

SEISMIC HAZARD ASSESSMENT FOR THE WYLFA NEWYDD NUCLEAR POWER PLANT

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Abstract: *This paper presents an overview of the seismic hazard assessment commissioned by Horizon Nuclear Power for the Wylfa Newydd site. The project was developed to utilise both UK experience and aspects of the Senior Seismic Hazard Analysis Committee (SSHAC) approach, including facilitation and independent peer review. The project aimed to assess the potential for capable faulting, define the seismic criteria directly from a probabilistic seismic hazard assessment (PSHA) and assess the impact of potential tsunami inundation. An overview of selected aspects of the hazard assessment is presented and related key issues and insights are discussed in detail. This includes the development of a 3D geological model from historical and project ground investigations, including the mapping of coastal fault exposures. It continues to describe how age dating of core samples was used to exclude the risk of capable faulting in the vicinity of the site. It explains why the PSHA was developed at an outcropping hard rock horizon and how the centre, body and range of technically defensible interpretations were captured. The logic trees are presented showing the epistemic uncertainties in the definition of both the seismic source models and the ground motion attenuation. The paper concludes by discussing the tsunami hazard assessment, which investigated the history of UK tsunami events and undertook analyses to assess the risk from extreme events to show the impact was limited.*

Introduction

Arup was appointed by Horizon Nuclear Power (Horizon) in 2010 to undertake Seismic Hazard Assessment consultancy services for the proposed Wylfa Newydd Nuclear Power Plant (NPP) on the Isle of Anglesey in North Wales as shown in Figure 1. The site is located to the south of the existing Wylfa A station. The principal aim of the study is to assess the impact of potential seismic events on the Wylfa Newydd Development Platform, with appropriate consideration of uncertainty and to the regulatory satisfaction of the Office for Nuclear Regulation (ONR).

The study was subdivided into three main tasks, a capable faulting assessment; a probabilistic seismic hazard assessment (PSHA); and a tsunami hazard assessment.

The project team includes experts from British Geological Survey (BGS), University of Liverpool, Amec Environment and Infrastructure (now Wood Group), HR Wallingford, and eCoast. The work was carried out in close conjunction with the site investigation studies led by Atkins. The work was reviewed by an independent peer review (IPR) panel and Horizon's subject matter experts.

Methodology

The process looked at techniques and methods previously employed in the UK and worldwide to meet relevant good practice as determined by the ONR and ensure that this comprehensive and

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systematic review of seismo-tectonic hazards, overseen by independent and regulator experts, meets the expectations for risk insight and design input.

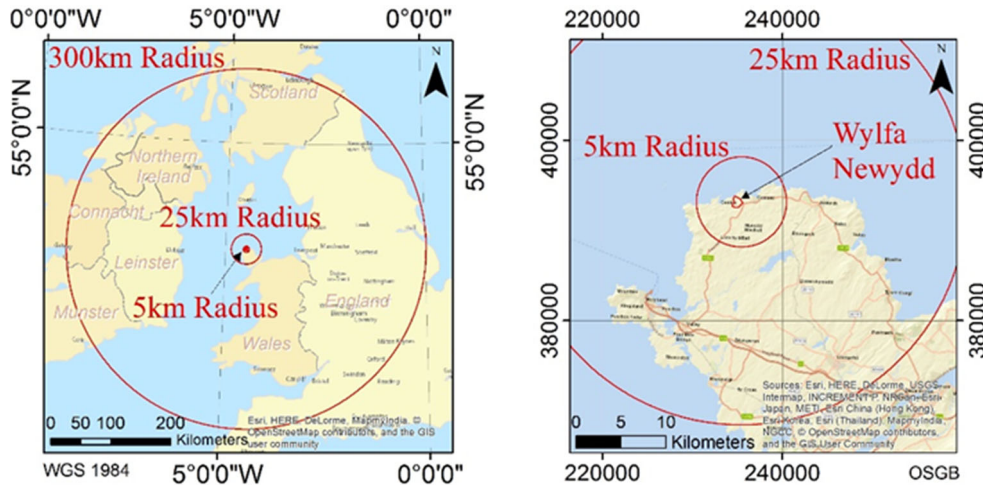


Figure 1: Wylfa Newydd site location and study regions (Free *et al.*, 2018)

