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SELECTION AND MODIFICATION OF REAL ACCELERATION TIME HISTORIES FOR NON-LINEAR SEISMIC EVALUATION IN THE UK NUCLEAR INDUSTRY

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Abstract: *Fully dynamic non-linear seismic analyses are required for the evaluation of safety related systems and components in UK nuclear licenced sites. Traditionally, these analyses had been carried out using synthetic acceleration time histories derived in the 1980s, and generated to match the design spectrum. However, those time histories are now considered an unrealistic representation of real earthquake ground motions, mainly in terms of duration and ground displacements, their main limitation being their failure to capture the randomness in the earthquake phenomenon. Therefore, a new set of acceleration time histories, compliant with modern best practice, was needed to improve the reliability of the predictions from seismic analyses. The new set of time histories incorporates current relevant best practice in the UK and elsewhere, as well as recent understanding of the UK seismicity. This paper presents the process for the selection and modification of the new set of time histories, comprised of five three-orthogonal-component records, based on ASCE 43-05 and ASCE 4-16 guidelines, while considering project specific requirements. This new set of records is based on real acceleration time histories (seed records) modified to spectrally match the design spectrum, while ensuring that no significant deviations from the main parameters of the seed records were observed.*

Introduction

As part of their safety case review, EdF Nuclear Generation Ltd (NGL) required to undertake fully dynamic non-linear seismic analysis of the systems and components at the Hunterston B (HNB) and Hinkley Point B (HPB) nuclear power plants (NPPs). As part of this review, a new set of acceleration time histories (THs) were derived to modern standards, compliant with current relevant good practice (RGP), and consistent with ground-motion characteristics of UK earthquakes.

The new sets of THs were required to comprise five three-orthogonal-component records (two horizontal and one vertical), spectrally matched to a number of target spectra defined for each of the NPPs, and to be compliant with ASCE 43-05 (ASCE/SEI 2005) and ASCE 4-16 (ASCE/SEI 2017) standards. In addition to ASCE 43-05 and ASCE4-16, McGuire et al. (2001) (NUREG/CR-6728 report) and USNRC RG 1.208 guidelines (USNRC 2007) were considered for the derivation of the THs as they are referred by the ASCE 43-05 and / or ASCE 4-16 as supplementary guidelines and they are part of the USNRC set of technical guidelines. Relevant information on selecting and scaling earthquake ground motions is also provided in NEHRP (2011).

This paper summarises the selection and modification of recorded accelerations THs (seed records) to comply with code and project-specific requirements. Due to paper length constraints only the THs developed for the HPB site, considering the site-specific mean uniform hazard spectrum (UHS) with an annual frequency of exceedance (AFoE) of 10^{-4}, are discussed. However, the same process and conclusions apply to alternative target spectra defined for the HPB site (e.g., the 10^{-4} 84th percentile UHS), and the uniform response spectra (URS) for the HNB site.

To ensure compliance with the ASCE standards, checks were carried out for all THs to verify that the modifications to the seed THs did not have a significant impact on the main characteristics of the ground-motion records.

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Selection and Modification Requirements

ASCE 43-05 requires that acceleration THs that are modified or generated to “match” or “envelop” a given design spectrum shall comply with criteria (a) to (f) listed in Section 2.4 of ASCE 43-05, the general objective being to achieve an approximate fit to the target spectrum for the mean of the selected and modified THs. A short summary of ASCE 43-05 - Section 2.4 requirements is listed below. It should be noted that ASCE 4-16 mainly refers to ASCE 43-05 for the selection and modification of time histories, with only a few more technical details on some steps of the approach, which are already considered in the list below.

1. The time history shall have a sufficiently small time step and sufficiently long duration. The time step shall not be larger than 0.01 s and the record length not shorter than 20 s;
2. The average spectral acceleration from the suite of time histories shall not fall more than 10% below the target and not exceed the target by more than 30% within a frequency window between 0.2 and 25 Hz. If a single modified record is used, the spectral accelerations from the single record shall comply with this requirement;
3. The three components of the ground-motion record shall be statistically independent. The directional correlation coefficients between any two components shall not exceed a value of 0.30 to avoid statistical dependency. In this study, this requirement is already fulfilled by using three-component ground motions recorded on orthogonal sensors which by nature are statistically independent;
4. The selection of recorded or modified acceleration time histories shall be based on the magnitude-distance bin for the scenarios controlling the hazard at the site for the design return period;
5. The strong-motion duration [D_S(5-75%)], defined as the duration from the 5% to 75% of Arias intensity (I_A), shall fall within the range appropriate for the magnitude-distance bin of the controlling scenario;
6. When considering a suite of time histories, the range in variation in rise time of the I_A shall be considered, such that all do not have the same rise time characteristics.

