Probabilistic Seismic Hazard Assessment for a New-build Nuclear Power Plant Site in the UK

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A probabilistic seismic hazard analysis (PSHA) has been conducted as part of the Safety Case justification for a new-build nuclear power plant in the UK. The study followed a cost-efficient methodology developed by CH2M and associates for safety-significant infrastructure where high-level regulatory assurance is required. Historical seismicity was re-evaluated from original sources. The seismicity model considered fourteen seismic sources which, when combined, formed six alternative seismic source models. Separate models for the median ground-motion and aleatory variability were considered. The median ground-motion model comprised a suite of ground-motion equations adjusted to the site-specific conditions using V_S-kappa factors. A partially non-ergodic sigma model was adopted with separate components for the inter-event variability, and single-station intra-event variability, adjusted by a partially ergodic site-to-site variability term. Site response analysis was performed using equivalent-linear random vibration theory with explicit incorporation of the variability in the ground properties using Monte Carlo simulations. The final PSHA results were obtained by convolution of the hazard at the reference rock horizon with the site amplification factors. The overall epistemic uncertainty captured by the logic tree was assessed and compared against results from earlier PSHA studies for the same site.

Keywords: PSHA, Nuclear Power Plants, Seismic Hazard, Hinkley Point, UK

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1. Introduction

Ageing energy infrastructure along with requirements for reliable, low-carbon electricity has led the UK government to plan a new fleet of nuclear power plants (NPPs) (BERR 2007). The first of these NPPs to be constructed is Hinkley Point C (HPC), in Somerset, South West England, which is being developed by NNB GenCo, a subsidiary of EDF Energy. HPC will be the first NPP to be built in the UK for over 25 years and will consist of a twin UK European Pressurized Reactor (EPR) which is expected to provide 7% of the UK's electricity needs once completed.

In March 2014, NNB GenCo appointed CH2M (now Jacobs) to carry out a site-specific PSHA for the HPC site. In order to meet UK regulatory requirements and provide long-term support to the safety case, the utility operator (NNB GenCo) requires a probabilistic seismic hazard assessment (PSHA) to be undertaken for the site under consideration. The PSHA must include a robust assessment of the earthquake-related hazards to modern standards, and to the satisfaction of the Office for Nuclear Regulation (ONR).

However, given the ONR's non-prescriptive regulatory approach and that the last seismic safety case for a NPP presented to the UK regulator was over 25 years ago, there was a lack of detailed guidance as to the level of sophistication of the PSHA needed to satisfy the ONR's regulatory requirements for the new generation of NPPs.

Based on experience with the UK regulatory environment, through decades of involvement in nuclear-related projects, and on the understanding of international best practice for the evaluation of the seismic hazard for nuclear facilities, core members of the project delivery team developed a cost-efficient methodology for the PSHA, presented in the companion paper by Aldama-Bustos et al. (2018). The proposed methodology incorporated "relevant good practice", likely to satisfy ONR's requirements, whilst acknowledging commercial and program constraints associated with the development of NPPs faced by utility operators in the UK. The current paper focuses more specifically on the technical aspects of the PSHA undertaken for the HPC site. The results of this study underpinned the HPC design basis spectrum and provided inputs to inform the probabilistic safety assessment for the Safety Case.

2. Gap Analysis and Data Collection

The initial stage of the HPC study consisted of a high-level review of previous studies and existing data relevant to the site with the objective of identifying data gaps and streamlining the proposed PSHA methodology. This gap analysis was followed by a more detailed assessment of the available data and collation of additional data, mainly regarding the earthquake catalogue, instrumental and macroseismic ground-motion data and ambient-noise measurements, with the aim of informing the development of the Seismicity Model and Ground Motion Model. Key findings from this phase are summarized below.

2.1. Geology and Tectonics

The data-review efforts focused on four spatial areas colloquially referred to as the ‘study areas’ (Figure 1). These were adapted from the International Atomic Energy Agency (IAEA) guidelines SSG-9 (IAEA 2010) which recognize four review extents (from local to regional): Site Area, Site Vicinity, Near Region and Region. For this study, the IAEA ‘Region’ was sub-divided into a Mid Region (<100 km) and Far Region (<300 km), to achieve a more gradational coverage towards the limit of the study area, to help assess major structural features and to be consistent with the approach adopted for the development of the earthquake catalogue.

The review focused on the tectonic evolution of the Far Region (principal stress directions, relative crustal movements) and geological evolution and neotectonic characteristics of the Mid Region (evidence of faulting and seismicity). New data sources within 100 km of the site were identified and reviewed to ascertain if any could be used to validate the published interpretations. No investigations providing data on the basement geology (deep boreholes or seismic reflection profiles) had been undertaken in the last 25 years. Consideration was given to acquiring and reprocessing existing geophysical and neotectonic datasets, but this was discounted on the basis that reprocessing would not significantly improve the resolution to an extent that would enable markedly different interpretations to be made. In addition, given the limited time for the current study, the assessment was reliant on existing published interpretations.

