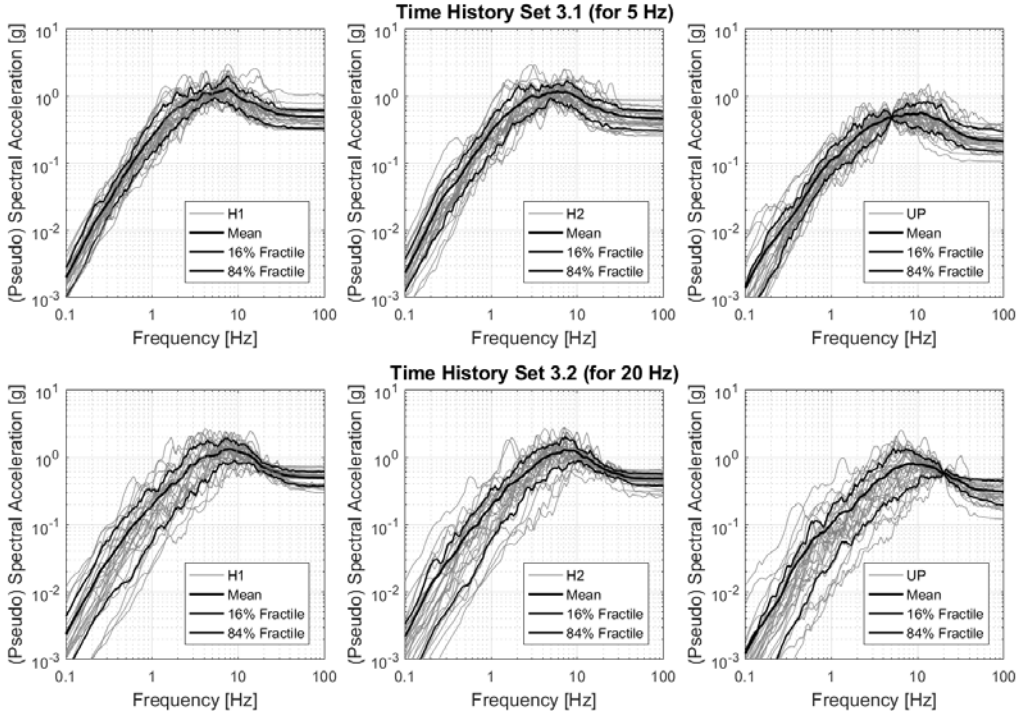

Figure 7. All three components of the time history Set 3 and their mean and fractiles for each component.

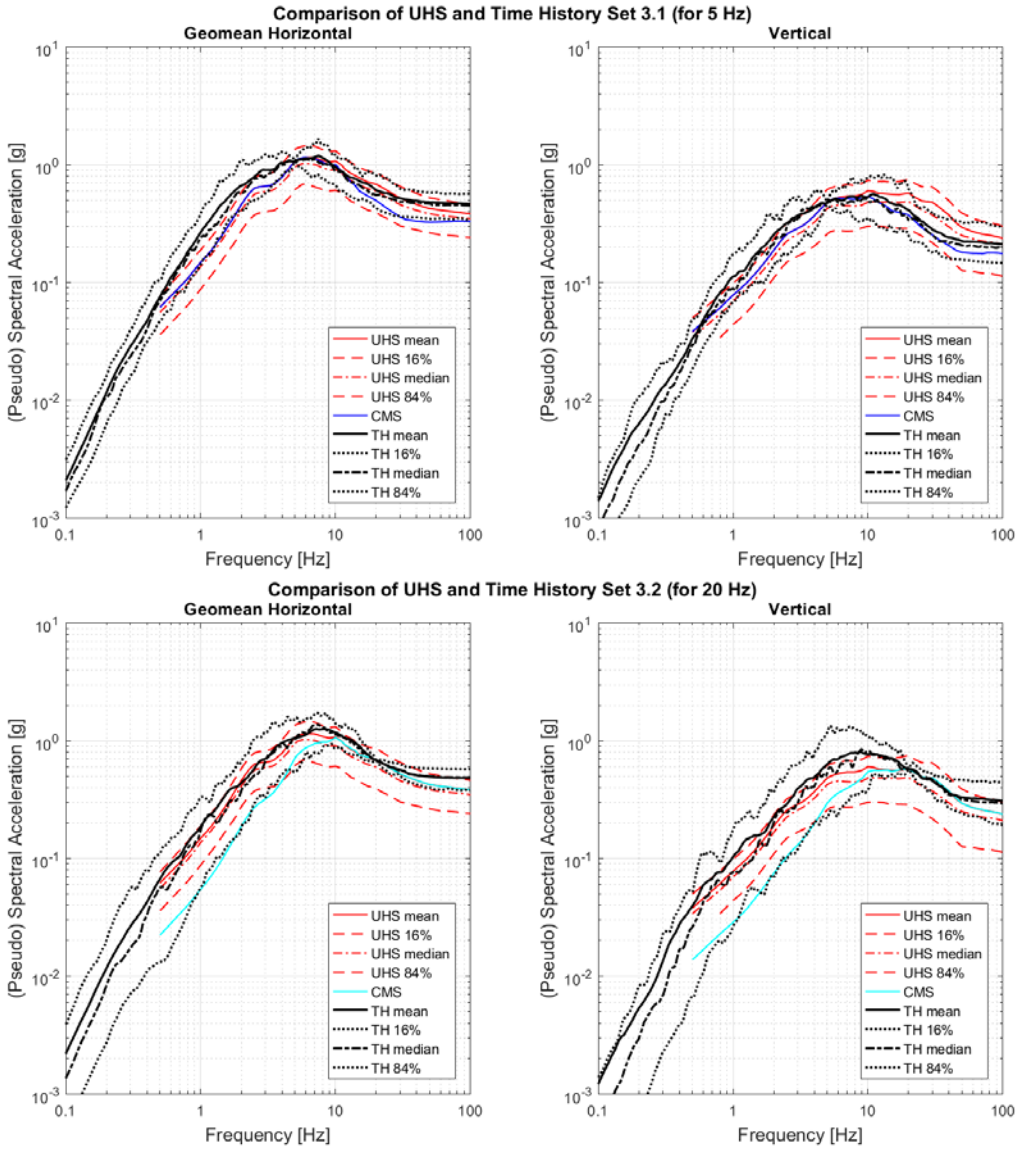

Figure 8. Comparison of target UHS for an APE of 1E-4 and time history Set 3.

