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TIME HISTORY GENERATION METHODOLOGY FOR NONLINEAR SITE REPONSE ANALYSIS IN THE UK NUCLEAR INDUSTRY

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Abstract: *Dynamic nonlinear analyses are becoming routine for the seismic design of nuclear facilities and their components. Historically in the UK, synthetic time histories were developed to match the design target spectrum. However, synthetic time histories have limitations, particularly for the analysis of non-linear systems, and they do not capture the natural variability of real seismic events. Foundation studies for the new Bradwell B (BRB) power station project in the UK required site response analysis in advance of the main probabilistic seismic hazard assessment (PSHA), to inform initial assessment of foundation level seismic hazard. The BRB founding strata include a considerable thickness of London Clay which has low stiffness relative to most other UK nuclear power station sites' founding strata. Site response with both synthetic and modified-real time histories was carried out to address the potential for 'overdrive' by synthetic time histories resulting in excessive non-linearity and hysteretic damping in the London Clay. Modified-real time histories were developed to match Conditional Mean Spectra (CMS) selected to envelope on-rock input spectra. Equivalent-linear 1D site response was carried out following a deterministic approach to assess site amplification functions to convolve an on-rock input spectra to foundation levels. From site response analysis results, there was no evidence of excessive non-linearity and material damping in the London Clay when synthetic time histories were used. However, the use of modified-real time histories for site response analysis provided improved certainty in the initial site response assessment, and hence more robust assessment of seismic hazard for use in design.*

Introduction

A partnership between China General Nuclear (CGN) and EDF Energy (EDF) has been developing proposals to construct a nuclear power station at a site near Bradwell, Essex, UK. The ground conditions comprise a significant depth of London Clay which has low strength and stiffness compared to the ground conditions at most of the existing nuclear power station sites in the UK.

A high-level assessment of foundation level design spectrum was undertaken to inform initial seismic analysis of the nuclear island structures before completion of the site's full probabilistic seismic hazard assessment (PSHA). The design spectrum was developed to meet the structural analysis requirements, ONR guidance (Office for Nuclear Regulation (ONR), 2018), and relevant good practice as given by ASCE 43-05 (American Society of Civil Engineers (ASCE), 2005), and ASCE 4-16 (American Society of Civil Engineers (ASCE), 2017). As the purpose of the study was to provide an initial assessment of foundation level motion, several simplifications were made to fully code compliant methods of determining foundation level design spectra.

Historic practice within the nuclear industry has been to use synthetic time histories, generated from filtered white noise to match a target response spectrum (Aldama-Bustos, et al., 2019); (Office for Nuclear Regulation (ONR), 2018a). However, synthetic time histories are now recognised to rarely possess the characteristics of real earthquake recordings and are not best suited for non-linear dynamic analyses (Office for Nuclear Regulation (ONR), 2018a). For site response analysis, the use of synthetic time histories can generate unrealistically high strains in

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the soil column, referred to as 'overdrive' (American Society of Civil Engineers (ASCE), 2017), (American Society of Civil Engineers (ASCE), 2005). In non-linear analysis this can result in unrealistically low soil stiffness and excessive hysteretic damping.

Site response analysis was carried out using both synthetic and modified-real time histories to assess the motion at foundation level. Due to programme constraints, synthetic time histories were initially used for site response analysis. Modified-real time histories were used to check the potential development of overdrive in the low stiffness soil profile.

This paper discusses the site response analysis methodology and limitations, for the derivation of the foundation level design spectra, using both synthetic and modified-real time histories. The horizontal site response from the synthetic and modified-real time histories are compared.

Methodology

The methodology for the development of the foundation level design spectrum comprised:

1. Matching synthetic and modified-real time histories to the on-rock Uniform Hazard Response Spectra (UHRS)
2. Conducting deterministic site response analysis to determine on-rock to foundation level amplification functions
3. Determination of foundation level spectra using the amplification functions to from synthetic and modified-real time history convolutions.
4. Calculate of the foundation level design spectrum, taken as the more onerous of:
   a. UHRS for annual frequency of exceedance of 1x10^{-4} (84th percentile) at foundation level.
   b. Design Earthquake Response Spectra (DRS), determined from the change in accelerations between the mean UHRS for annual frequency of exceedance of 1x10^{-4} and 1x10^{-5}.

   Further discussion on the basis of the design spectrum is provided in the following sections.