The current state of the art practice in seismic hazard studies is to follow the SSHAC guidelines (Budnitz *et al.*, 1997) initially published in 1997 and updated late 2018 (Ake *et al.*, 2018). When the project started in 2010 a traditional approach, that had historically been used in the UK for similar studies, was adopted as opposed to the SSHAC guidelines.

The study followed the ONR's safety assessment principles (SAPs), with the intent of defining a conservative design basis event and showing that the geological faults that traverse the site did not present an exclusionary criterion. The guidance was supplemented by the International Atomic Energy Agency (IAEA) site assessment document SSG-9, which was considered to define relevant good practice at the start of the project.

As the project has matured, and Horizon changed its ownership from E.ON and RWE to Hitachi, so the approach has changed. In addition, both the IAEA published several new guidelines documents (e.g. IAEA, 2015, 2016a, b, c), but also the ONR updated their technical assessment guide number 13 (ONR, 2018) with input from their Expert Panel.

As a consequence of these changes the project reviewed and updated the methodology as appropriate. The project has incorporated many elements of the SSHAC guidelines including facilitation of workshops, definition of key roles and responsibilities and participatory peer review. Whilst not a formal SSHAC compliant approach, the project has undertaken benchmarking to establish an enhanced Level 2 study has been achieved, with elements of Level 3 and 4.

Database

In line with the requirements of IAEA (2010) on site evaluation, a comprehensive and integrated database of geological, geophysical, geotechnical and seismological information was collected and incorporated in a coherent form. The investigations were conducted on four spatial scales, namely regional, near regional, site vicinity and site area. All spatial geological, geophysical, geodetic and seismological datasets gathered and interpreted for the study were compiled into a project geographical information system (GIS) database to facilitate comparisons between various combinations of the datasets, including interpretations from previous studies, in 2D and 3D.

Earthquake Catalogue

The project earthquake catalogue, including all events with 300km of the site, was initially collated for the period up to December 2010. One of the key events near the site was the 5.4M_L Lleyn Peninsula earthquake on 19 July 1984. This is the largest onshore UK earthquake for which a magnitude can be reasonably determined (Musson *et al.*, 2001). The felt area encompassed all of Wales, most of England, the east coast of Ireland and extended slightly into southern Scotland. The event was felt at the Wylfa A station. The catalogue was principally based on the BGS database and more detailed studies carried out for the Wylfa A station (Musson *et al.*, 2001). Macroseismic and instrumental earthquake records were collated and processed, including

consistent conversion to the moment magnitude (M_w) scale that is compatible with the latest ground motion prediction equations (GMPEs). Conversion correlations developed for the UK catalogue were reviewed (Sargeant and Ottomöller, 2009; Edwards and Rietbrock, 2008). These were rejected as they were only valid for small magnitude events, and the Grünthal *et al.* (2009) relationship for North West Europe was selected, as indicated in Figure 2. Aftershocks, foreshocks and manmade events were removed from the catalogue by expert judgement. Particular attention was given to the long series of aftershocks that followed the 1984 Lleyl Peninsula event.

