Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
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A probabilistic site response analysis for Wylfa Newydd, a new nuclear power plant in the UK

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ABSTRACT: Good practice for defining the surface response spectra (RS) in a seismic hazard assessment often requires two steps: a probabilistic seismic hazard assessment (PSHA) at bedrock level and a site response analysis (SRA) that accounts for the amplification of the near surface deposits. The soil profile is typically modelled accounting for its variability in a simplified way (best estimate, lower and upper bounds of the soil properties, as per ASCE4-98). The uniform hazard response spectra (UHRS) at bedrock derived from the PSHA are then scaled by amplification factors (AFs) derived from the SRA. This approach produces a RS on the surface that is not associated with a uniform annual probability of exceedance. To overcome this limitation, at Wylfa Newydd a probabilistic SRA was performed site using a Monte Carlo approach to characterize the soil profile and by then convolving the bedrock hazard curves with the probability distribution of the AFs to generate surface hazard curves, following ASCE4-16.

The study was carried out using equivalent-linear one-dimensional SRA with a random vibration theory (RVT) approach. The input motions were defined as response spectra for 12 earthquake scenarios based on the PSHA deaggregation for a suite of spectral frequencies and annual probabilities of exceedance. The input soil profile and its uncertainty were based on a large dataset of in-situ and laboratory geotechnical tests. The Monte Carlo method was used to simulate 500 random realizations for each earthquake scenario where the shear wave velocity (V_S), the thickness of the layers, the depth to bedrock, and the nonlinear properties (G/G_0 and damping) were randomized. The effect of a non-uniform thin layer (0-5m) of superficial soil deposit (V_S~450m/s) on the AF was quantified and incorporated in the study.

The resulting surface UHRS show significant amplification at high frequencies (>10Hz) due to resonance in the thin glacial till layer exacerbated by the impedance contrast with the underlying rock. The results were compared with simplified approaches. A deterministic SRA where only the best estimate, upper and lower bounds of the soil properties are adopted could not account for the overall uncertainty and would not be able to properly model the variability of the till layer thickness. The resulting surface RS is strongly dependent on the assumed input with a peak at the fundamental frequency of the superficial soil layer. When a probabilistic SRA is performed but only the median AF is adopted, the surface RS is underestimated.

1 INTRODUCTION

Nuclear energy is an important part of a sustainable, economic and secure energy balance for the United Kingdom (UK), HM Government (2013). Ove Arup and Partners Ltd. (Arup), supported by the British Geological Survey (BGS), was appointed by Horizon Nuclear Power (Horizon) to provide Seismic Hazard Assessment (SHA) Consultancy Services for the proposed Wylfa Newydd Nuclear Power Plant on the Isle of Anglesey, North Wales. Horizon will be constructing Advanced Boiling Water Reactors to provide at least 5,400MW, enough to power

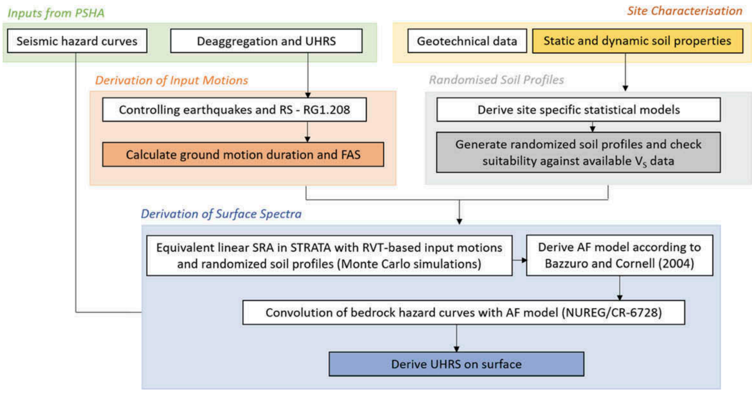

Figure 1. Flowchart of the methodology followed in this study.

around 10 million homes. The SHA comprised a probabilistic seismic hazard assessment (PSHA) of ground motion, a tsunami hazard assessment and a capable faulting assessment.