Determination of on-rock synthetic time histories

Six synthetic time histories were derived in accordance with ASCE 43-05 (American Society of Civil Engineers (ASCE), 2005) criteria to fit the on-rock UHRS. Time history duration was determined as a function of magnitude criteria, using guidance as given in ASCE 4-98 (American Society of Civil Engineers (ASCE), 2000), as there is no information on synthetic time history generation and duration in ASCE 4-16 (American Society of Civil Engineers (ASCE), 2017). Earthquake magnitude was assessed based on disaggregated hazard. Time histories were generated to match the UHRS within the following bounds given by ASCE 43-05 (American Society of Civil Engineers (ASCE), 2005):

- The average of the spectra of the suite of motions to be > 90% of the UHRS
- The average of the spectra of the suite of motions to be < 130% of the UHRS
- Above criteria applied over frequency range 0.2 – 25 Hz

Determination of on-rock modified-real time histories

Modified-real time histories were developed based on the on-rock UHRS. ASCE 43-05 (American Society of Civil Engineers (ASCE), 2005) and ASCE 4-16 (American Society of Civil Engineers (ASCE), 2017) require real time histories are enveloped or matched to target spectra. Conditional mean spectra (CMS) (Baker & Cornell, 2006) were adopted to represent the on-rock UHRS target spectra. The use of CMS is consistent with ASCE 43-05 'spectral shapes' of the characteristic events and is recommended in the literature (National Institute of Standards and Technology (NIST), 2011); (FEMA P-58-1, 2012); (Office for Nuclear Regulation (ONR), 2018a).

The CMS represents the expected response spectrum for the defined ground motion scenario, which is based on a target spectral acceleration value at a user-specified single frequency, as well as its associated magnitude M, Distance R and epsilon (ε) and a number of motion characteristics, such as the type of fault, the average shear wave velocity for the upper 30m, V_{s30} etc. Epsilon ε is a measure of the deviation of the UHRS from the mean spectral acceleration from the ground motion prediction equation (GMPE) at a given frequency and indicates the spectral shape.

To fully represent the UHRS, several CMS were utilised at differing target frequencies to bound the UHRS at all frequency ranges. Each calculated CMS was scaled to match the target spectrum at the selected target frequency.

The key steps for the calculation of the horizontal CMS (FEMA P-58-1, 2012) are given below:

1. Determine target spectral acceleration based on a PSHA at the required annual frequency of exceedance.
2. Disaggregate the hazard at the target spectral acceleration value and identify the dominating M, R and ε.
3. Select an appropriate GMPE to generate the CMS.
4. Generate spectrum using CMS expressions and the selected GMPE (equation 1).
5. Scale the CMS to give the target spectral acceleration as per the UHRS.

The CMS at a target period T_i^* can be computed using the following equation (Pacific Earthquake Engineering Research (PEER), 2009):

$$\ln Sa_H(T_i^*) = \overline{\ln Sa_H}\,(M,R,T_i) + \sigma_{\ln Sa_h}(T_i) \times \overline{\varepsilon_H}(T_i) \tag{1}$$

Where:

$\overline{\ln Sa_H}\,(M,R,T_i)$: mean ln of target spectral acceleration from GMPE.

$\sigma_{\ln Sa_h}(T_i)$: standard deviation of ln of target spectral acceleration from the GMPE at the target period.

The BSSA14 GMPE model (Boore, et al., 2014) was used in the present calculation as this was used in the UHRS calculation. No epsilon ε values were available in the disaggregated hazard information, and hence ε was taken as zero, hence no deviation from the median prediction was considered. This means the CMS may not be fully consistent with the UHRS. The geometric mean of the two horizontal time history components was used as the ground motion parameter for the CMS and time history selection, as most GMPEs, and hence the CMS, are defined in terms of geometric mean (geomean) spectral response accelerations.

The real time histories (seed motions) were selected based on the characteristic earthquake parameters (magnitude M, and distance R), to be consistent with the site conditions and in agreement with the ASCE 43-05 (American Society of Civil Engineers (ASCE), 2005) criteria for time history selection, where possible.

