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ASSESSING THE EFFECT OF EPISTEMIC UNCERTAINTY ON THE SURFACE RESPONSE FOR THE WYLFA NEWYDD NUCLEAR POWER PLANT IN ANGLESEY, UK

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Abstract: *A seismic hazard assessment was performed for the Wylfa Newydd Nuclear Power Plant following the US Regulatory guidelines for nuclear facilities, which require a probabilistic seismic hazard assessment at an outcropping bedrock alongside a probabilistic site response analysis incorporating the epistemic uncertainty due to the inherent heterogeneity of the soil conditions. This paper identifies the main sources of aleatory and epistemic uncertainty for the Wylfa Newydd site and presents the development of the ground model and its uncertainty used in the probabilistic site response analysis. Based on the site characterisation, the main sources of uncertainty were: the thickness of the overburden soils due to the spatial variability across the examined area, the stiffness of the soil profile due to the various in-situ methods used to measure the shear wave velocity (V_S) and the modelling of the nonlinear site properties (degradation and damping). Different approaches were investigated to assess whether the use of a logic tree approach or a Monte Carlo approach would better capture the epistemic uncertainty of the site conditions. The results showed that if the uncertainty in the input properties is appropriately considered, a Monte Carlo approach could best capture the range of uncertainty for the site.*

Introduction

Ove Arup and Partners Ltd (Arup), appointed by Horizon Nuclear Power (Horizon), undertook seismic hazard assessment consultancy services for the Wylfa Newydd Nuclear Power Plant (Lubkowski et al, 2019) on the Isle of Anglesey, north Wales. The study was performed in accordance with the US Regulatory approach for the seismic hazard assessment of nuclear facilities, as described in the US NRC Regulatory Guide 1.208 and ASCE 43 (2005). Figure 1 summarises the two steps required: a probabilistic seismic hazard assessment (PSHA) at the outcropping bedrock and a probabilistic site response analysis to characterize the seismic hazard at ground surface level accounting for the soil amplification of the overburden deposits.

The PSHA study was performed for an outcropping bedrock with a shear velocity (V_S) of 3000m/s, which corresponds approximately to a depth between 80-100m below platform level. The probabilistic site response analysis (Villani et al., 2019a) was performed based on the Random Vibration Theory (RVT) approach using the software Strata (Kottke and Rathje, 2009). The aleatory variability reflecting the inherent randomness of the soil properties and the epistemic uncertainty due to the inherent heterogeneity of the site conditions were both captured in the probabilistic site response analyses.

This paper presents the main sources of uncertainty identified during the site characterisation and describes the parametric studies performed to develop the ground model used in the site response analysis. Acknowledging that the epistemic uncertainty has a major influence on the surface response and can significantly affect the seismic design, different approaches, including the use of logic tree and Monte Carlo simulations, were investigated to derive the ground model and its uncertainty that could best capture the centre, body and range of soil conditions encountered at the Wylfa Newydd site.

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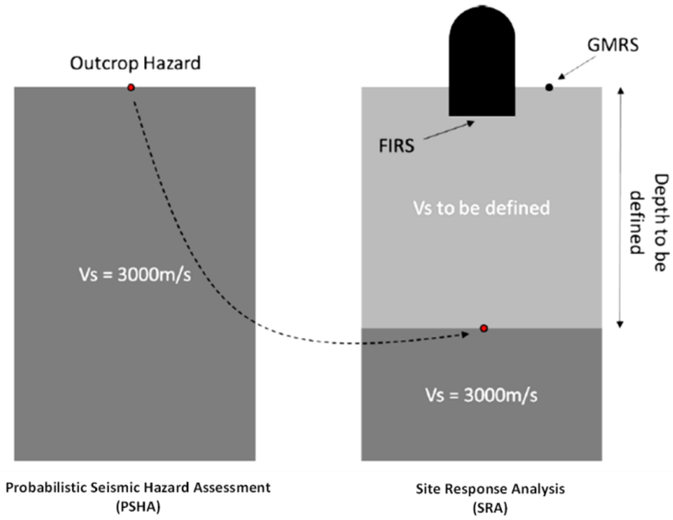

Figure 1: PSHA at bedrock and site response analysis for the surface UHRS

Site Characterisation

The proposed Wylfa Newydd site is shown in Figure 2. Within the Development Platform (red shaded polygon) are located the safety critical facilities, including the proposed location of Unit 1 (yellow shaded box) and Unit 2 (blue shaded box) reactor buildings and the examined area (grey shaded box) adjacent to the reactor buildings. The site characterisation of the geological formations was based on interpretative ground investigation reports, known as DOnGI and SSOnGI developed specifically for the project (Atkins, 2017a,b). The location of the in situ geophysical tests (downhole, crosshole, sonic and suspension logging tests) and geological cross sections (green and brown lines) are shown in Figure 2. Both the ground investigation data and geological cross sections were used to characterise the site, assuming a finished platform elevation of +18mOD within the examined area.