The review identified major geological structures and regions having similar crustal composition, and the confidence levels that could be placed on such interpretations, to assist the subsequent development of the seismic source model.

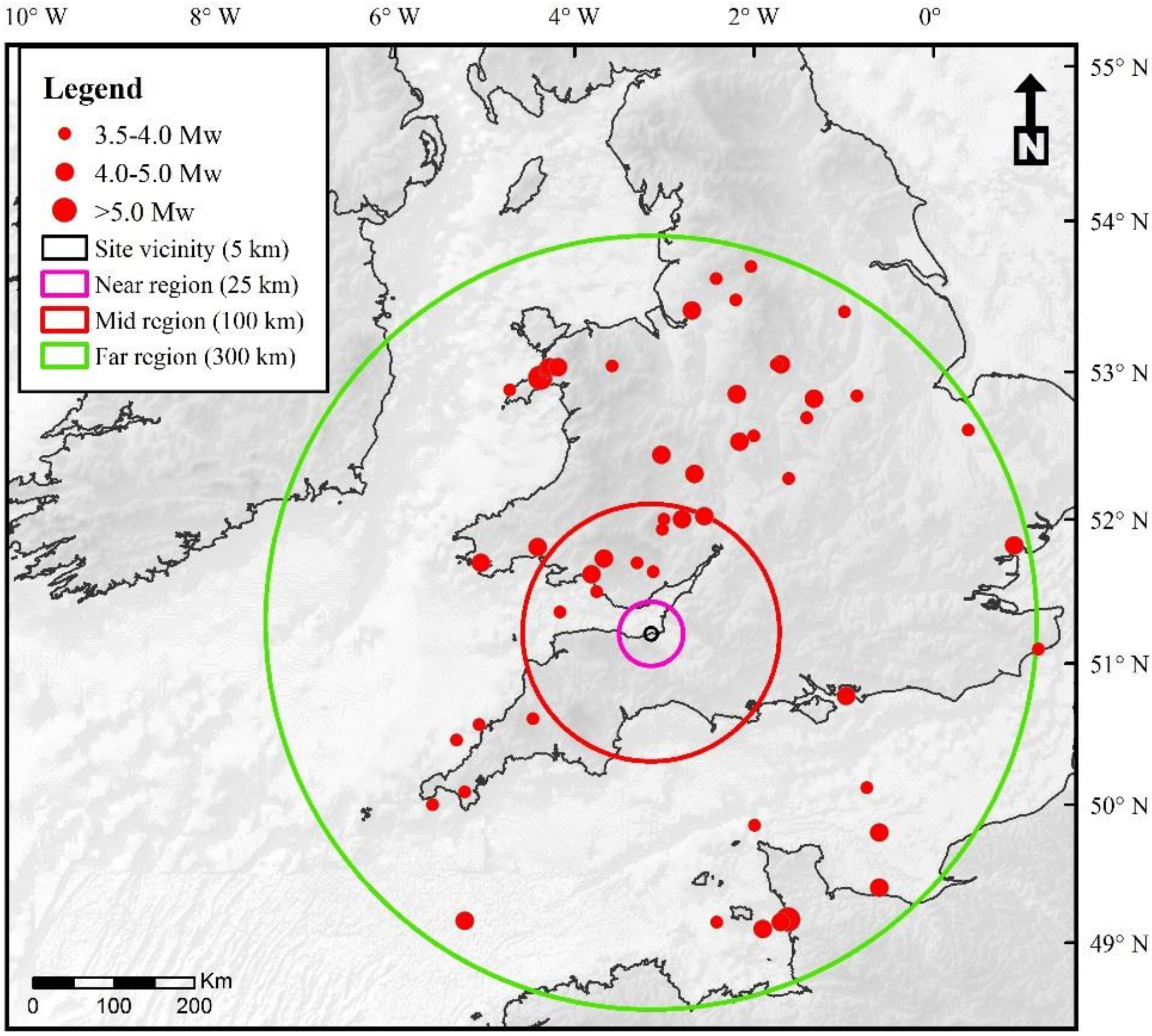

Fig. 1 Earthquakes within 300 km of Hinkley Point with **M** ≥ 3.5 since 1850, and study review extends (i.e., Site Area, Site Vicinity, Near Region, Mid Region and Far Region)

2.2. Earthquake Catalogue

A project-specific earthquake catalogue was developed. This comprised all events (and associated parameters) from the BGS earthquake database that occurred within 300 km of the site since 1970, the start of modern instrumental seismic monitoring in the UK. Historical events (those prior to 1970) within 100 km of the site were reassessed as part of the current study. Other relevant available publications (i.e., Principia Mechanica Ltd. 1982; Soil Mechanics Ltd. 1982; Burton et al. 1984; SHWP 1987; Musson 1989, 1994, 2008) were also reviewed to ensure completeness of the catalogue.