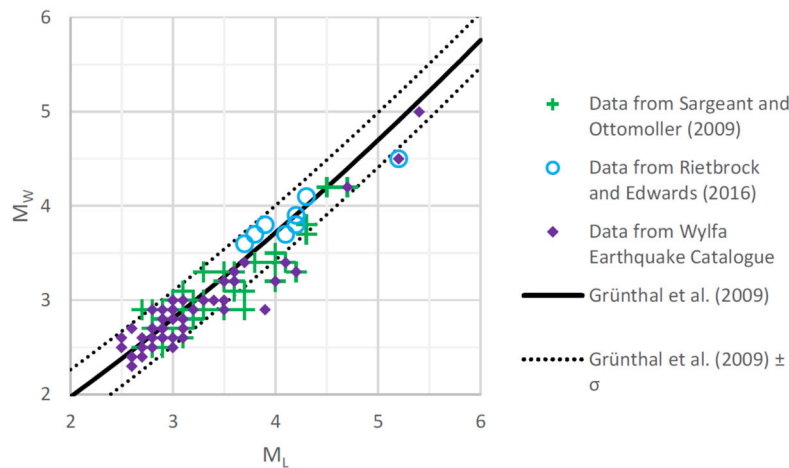


Figure 2: Conversion Relationship and UK Earthquake Data

The statistical completeness of the catalogue was assessed using the procedure originally proposed by Stepp (1972), supplemented by a review of historical sources. For the historical macroseismic events, account for uncertainty in their epicentre locations was made using four different error categories.

Subsequently the catalogue was extended for the period up to the end of June 2015. The update included a search of the online British Library newspaper collection, which identified two additional small events reported in the North Wales Chronicle, interpreted as a 3.2 M_L event near Almwch on 13 October 1830 and a 2.0 M_L event on 21 June 1864 near Tremadoc.

Geological and Tectonic Studies

The purpose of these studies was to review and consider the geological, tectonic and seismological data for the wider region to provide context and input to the PSHA and capable faulting assessment. Extensive geological desk studies and reconnaissance provided an understanding of the regional and local geology and tectonics, enabling detailed ground investigations to be carried out across the site area. The geology and tectonic history of the Isle of Anglesey is highly complex spanning hundreds of millions of years, with multiple phases of faulting. It was the focus of detailed multidisciplinary mapping and reinterpretation by the BGS (Phillips, 2010) during this project.

Within the British Isles the resulting main tectonic terranes have a prominent north-east to south-west orientation. The major fault systems in north Wales and Anglesey (e.g. Menai Strait Fault System) follow this trend. There is evidence to suggest that the Palaeocene (66 to 56Ma) transpression may have reactivated some of these faults, resulting in sinistral strike slip displacements, and reactivated or initiated north-northwest to south-southeast oriented faulting resulting in dextral strike slip displacements.

Earthquake focal mechanisms in the British Isles, reported by Baptie (2010), are predominantly strike slip. This is consistent with north-west to south-east compression and north-east to south-west tension associated with the combined tectonic effects of Africa Europe collision and Alpine Orogeny focussed in the Mediterranean and ocean spreading in the Atlantic, referred to as the current tectonic regime.

The British Isles were subjected to Quaternary glaciations with ice sheets passing across the Irish Sea and Anglesey from north-east to south-west. The last phase of glaciation in the Late

Devensian glaciation reached its maximum extent at around 24,000 years ago with the region becoming ice free again by 15,000 years ago. The impact of glaciations on Anglesey was significant and included: erosion of a significant thickness of geologically younger rocks; deposition of glacial deposits and isostatic rebound following removal of the ice.

Capable Faulting Study

The purpose of the capable faulting study was to investigate the site in detail to ensure that none of the faults on the site show evidence of seismic activity and related movement (a capable fault) during the current tectonic regime, which is postulated to be the last 8 million years (Mallard and Woo, 1991).

The regional investigation of available sources found that none of the observed seismicity within 25km of the site can be associated with known mapped faults, although more distant faults are identified with possible neotectonic activity. In addition, no earthquake in the UK earthquake catalogue is known to have resulted in geological fault rupture through to the surface or caused permanent ground deformation at or near the surface (SHWP, 2001 and ONR, 2018).

Fault modelling at Wylfa Newydd has mapped 40 geological at or near surface faults, some of which cross the site area and numerous other faults that could not be mapped between adjacent data points and are interpreted to be of limited length. Figure 3 shows the 3D model which was developed for the site and surrounding area. Data from historical and project ground investigations were used, as well as the mapping of coastal fault exposures. Successive stages of ground investigation for Wylfa Newydd have confirmed and enhanced our understanding of the mapped faults. Details of the development of the geological fault model are discussed in Free et al. (2018).