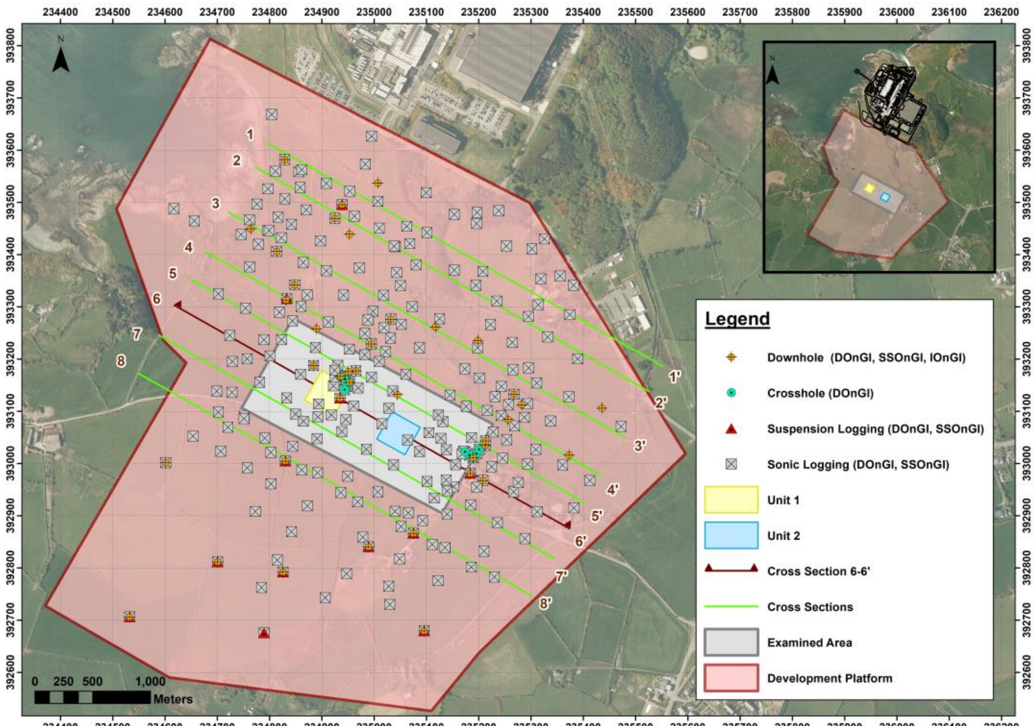

Figure 2: Location of Development Platform, reactors buildings (Unit 1 and 2), cross sections and ground investigation data.

The site geology within the Development Platform comprised superficial glacial till deposits overlying metamorphic rock of late pre-Cambrian and Cambrian age. The metamorphic rock is of the New Harbour Group, described as fresh to slightly weathered, medium strong to strong, interbedded phyllite and psammite. In general, the rock mass was classified as good quality rock, however, some portion of weathered and fractured rock was observed, mainly at depths close to rockhead elevation.

Thickness of Superficial Deposits

Based on the geological cross sections, the thickness of the superficial glacial till deposits between the rockhead elevation and the assumed finished platform elevation of +18mOD varied across the examined area. Figure 3 shows the cross section 6-6' which passes through the footprints of the reactors. The black dashed line shows the finished platform elevation of +18mOD. The cyan shaded areas represent zones where excavation of the superficial deposits will be required, and the purple shaded areas show the thickness of the superficial deposits between the rockhead elevation and the finished elevation. Based on the cross section, the superficial deposits are either absent or up to 5m thick and have an average thickness of 2m.

Figure 4 shows the contour map of the thickness of the superficial deposits or fill material between the rockhead elevation and the finished elevation of +18mOD derived based on the geological cross sections and ground investigation data. The intent of this study was to characterise the site conditions applicable to the examined area near the reactor buildings. Across most of the examined area, it is expected that rock will be exposed. The immediate vicinity of Unit 1 is anticipated to have no superficial deposits, whilst the immediate vicinity of Unit 2 has about 2m of superficial deposits. In the southeastern portion of the examined area, the superficial deposits may reach a thickness greater than 5m.