A comprehensive archive search was undertaken to collect data on known events and to identify previously undiscovered earthquakes. The search documented 120 events within 100 km of HPC between 1000 and 1969. A total of 72 earthquakes were reassessed from original data. Of these, 27 do not appear in existing catalogues, and 25 of these were previously unknown, although most of these proved to be mining-related events.

The parameters for reassessed events were derived using the methods outlined in Musson (1996) and Musson et al. (2001). The BGS database does not generally contain parameters for earthquakes before 1700, except for a few large and well-documented events. For this study, and where data existed, an effort was made to obtain at least approximate source parameters for these earthquakes. New parameters were not assigned for events before 1600 occurring more than 100 km from the site.

The parameters for post-1970 events were taken directly from the BGS earthquake catalogue. This lists 393 events within 100 km of Hinkley Point between 1 January 1970 and 31 July 2014. Of these, seven are larger than **M** 3 (where **M** is the moment magnitude), one being a foreshock. Magnitudes expressed as M_L were converted to **M** using a well-constrained formula taken from Grünthal et al. (2009). M_L-**M** relationships derived using UK data were explored (Musson 2005; Edwards et al. 2008; Sargeant and Ottemöller 2009); however, these were disregarded as they are constrained only for small magnitudes (**M** < 5) using a relatively limited database. Uncertainty in magnitudes, both as a result of inherent uncertainty and conversion, was not taken into account, as has been the practice in UK PSHA in the past. It is shown in Musson (2012) that this complex issue is not easily dealt with.

The final earthquake catalogue used for the study contains 155 earthquakes (prior to declustering). Figure 1 shows only those events in the catalogue with **M** ≥ 3.5 since 1850, providing a reflection of the spatial pattern of seismicity. What emerges is that the seismicity of the study area is neither uniform nor random. The distribution is dominated by a band of seismicity running SW-NE from South Wales up to the East Midlands, while a cluster of earthquake activity occurs in North-Western Wales. Elsewhere there is a scattering of activity, but with a general scarcity of events in the south and east of England (Whittaker et al. 1989; Chadwick et al. 1996, Musson 2007).

2.3. Ground Motion Data Collation

Ground-motion data relevant to the HPC site was collected and reviewed at an early stage of the study. These data included instrumental and macroseismic ground-motion data from permanent networks and historical documentation as well as recordings from a temporary microseismic network installed and operated by the Seismic Hazard Working Party (SHWP) between 1985 and the early 1990s.

2.3.1. Instrumental and Macroseismic Data

The main objective of the collation, review and assessment of instrumental and macroseismic data was to inform the assessment and final selection of the suite of GMPEs to be considered in the site-specific ground-motion model (GMM) for HPC. With this objective in mind, selection criteria were defined to identify suitable events, from which useful data might be available, as follows:

- From 1970 to the present for UK events, and from 1962 (the date of the establishment of the CEA LDG network) for events in northern France reported in the SI-Hex earthquake catalogue (Franceseisme 2014; Cara et al. 2015). This criterion was established to include only events with good quality data and with reliable magnitude estimates.
- Events with epicentral locations within 600 km of HPC and within the stable continental region as defined by Delavaud et al. (2012). This limited the selection to events occurring in the same tectonic region as Hinkley Point.
- Events with moment magnitude **M** ≥ 4.0 which is the lower magnitude limit covered by most of the modern GMPEs considered likely to be included in the HPC GMM [Note: An initial search was carried out using the criterion $M_L > 4.0$ (where M_L is local magnitude) which resulted in some events with magnitude slightly below **M** 4.0 being included in the final database].
- Events with macroseismic data for at least three different intensity levels to exclude events with insufficient number of intensity observations to demonstrate the attenuation of the ground motion with distance. Events with instrumental but no macroseismic data were retained.

Using the above criteria, a total of 21 events were initially identified from the data sources. Following the pre-processing of the macroseismic raw data, the final data set comprised: 19 events with macroseismic data, and six events with instrumental data, five of which also included macroseismic data. A map showing the epicentral locations of all events in the final dataset is presented in Figure 2.

2.3.2. SHWP Microseismic Network

A site-specific seismic hazard study for Hinkley Point A power station, adjacent to the proposed location for HPC, was carried out in the late 1980s by the Seismic Hazard Working Party (SHWP 1987, 1989). A temporary microseimic network was established as part of the

SHWP investigation which began in the 1980s (SHWP 1987). The network, which operated from May 1985, comprised seven stations within a 40-km radius of Hinkley Point and included a station at the existing NPP.