SSI time histories Set 4 CMS (tight spectral matching)

The fourth set of time histories represents a modified version of the Set 3. In Set 3 the response spectra of the time histories were not modified in spectral content. For Set 4 the same two seeds as for Set 3 are used, but this time the time histories were all tightly matched to the two CMS. This is more in line in what is done in practical applications and also comparable to the approach used for Set 1. The effect can clearly be seen in the distribution of the response spectra in Figure 10 which is almost not visible compared to the distribution seen from the 16% and 84% fractiles in Figure 8.

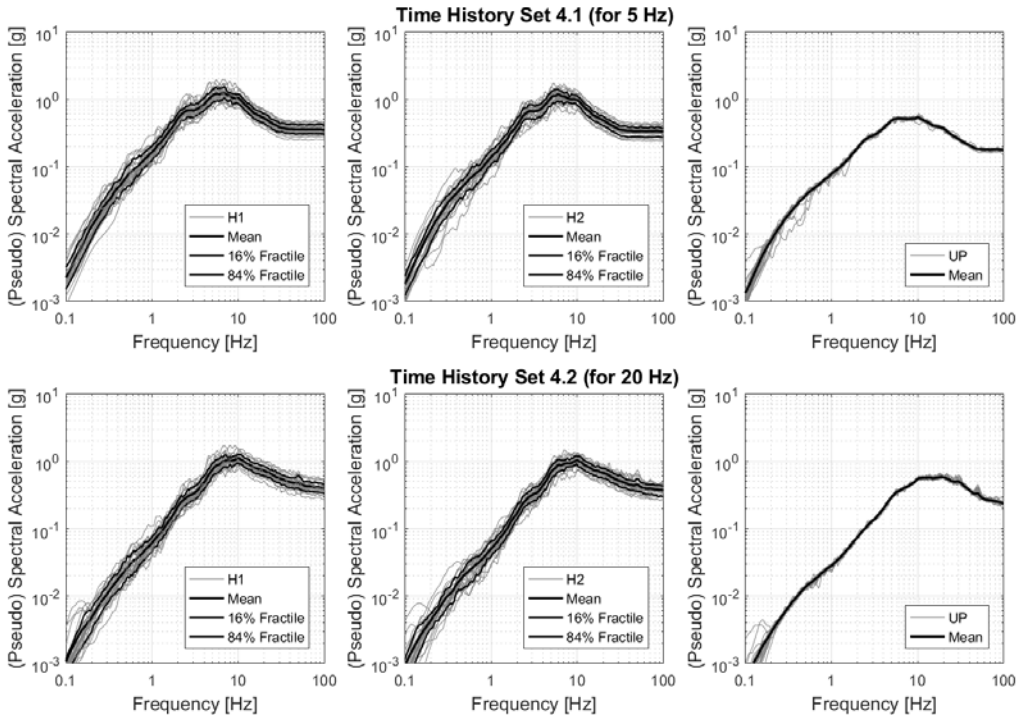

Figure 9. All three components of the time history Set 4 and their mean and fractiles for each component.

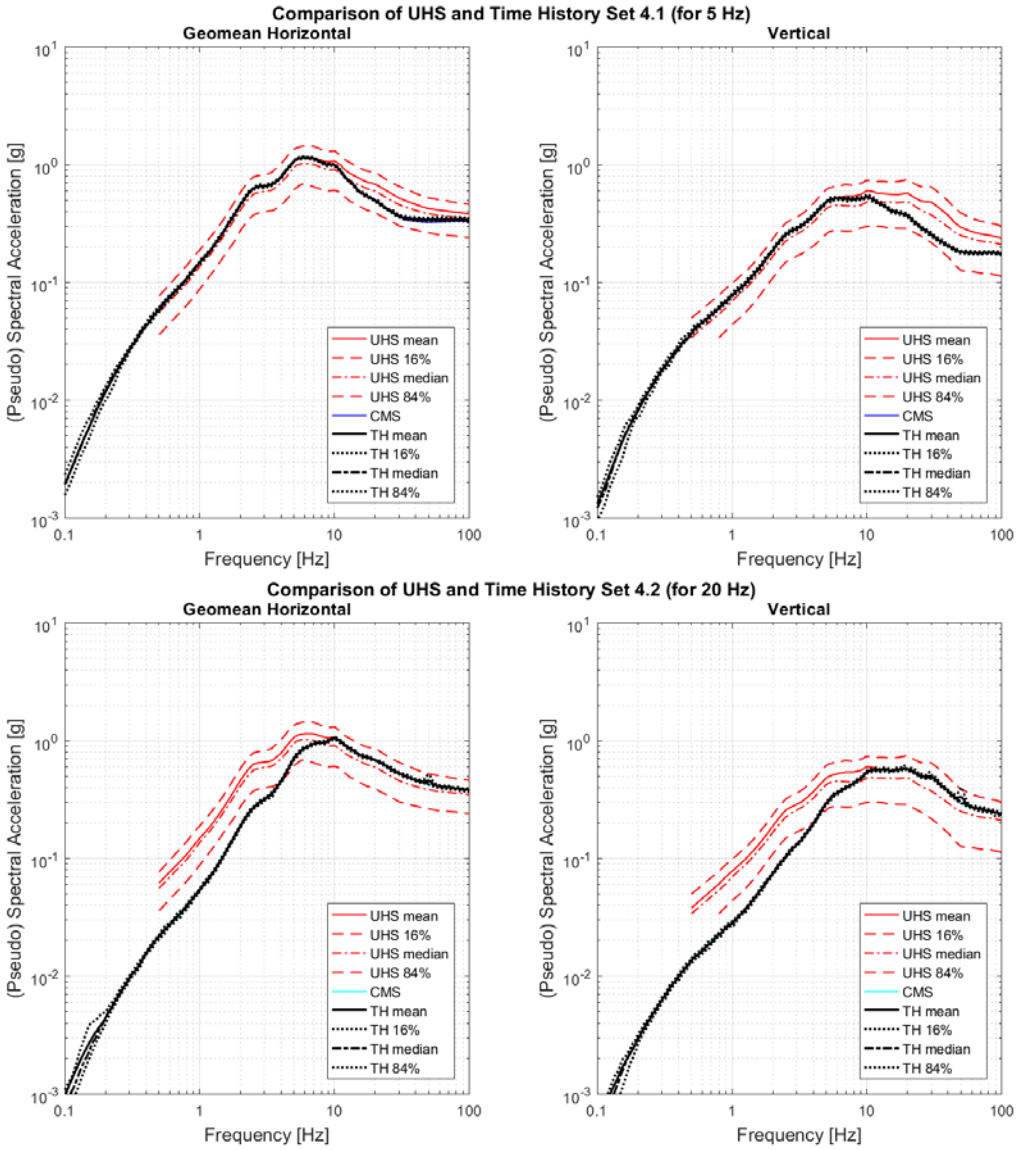

Figure 10. Comparison of target UHS for an APE of 1E-4 and time history Set 4.