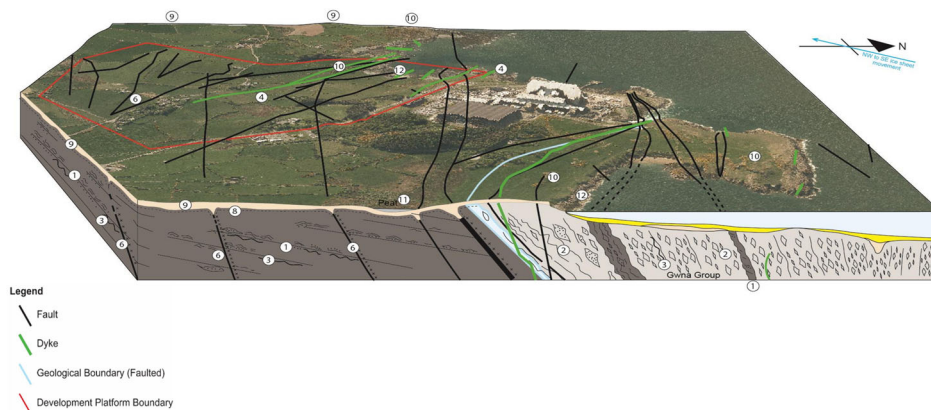


Figure 3: Conceptual geological fault model

Due to the geologically recent glaciation it is not possible to use the superficial deposits (Glacial Till) as evidence of last movement on the faults. Similarly, due to the geologically old New Harbour bedrock and subsequent intrusions, it is not possible to constrain the last age of faulting relative to the current tectonic regime. Therefore, core samples of fault materials from boreholes within the New Harbour rocks were dated by specialists at the BGS and CSIRO, to demonstrate that no fault movement has occurred within the current tectonic regime. Following development of a fracturing event chronology, absolute age dating of clay growth observed on fracture surfaces of fault gouge was undertaken to constrain the age of the last displacement on the geological faults.

The interpreted youngest ages from K-Ar age dating was older than 30Ma, using two independent innovative interpretation methods. The interpreted youngest age from supplementary U-Pb age dating of calcite crystals within and truncated by fault gouge was consistent with these dates. These ages are very much older than the current tectonic regime, which has prevailed for a period not longer than eight million years. The evidence assembled and reviewed shows that the geological faults within the Wylfa Newydd site are not capable as defined by IAEA (2016a).

Seismic Hazard Assessment

The PSHA was developed with the aim of capturing the uncertainties in all the key input parameters and hence calculating a mean uniform hazard response spectrum, which captures

the centre, body and range of all technical defensible interpretations. The key purpose was to then use the performance based methodology to define a design spectrum following the intent of ASCE 43-05 (ASCE, 2005) and US NRC Reg Guide 1.208 (US NRC, 2007).

Site Characterisation

Preliminary geophysical investigation data suggested the site is underlain by hard rock, with a shear wave velocity (V_s) in excess of 1,500m/s, notably higher than previously considered for seismic hazard studies in the UK.

Following review of the geophysical data it was decided to carry out the PSHA to provide the ground motions for a very hard rock outcrop with a V_s of 3,000m/s. This is considered representative of the very hard rocks of the New Harbour Group that underlie the Wylfa Newydd site, where the rock mass is not significantly weathered or fractured. Details of the ground investigations used to define the V_s can be found in Tripe *et al.*, (2018).

Seismic Source Characterisation

Based on detailed review of the geology and tectonic setting, there was no clear association of seismicity with the regional faults. It was therefore considered appropriate to only use area sources in the development of the source models for this study. The kernel method (Woo, 1996) was adopted for a sensitivity study and found to have broadly consistent results.