Relevant data associated with events recorded between 1985 and 1994 were made available by Dr Willy Aspinall, an original SHWP member who set up and ran the network. These data comprised a total of 368 velocity time-histories from 26 earthquakes, with magnitudes ranging between 1.0 and 5.1 M_L, and two underwater explosions. Of these records, only 143 were considered usable, with a signal-to-noise ratio higher than 3 within the frequency range of interest for the derivation of κ, which in this case was defined as 10-20 Hz. These 143 records were then used in an attempt to obtain an estimate of site-specific κ for the Hinkley PSHA as described in Section 4.1.2.

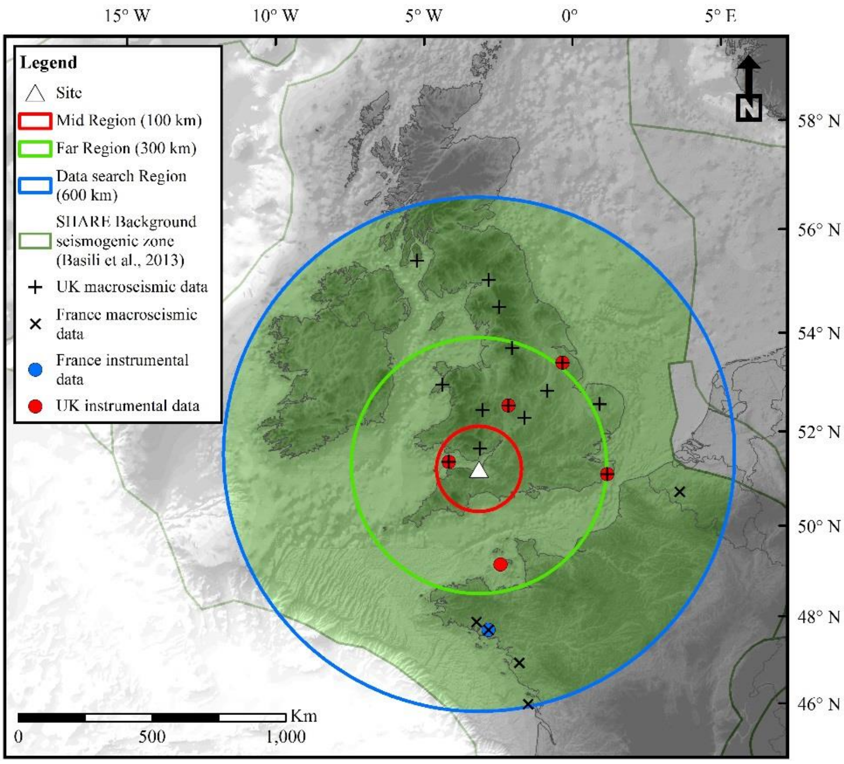

Fig. 2 Map of epicentral locations for events with macroseismic and / or instrumental data available. Base map shows the tectonic regions as defined for the SHARE project (Delavaud et al. 2012, Basili et al. 2013). The green shaded region indicates the stable continental region within the 600-km radius

2.4. Site Characterization

The initial site characterization gap analysis and data evaluation involved review of information from ground investigations spanning close to five decades, which included almost 300 boreholes drilled within the area of the Hinkley Point C site, of which more than 30 were deeper than 100 m. This information, together with data from several rounds of geophysical investigations, were used by the client to create a comprehensive geological model of the site, which was available for use in this study. Following completion of the gap analysis, it was considered beneficial to undertake additional non-intrusive field investigations at the HPC site to improve the understanding of the site response. Two phases of microtremor surveys, based on ambient noise vibration, were carried out. The Phase 1 survey involved single-station ambient noise measurements at four distinct locations across the site, while the Phase 2 survey extended the spatial coverage across a wider range of geological conditions to help in the interpretation of the Phase 1 results. Both surveys were undertaken by BRGM and followed the well-established SESAME guidelines (Bard et al. 2004; Bard 2008).

3. Seismicity Model

The UK lies within an intraplate area with low to moderate levels of seismicity and no distinct seismogenic structures. In this setting, the seismicity model development was subdivided into the following phases:

- Seismic source zonation: Define areas with similar tectonic and geological characteristics within which one may expect broadly consistent levels of seismicity (i.e., recurrence rates and magnitude distribution of future earthquake can be reasonably expected to be uniform).
- Seismogenic fault identification: Determine if any faults within the defined sources zones localize seismicity above the background levels for the zone.
- Seismic source model (SSM) development: Develop SSM logic tree to account for alternative interpretations of zone boundaries and activity rates, and assign weights to each alternative branch.

The development approach is deemed to be consistent with the principles for source model development suggested in IAEA SSG-9.

3.1. Definition of Alternative SSMs

The development of alternative SSMs focused mainly on the Mid Region (see Figure 1) and in particular the variation in seismicity north of the Bristol Channel. Definition of the source zone boundaries and associated uncertainty used both geological and seismological evidence and hypotheses, coupled with the spatial variation of the earthquake catalogue completeness.