The PSHA was defined at a bedrock outcrop with a V_S of 3,000m/s, which corresponds approximately to a depth between 80-100mOD. This study presents the site response analysis (SRA) performed to compute the surface spectra starting from the uniform hazard response spectra (UHRS) at bedrock, derived by the PSHA.

In standard SRA, the soil profile is modelled accounting for its variability in a simplified way using the best estimate, lower and upper bounds of the soil properties, as per ASCE4-98. The UHRS at bedrock derived from the PSHA are then scaled by amplification factors (AFs) derived from the SRA. This approach produces a response spectrum (RS) on the surface that is not associated with a uniform annual probability of exceedance. To overcome this limitation, NUREG/CR-6728 Approach 3 (McGuire et al. 2001) was selected for this study since it is a probabilistic framework of incorporating site amplifications and it generates soil hazard curves from the integration over rock hazard curves. The general methodology used in this study is summarized in Figure 1.

The program Strata (version 0.5.8-3e3a7fd) by Kottke & Rathje (2009) was used to perform the analysis. Strata is an open source code allowing users to understand the program in detail and aids in the verification and validation process.

2 SITE CHARACTERIZATION

The site characterization was based on the interpretative Ground Investigation Reports by Atkins (2017a and b). Figure 2(a) shows the location of the in situ geophysical tests and geological cross sections, performed within the development platform. These were used to characterize the site considering a finished ground elevation of +18mOD.

The site is underlain by superficial deposits of predominantly glacial origin overlying metamorphic rock of late pre-Cambrian and Cambrian age with some minor intrusions of Paleozoic and Tertiary age. The superficial deposits are generally composed of glacial till deposits (~85%), granular deposits (12%) and the rest are periglacial, lacustrine and alluvium deposits. The available cross sections show that the thickness of the superficial deposits (between rockhead elevation and +18mOD) varies across the area and it is thicker toward north west, between 6 to 18m and decreases towards the south. Near the reactor buildings, the thickness of the superficial deposits ranges from 0m to 5m with an average of 2m.

Based on downhole and crosshole seismic tests, an increasing V_s profile with a V_s value of 450m/s at 2m and of 675m/s at 22m is adopted. The model of Darendeli & Stokoe (2001) was modified to fit the available data with an overconsolidation ratio (OCR) of 2, a plasticity index of 13% and σ_o'=12kPa.

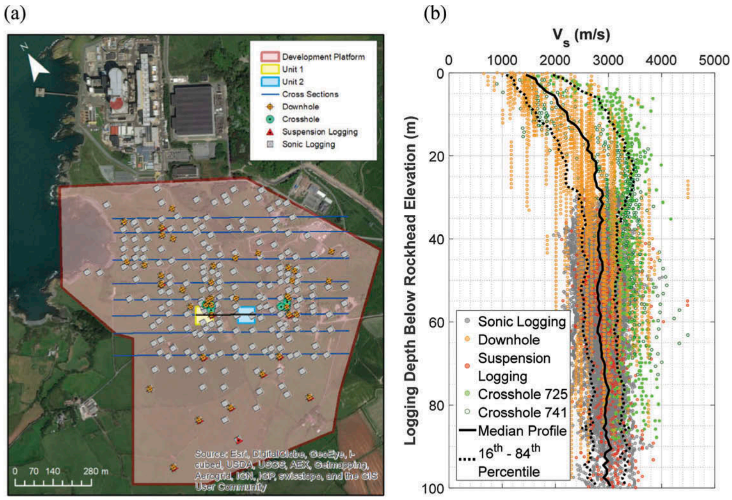

Figure 2. (a) Location of the Development Platform, reactors buildings (Units 1 and 2), available cross sections and ground investigation (GI) data. (b) V_s profiles from the single GI datasets and median and variability over all datasets (black).

The rock underlying the area consists of metamorphic rocks of the New Harbour Group (NHG), described as fresh to slightly weathered, medium strong to strong, interbedded phyllite and psammite. Atkins (2017a) classified most of rock mass (~90%) as good quality metamorphic rock. Some portion of weathered and fractured rock was observed, mainly at depths close to rockhead elevation, which varies varies from 0 to 20mOD.