The time history selection criteria were:

- Magnitude (M) / distance (R) bins: a magnitude within ±0.5 and a source to site distance based on 0 – 10km, 10 – 50km and 100 – 200km ranges were selected as per USNRC (United States Nuclear Regulatory Commission (U.S.NRC), 2001).
- Motion duration: records were selected to have 5% to 75% of Arias intensity duration consistent with magnitude M and distance R. A minimum overall duration of 20s was chosen.
- Time increment: a maximum time step of 0.01s was selected to achieve a Nyquist frequency of at least 50 Hz as per ASCE 43-05 (American Society of Civil Engineers (ASCE), 2005).
- Shear wave velocity V_{s30}: a range between 760 and 3000 m/s was preferred, to be consistent with the chalk bedrock at the site, expanding to 360 m/s on the lower bound in cases of limited number of potentially suitable records
- Fault type: strike slip and normal fault types were chosen to match the general intraplate tectonic regime in the UK
- Spectral acceleration S_a(g): when possible, motions were selected with spectral accelerations close to CMS S_a at the target frequency to minimise motion modification. Initially limiting scale factors of approximately 0.75 to 1.5 were considered (i.e. spectral accelerations within 20 – 30% of the CMS S_a), but this was increased to 0.5 to 3.5 to give adequate number of time histories
- Spectral shape: ground motions were selected which has a spectral shape similar to the target spectrum over the period range of interest to minimise modification in later stages and to allow motions to maintain their characteristics.
- Number of motions: seven time histories were selected for each CMS to provide reasonable representation of earthquake variability (Haselton, et al., 2012) which meets the minimum code recommendations USNRC (United States Nuclear Regulatory Commission (U.S.NRC), 2001). A maximum of one record from the same earthquake was considered to increase variability.

Following selection of time histories, the raw data were baseline corrected to ensure the ground velocity is zero at the end of the motion and filtered with a Butterworth (band pass) filter of 0.1 Hz to 50 Hz to remove any high and low frequency noise. The data were then modified to match the CMS over the frequency range of interest using SeismoMatch software and considering the wavelet method (Atik & Abrahamson, 2010). Spectral matching was separately carried out for each horizontal component of the motions to the geometric mean. As the two horizontal components are both matched for the geomean, this may result in slight increase in the two components than if matching was carried using the geomean of the two horizontal components. The matching was carried out using the same ASCE 43-05 (American Society of Civil Engineers (ASCE), 2005) matching criteria adopted for the synthetic time histories.

Site response analysis

The convolution of the on-rock UHRS to foundation level was carried out using spectral amplification functions. These amplification functions were determined from deterministic site response analysis, using the time history method, considering both the on-rock synthetic and the modified-real time histories separately. Due to programme constraints and a compressed scope of works, the site response analysis was initially based on synthetic time histories to expedite the assessment. Parallel to this approach, modified-real time histories were developed to address the potential for overdrive effects, an initial concern for use of synthetic time histories fitted to UHRS for a relatively low stiffness site.

The site response analysis was undertaken using equivalent linear analysis using SHAKE software, which is based on 1D frequency domain analytical solutions. Input motions were applied as outcrop seismic motions and a 50 Hz frequency cut-off was used in analysis.

A deterministic approach (American Society of Civil Engineers (ASCE), 2017), with analysis of lower bound (LB), best estimate (BE) and upper bound (UB) soil stiffness profiles, was adopted to capture the effects of soil property variability. LB of BE divided by (1 + C_v), and UB of BE times (1 + C_v) were used, with a C_v of 1.0 adopted. For analysis using modified-real time histories, average amplification functions were determined from the results. This approach allows for the potential increased stiffness degradation for the lower bound stiffness, which may modify the overall site response. For analysis using synthetic time histories, due to time constraints, analysis was only carried out using the BE profile. It is noted the deterministic treatment in site response analysis may not capture the full range of variation in soil parameters and hence lead to underestimation of the site response.

Determination of foundation level design spectra

The ONR (Office for Nuclear Regulation (ONR), 2018) recommends the starting point for the Design Basis Earthquake (DBE) is the seismic motion associated with the 84th percentile of the on-rock UHRS with annual frequency of exceedance of $1x10^{-4}$, derived from a PSHA. ASCE 43-05 (American Society of Civil Engineers (ASCE), 2005) states the DRS should be based on the on-rock UHRS associated with a hazard level with annual frequency of exceedance of $1x10^{-4}$, with the spectra increased to achieve a target performance level. The increase applied to the UHRS is a function of the change in UHRS spectral accelerations between an annual frequency of exceedance of $1x10^{-4}$ and $1x10^{-5}$.