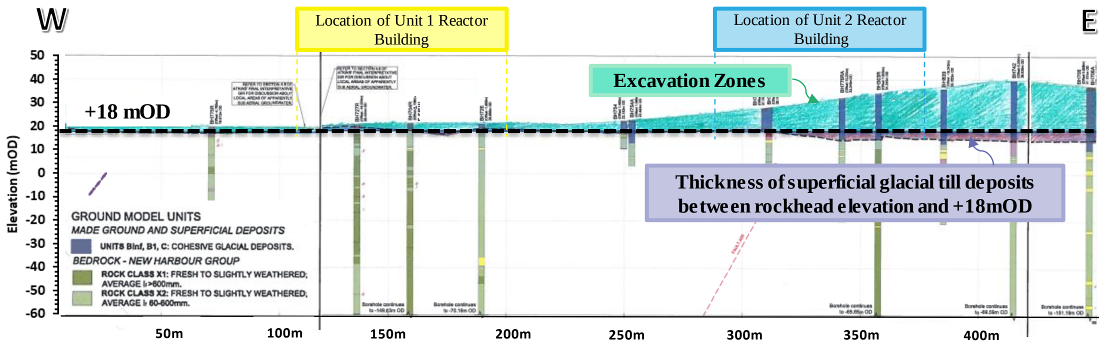

Figure 3: Geological cross section 6-6'within the examined area (Modified from Atkins (2017a))

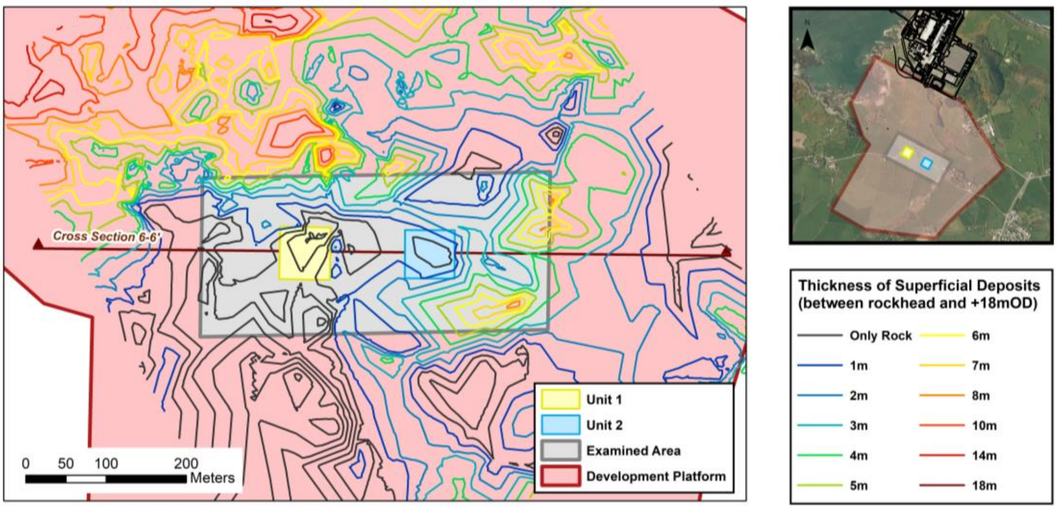

Figure 4: Contour map showing the thickness of superficial deposits and/or fill material between the New Harbour Group rockhead and finished elevation of +18mOD

Stiffness Profiles

For the superficial glacial till deposits, the V_S profile was determined based on in-situ downhole and crosshole seismic tests. An increasing V_S profile was adopted with a V_S of 450m/s at 2m and of 675m/s at 22m. The standard deviation was constant with depth and equal to 90m/s.

For the New Harbour Group rock, 183 sets of V_S interpretations were available. The V_S data consisted of 40 downhole tests, 3 crosshole arrays, 107 sonic logging tests and 12 suspension logging tests as shown in Figure 5. Details on the V_S interpretations can be found in Triple et al (2018) which showed that both the sonic logging and the suspension logging were not considered reliable in the shallow depths and therefore the V_S data above -25mOD were excluded from the datasets. To reflect the general weathering profile in the Development Platform, all V_S data were normalised relative to the top of rockhead.

Statistical analysis was performed to establish whether the New Harbour Group rock V_S data follow a normal or a lognormal distribution. Visual tests and goodness of fit tests showed that either distribution could be assumed for the V_S data. Based on US practice, the V_S data were assumed lognormally distributed. Figure 5 shows the available New Harbour Group rock V_S data along with the median (black solid line) and 16th and 84th percentiles (black dashed lines) V_S profiles.