STRUCTURAL RESPONSE – FLOOR RESPONSE SPECTRA

The various SSI analyses were evaluated for ten representative nodes and some of them are selected for illustrating the results in the following. The position of the nodes and the orientations can be found in the appendix.

Results for SSI time history Set 1 vs. Set 2.1 and Set 2.2

Exemplarily, the following figures show the floor response spectra comparison between the input time history sets 1, 2.1 and 2.2. As can be seen from Figure 11 the mean between the three FRS agree well. Nevertheless, in the peaks the mean due to Set 1 is larger than for Set 2. Furthermore, the two fractiles are also in good agreement, but at higher frequencies there are some differences. For a more systematic evaluation of all the results the ratio between the FRS was taken and is for the same node shown exemplarily

in Figure 12. From the ratios it can be seen that for the frequencies below 1 Hz there is a larger difference in the FRS, but for the assessed building those are not relevant frequencies.

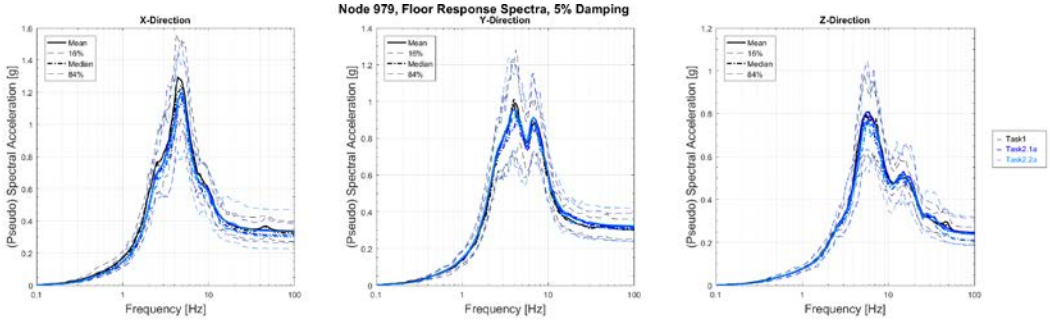

Figure 11. Comparison of FRS for Set 1, Set 2.1 and Set 2.2 for Node 979.

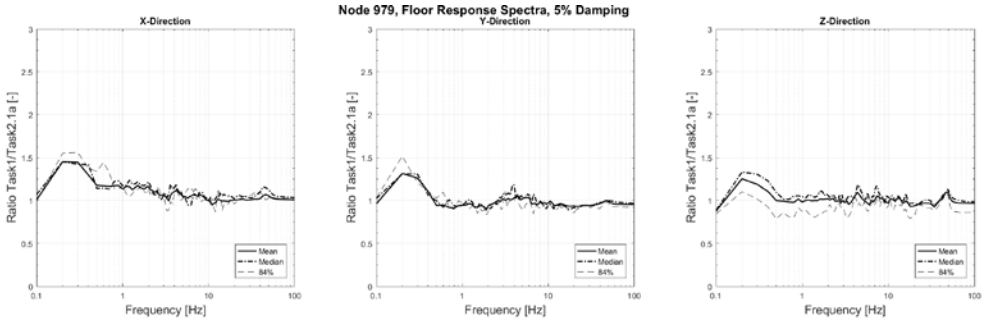

Figure 12. Ratio of the FRS for Set 1 and Set 2.1 for Node 979.

As Set 1 was tightly matched to the target UHS, this set has almost no variability around the mean of the input motion. Set 2.1 and 2.2 were both developed to cover the distribution of the input ground motion up to the 84% fractile and lead to a very similar distribution of the FRS as Set 1.

The resulting ratios of all ten nodes have been averaged to simplify the comparative evaluation (Figure 13), even though of course for the individual results need to be taken into account when evaluating individual systems or components within the structure. When looking in detail at the results, it can be seen that the FRS due to Set 1 are slightly larger than those for Set 2.1 and 2.2, mainly for the peaks, not necessarily at PGA.

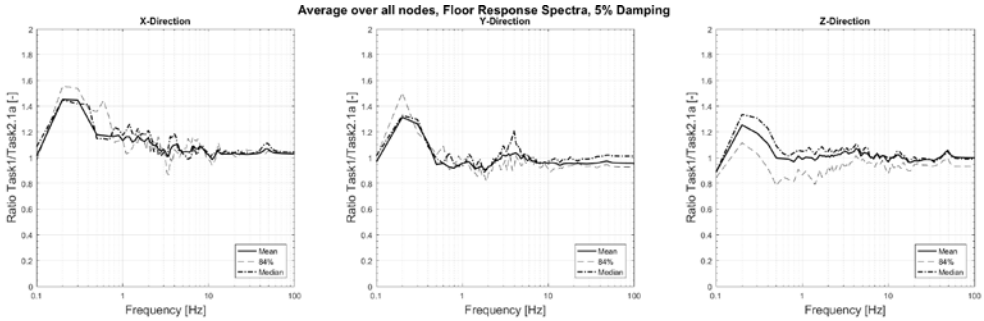

Figure 13. Average ratio of the FRS for Set 1 and Set 2.1.

The results show that there is almost no difference between the results due to the two different time history sets 2.1 and 2.2. As can be seen from Figure 14 and Figure 15 the mean and the fractiles are stable with only some spikes in the frequency range between 1-10 Hz, and which can go up to 20%.
This shows that the choice of the 30 input motions is not relevant and still leads to robust mean and 84% fractile results.

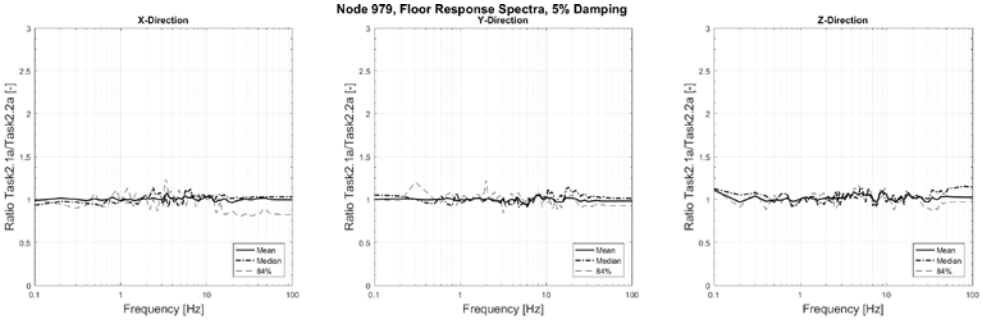

Figure 14. Ratio of the FRS for Set 2.1 and Set 2.2 for Node 979.