The controlling scenarios in terms of magnitude and distance were defined based on the disaggregated results from the recent probabilistic seismic hazard assessment carried out for Hinkley Point C (HPC) (Tromans et al. 2019), which is adjacent to the HPB site. Based on the HPC study the controlling scenarios for the 10^{-4} AFoE were defined as **M** 5.5 to 6.0 and 30 to 50 km (R_{JB} – Joyner-and-Boore distance definition). It was considered that the controlling scenarios from the HPC study could be considered representative of the entire UK; therefore, also applicable to the HNB site.

D_S(5-75%) durations were defined to range between 3.5 and 11.5 s, based on the recommendations by Aldama-Bustos and Strasser (2019) considering the magnitude and distance ranges of the controlling scenarios previously stated. Ground conditions at both sides can be classified as “soft rock”, corresponding to a Ground Type A as per Eurocode, or NEHRP Site Class B as per US standards.

A number of target spectra were considered for this study, including the PML spectrum, anchored at a horizontal peak ground acceleration (PGA) of 0.14 g, the URS for the HNB site, and the site-specific mean UHS and 84th response spectra for the HPB site. The response spectra for the HPB site were derived as part of this study, but not discussed here in any detail, as an extension of the HPC PSHA where the site-specific geology and foundation levels at the HPB site where considered. As previously mentioned, only results for the 10^{-4} mean UHS, for the HPB site, are presented in this paper.

In addition to the ASCE 43-05 and ASCE 4-16 requirements, the following project-specific requirements were considered:

7. Each three-component record should individually comply with the ASCE 43-05 and ASCE 4-16 requirement on the spectral acceleration not falling beyond the limits described in Point 2 of the list above. This allows to interpret the results of the soil structure interaction analysis for each set of THs individually rather than having to obtain the mean response from the five sets of THs;
8. The time step for all THs should be uniformly set to 0.01 s, to allow an easy comparison of the results of the dynamic analysis at each time step of the THs;

9. THs were to be either clipped, or zero-padded, at the start of the record so as to obtain a "reasonable" overlap of the time window defined by the 5% and the 75% of I_A from all sets of THs, with the same objective as for Point 8.;
10. THs should preferably be shorter than 30 s, in order to minimise the computational time required to perform the dynamic non-linear analyses. For THs with total lengths longer than 30 s, alternative versions of the THs set were produced, one version providing the full-length records, and a second version providing records truncated to 30 s. However, it should be ensured that this truncation does not affect the conclusions from the dynamic non-linear analysis.

Records Selection and Modification Approach

Search Criteria and Initial Selection

The first step on the selection of the seed records consisted of compiling a subset of the PEER 2013/03 NGA-West2 strong motion database (Ancheta et al. 2013), using the search tools available on the PEER web page (https://ngawest2.berkeley.edu/site), and considering the following criteria:

- Magnitude in the range: **M** 5-7;
- Distance (R_{JB}) in the range: 20-60 km;
- Shear wave velocity in the upper 30 m (V_{s30}) in the range: 600-1,500 m/s;
- Fit of the mean response spectra from all events in selected subset to target design spectrum;
- Scaling factors in the 0.1 to 10 range.

The magnitude and distance ranges used for the compilation of database for each target design spectrum were slightly relaxed compared to the magnitude and distance ranges from the controlling scenarios previously discussed. This was done to allow for a "safety margin" and not being overly restrictive with the initial selection criteria, and resulted in subsets of about 100 three-component records for each target design spectrum.

The fit of the mean response spectra was calculated on the horizontal components only as the tools available on the PEER web page do not allow to perform a search for both components simultaneously.

Although the search criteria considered the comparison of scaled records against the target design spectrum, the compiled database for each target design spectrum considered only unscaled records. This allowed the final selection process to find the best suite of scaling factors for a set of only five records, as discussed in the following section.