For Wylfa Newydd, two principal source zonation models were developed, SM1 and SM2 as shown in Figure 4. After initial investigation it became clear that the seismic hazard at Wylfa Newydd was controlled by two key zones, the relatively lower seismicity ANG zone, which encompasses Anglesey and the site, and the relatively higher seismicity LLYN zone, which encompasses the Lleyn Peninsula and Menai Straits. Therefore, it was decided to manipulate the key hazard controlling parameter, the boundary between the ANG and LNG zones to assess the uncertainty in its definition and location. This resulted in two variations of SM1 and three variations of SM2.

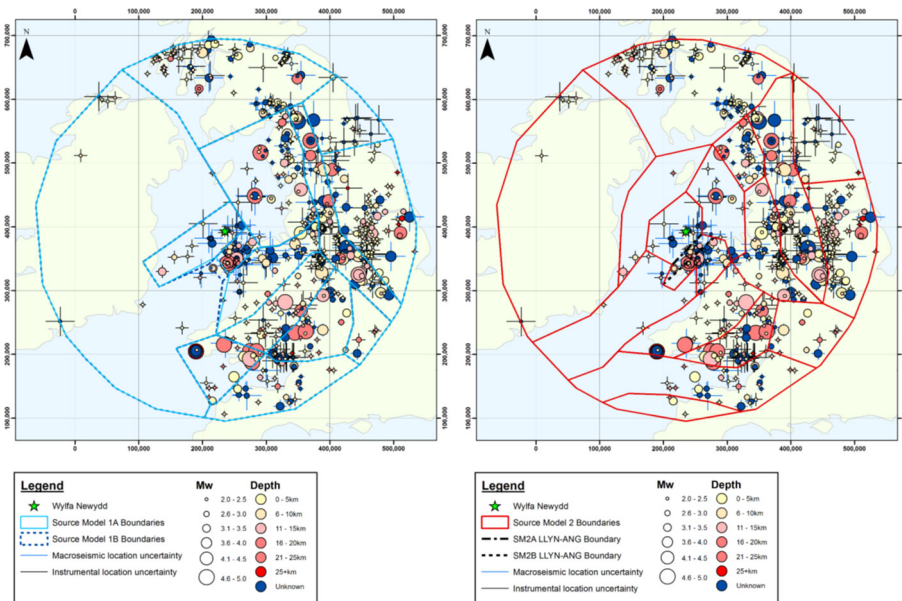


Figure 4: Source Models 1 and 2 and Entire Earthquake Catalogue

The source zone models and their boundaries were defined based on observed historical and instrumentally recorded seismicity, based on the state of knowledge, with a cautious view regarding their locational uncertainty. The models also considered historic seismic source models (e.g. Musson and Sargeant, 2007) and the interpretation of various regional and local geology, tectonics, geophysical features and topographic and bathymetric data contained within the GIS database. Finally, the interpretation of regional tectonics and the potential kinematic interactions of structural blocks from models such as Chadwick *et al.* (1996) was considered.

Magnitude Recurrence

Due to the low level of seismicity in the UK it was decided to use the penalised maximum likelihood method (PMLM) as developed by Veneziano and Van Dyke (1985) to define activity rates and b-values. The PMLM has been used in recent nuclear projects in low seismicity regions including PEGASOS (Abrahamson *et al.*, 2004), CEUS-SSC (CEUS-SSC, 2012) and Eskom South Africa (Bommer *et al.*, 2015).

A prior b-value of 1.0 was selected for the PMLM based on the magnitude recurrence of the entire catalogue. A weight of 25 was chosen as it ensures a realistic range of b-values was obtained. A sensitivity analysis was undertaken to investigate the impact.

It was observed that the PMLM did not match the observed seismicity in the LLYN zone, with potential underestimated the activity rates for magnitudes greater than 4.5M_w as shown in Figure 5. This appears to be because an event of 4.5M_w or greater occurs within the Lleyn peninsula approximately every 150 years. Musson (2015) has previously made similar observations for Italy and the UK. It was decided to split the catalogue for the LLYN zone into two; one catalogue capturing events less than 4.5M_w, the other catalogue capturing all events equal to or greater than 4.5M_w. This approach better represents the observed recurrence of the larger magnitude events, as well as the smaller ones.