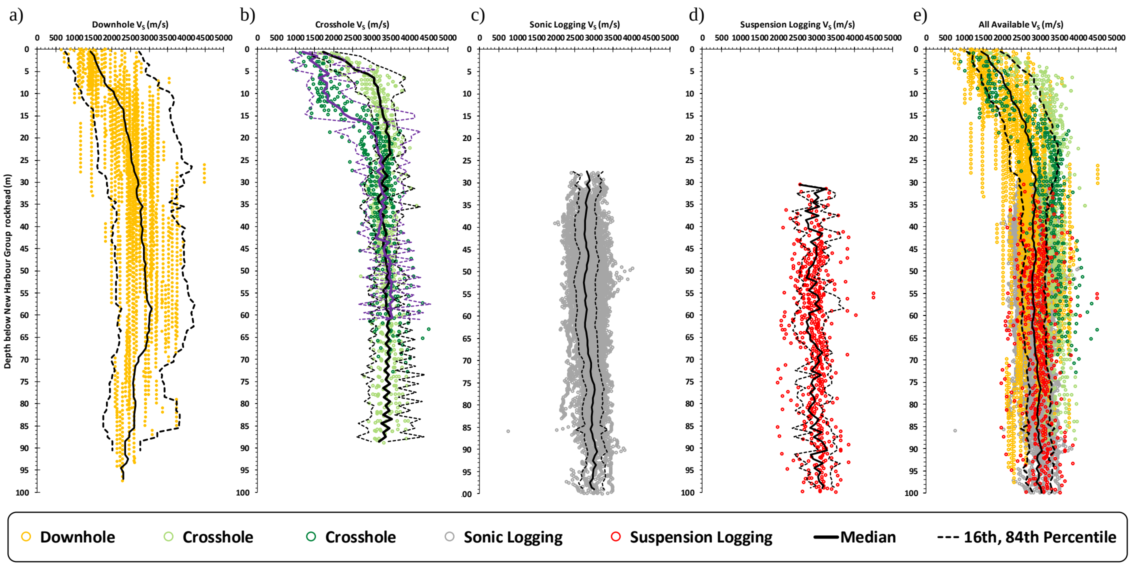

Figure 5: Downhole, crosshole, sonic and suspension logging New Harbour Group rock V_S datasets along with the median (solid line), 16th and 84th (dashed lines) V_S profiles.

The comparison of the New Harbour Group rock V_S profiles showed that:

1. The downhole V_S dataset (Figure 5a) defines the lower bound of the V_S data in the layers near rockhead elevation and at depths greater than 70m. The median V_S profile is about 1500m/s near the top of the rockhead and reaches 3000m/s at around 60m;
2. There is significant scatter in the crosshole V_S values (Figure 5b) near the rockhead. One crosshole array is observed to have lower V_S values due to the high presence of weathered New Harbour Group rock, while the other array has higher V_S values due to a higher proportion of the better-quality rock. For depths of about 30m below rockhead elevation, the V_S data converge. The median V_S for the stiffer array starts from 1700m/s and reaches 3000m/s at 7m depth while the median V_S for the more weathered array starts from 1200m/s and reaches 3000m/s at 18m depth;
3. The sonic (Figure 5c) and suspension logging (Figure 5d) V_S data have smaller spreads, albeit at deeper depths. The sonic logging median V_S profile generally ranges from 2800 to 3100m/s and reaches 3000m/s at a depth of 75m. The suspension logging median V_S profile ranges from 2500 to 3300m/s and reaches 3000m/s at a depth of 32m; and
4. The crosshole (Figure 5b) and suspension logging Figure 5d) V_S profiles present a saw-toothed shape at certain depths, which is a function of the scarcity of V_S data at these depths. This is not an issue once all the datasets are combined.

5. The median V_S profile derived from all V_S datasets (Figure 5e) is defined by the downhole and crosshole V_S data for the top 30m, while at depth, the sonic and suspension logging V_S datasets govern due to the larger number of V_S data points. In general, the median shows increasing V_S with depth, ranging from 1500 to 3100m/s and reaches approximately 3000m/s at around 100m. The σ_{lnVs} generally decreases with depth from 0.3 near rockhead elevation to less than 0.1 at 100m. The smaller σ_{lnVs} at depth is constrained by the sonic and suspension logging V_S datasets.

Nonlinear Properties

The degradation (G/G_0) and damping curves for the superficial glacial till deposits were based on a hyperbolic fit of the resonant column, cyclic triaxial and cyclic simple shear testing data. The proposed G/G_0 curve by Atkins (2017a) resulted in G/G_0 values higher than unity for strains lower than 0.001%. To overcome this, the model of Darendeli and Stokoe (2001) with an over consolidation ratio of 2, a plasticity index of 13% and σ_o'=12kPa was used in this study.

The G/G_0 curve by Worthington et al. (2001) for sedimentary rock was used for the New Harbour Group rock. The fitting parameters B=10,000 and n=0.5, along with a consistent damping curve were used. The minimum damping was selected considering the recommended value by Atkins (2017a) of 1.5% and the minimum limit of 2% in ASCE/SEI 4-16 when no data are available for the site. The consistency with the kappa value (attenuation of the high frequency in the Fourier Amplitude spectra) used for the bedrock at the PSHA study (Villani et al., 2019b) was also checked. A value D_{min} of 1.5% was selected for the analysis.

Both for the superficial deposits and for the New Harbour Group rock, the damping curves were constrained at large strains with the maximum critical damping value of 15% in accordance with US NRC Regulatory Guide 1.208.