An example of this process is shown in Figure 1, which reproduces the comparison of the response spectra of the selected subset of ground-motion records against the HPB 10^{-4} mean UHS (target spectrum) as produced by the PEER web page.

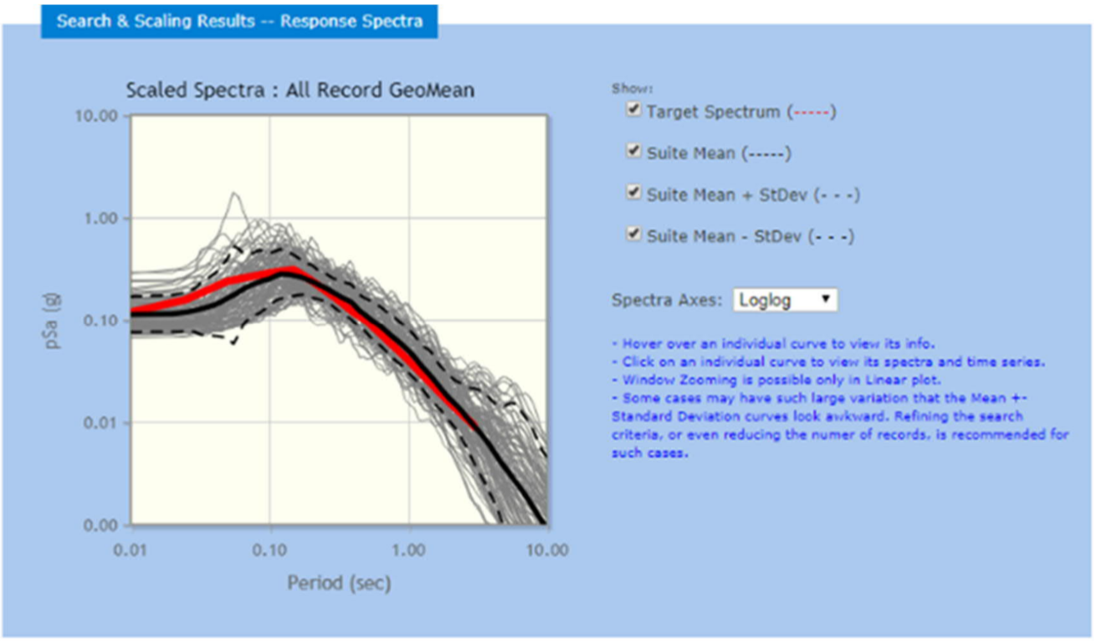

Figure 1. Comparison between the response spectra of the ground-motion records selected from the PEER database against the HPB mean UHS (target spectrum) as produced by the PEER web page (https://ngawest2.berkeley.edu/site).

Final Selection and Scaling

Using the subset of records downloaded from the NGA-West2 database, the selection and scaling of the final suite of five three-component records for each target spectrum was carried out using SigmaSpectra software developed by Kottke and Rathje (2008). SigmaSpectra selects and scales suites of earthquake records from a ground-motion database such that the median of the scaled suite matches a target spectrum at all defined response periods.

The software allows the user to visually inspect all the selected records and exclude or include specific records to be considered in the final suite. Therefore, records with extremely long durations or time steps not compatible with the project requirements were removed from the search using this functionality. Records that showed undesirable response spectra (e.g., spectra with strong peaks within a narrow frequency range), or atypical times series, were similarly removed from the search.

The best fit to the target spectrum was assessed based on the comparison of the average geometric mean for any given five-record suite against the target spectrum. This selection was based on the best fit of the horizontal component only. The scaling factor for the vertical component of each record was calculated by forcing SigmaSpectra to use the five selected records only and find the set of scaling factors that produced the best fit against the vertical target spectrum. This resulted in some minor exceedances of the upper and lower limits of the average response spectrum for the vertical component; however, this was considered non-critical as the dynamic non-linear analysis is not sensitive to the vertical component and spectral matching would be performed in a subsequent step.

The fitting of the mean response spectra for the horizontal component of the selected suite of scaled THs for the 10^{-4} HPB mean UHS is reproduced in Figure 2. A summary of the main characteristics of the final set of THs for the HPB site is presented in Table 1.