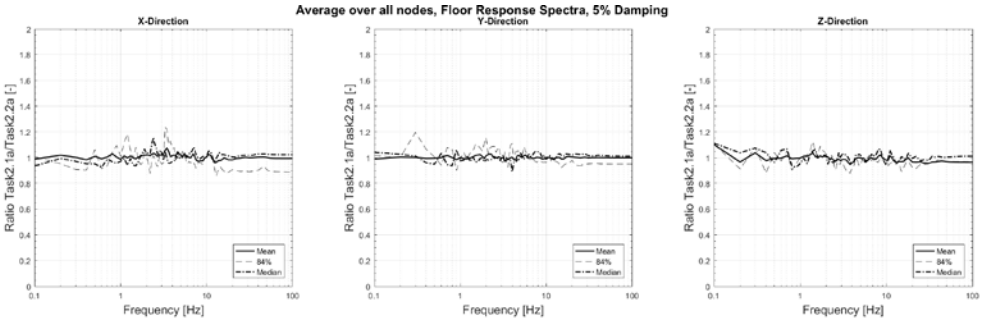

Figure 15. Average ratio of the FRS for Set 2.1 and Set 2.2.

Results for SSI time history Set 3 vs 4

The comparison of the Set 3 and 4, both based on the CMS approach is shown in figures below. For both cases the envelope of the FRS due to the 5 and 20 Hz CMS were derived. When performing structural analysis to quantify in-structure seismic demands, the use of CMS is still under discussion. Because components inside the analyzed structure can have important natural frequencies very different from the structure itself, some practitioners have questioned whether the in-structure response spectra produced from analysis using CMS input is appropriate (or potentially un-conservative) for component qualification and assessment. Thus, there is a thought and US practice that the envelope of a full suite of target frequencies should be used for CMS when considering in-structure response, which tends to minimize the benefit that CMS provided to begin with.

It is obvious that the FRS originating from Set 3 are significantly larger than those from Set 4. For the vertical components below 0.5 Hz this is not the case, but as explained earlier, for this building this is not the region of interest.

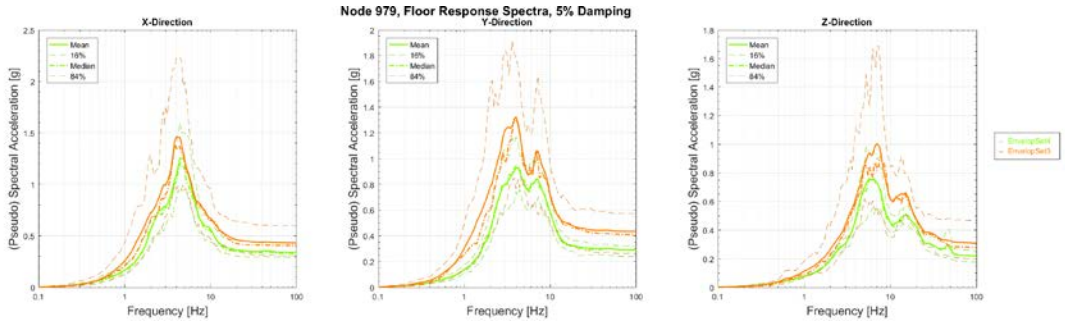

Figure 16. Comparison of FRS for Set 3 and Set 4 for Node 979.

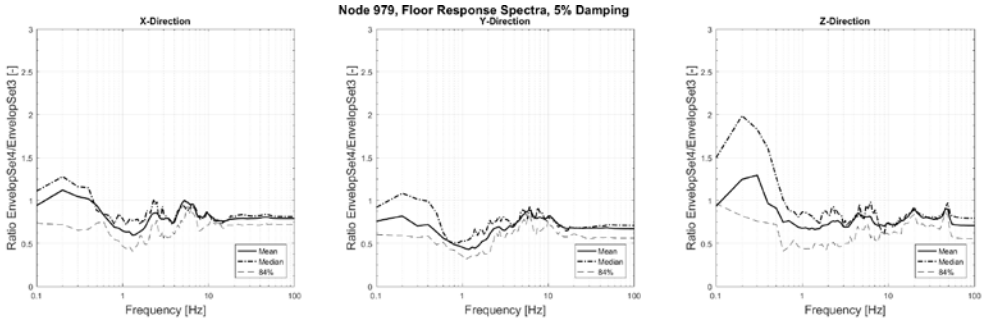

Figure 17. Ratio of the FRS for Set 3 and Set 4 for Node 979.

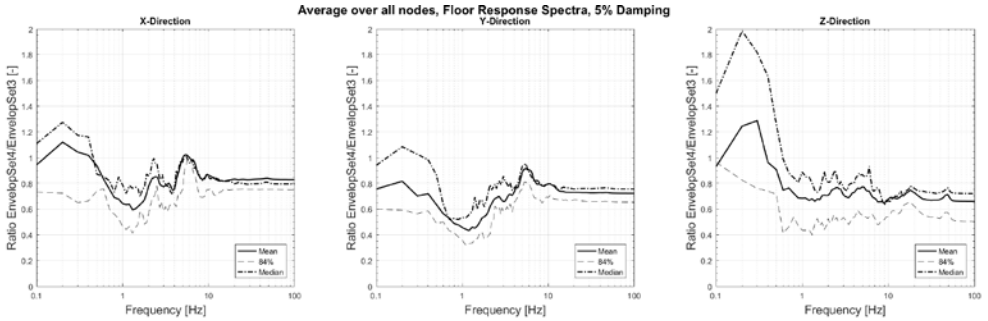

Figure 18. Average ratio of the FRS for Set 3 and Set 4.

Results for SSI time history Set 1 vs. Set 4

For Set 1 and Set 4 in both cases the time histories were tightly spectrally matched to the target spectrum, to the UHS for Set 1 and to the two CMS for Set 4. For Set 4 the envelope of the FRS is considered again to compare to Set 1.