The sequence for convolution of UHRS to foundation level is summarised below:

1. Carry out site response analysis using on-rock synthetic or modified-real time histories (spectrally matched to target spectra) to give time histories at foundation level.
2. Determine response spectra for individual time histories at rock and foundation level.
3. Determine mean spectral amplification functions from individual time history spectral amplification functions from on-rock and foundation level spectrum, as per equation 2.
4. Apply mean spectral amplification functions to on-rock UHRS to give foundation level UHRS.

$$\text{Spectral amplification function} = \frac{\text{Spectral acceleration}\left(\text{Sa (f)}\right)\text{ foundation level}}{\text{Spectral acceleration}\left(\text{Sa (f)}\right)\text{ on} - \text{rock}} \qquad (2)$$

This approach of convolving specific UHRS at different annual frequency of exceedances does not explicitly integrate the PSHA and site response analysis (as per Approach 3 & 4 as given in ASCE 4-16 and USNRC 2001). Hence the approach may underestimate the amplification functions compared to more rigorous methods.

Input parameters

Ground conditions

The ground model and material properties for the analysis are presented in Table 1. The Newhaven Chalk Formation was considered as bedrock for the purposes of this analysis. The stiffness degradation and damping change curves for the different units are based on published correlations (Darendeli, 2001) benchmarked against resonant column testing.

Stratum	**Elevation**		**V_s**		**V_p**	
	Top (mOD)	**Base (mOD)**	**Top (m/s)**	**Bottom (m/s)**	**Top (m/s)**	**Bottom (m/s)**
Superficial Deposits	5.5	2.0	150.0	150.0	1550[1]	1550[1]
Weathered London Clay	2.0	-3.0	150.0	150.0	1550[1]	1550[1]
London Clay – Aveley Member	-3.0	-13.5	150.0	180.8	1550[1]	1575[1]
London Clay – Ockendon Member	-13.5	-26.0	180.8	217.5	1575	1605
London Clay – Walton Member	-26.0	-40.5	217.5	260.0	1605	1640
Harwich Formation	-40.5	-54.0	260.0	380.0	1640	1770
Woolwich Formation	-54.0	-55.5	380.0	380.0	1770	1770
Reading Formation	-55.5	-59.0	380.0	380.0	1770	1770
Upnor Formation	-59.0	-66.0	280.0	370.0	1626	1700
Thanet Formation	-66.0	-83.0	370.0	550.0	1700	1770
Newhaven Chalk Formation	-83.0	-	1080.0	-	2350	-

Note: 1. V_p values consistent with ground water near ground level.

Table 1. Ground Model

On-rock horizontal UHRS

Horizontal on-rock UHRS and disaggregated hazard information were based on preliminary seismic hazard studies. The horizontal on-rock UHRS are presented in Figure 1.