The main source of uncertainty in the seismicity model was the position of the boundary between the higher levels of seismicity in South Wales and the lower levels observed south of the Bristol Channel. This boundary was linked to the Variscan Front, a vague term for the linear region which runs east-west along the northern part of the Bristol Channel, and that defines the northern limit of Variscide-type deformation. To the south occurs a zone of shallow, southerly dipping, broadly east-west trending Variscan thrust, and NW-SE trending strike-slip faults (i.e., SOME seismic source in Figure 3). To the north is the Wrekin Terrane, an area of meta-sedimentary and plutonic basement rocks overlain by volcano-sedimentary successions (i.e., WMAR/SWAL seismic sources in Figure 3). The position of the boundary between these sources was primarily defined from interpretations of regional gravity, magnetic anomalies, geological mapping, and to a lesser extent the distribution of seismicity. The best estimate position, based on the weight of evidence from all of the above, was represented by the SSMs with a northern boundary position (SSM-A, SSM-B, SSM-C and SSM-D). Epistemic uncertainty was captured by the inclusion of alternative SSMs with a southern boundary position located 10 km to the south (SSM-E and SSM-F). At its closest, this boundary is located either 12 km from the site (southern position) or 22 km from the site (northern position).

The second most important source of uncertainty was the definition of the seismic source enclosing the higher level of seismicity observed in South Wales. Four different theories were postulated which could explain this higher level of seismicity:

- Seismicity is associated with the Wrekin Terrane (WMAR-A, WMAR-E) and the increased seismicity in South Wales is due to chance.
- The increased seismicity in South Wales is associated with a stronger tectonic fabric imparted by the Variscan Orogeny on the southern part of the Wrekin Terrane (SWAL-B, SWAL-E), and this fabric is not present across the remainder of the terrane (WMAR-B, WMAR-F).
- The increased seismicity is associated with the Welsh Coalfield (SWAL-C), leaving a residual zone encompassing the remainder of the terrane (WMAR-C).
- The increased seismicity is associated with clustering in the Swansea area due to the intersection of major faults (SWAL-D), leaving a residual zone encompassing the remainder of the terrane (WMAR-D).