As can bee seen from the comparison figures below, the FRS due to Set 1 and 4 are very similar. This applies to the mean, median and 84% fractile. The latter is of course not very meaningful, as in both Sets the variability around the mean was suppressed by the tight spectral matching. The average ratio shows that at lower frequencies below 1 Hz the Task1 results for both horizontal components are slightly larger than those due to Set 4. On average the vertical component shows to have slightly higher amplitudes at higher frequencies.

This leads to the overall conclusion that the results of both sets lead to almost the same mean and 16% and 84% fractile, but performing the CMS development is much more time consuming than simply using the conventional UHS as target. Especially, as for the CMS here two SSI sets had to be carried out and afterwards combined to an envelope again.

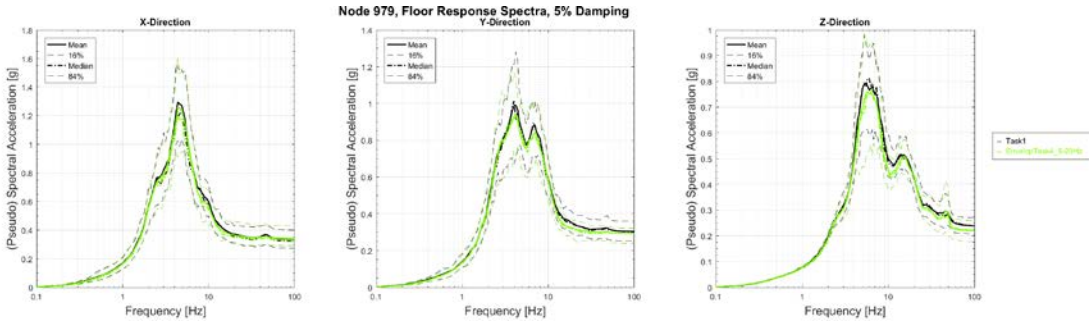

Figure 19. Comparison of FRS for Set 1 and Set 4 for Node 979.

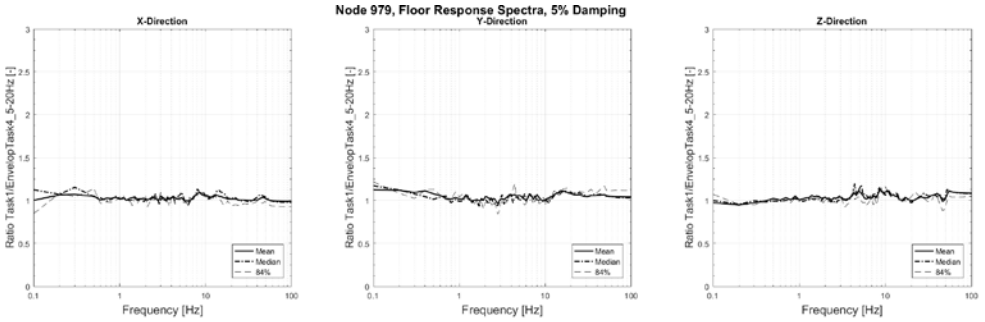

Figure 20. Ratio of the FRS for Set 1 and Set 4 for Node 979.

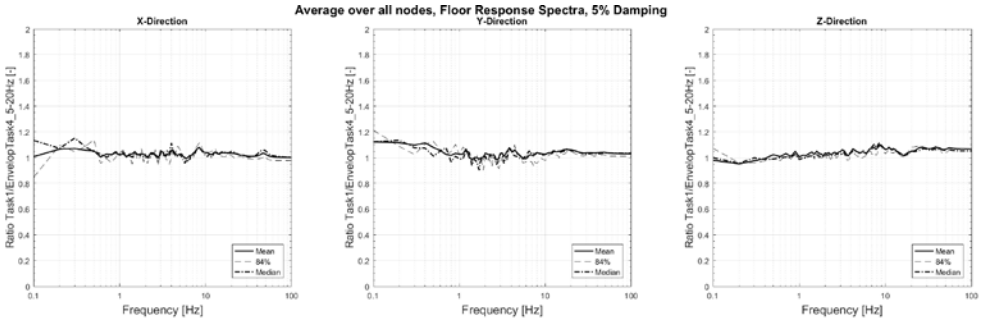

Figure 21. Average ratio of the FRS for Set 1 and Set 4.

Results for SSI time history Set 2 and Set 3

The comparison of FRS due to the Set 2 and Set 3 shows that the Set 2 results are lower than those produced by the Set 3. For illustration, only the Set 2.1 comparison is shown here, but as discussed earlier the same applies to Set 2.2, as both are almost identical. As the Set 1 results also show to be smaller than those due to Set 3, but the Set 1 is leading to slightly larger results than the Set 2, it can be concluded that the Set 2 results are leading to the lowest FRS of all sets.

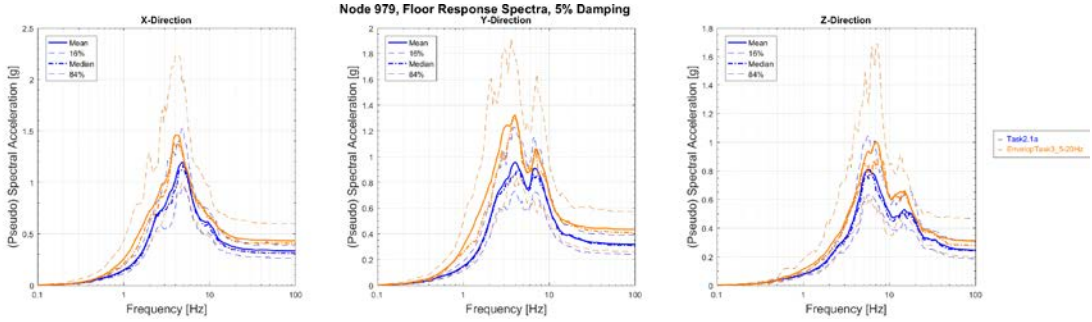

Figure 22. Comparison of FRS for Set 2.1 and Set 3 for Node 979.