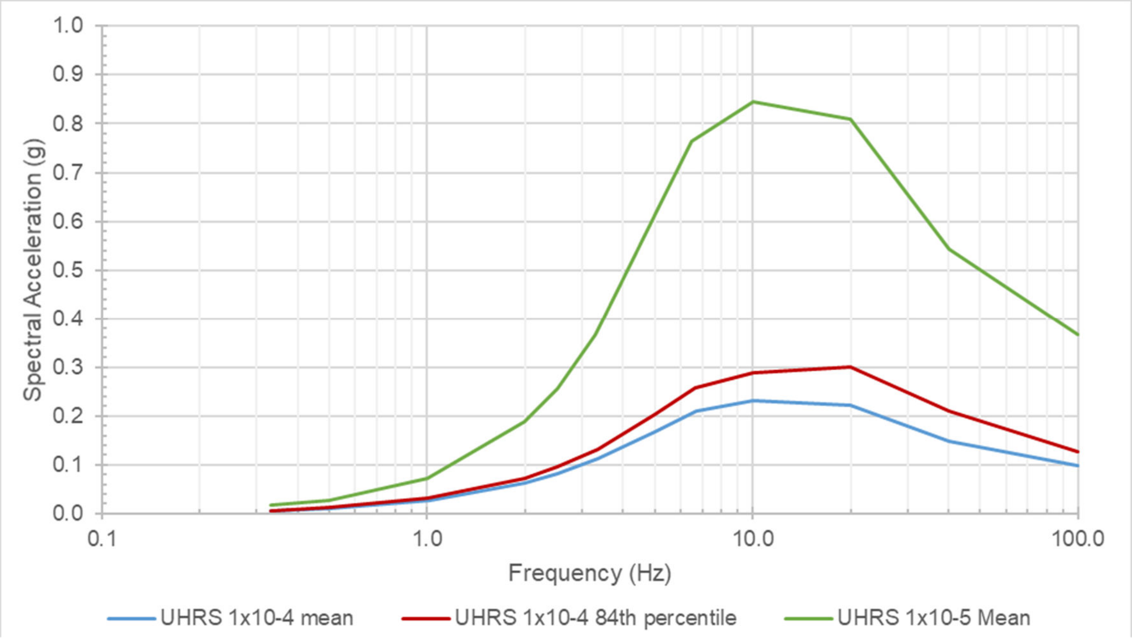

Figure 1. On-rock horizontal UHRS for annual frequency of exceedance of $1x10^{-4}$ mean, $1x10^{-5}$ mean and $1x10^{-4}$ 84th percentile

Results

On-rock synthetic time histories

Six synthetic time histories were fitted to match the on-rock horizontal mean UHRS spectra for annual frequency of exceedance of 1 x 10^{-4} (Figure 2). Time histories were derived with a total duration of 11s, based on ASCE 4-98 guidance (American Society of Civil Engineers (ASCE), 2000) and a minimum time step of 0.01s to have a Nyquist frequency of 50Hz.

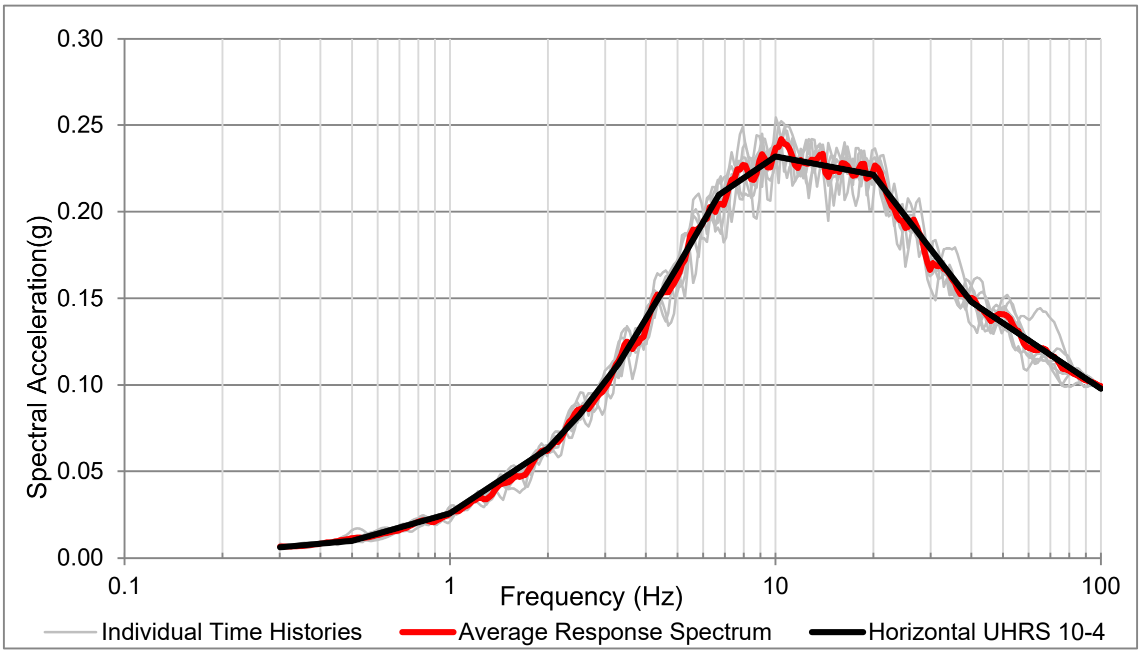

Figure 2. Synthetic time histories (marked in light grey) matched for the on-rock horizontal UHRS for annual frequency of exceedance of 1x10^{-4} mean

On-rock modified-real time histories

Following ASCE 43-05 (American Society of Civil Engineers (ASCE), 2005), high and low target frequencies were adopted, with values selected to suit the disaggregated hazard information and the CMS calculations. The results from the preliminary site seismic hazard study gave disaggregated hazard information for the on-rock UHRS for high and low frequency ranges. A low and high target frequency of 2 Hz and 6.67 Hz respectively was selected for the CMS, close to the median values of the ranges considered in the hazard study.