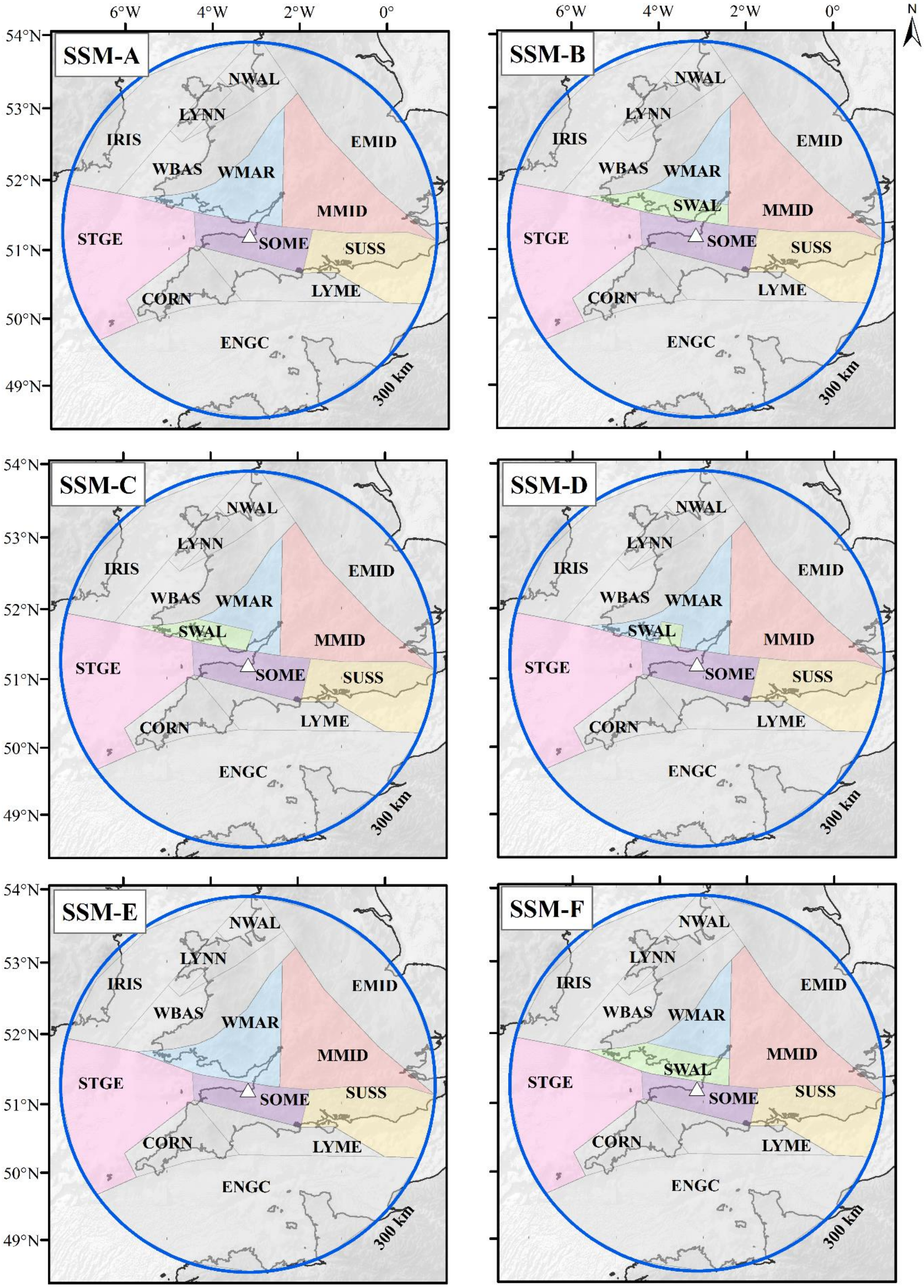

Fig. 3 Seismic source models (SSM) A to F coloured areas indicate those seismic sources with geometries which vary across the various SSMs, greyed sources have constant geometries for all models

The consideration of these uncertainties through a logic tree framework resulted in the six SSMs shown in Figure 3. Only area sources were included in the SSMs, as there was insufficient evidence to support the inclusion of any seismogenic faults (i.e. distinct seismogenic features that would be the focus of future seismic activity) in the source models. This conclusion is consistent for a site that occurs in a low, relatively homogenous, tectonic stress regime, which has only experienced low to moderate levels of seismicity. The resulting logic tree and weights assigned to each alternative branch are shown in Figure 4. The process for the weighting of the logic tree resulted in assigning almost equal weights to the two hypotheses of the strength of the association with the Wrekin Terrane. However, it is likely that the effect on the hazard of weighting them equally (both at 0.5) as opposed to 0.53 and 0.47 would be small.

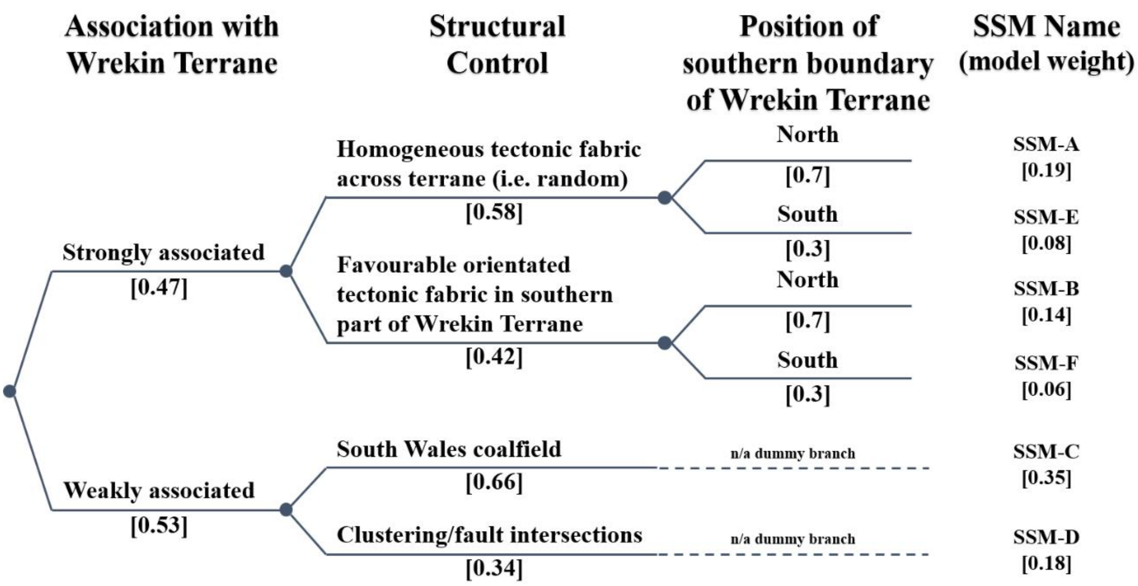

Fig. 4 Seismic source model logic tree for source zonation. Numbers in square brackets are weights assigned to each alternative branch

3.2. Seismic Source Zones Parameterization

Recurrence rates were determined for all the seismic source zones considering the doubly-truncated exponential Gutenberg-Richter model. To capture epistemic uncertainties associated with the activity rate (a) and b-value parameters characterizing the Gutenberg-Richter relation, the logic-tree considered nine combinations of a and b values (three values for a, three values for b, with the three values comprising the central estimate, and the central estimate plus and minus one standard deviation) for the host seismic source (SOME) and the two seismic sources in southern Wales (SWAL and WMAR), which were identified as the most hazard-significant seismic sources in the model. The weights for these alternative (a, b) combinations were source-specific as they were based on a maximum-likelihood fit to the data in each source. Calculations were performed using the penalized maximum likelihood method (EPRI 1994), which ensures that the complete space of possible (a,b) combinations is captured and weighted appropriately (i.e., considering that the uncertainty in a and b are correlated). For all other seismic sources, a single best estimate (a, b) combination was adopted with a weight of 1.0.