A total of 183 sets of V_S interpretations were made available to Arup at the time of this study (Atkins 2017a, b) and are shown in Figure 2(a): downhole (40 tests), crosshole (24), sonic logging (107) and suspension logging (12). All the Vs profiles are shown in Figure 2(b) along with their median and variability. The median V_S profile varies from 1,500 at 0mOD to about 3,000m/s at approx. 70mOD. The two crosshole sets (741 and 725) are shown separately in the figure to highlight significant scatter in the V_S values in the top section of rock. According to Atkins (2017a), both the sonic logging and the suspension logging tests are considered reliable only for depths below -25mOD.

The G/G_0 curve by Worthington et al. (2001) for sedimentary rock, with fitting parameters B=10,000 and n=0.5, was recommended by Atkins (2017a) along with a consistent damping curve. The minimum damping was selected considering the recommended value by Atkins (2017a) of 1.5%, the recommended minimum limit in ASCE/SEI4-16 when no data are available for the site of 2% and the consistency with the kappa value (attenuation of the high frequency in the Fourier Amplitude spectra) used for the PSHA at bedrock. A value D_{min} of 1.5% was deemed appropriate for the analysis.

Both for the superficial deposit and for the NHG, damping curves were constrained at large strains with the maximum critical damping value of 15% in accordance RG1.208.

2.1 *Randomization of the soil profiles*

Based on statistical analyses of the Wylfa GI data, past studies (Rodriguez-Marek et al. 2014) and Strata (Kottke & Rathje 2009), a lognormal distribution was assumed to model the V_S data.

As part of the randomisation process, two parameters were defined:

- the interlayer correlation coefficient (ρ) which measures the correlation of the V_S at adjacent layers (Toro 1995). This was computed using downhole and crosshole datasets and a value of 0.8 was found.

- The average layer transition rate (λ) which represents the number of layer boundaries per meter. Following Toro (1995), the generic depth dependent layer transition rate model was used $\lambda\ (d) = a\ (d + b)^c$ and the coefficients a, b, and c were computed based on the Wylfa profiles for till and rock.

Uncertainties in the G/G_0 and damping curves were included by randomizing the Worthington et al. (2001) curves assuming a lognormal distribution of the standard distribution and the SPID (Screening Prioritization and Implementation Details, Coppersmith et al. 2014) sigma model.

3 SITE RESPONSE ANALYSIS

The study was carried out using equivalent-linear one-dimensional SRA with a random vibration theory (RVT) approach as presented in Figure 1. In the RVT, the input motions are Fourier amplitude spectra defined through the two inputs: (1) a response spectrum of controlling earthquake scenarios and (2) the corresponding durations.

The controlling earthquakes represent the scenarios most likely to affect the site and are determined by deaggregating the mean hazard PSHA results. Following RG1.208 (US NRC, 2007) the controlling earthquakes should be defined at 10^{-4}, 10^{-5} and 10^{-6} APE for spectral frequencies of 1, 2.5, 5 and 10Hz. In addition to these scenarios, the 10^{-2} APE was included in the analysis to ensure the regression of the amplification function is constrained at low bedrock accelerations. Moreover, a spectral frequency of 20Hz was included, since it corresponds to the peak of the bedrock response spectrum. The resulting controlling earthquake scenarios are shown in Table 1. The earthquake scenario response spectra are derived using the same logic tree for the ground motion characterization adopted for the bedrock PSHA. The earthquake scenario response spectra are then scaled to match the bedrock UHRS at 20Hz, 7.5Hz (5-10Hz) and 1.75Hz (1-2.5Hz). Figure 3 shows two examples for 10^{-4} and 10^{-5} APE.

The ground motion duration (T_{gm}) is calculated as a function of the epicentral distance, R_{epi}, and the corner frequency, f_c (Brune 1970) as $T_{gm} = \frac{1}{f_c} + 0.05R_{epi}$.

3.1 *Sensitivity analyses*

Prior to defining the final ground motion model and the parameters for the Monte Carlo simulations, sensitivity analyses on the impact of the definition of the ground motion models and the type and number of Monte Carlo simulations were performed. The sensitivity analyses are described below and shown in Figure 4 in terms of amplification factor (AF) for the APE of 10^{-4}.