A check of the CMS using the 2 Hz and 6.67 Hz target frequencies found that the envelope fell more than 10% below the on-rock UHRS and hence a further target frequency has been adopted at 20 Hz to meet or exceed the UHRS over suitable frequency range, following ASCE 43-05 requirements (American Society of Civil Engineers (ASCE), 2005). The CMS for target frequency of 20 Hz has spectral acceleration values generally greater than the UHRS and other CMS. However, from inspection of the resulting amplification functions (Figure 5), this CMS does not give significantly differing amplification and so was included in the analysis.

Horizontal CMS for annual frequency of exceedance 10^{-4} are given in Figure 3.

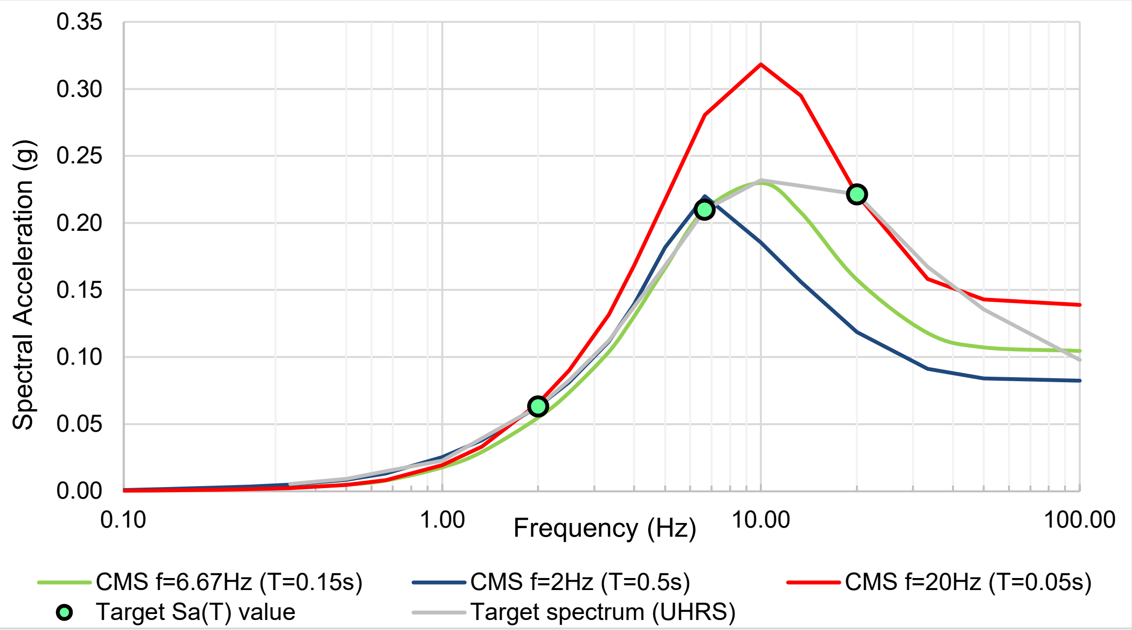

Figure 3. Horizontal on-rock CMS compared to the on-rock horizontal UHRS for annual frequency of exceedance of 1x10^{-4} mean (target frequency 2Hz, 6.67Hz and 20Hz)

Seven earthquake records consisting of two horizontal time histories were selected for each CMS, a total of 21 earthquakes for each UHRS. An example of one horizontal time history seed motion pre filtering and matching and the real-modified motion after the filtering and matching process for the CMS of target frequency of 2 Hz is given in Figure 4.

Site response convolutions

Comparing amplification functions for synthetic and modified-real time history analysis on Figure 5 results are in general agreement although at high frequencies, above approximately 20 Hz, differences in amplification functions are observed. Synthetic time history results show distinct peaks, associated with fundamental periods of the best estimate soil profile (the only soil profile considered) (grey line in Figure 5). Similar peaks are also observed in the amplification function of the modified-real time history best estimate soil profile results which are the average of the three CMS (black dashed line in Figure 5). However, they are not seen in the average modified-real time history analysis results due the averaging of the lower bound, best estimate and upper bound results.

For the modified-real time history analysis, the average amplification functions (average of the LE, BE and HE soil profiles) for the three CMS show similar results for the full frequency range.