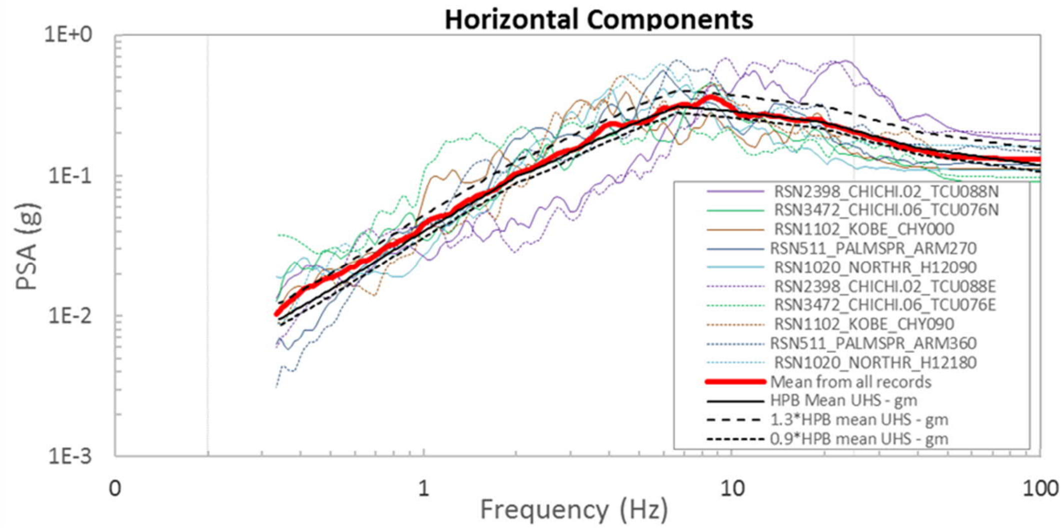

Figure 2. Comparison between the scaled acceleration response spectra for the suite of five selected three-component time histories, including their mean spectra, against the 10^{-4} HPB mean UHS (target spectrum) and the upper and lower bounds as defined in ASCE 43-05.

The set of records obtained from this process is fully compliant with ASCE 43-05 and ASCE 4-16 requirements and could be used directly as input for the dynamic non-linear analysis. However, this would require having to assess the results based on the mean response from all five sets of THs.

Earthquake	**Year**	**Station**	**M***	**R_{JB}** (km)**	**V_{S30} (m/s)**	**Record Name*****
Northridge-01	1994	Lake Hughes #12A	6.7	21	602	RSN1020_NORTHR_H12
Kobe_ Japan	1995	Chihaya	6.9	50	609	RSN1102_KOBE_CHY
Chi-Chi_ Taiwan-02	1999	TCU088	5.9	28	665	RSN2398_CHICHI.02_TCU088
Chi-Chi_ Taiwan-06	1999	TCU076	6.3	24	615	RSN3472_CHICHI.06_TCU076
N. Palm Springs	1986	Anza - Red Mountain	6.1	38	680	RSN511_PALMSPR_ARM
Notes: * Moment magnitude; ** Joyner and Boore distance metric definition; *** PEER Record name.						

Table 1. Summary of the events and recording station characteristics for the final set of acceleration THs for the 10^{-4} HPB mean UHS target design spectra.

Spectral matching

As mentioned before, one of the project-specific requirements was that each individual set of THs should comply with the ASCE 43-05 spectral fitting criteria (i.e., +30% and -10% of the target spectrum), such that the structural response from each set of THs could be considered independently, rather than having to calculate the mean response. To comply with this requirement, the final sets of scaled time histories selected using SigmaSpectra were “spectrally matched” against the relevant target design spectrum using the software RSPMatch, version 2005 (Hancock et al. 2006).

RSPMatch modifies the acceleration response spectrum of a given time history to match a target spectrum by adding wavelets to the time history in the time domain, while preserving the non-stationary characteristics of the original time history. As an example of the effects of the spectral matching on the THs, a comparison between the scaled and spectrally matched acceleration THs against the 10^{-4} HPB mean UHS, for the 180º azimuth component of the Northridge-01 record (see Table 1), is reproduced in Figure 3.