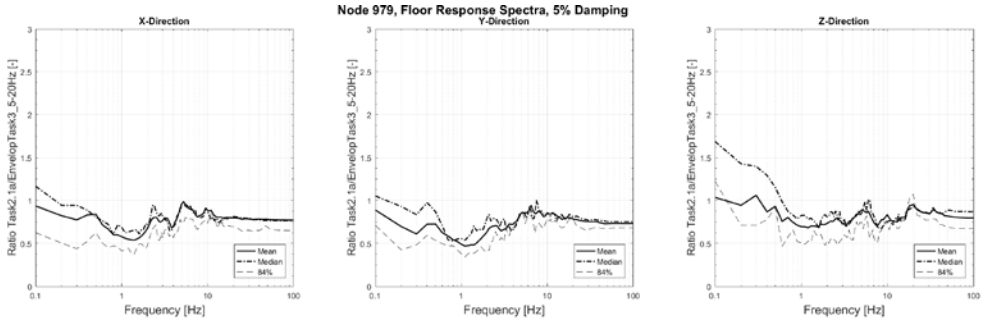

Figure 23. Ratio of the FRS for Set 2.1 and Set 3 for Node 979.

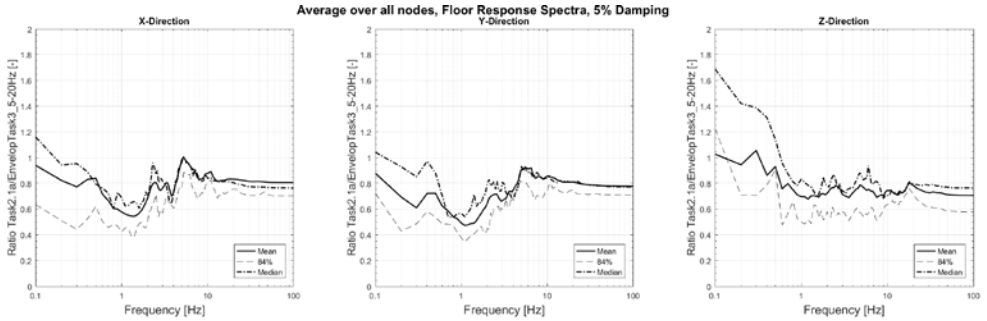

Figure 24. Average ratio of the FRS for Set 2.1 and Set 3.

Evaluation for PGA and spectral peaks

For all three components the PGA value of the different sets were compared to the PGA value resulting from the Set 1, which was used as reference point here (see Figure 25). Thus, the boxplot shows only a horizontal line at 1 there for Set 1. On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using a red '+' symbol. The default value for 'Whisker' corresponds to approximately +/–2.7σ and 99.3% coverage if the data are normally distributed. The plotted whisker extends to the adjacent value, which is the most extreme data value that is not an outlier.

The individual sets for Set 3 and 4 for 5 and 20 Hz are integrated in the plot for comparison purposes only. Nevertheless, the fair comparison with the other Set 1 and 2 must be done based on the envelopes of the FRS. Quantitatively, the Set 3 time histories lead to the largest margin compared to Set 1 for all three components. For the vertical component the Set 4 leads to the smallest PGA value.

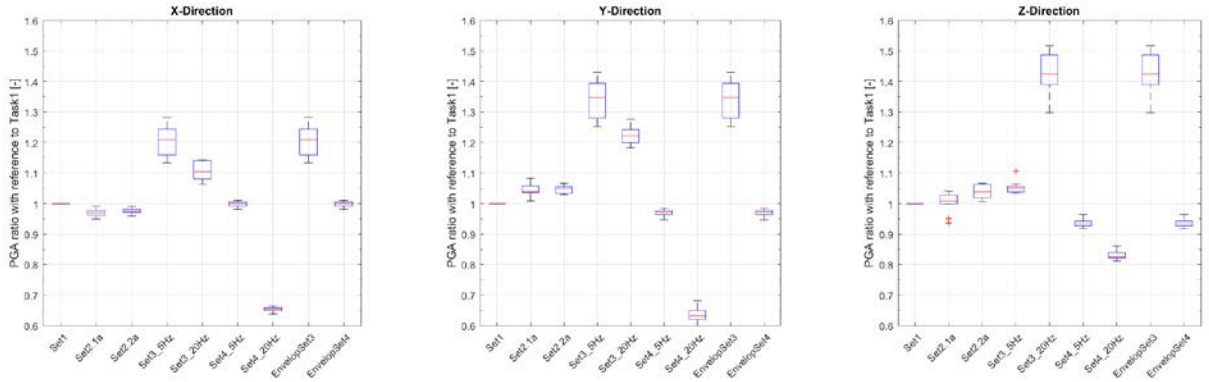

Figure 25. Comparison of PGA values for all time history sets.

Analogously, in Figure 26 the ratio of the maximum peak values with reference to Set 1 is shown. The fact that the peaks do not occur at exactly the same frequency was ignored, as for a designer the peak value is usually relevant. For the peak values the Set 2 is leading to the lower spectral amplitudes compared with the other Sets in the horizontal directions. For the vertical component it is the Set 4.

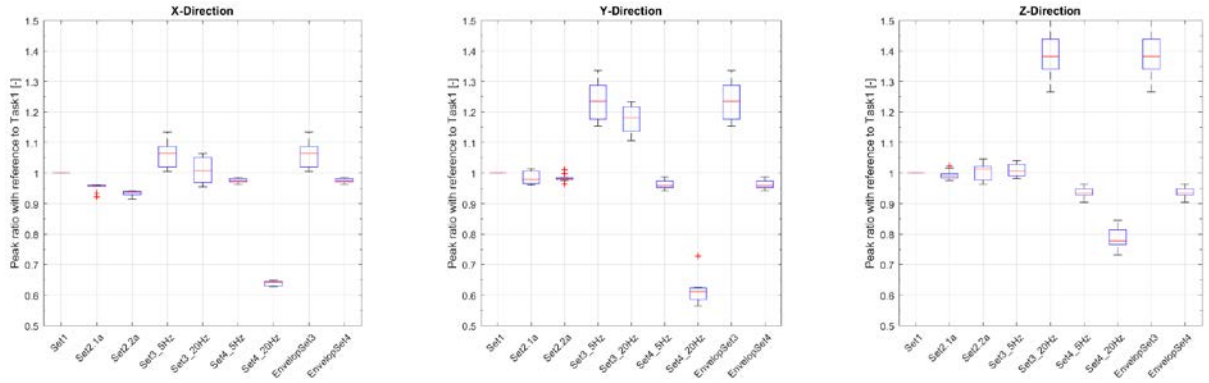

Figure 26. Comparison of spectral peak values for all time history sets.