Statistical Parameters

To carry out a probabilistic site response analysis using the Monte Carlo approach, it is necessary to develop randomised soil profiles from the known data. For the randomisation of the V_S and layering thickness, two more parameters were required:

- the interlayer correlation coefficient (ρ); and
- the average layer transition rate (λ).

The interlayer coefficient (ρ) measures the correlation of the V_S at adjacent layers (Toro, 1995) and was computed equal to 0.8 using downhole and crosshole New Harbour Group rock V_S data.

The average layer transition rate (λ), which is depth dependent, represents the number of layer boundaries per metre. Toro (1995) proposed the following generic depth dependent layer transition rate model:

$$\lambda\,(d) = a\,(d + b)^c \tag{1}$$

and provided generic coefficients based on V_S profiles predominantly from soil sites. The coefficients a, b, and c were computed based on the superficial deposits and New Harbour Group rock V_S profiles.

Definition of Ground Model and Uncertainty for the Site Response Analysis

The effect of the input soil parameters and modelling assumptions used to define the ground model and its uncertainty for the probabilistic site response analysis was investigated through parametric studies. The following parameters were assessed:

- Uncertainty on the New Harbour Group rock V_S profiles;
- Uncertainty on the thickness of the superficial glacial till deposits;
- Uncertainty on the modelling of the nonlinear properties;
- Uncertainty on the modelling of the depth to bedrock; and
- Effect of selected Monte Carlo randomisations.

The results are compared in terms of median, 16th and 84th percentiles of amplification factors for the 10^{-4} annual probability of exceedance. The percentage differences on the median responses are also presented to better understand the results. Percentage differences lower than 5% were considered to provide statistically stable responses.

Uncertainty on the New Harbour Group rock V_S profiles

A parametric study was performed to assess the effect of epistemic uncertainty due to the different in-situ test methods (crosshole, downhole, suspension logging and sonic logging) used to measure the New Harbour Group rock V_S profiles. To determine whether a logic tree approach is required, or a Monte Carlo approach can be used, the following two cases were considered:

1. A logic tree approach using the downhole dataset with a weighting of 80% and the crosshole dataset with a weighting of 20%. The weightings were proportional to the respective number of tests of each dataset within the Development Platform. For each dataset, the amplification factor was derived based on the median V_S profile (and its uncertainty). The amplification factors of each dataset were then weighted and combined to derive the final amplification factor;
2. A Monte Carlo approach where the weightings were applied on the stiffness profile. A weighted median V_S profile (and its uncertainty) was computed using the downhole and crosshole datasets and applying the same weightings as in Case 1. The amplification factor was derived directly from the Monte Carlo approach based on the weighted median V_S profile and its uncertainty;

Figure 6 shows the median, 16th, 84th percentiles of the amplification factors along with the percentage differences with respect to the logic tree approach (Case 1). The difference between Case 1 and 2, which is less than 5%, shows that a logic tree approach is not necessary to appropriately account for the epistemic uncertainty in the investigation technique.

To further determine whether the V_S datasets should be weighted, or all V_S datasets should be included in the analysis, two additional cases were examined using the Monte Carlo approach:

3. A median V_S profile using only the downhole and crosshole datasets and assuming equal weightings among the datasets;
4. A median V_S profile using all available V_S datasets (downhole, crosshole, sonic and suspension logging) and assuming equal weightings among the datasets. In this case, the sonic and suspension dataset better constrain the V_S profile at depth.

Figure 6 shows that slightly lower amplification factors were observed when the median V_S profile (Case 3) was used compared to the weighted median V_S profile (Case 2) using only downhole and crosshole data. The percentage differences are also in this case lower than 5%.

Figure 7 further compares the amplification factors derived from the median V_S profile using only downhole and crosshole data (Case 3) and from the median V_S profile using all available V_S datasets (Case 4). The percentage differences were lower than 5% except for frequencies close to the peak of the spectrum where a percentage difference of 7% was noted. However, the inclusion of all data was considered more accurate to better constrain the profile at depth and therefore, the V_S profile and its uncertainty were based on all the available datasets (Case 4).