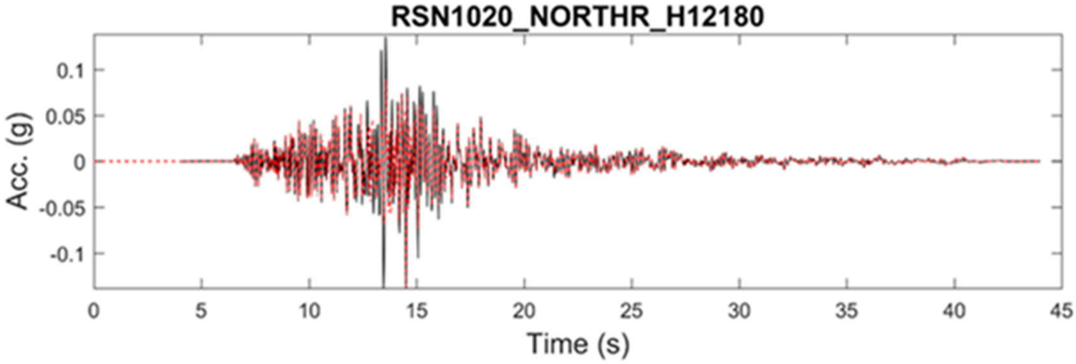

Figure 3. Comparison between the scaled and spectrally matched acceleration THs for the RSN1020_NORTHR_H12 record (180º azimuth component), for the HPB mean UHS.

The resemblance should be noted between the spectrally matched and the original THs in the time domain (Figure 3), with only minor differences observed. Thus, most of the characteristics of a real earthquake recording are preserved after the spectral matching. This is one of the major advantages of using modified recordings from real earthquakes instead of synthetics. Figure 4 shows a comparison between the target spectrum and the response spectra from the scaled and spectrally matched THs, with the spectrally matched THs now fully compliant with the ASCE 43-05 requirements.

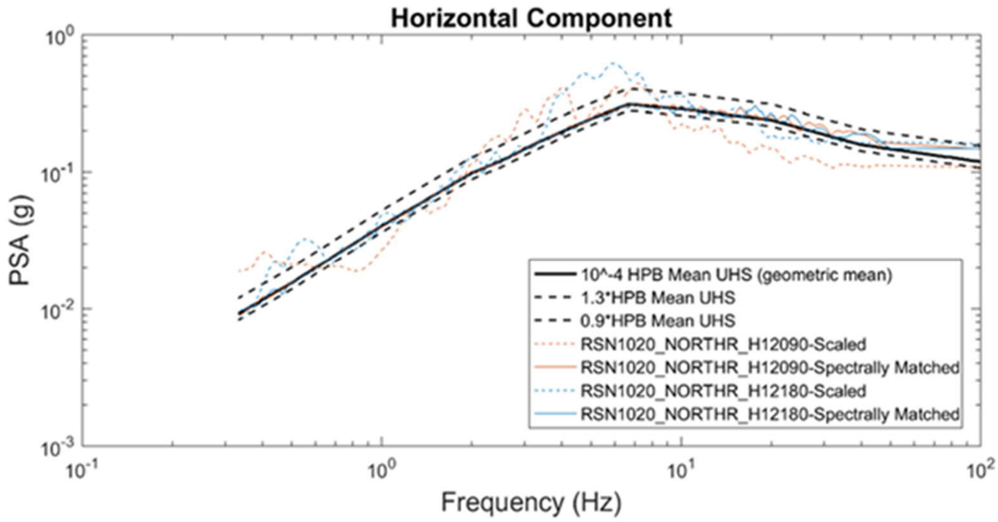

Figure 4. Comparison of the pseudo-acceleration response spectra for the scaled and spectrally matched RSN1020_NORTHR_H12 time histories, horizontal component, against the 10^{-4} HPB mean UHS.

Code Compliance and Measure of Change Checks

A number of ground-motion parameters were calculated for all THs at various stages of the selection and modification process. This was done to ensure sufficient variability of the selected parameters is being captured by the suite or records, and that these fall within the range of values expected for the magnitude-distance range of the controlling scenarios. It also helped to assess the effects of the scaling, spectral matching and post-processing (i.e., clipping, zero-padding and truncation to 30 s length) of the records on the THs and to ensure that no significant deviations from the parameters of the original (seed) records are observed. The following ground-motion parameters were calculated:

- Peak ground acceleration (PGA)
- Peak ground velocity (PGV)
- Peak ground displacement (PGD)
- Arias intensity (I_A)
- 5% to 75% of I_A significant duration [D_S(5-75%)]