CONCLUSION

This study has compared multiple approaches adopted in practice to select and adjust time histories for use in probabilistic fragility analyses. It has been shown that all approaches satisfy the guidances and requirements in terms of mean and statistics on the level of the input motion. Nevertheless, the resulting structural response and its associated statistics show a variability with is for some cases not negligible and requires attention for the engineering side of the evaluation. Although, the differences are not of direct concern, it has been shown that the CMS based time histories lead to a large margin compared to all other approaches. When using the CMS based time histories, but with a tight spectral matching to the UHS the structural response at higher frequencies (here e.g. 20 Hz) show to be much smaller than for all other selected time history inputs. Only if the envelope for this case is used, as suggested by some expert groups, the results are again comparable to the ones of the other approaches. Thus, depending on the purpose and frequency range, time histories should be selected with care and appropriate justification.

DISCLAIMER

This paper is intended for educational purposes only and does not replace independent professional judgment. Statements of fact and opinions expressed are those of the presenter and, not necessarily the opinion or position of swissnuclear, its sponsors or its committees. Swissnuclear makes no representation or warranty, express or implied, regarding the content, accuracy, completeness or fitness for use for any purpose of the information presented.

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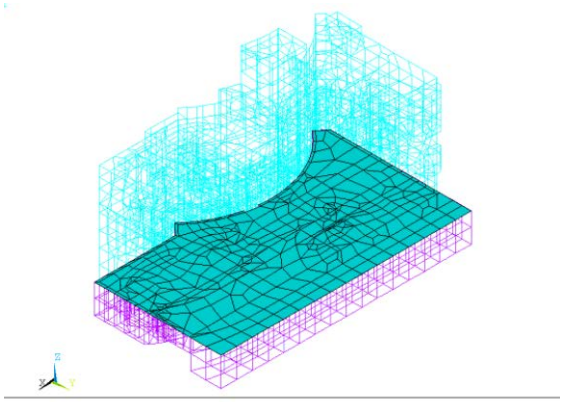
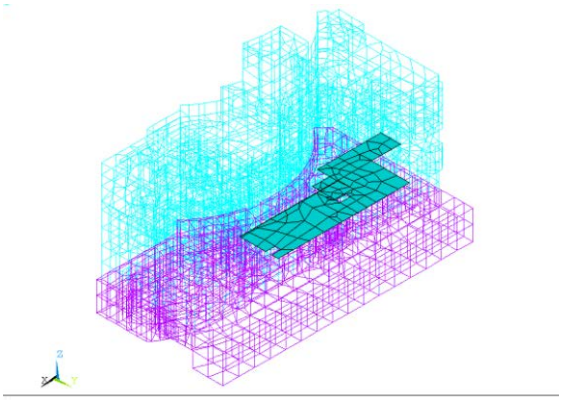
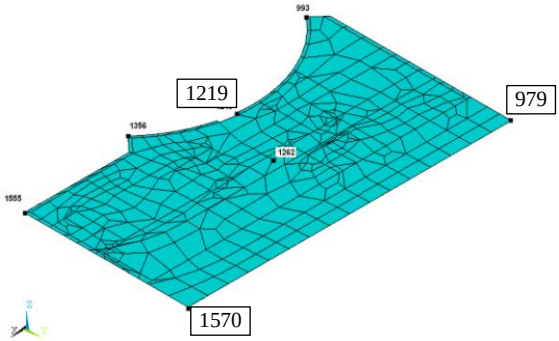
APPENDIX

Floor 1, Elev. 326.57 m



Floor 2, Elev. 330.70 m





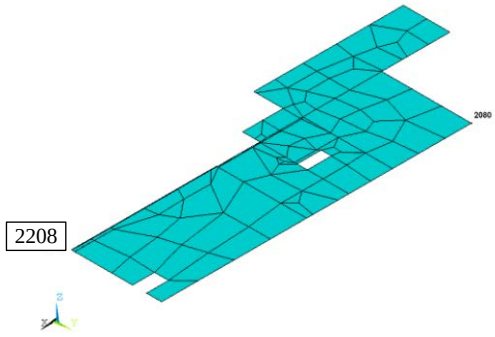
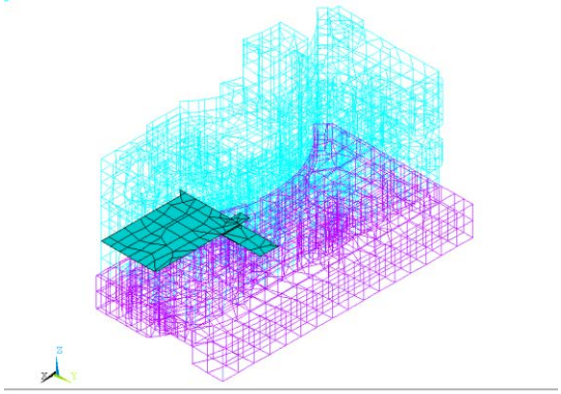
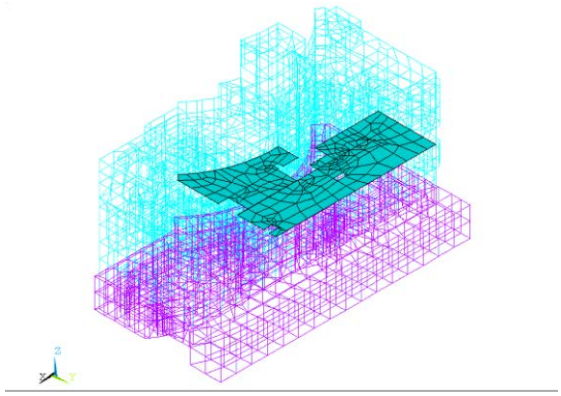


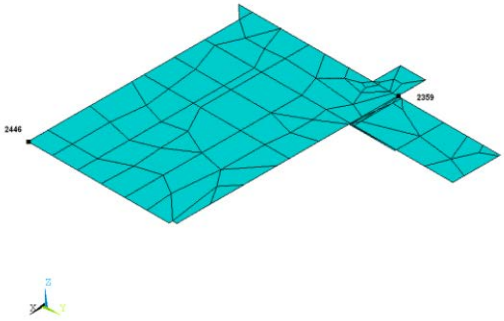
Figure 27. Location of Acceleration In-Structure Response Spectra