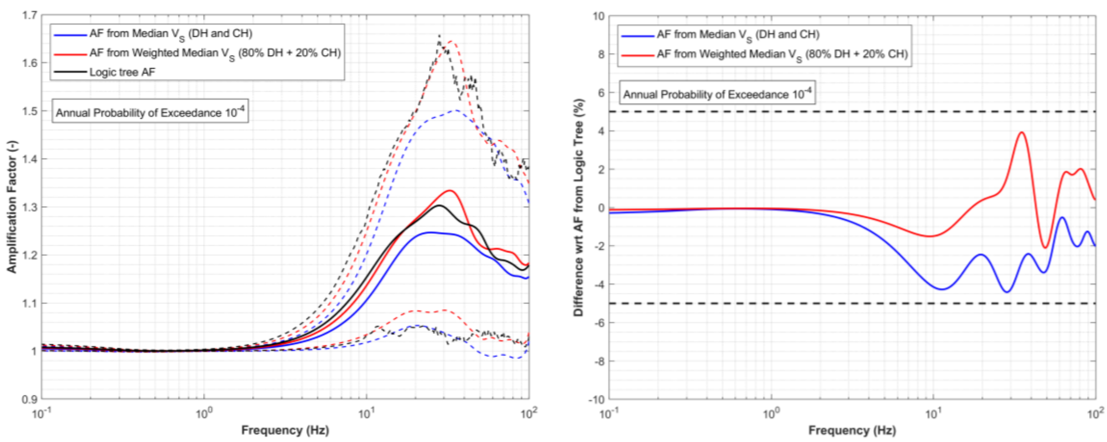

Figure 6: Comparison of Median, 16th and 84th Percentile Amplification Factors Computed with the Median V_S Profile, Weighted Median V_S Profile and a Logic Tree Approach

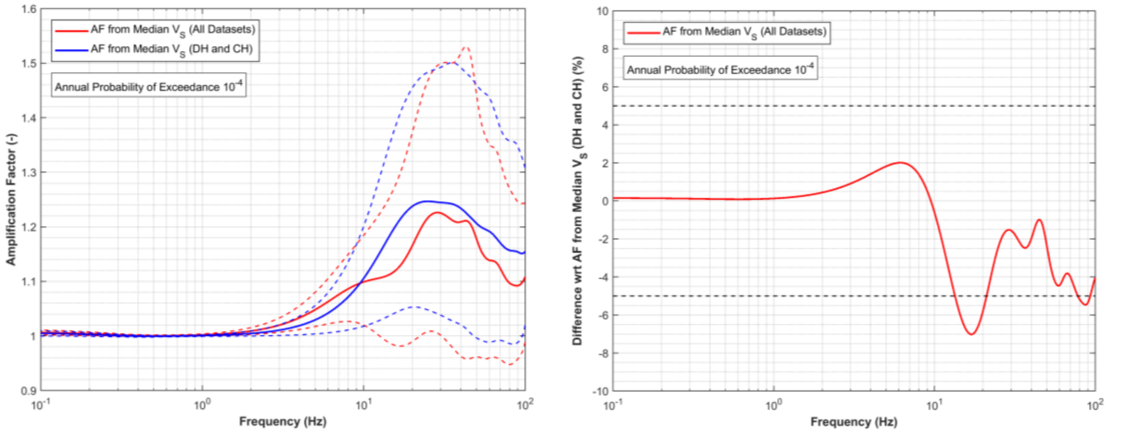

Figure 7: Comparison of Median, 16th and 84th Percentile Amplification Factors Computed with the Median V_S Profile Using All Available Datasets and with the Median V_S Profile Using Downhole and Crosshole Data

Uncertainty on the Thickness of Superficial Deposits

The thickness of the superficial deposits between the rockhead elevation and finished platform elevation of +18mOD varies across the examined area as seen in the geological cross sections (see Figure 4). Sensitivity studies were performed to incorporate the varying thickness of the superficial deposits within the examined area. The following cases were analysed to determine whether a logic tree approach is required, or the thickness variability of the superficial deposits could be captured by randomisation of the layer thickness using a Monte Carlo approach:

1. A logic tree approach using the following scenarios:
    a. Only New Harbour Group rock profile with weighting of 50%;
    b. New Harbour Group rock and 2m thick superficial deposits profile with weighting of 25%;
    c. New Harbour Group rock and 3m thick superficial deposits profile with weighting of 25%;
2. Layer thickness randomisation within the Monte Carlo approach based on an input profile with New Harbour Group rock and 2m thick superficial deposits.

For Case 1, the soil profiles were generated by randomising only the V_S and nonlinear properties. For Case 2, the layer thickness was also randomised which yields 22% of the randomised profiles with no superficial deposits, 38% with 0 to 2m of superficial deposits, 25% with 2 to 3m and 15% with 3 to 5m. This seems to represent quite well the expected conditions within the examined area.

Figure 8 shows the comparison of the computed amplification factors for the 10^{-4} annual probability of exceedance. As expected, the scenario with no superficial deposits produced the lowest amplification. As the thickness of the superficial deposits increases, the amplification factors increase and the predominant frequency decreases. The expected predominant frequency was estimated as:

$$f = \frac{V_S}{4\,H} \tag{2}$$

where V_S is the shear wave velocity and H is the thickness of the superficial deposits. The predominant frequency varies from 50 to 20Hz for 2 and 5m of superficial deposits, respectively. When including the layer thickness randomization (Case 2), the median amplification factor is generally lower, with a wider frequency band, which is expected given that in these cases the profiles can have 0 or 5m superficial deposits. Figure 8 also shows the comparison between the 10^{-4} surface UHRS computed for Cases 1 and 2 along with the input bedrock (V_S = 3,000m/s) UHRS from the PSHA (Lubkowski et al., 2019). The two approaches lead to similar spectral parameters with percentage differences less than 5%. Case 2 was deemed better to capture the spatial variability of the thickness of the superficial deposits and was adopted for the ground model.