The range of values for D_S(5-75%) was based on the recommendations by Aldama-Bustos and Strasser (2019). In the case of PGA, upper and lower limits were taken using ASCE 43-05 bounds (i.e., -10% and +30% of target PGA). The target PGA was available from a site-specific hazard assessment for the HPB site. The target PGA and the upper and lower PGA limits are shown in Figure 4 as PSA for the HPB mean UHS at 100 Hz. Insufficient information was available to constrain the range of values for the other parameters; however, it was checked that sufficient variability remained for these parameters after the scaling and spectrally matching process. Figure 5 shows a comparison of the parameters listed above for the THs for HPB at the various stages of the process.

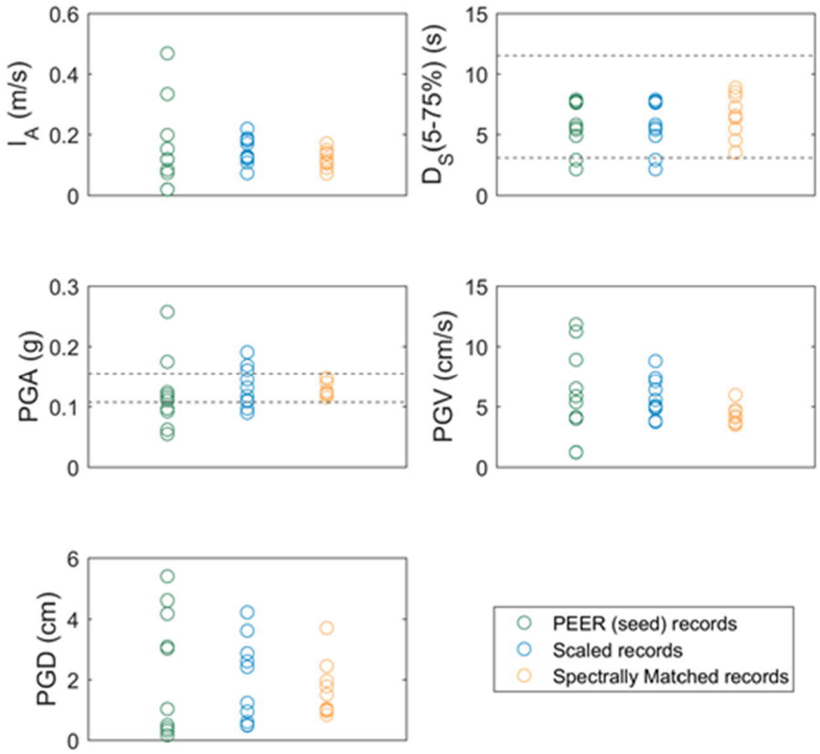

Figure 5. Summary plots of ground motion parameters for the set of records selected for the 10^{-4} HPB mean UHS at various stages of the process: PEER (seed), scaled and spectrally matched records. Dashed lines show recommended parameter ranges where available. All parameters are for the horizontal component of the ground motion.

A comparison of the normalised Husid plots for each component of the set of THs for the HPB site is shown in Figure 6. The variation in the rise of the Arias intensity shown in these figures satisfies the ASCE 43-05 requirement that not all THs should have the same rise time characteristics.

By examination of Figure 5 and Figure 6, and the closeness of the match between the response spectra of the spectrally matched THs and the target spectrum (Figure 4), it can be confirmed that the scaled records, as a suite of records, and the spectrally matched records, individually, comply with ASCE 43-05 and ASCE 4-16 requirements.

In addition to the checks discussed above, an important criterion in the assessment of the adequacy of the selected THs is that the spectral matching process (and any other pre- or post-processing steps) have not modified the original record in an unsuitable manner, resulting in a physically unrealistic time history.