Floor 3, Elev. 332.07 m



Floor 4, Elev. 333.70 m





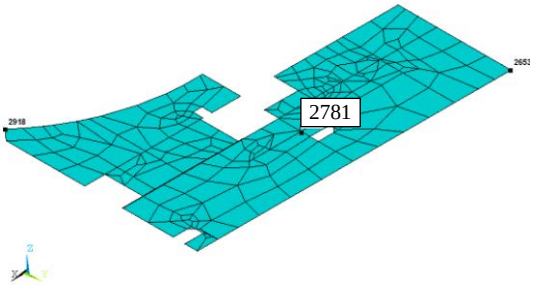


Figure 28. Location of Acceleration In-Structure Response Spectra

Floor 5, Elev. 337.77 m

Floor 6, Elev. 338.90 m

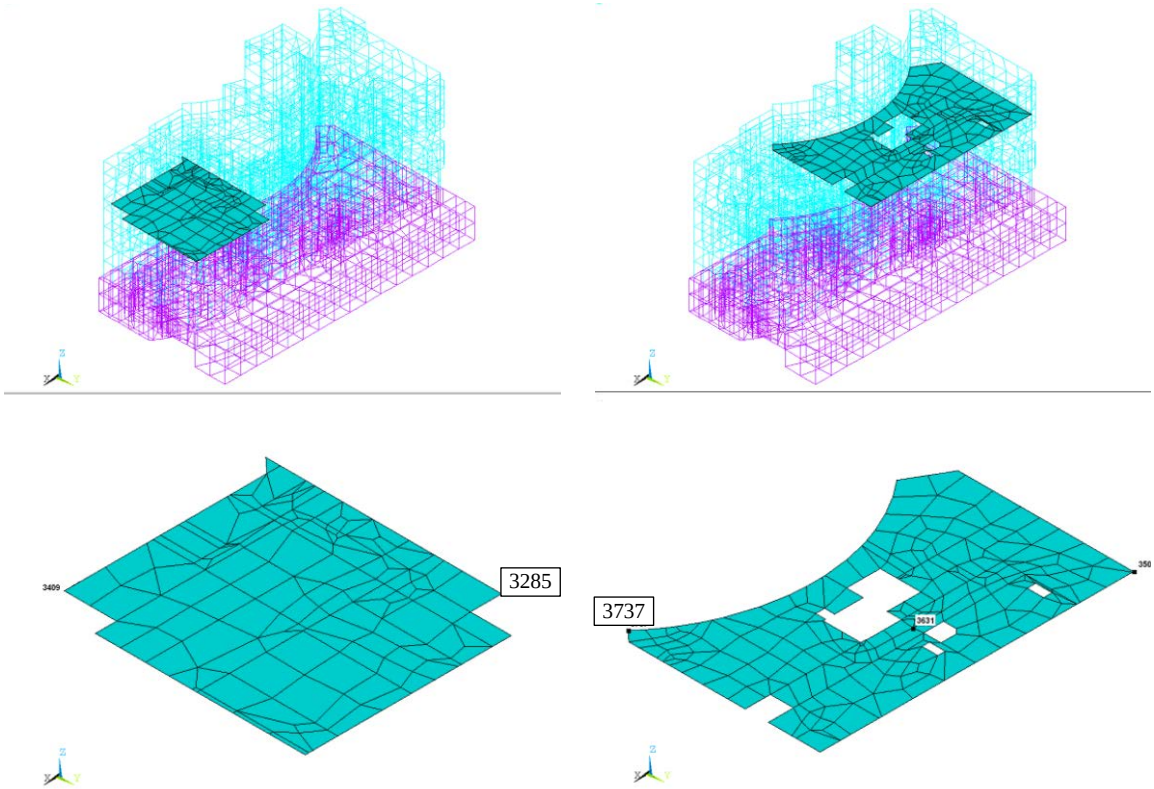


Figure 29. Location of Acceleration In-Structure Response Spectra

Floor 7, Elev. 340.80 m

Roof, Elev. 343.50 m

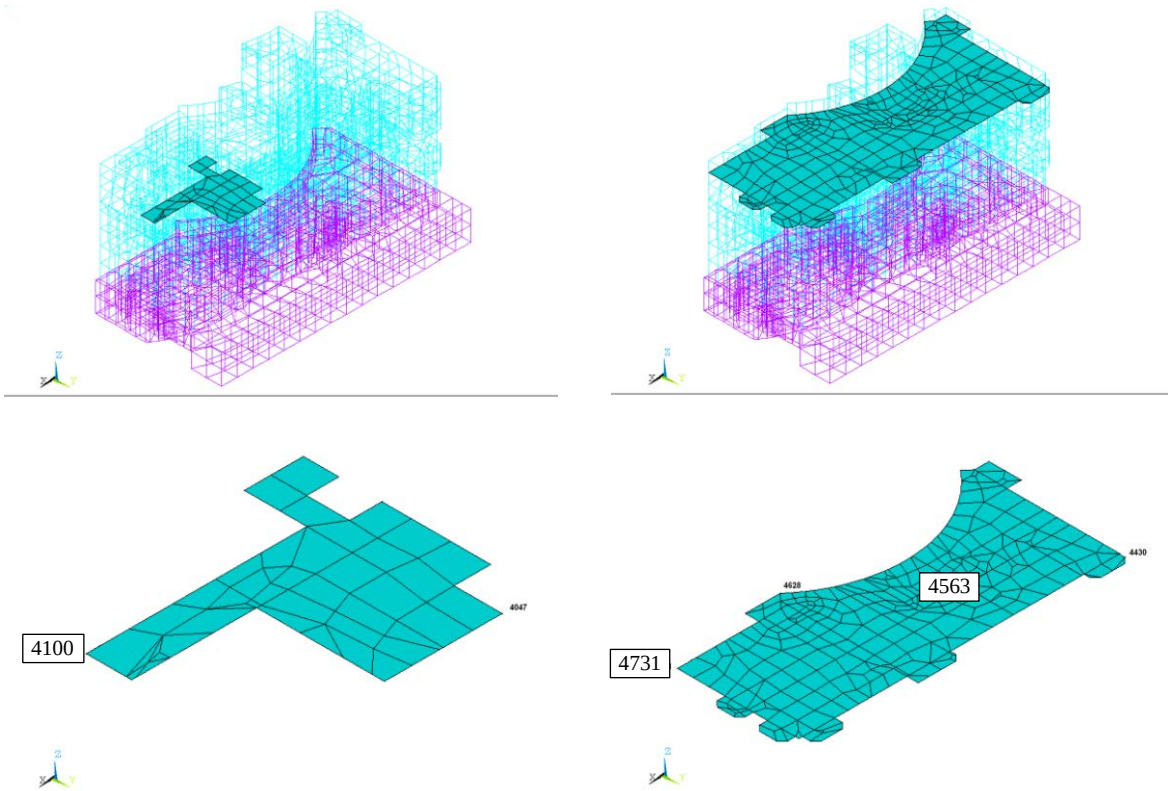


Figure 30. Location of Acceleration In-Structure Response Spectra