Three values of M_{max} were assigned: **M** 6.5, 6.8 and 7.1, with respective weights of 0.5, 0.4 and 0.1. These M_{max} values and corresponding weights represent a simplified version of those proposed for the British Isles by Meletti et al. (2010) as part of the SHARE project (Woessner et al. 2015). Cumulative earthquake magnitude rates for the most hazard-significant sources (only one variant of the SWAL and WMAR sources are presented due to space limitations), considering all (a,b) combinations and M_{max} = 7.1 are shown in Figure 5.

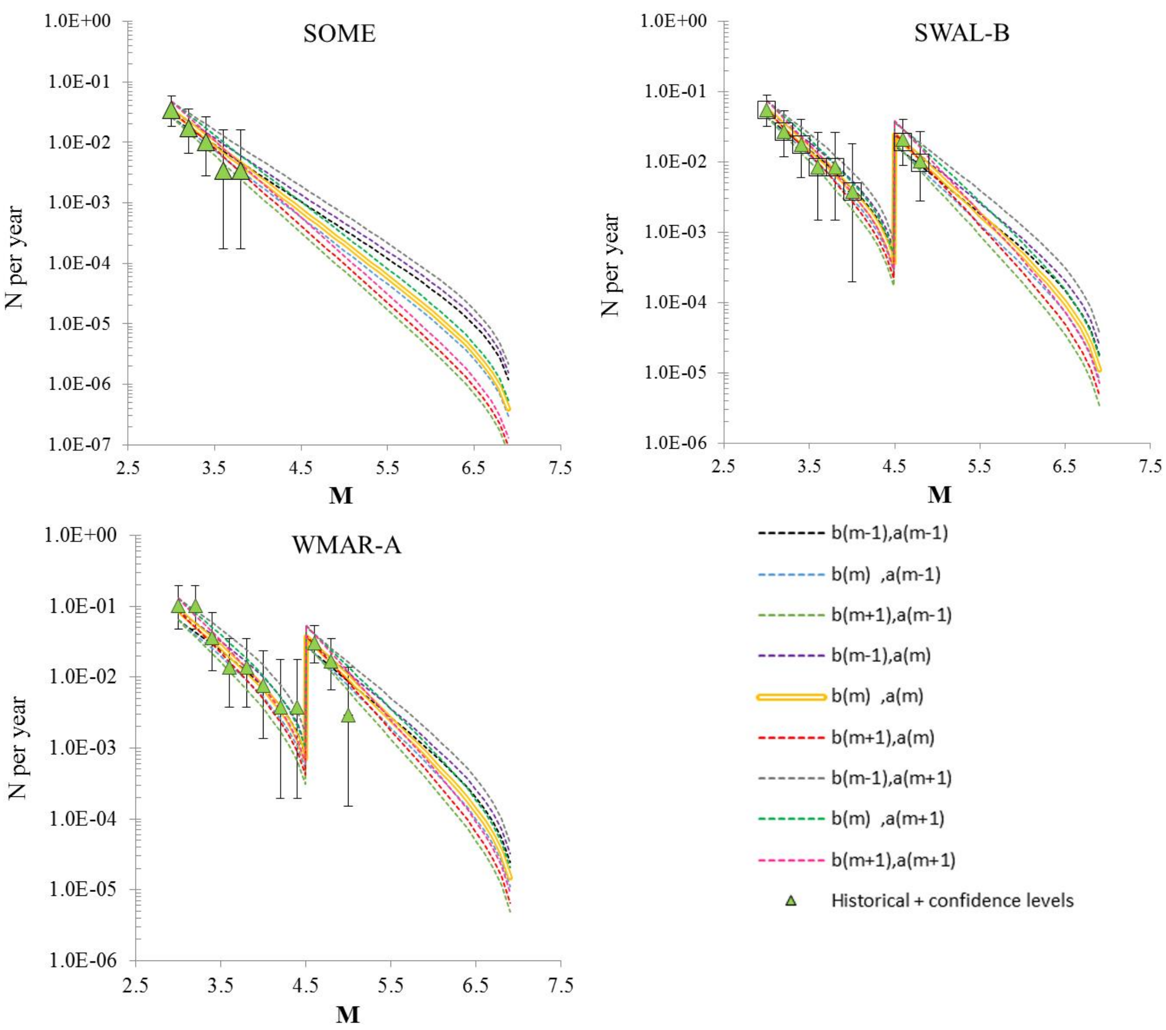

Fig. 5 Cumulative earthquake rates for the three most hazard-significant sources, and for M_{max} = 6.8. a(m) and b(m) correspond to the central a and b values, a(m+1) and a(m-1), and b(m+1) and b(m-1), correspond to the central a and b values plus and minus one standard deviation, respectively