Table 1. Earthquake scenarios for the SRA for four annual probabilities of exceedance and three spectral frequency ranges.

APE	Scenario	f_1-f_2 (Hz)	R_{epi} (km)	M_W	f_c (Hz)	T_{gm} (s)
10^{-2}	Scenario 1	20	45.7	5.9	0.4	4.7
	Scenario 2	5 to 10	51.7	5	1.1	3.5
	Scenario 3	1 to 2.5	66.1	5.2	0.9	4.4
	Scenario 4	1 to 2.5 (R>100km)	168.5	5.5	0.6	10.0
10^{-4}	Scenario 1	20	25.5	5.7	0.5	3.2
	Scenario 2	5 to 10	29.5	5.8	0.4	3.8
	Scenario 3	1 to 2.5	40	6.1	0.3	5.0
10^{-5}	Scenario 1	20	18	5.8	0.4	3.2
	Scenario 2	5 to 10	22	6	0.4	3.8
	Scenario 3	1 to 2.5	32.5	6.2	0.3	5.3
10^{-6}	Scenario 1	20	12	5.9	0.4	3.2
	Scenario 2	5 to 10	15	6.1	0.3	3.7
	Scenario 3	1 to 2.5	25	6.3	0.2	5.4

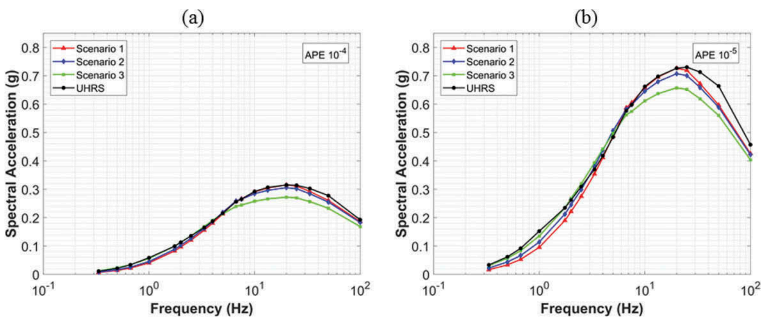

Figure 3. Earthquake Scenario Response Spectra for 10^{-4} (a) and 10^{-5} (b) APE

a. Impact of the definition of the rock V_S profile. Sensitivity studies were performed using: (1) the single datasets of downhole and crosshole; (2) a median V_S profile from the downhole and crosshole datasets and (3) a median V_S profile from all datasets. Figure 4(a) shows the median, the 16th and the 84th percentiles of the AFs. The median using all the datasets leads to slightly lower results, however the percentage difference is low (<5%). This has been adopted in the final SRA.
b. Since the thickness of the superficial deposits is highly variable within the studied area, between 0 and 18m, only the area close to the reactors buildings was herein used where the thickness it varies between 0 and 5m. The following cases were analyzed: till thickness of 0m (only rock), 2m, 3m, 5m, and 2m thick glacial till layer with layer thickness randomization. Figure 4(b) shows the results for the 10^{-4} APE. As expected, the AFs with no superficial deposits are close to 1. As the thickness of the superficial deposits increases AFs increase and the predominant frequency decreases from 50 to 20Hz for 2 and 5m of superficial deposits respectively. The inclusion of the layer thickness randomization with 2m