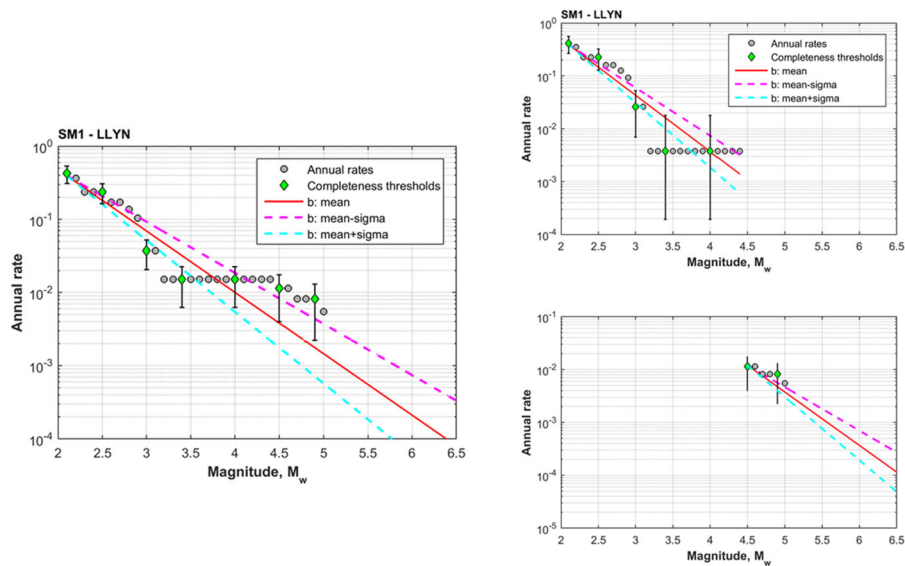


Figure 5: Magnitude Recurrence Results for Zone SM1_LLYN

The details of the seismic source characterisation logic tree are presented in Figure 6. It should be noted that variation in activity rate and b-value was only considered in the LLYN and ANG zones. For all other zones mean values from the PMLM results were used. This was shown to be a reasonable simplification since ANG and LLYN govern 99% of the hazard at the site. The variation in maximum magnitude was selected from a range of criteria selected following the CEUS-SSC (CEUS-SSC, 2012) approach.

Ground Motion Characterisation

Due to the high V_s of the rock it was recognized that any pre-existing GMPE would need to be modified to account for V_s and kappa site (κ₀), which is the high frequency decay of the Fourier amplitude spectra at zero epicentral distance within the first few kilometres beneath a given site (Hough *et al.*, 1988). Two approaches, one using acceleration Fourier amplitude spectrum (FAS), the other displacement FAS were used to define κ₀ based on the limited dataset of ground motions recorded at the site. Values of 0.012, 0.008 and 0.005s were derived and selected for the logic tree (Villani *et al.*, 2019a).

Eight empirical GMPEs were selected based on modified criteria proposed by Bommer *et al.* (2010). In addition, a site specific stochastic GMPE for Wylfa Newydd was commissioned by updating the pre-existing Rietbrock *et al.* (2013) model (Rietbrock and Edwards, 2017, 2019) considering the same values of κ₀ and three stress drops of 5, 10 and 20MPa. The suitability of

the nine GMPEs was assessed by carrying out statistical tests utilising both instrumental and macroseismic data (Villani *et al.*, 2019b). Finally, five GMPEs were selected using the Sammon's mapping approach (Sammon, 1969) to capture epistemic uncertainty. The resulting ground motion logic tree is shown in Figure 7.