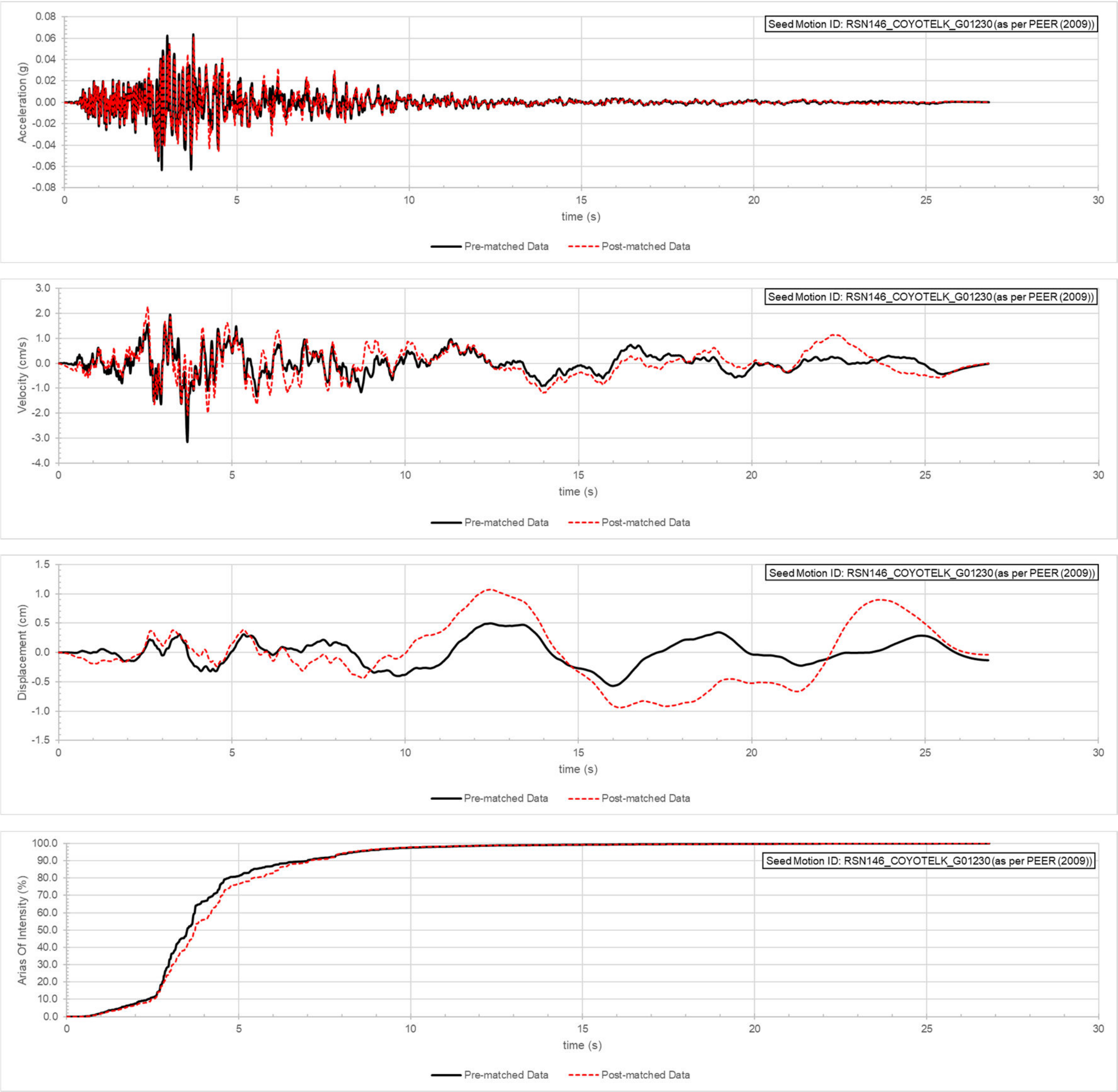

Figure 4. Single horizontal seed motion before and modified-real motion after the filtering and matching process for annual frequency of exceedance of 1x10^{-4} mean (CMS target frequency 2 Hz)

Differences between the real-modified and synthetic time history amplification functions above approximately 20 Hz is considered due to reduced accuracy of the convolution for higher frequencies. The accuracy of the convolved spectra (at foundation level) is reduced due to numerical limitations in the analysis, particulalry due to the filtering applied to the modified-real time histories and the frequency limits of the site response analysis.

The converged soil stiffness and damping with depth from the site responses analyses for the modified-real time history analysis and synthetic time history analysis are similar. This is consistent with the similar amplification functions between the two sets of analysis and indicates similar degrees of stiffness degradation and hysteretic damping in both the synthetic and modified-real convolutions, suggesting that that synthetic time history overdrive is not a significant issue for this site.