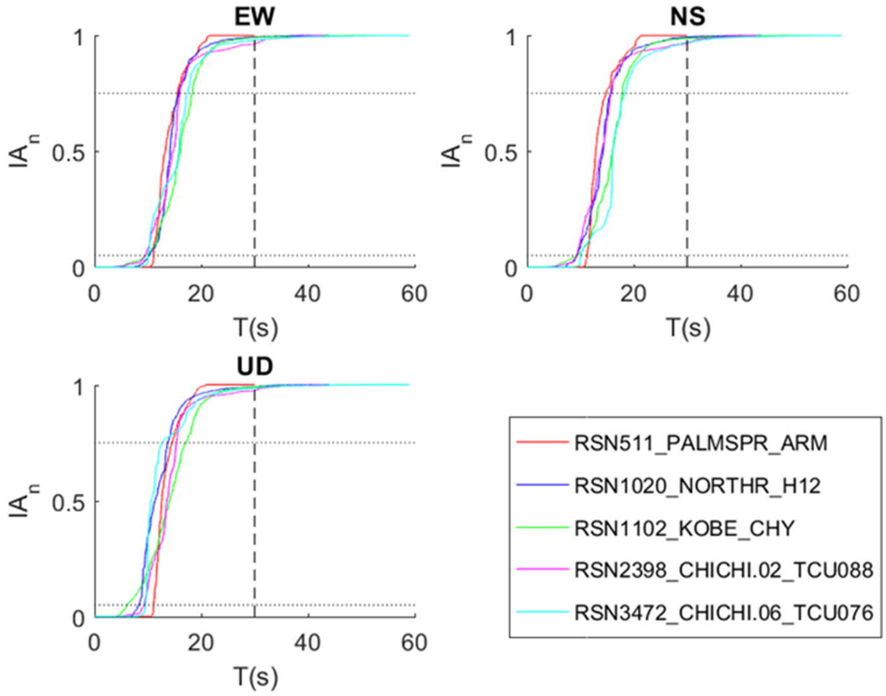

Figure 6. Combined Husid plots for the three components of all sets of TH matched to the 10-4 HPB mean UHS. Vertical dashed lines show the point of truncation for the 30s-length records; horizontal dotted lines show the 5% and 75% of I_A thresholds.

To check this, the parameters for “measure of change” defined in NIST GCR-917-15, Appendix B (NEHRP 2011) were computed and compared with the recommended range of values provided in this same reference. Definitions of these “measure of change” parameters are summarised in Table 2, along with recommended ranges of values provided by NEHRP (2011). NEHRP (2011) further note that the maximum absolute difference parameters Max(ΔAI_{norm}), Max(ΔCSV_{norm}) and Max(ΔCSD_{norm}), which measure the progressive build-up over time of cumulative squared ground motion as illustrated in Figure 7, *“may be the most relevant scalar quantities to check when assessing the quality of the spectrum matching process”*, since they are associated with the most restrictive criteria. These parameters were therefore given priority in the assessment of the adequacy of the spectrally matched records.

Type	Parameter	Description	Range
Peak ground motion parameters	ΔPGA	Ratio of peak ground acceleration in matched time history to seed time history	0.4-1.9
	ΔPGV	Ratio of peak ground velocity in in matched time history to seed time history	0.5-1.7
	ΔPGD	Ratio of peak ground displacement in matched time history to seed time history	0.5-3.8
Cumulative squared ground motion parameters	ΔAI	Ratio of Arias Intensity of matched time history to seed time history	0.4-2.0
	ΔCSV	Ratio of final value of cumulative squared velocity of matched time history to seed time history	0.4-2.7
	ΔCSD	Ratio of final value of cumulative squared displacement of matched time history to seed time history	0.4-7.1
Maximum absolute difference in normalised cumulative	Max(ΔAI_{norm})	Maximum difference over time of cumulative squared acceleration, normalised by final value, between	0.0-0.2

squared ground motion		matched time history and seed time history	
	Max(ΔCSV_{norm})	Maximum difference over time of cumulative squared velocity, normalised by final value, between matched time history and seed time history	0.0-0.2
	Max(ΔCSD_{norm})	Maximum difference over time of cumulative squared displacement, normalised by final value, between matched time history and seed time history	0.0-0.4
Maximum absolute difference in normalised cumulative squared ground motion, aligned in time.	Max(ΔAI_{norm})	Same as Max(ΔAI_{norm}), with times of median normalised cumulative squared acceleration made to coincide.	0.0-0.2
	Max(ΔCSV_{norm})	Same as Max(ΔCSV_{norm}), with times of median normalised cumulative squared velocity made to coincide.	0.0-0.2
	Max(ΔCSD_{norm})	Same as Max(ΔCSD_{norm}), with times of median normalised cumulative squared displacement made to coincide.	0.0-0.4

Table 2. Definition of "measure of change" parameter, with recommended range of values [modified from Tables B-2 and B-6 in NEHRP (2011)].