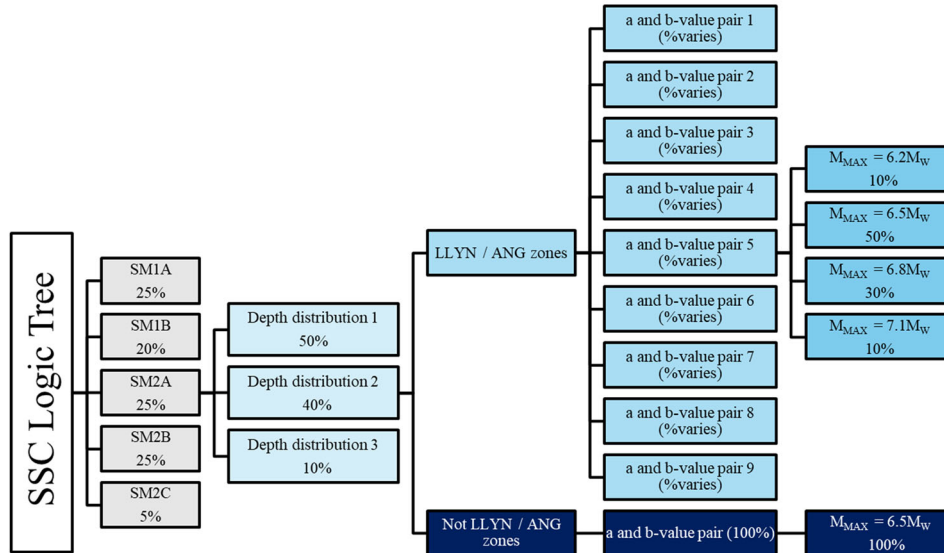


Figure 6: Seismic Source Characterisation Logic tree

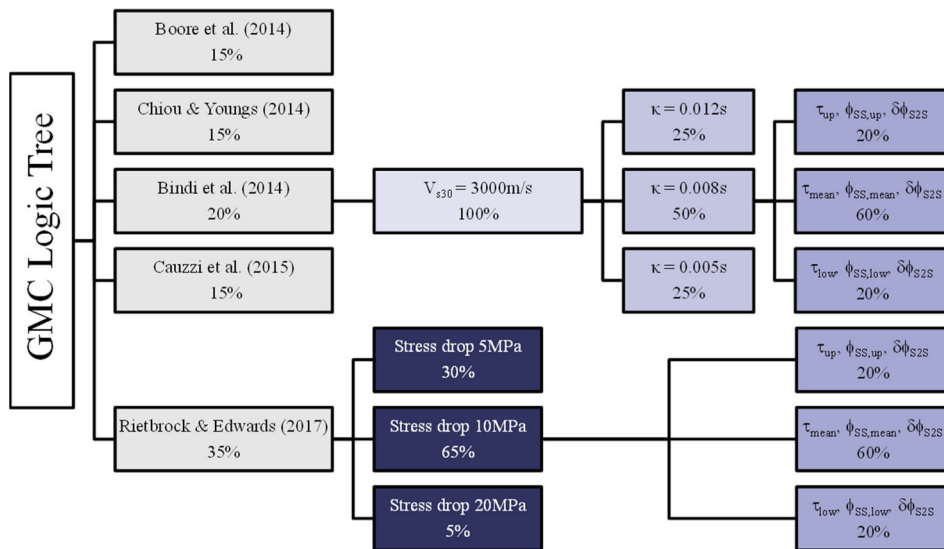


Figure 7: Ground Motion Characterisation Logic Tree

Seismic Hazard Results

The analyses were carried out using Oasys SISMIC, which has been used for previous nuclear seismic hazard studies in Hungary (Lubkowski and Pappin, 1998) and has successfully completed the Pacific Earthquake Engineering Research (PEER) project for the verification of seismic hazard codes (Hale *et al.*, 2018).

The PSHA was computed in terms of the geometric mean component of horizontal ground motion. The PSHA results are presented for annual probabilities of exceedance between 10^{-2} and 10^{-7} inclusive, for frequencies between 0.33 and 100Hz (PGA being considered equivalent to the spectral acceleration at 100Hz). The mean PGA value for an annual probability of exceedance of 10^{-4} is 0.192g, and the corresponding mean UHRS is presented in Figure 8.