The UHRS for annual frequency of exceedance of 1x10^{-4} (84th percentile) at foundation level had lower spectral accelerations compared to the DRS at foundation level, therefore the latter was adopted as the foundation level design spectrum.

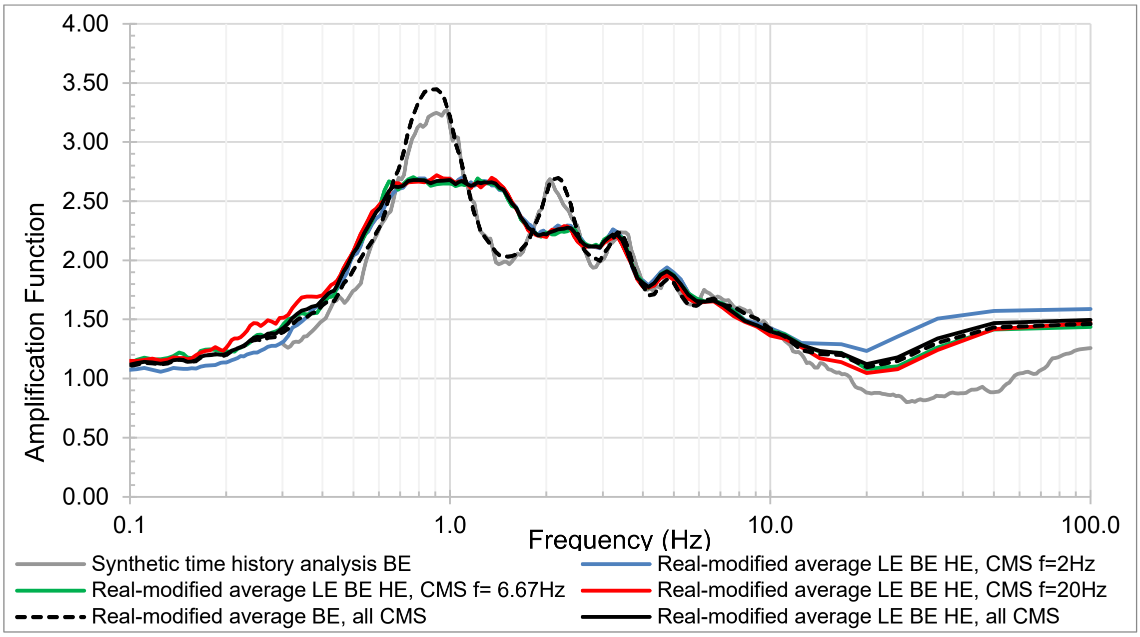

Figure 5. Amplification functions for real-modified site response analysis and synthetic time history site response analysis for annual frequency of exceedance of 1x10^{-4} mean

Conclusion

To determine initial foundation level design spectrum for the BRB power station project in the UK, a site response analysis was undertaken using both synthetic and modified-real time histories. Synthetic time histories were generated to match the on-rock UHRS. Earthquake time histories were selected and spectrally matched to CMS to envelope the on-rock UHRS to generate the modified-real time histories. Site response analysis was carried out to provide amplification functions used to convolve the on-rock UHRS to foundation level to calculate a foundation level design spectrum.

A number of assumptions and simplifications were made for the purposes of this initial study. In particular the response analysis was carried out following a deterministic approach, and the method used of convolving specific UHRS at different annual frequency of exceedances does not explicitly integrate the PSHA and site response analysis. These simplifications mean the assessment may not capture the full range of variability in response and hence approximates the hazard compared to a full probabilistic site response.

The study was carried out using preliminary seismic hazard data which did not include disaggregated epsilon (ε) values. Epsilon values were taken as zero, hence no deviation from the median prediction was considered. This means the CMS may not be fully consistent with the UHRS. These limitations on input data result in uncertainty in the resulting foundation level design spectra.

The two approaches undertaken for the site response analysis showed similar amplification function results, deviating only for frequency ranges higher than 15 Hz. For these site conditions and levels of seismic motion, site response analysis using synthetic time histories gave similar results with no evidence of overdrive, and hence could be used for the purpose of determining amplification functions. The use of modified-real time histories fitted to CMS provided robust confirmation of the site response analysis and increased certainty in the assessment of foundation level spectra.

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