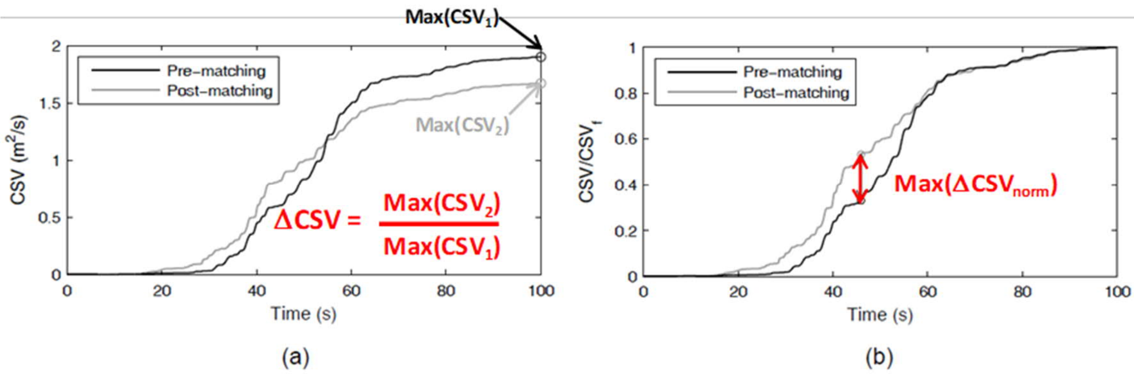

Figure 7. Example definition of "measure of change" parameters based on velocity [modified from Figure B-17 of NEHRP (2011)].

In most cases, the results of the "measure of change" checks fall within or close to the recommended ranges. Records that fell outside the recommended ranges were subjected to an additional visual inspection of the acceleration, velocity and displacement time histories to ensure that the spectral matching and other processing steps had not led to unphysical features in the final record.

Discussion and Conclusions

Suites of five three-component time histories have been developed to match alternative target spectra defined for the HPB and HNB sites. All sets of THs are appropriately compliant with ASCE 43-05 and ASCE 4-16, and additional project-specific requirements. The methodology implemented for the selection and modification of the recorded ground motions followed RGP and benefited from detailed guidelines available in the literature, primarily USNRC guidelines and standards.

The range of magnitudes and distances of the selected events for the various suites of THs, between **M** 5.5-6.9 and 21-50 km R_{JB}, are in good agreement with the magnitude-distance of the controlling scenarios at 10^{-4} AFoE from the disaggregated results of the HPC PSHA [i.e. **M** 5.5-6.5 and 30-50 km R_{JB}; Tromans et al. (2019)]. The small deviations from the magnitude-distance range of the controlling scenarios are well within acceptable levels, and most importantly, the good spread observed from the magnitudes and distances of the selected events provides confidence that the variability of the ground motion associated with the magnitude-distance bins of interest is well captured. In all cases, V_{S30} values correspond to "soft rock" conditions, which are consistent with the ground conditions at the HPB and HNB sites.

One of the main reasons for using modified recorded ground motions for seismic design is to capture the random variability in the ground motion for a given range of magnitude-distance scenarios, which is reflected on the variability on the ground-motion parameters of interest for seismic design associated with such ground-motion records. These parameters include PGA (although the correlation between PGA and structural damage is generally rather poor, it still remains a point of reference for engineers), PGV, PGD, pseudo-spectral accelerations (PSA), D_S(5-75%), I_A and the variation in the rise time of the I_A.

The spread on the values of the parameters plotted in Figure 5 and Husid plots shown in Figure 6, provide confidence on that the random variability of the ground motion, for the magnitude-distance scenarios controlling the hazard at the HPB site, is adequately captured and in full compliance with ASCE 43-05 and ASCE 4-16.

In all cases, differences in the ground-motion parameters listed above between the PEER (seed) files, and the scaled and post-processed spectrally matched records, were within acceptable ranges. The measure of the changes in the ground-motion parameters between the scaled and spectrally matched records, provides an additional level of confidence that the spectrally matched records are a reliable representation of "natural" (recorded) ground motions.

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