It was observed that the epistemic uncertainty captured by SSC and GMC logic trees is large, with the individual source models yielding mean PGA results at an annual probability of

exceedance of 10^{-4} varying between 0.141g to 0.308g. For individual GMPEs the mean results vary between 0.115g and 0.264g. This range of values is wide but lies well within two standard deviations of the median hazard and is considered reasonable given the limited data in the UK. This level of variation is consistent with other studies, for example PEGASOS (Abrahamson *et al.*, 2004).

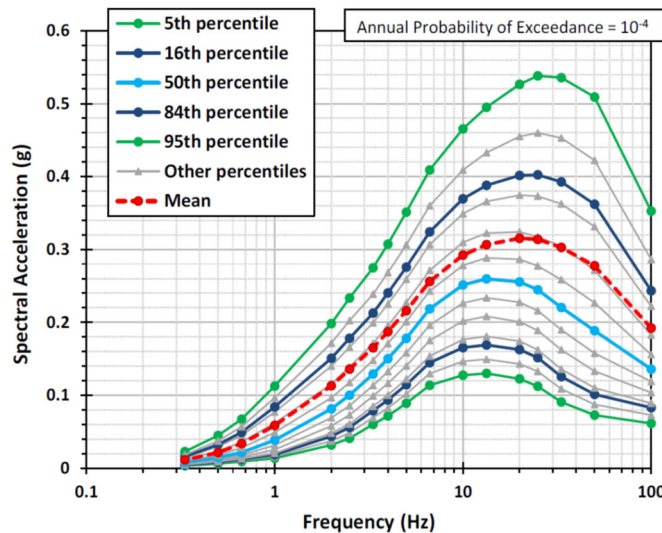


Figure 8: UHRS (5% Damping) for an Annual Probability of Exceedance of 10^{-4}

A range of sensitivity studies has been undertaken to test a number of key modelling assumptions, some of which have been discussed previously. In the authors' opinion they confirm that the mean hazard captures the centre, body and range of technical defensible interpretations.

A probabilistic site response study has also been undertaken, but this is beyond the scope of this paper. More details can be found in Villani *et al.* (2019c).

Tsunami Hazard Assessment

The purpose of this study was to show that the potential impact of tsunami waves on the Wylfa development platform was negligible, both in terms of amplitude and likelihood. To achieve this, the following steps were undertaken. Three independent tsunami catalogues were reviewed to identify confirmed and postulated tsunami that have affected the British Isles. The potential sources of tsunami affecting Wylfa were assessed with consideration of previous UK studies for Defra and the HSE (Richardson, 2006). The only plausible significant source is an earthquake off Portugal, similar to the 1755 Lisbon earthquake. An assessment of the geology and tectonics offshore from Portugal and consideration of a number of earlier studies regarding different possible tsunami source locations has shown the Goringe Bank is a likely candidate and also the most conservative of the mapped faults for tsunami waves propagating into UK waters. Modelling of a Lisbon like event was performed for extreme 8.7M_w and 9.0M_w events and an improbable 9.5M_w event using two different tsunami analysis software. The source dimensions were selected to exceed the dimensions of the known tectonic structures.

Modelling results offshore from Wylfa provide maximum wave heights of 30cm (zero to peak). Even allowing for run-up, wave heights are much lower than the normal tidal range at Wylfa.

Conclusions

This paper presents an overview of the seismic hazard assessment commissioned by Horizon Nuclear Power for the Wylfa Newydd site. It presents the geological and seismological evidence assembled and reviewed to show that the geological faults within the Wylfa Newydd site are not capable. A PSHA has been developed following relevant good practice as determined by the UK nuclear regulator and will, together with a probabilistic site response analysis, be used to define a conservative design spectrum for design following the requirements of ASCE 43 (2005) and US NRC Regulatory Guide 1.208 (2007). Tsunami modelling results offshore from Wylfa provide maximum wave heights which are much lower than the normal tidal range at Wylfa.

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