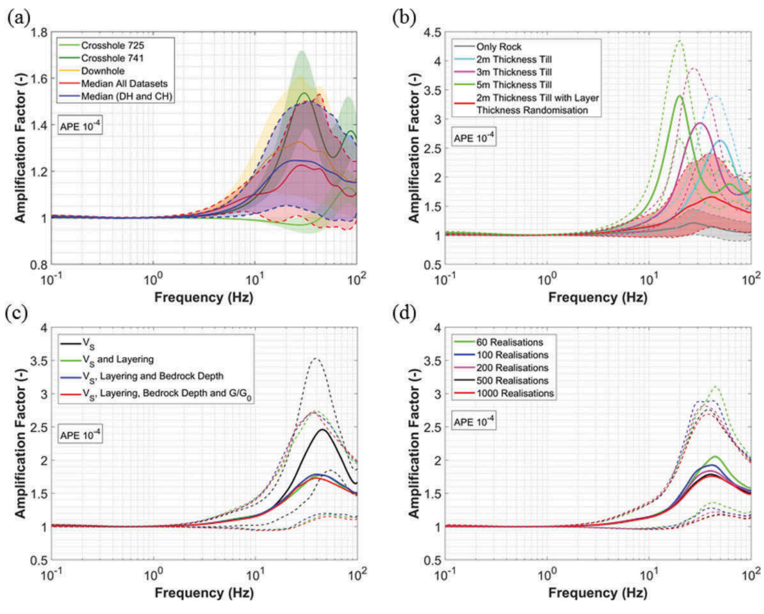

Figure 4. (a) Impact of the definition of the rock Vs profile; (b) Impact of the type of randomizations. (c) Impact of the modelling of the superficial deposits. (d) Impact of the number of Monte Carlo simulations.

glacial till allows reflects the variability of the thickness within the examined area since the randomized profiles have a till layer between 0 and 5m. The resulting AFs are shown in red in Figure 4(b) along with their band of variability.

c. In the Monte Carlo simulations, different types of randomization can be chosen: V_S, layer thickness, depth to bedrock and nonlinear properties. Figure 4(c) shows the AFs for a rock profile derived through different combinations. The layer thickness randomization generally lowers the AFs while including the nonlinear properties randomization increases the AFs. The randomization of depth to bedrock was modelled as a normal distribution between 70 and 130m. A check with the uniform distribution was performed with negligible differences in AFs.
d. The number of simulations required to obtained a stable result was also investigated. AFs were derived using 60 (minimum required by ASCE4-16), 100, 200, 500 and 1000 realizations, where the latter was assumed as the reference result. The results, Figure 4(d), suggested that 500 Monte Carlo simulations were required to obtain a percentage difference with the reference less than 5%.

3.2 *Results*

Monte Carlo simulations were used to randomise the soil profiles including variation of V_S, layer thickness, nonlinear properties and depth to bedrock. The analysis was performed for 500 realizations for each earthquake scenario. Figure 5(a) presents the randomized soil profiles (grey lines) along with their median and percentiles (red lines) and the input profiles (blue lines). Figures 5(b) and 5(c) show the randomized profiles of the G/G_0 curves for the till and rock layers respectively.

The resulting amplification factors at the four APE are shown in Figure 6(a) in terms of median and 16^{th} and 84^{th} percentiles (black lines). Only 50 selected random AFs are shown for ease of reference (grey). The surface response spectra are determined following the procedure by Bazzurro & Cornell (2004):

- The AFs are assumed to be lognormally distributed.
- The AFs at a selected frequency, see colored circles in Figure 6(a), are plotted against the input bedrock spectral accelerations $Sa_{Bedrock}$, Figure 6(b).
- The mean of the logarithm of AF, μ_{lnAF}, is determined through non-linear regression as a function of the natural logarithm of $Sa_{Bedrock}$,, Figure 6(b).

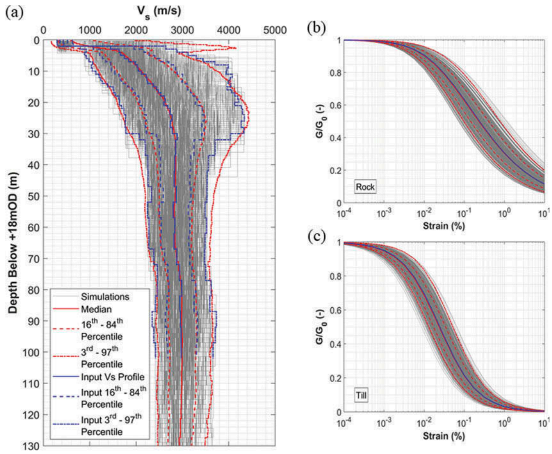

Figure 5. Randomized profiles for the Monte Carlo simulations and their median and band of variability in red. The input profiles are also shown for comparison in blue. (a) Vs profiles, (b) G/G_0 random curves for rock and (c) G/G_0 random curves for superficial deposits (till).