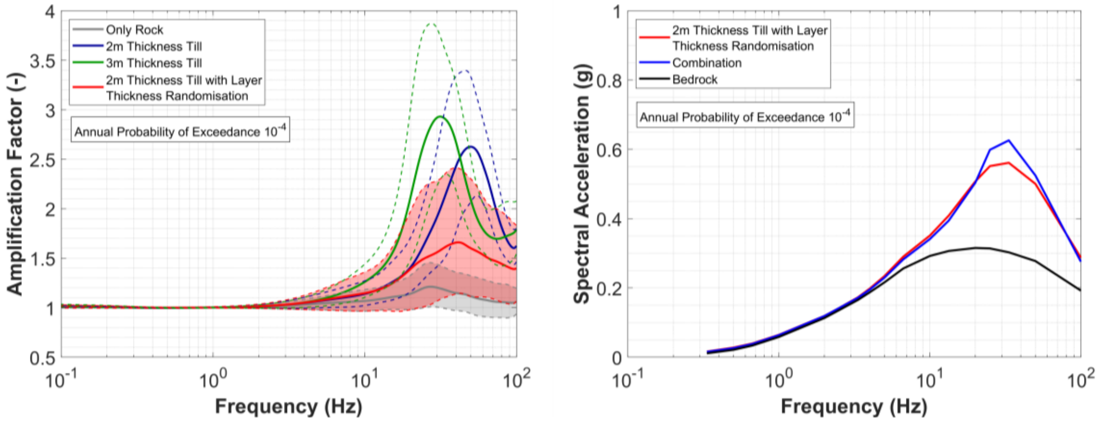

Figure 8: (Left) Comparison of median, 16th and 84th percentile amplification factors and (right) Comparison of surface UHRS computed for different glacial till thicknesses assumptions

Uncertainty on the Nonlinear Properties

Uncertainties in nonlinear properties were included by randomizing the G/G_0 and damping curves of the superficial deposits and New Harbour Group rock layer. Two approaches were considered for the modelling of the standard deviation of the nonlinear properties:

1. Darendeli and Stokoe (2001) model; and
2. Screening Prioritization and Implementation Details (SPID) according to Coppersmith et al. (2014).

Darendeli and Stokoe (2001) model assumes a normal distribution and the standard deviation is a function of the amplitude of the nonlinear property. SPID model assumes a lognormal distribution and uses a standard deviation of 0.15 for the G/G_0 curve and 0.3 for the damping curve at the reference strain level (G/G_0 is equal to 0.5).

The Darendeli and Stokoe (2001) model results in a larger scatter since the standard deviation is correlated to the input amplitude. In the SPID model, the general shape of the input curves is preserved as the model reduces the standard deviation near the ends of the strain range (Figure 9). Unrealistic results are observed in the amplification factors for a number of realisations in the Darendeli and Stokoe (2001) model, de-amplification is predicted in the high frequency range and amplification in the intermediate frequency range. The results are due to the unlikely combination of low G/G_0 curves and low V_S profiles leading to great nonlinearity and inability of the equivalent analysis to converge. In general, both modelling approaches have shown similar results with percentage differences slightly exceeding 5%, as shown in Figure 9. Therefore, the SPID model was adopted in the ground model.

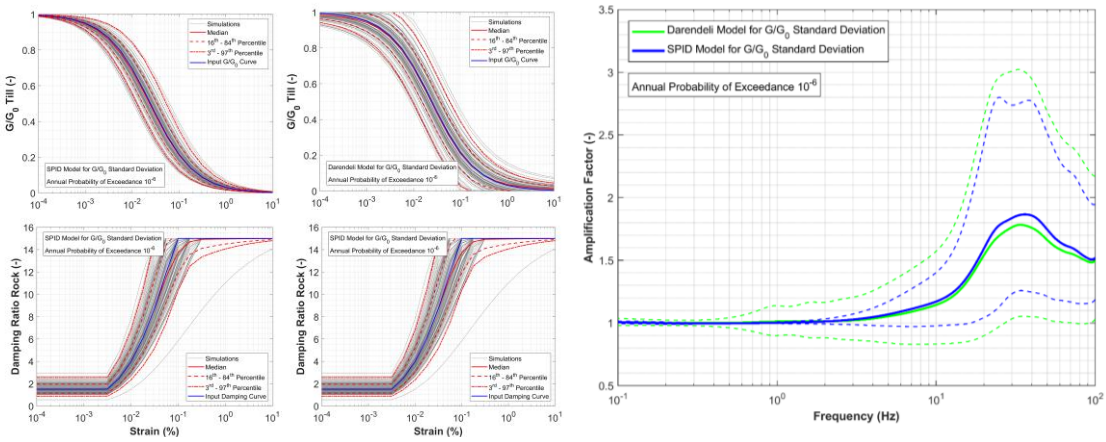

Figure 9: (Left) G/Go and Damping curves, (Right) Median, 16th and 84th percentile amplification factors for the different modelling assumptions of the nonlinear properties.