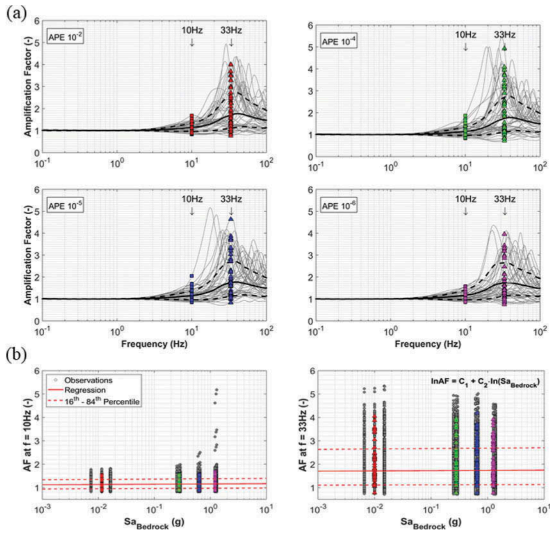

Figure 6. (a) Amplification factors from Strata for 10^{-2}, 10^{-4}, 10^{-5} and 10^{-6} APE and (b) regression of the at two selected frequencies (10 and 33.33Hz).

- For each spectral frequency, the surface hazard curve is obtained by convolving the bedrock hazard curve from the PSHA with the AF function.
- The response spectra are determined through interpolation of the hazard curves at the chosen APE (red curve in Figure 7).

The surface UHRS shows significant amplification at high frequencies (>10Hz) due to resonance in the thin glacial till layer and by the impedance contrast with the underlying rock. The results were compared with two simplified approaches:

- A deterministic SRA used only the best estimate, upper and lower bounds of the soil properties. This does not account for the overall uncertainty and is not able to properly model the variability of the till layer thickness. The resulting surface RS is strongly dependent on the assumed input with a peak at the fundamental frequency of the superficial soil layer as shown by the blue dashed curve in Figure 7.
- A Monte Carlo approach is used to model the variability of the soil profile. The surface response spectra are determined by multiplying the median AF from the Monte Carlo SRA

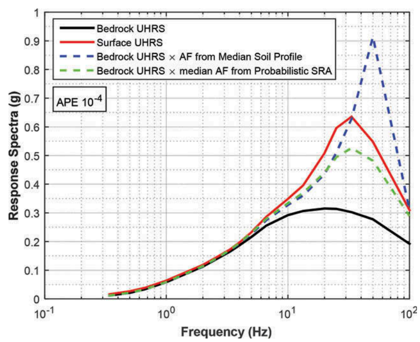

Figure 7. Results of the SRA for an annual probability of exceedance of 10-4. The bedrock UHRS (black) is compared with the surface UHRS from this study (red) and the response spectra from simplified approaches (green and blue).

by the bedrock UHRS (green dashed curve in Figure 7). In this case the peak and the shape of the resulting spectrum are similar to those derived by the fully probabilistic approach. However, the amplitudes are lower since the uncertainty of the AFs is not included in the final RS.

4 SUMMARY AND CONCLUSIONS

This paper presented a fully probabilistic site response analysis performed for a new nuclear site in the UK, Wylfa Newydd in North Wales. A Monte Carlo approach was used to simulate 500 random realizations for each earthquake scenario varying V_S, the thickness of the layers, the depth to bedrock, and the nonlinear properties. The randomization of the thickness helped incorporate in the results the effect of a non-uniform thin layer (0-5m) of superficial soil deposits (V_S~450m/s). The input bedrock UHRS had a peak at around 20Hz. As a consequence of the presence of thin glacial till layer and the impedance contrast with the underlying rock, the surface UHRS show significant amplification at high frequencies. Comparison against more simplified approaches shows that with a deterministic SRA the non-uniformity of the thin layer cannot be captured and the resulting RS is strongly dependent on the assumed input. When a Monte Carlo approach is instead used to define the amplification factors but only the median AF is adopted, the surface RS is underestimated since the uncertainty around the AFs is not included.

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