Uncertainty on the Bedrock Depth

The depth to bedrock was randomised accounting for uncertainty on the depth where the bedrock with a V_S of 3000m/s is expected. Based on the V_S profiles, the upper and lower depth limits were constrained to 70 and 130m. A normal distribution was adopted in this study, and a check with the uniform distribution was also performed but the differences were negligible.

Effect of Monte Carlo Randomisations

The effect of the Monte Carlo randomisations (V_S, layer thickness, depth to bedrock, and nonlinear properties) was explored using a soil profile consisting only of New Harbour Group rock material (no superficial deposits). The amplification factors were calculated for the following scenarios:

1. V_S randomisation;
2. V_S and layer thickness randomisation;
3. V_S, layer thickness and depth to bedrock randomisation;
4. V_S and nonlinear properties randomisation;
5. V_S, layer thickness and nonlinear properties randomisation; and
6. V_S, layer thickness, depth to bedrock and nonlinear properties randomisation.

Figure 10 shows the amplification factors computed for the different modelling assumptions. Overall, the range of amplification factors fits a narrow band and have percentage differences generally within the 5% difference range. Including the layer thickness randomisation generally lowers the amplification factors. On the other hand, including the nonlinear properties randomisation increases the amplification factors. The randomisation of depth to bedrock has the smallest effect on the results. All randomisations were adopted for the ground model.

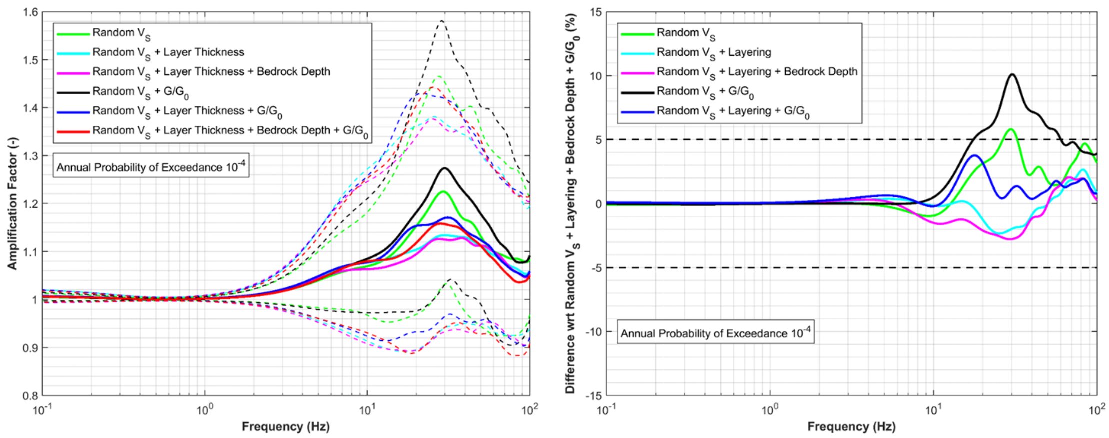

Figure 10: Median, 16th and 84th percentile amplification factors for different modelling assumptions

Summary and Conclusions

A fully probabilistic site response analysis was developed to characterize the surface hazard for the Wylfa Newydd site in North Wales. Epistemic uncertainties were included in the site response analysis to capture the soil variability encountered on site. The site response analysis was carried out in Strata (Kottke and Rathje, 2009) using the equivalent linear method and the input motions were derived based on the Random Vibration Theory approach.

The soil profile comprised superficial deposits (glacial till) underlain by the rocks of the New Harbour Group. The main sources of epistemic uncertainty were the stiffness of the New Harbour Group rock profiles, the thickness of the superficial deposits and the modelling of the nonlinear properties. To define the ground model and its uncertainty for the site response analysis, Monte Carlo simulations were used to generate randomised profiles in terms of V_S, layer thickness, depth to bedrock and nonlinear properties.

Different approaches were investigated including the use of logic trees to account for the epistemic uncertainty in the V_S datasets or the superficial deposits thickness. The results showed that if the uncertainty in the input properties is appropriately considered, a Monte Carlo approach leads to results that can capture the range of uncertainty for the site.

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