For the seismic sources covering the South Wales region, a departure from the exponential distribution assumed by the Gutenberg-Richer model was observed for magnitudes below **M** 4.5 (see Figure 5). This type of seismicity has been referred to as "semi-characteristic" seismicity by Musson and Sargeant (2007), who confronted a similar feature during the preparation of the UK national seismic hazard maps. This is explained as the presence of a bipartite magnitude-frequency distribution (Musson 2015).

The minimum magnitude (M_{min}) to be used in the hazard calculations is not specified by the UK regulator. This parameter defines the lower limit of integration over earthquake magnitudes such that using a smaller value would not alter the estimated risk to the structure under consideration (Bommer and Crowley 2017) and has traditionally been set to **M** 4.0 in UK nuclear-safety-related seismic hazard studies. For the host source (SOME) M_{min} was taken as **M** 4.0, consistent with this precedent. For all other sources, a pragmatic decision was taken to increase M_{min} from **M** 4.0 to **M** 4.5. This simplifies the modelling of the earthquake recurrence model in view of the bipartite magnitude-frequency distribution discussed above, which otherwise would result in unnecessarily increased complexity of the hazard calculations, since the difference in M_{min} has a negligible impact on the hazard. Indeed, sensitivity calculations showed that the contribution to the total hazard from earthquakes < **M** 4.5 outside the host zone was about 0.2%.

A common hypocentral depth (h) distribution was assumed for all seismic sources. This took the form of a discrete aleatory distribution, for depths between 5 and 25 km, reflecting the relative frequencies of occurrence estimated from the hypocentral distribution of the seismicity larger than **M** 4.

All seismic sources were modelled as area sources at specific depths; no linear fault sources were considered. Earthquake occurrences within the seismic sources were modelled using the "floating earthquake" concept, where a spatially uniform distribution of the earthquake epicenters is assumed, in combination with virtual fault ruptures. The simulated fault rupture characteristics were based on knowledge of the existing geological structure, earthquake focal mechanisms and the current stress regime. All virtual fault ruptures were assumed to occur on vertical fault planes, hypocenters were assumed to be located centrally (both along-strike and along-dip) of the virtual rupture plane, and the concept of leaky boundaries was assumed for all sources. The fault rupture plane in CRISIS2015 is fixed to a circular shape, which gives a 1:1 aspect ratio. The extent of the virtual fault ruptures was magnitude dependent, calculated using the area scaling relationship for stable continental regions of Leonard (2010). Randomization of the rupture area was not considered. The orientation of the virtual fault ruptures was common to all sources, but specific to the style-of-faulting assumed; when multiple rupture orientations were possible, these were modelled as a discrete aleatory distribution of strike angles with associated relative frequencies. Earthquake occurrence for all seismic sources was modelled using the double-truncated exponential Gutenberg-Richter model.

4. Ground-motion Model (GMM)

A rigorous and systematic approach was followed to develop a site-specific GMM for the HPC site. In line with state-of-the-practice PSHAs for high-value infrastructure, the site-specific GMM for the Hinkley PSHA comprised two separate models, the median ground-motion model and the aleatory variability (sigma) model. The GMM was developed to predict ground motions for the V_{S30} at the reference velocity horizon and then near-surface effects due to the shallow deposits were accounted for through a hazard-compatible site response analysis (see Site Response Analysis section below). In agreement with the principle of a site-specific PSHA, a partially non-ergodic sigma model was adopted (i.e., a sigma model where the site-to-site variability, normally included in the intrinsic sigma models of the GMPEs, is removed; Rodriguez-Marek et al. 2013).

4.1. Median Ground-motion Model

Traditionally in PSHA, epistemic uncertainty within ground-motion prediction is captured by selecting a suite of candidate GMPEs, which are considered to provide an adequate prediction of the ground-motion scaling in the region of interest. This approach can be referred to as the "traditional" or "multi-GMPE" approach. However, some recent studies have championed an alternative approach, normally referred to as "backbone" approach, where fewer GMPEs than in the traditional approach are selected (normally one or two) and epistemic uncertainty is captured by scaling up or down the median predictions of the selected GMPEs (e.g. Bommer 2012; Atkinson et al. 2014; Douglas 2018).

After careful consideration of the advantages and disadvantages of both approaches, the GMM team opted for the multi-GMPE approach for the Hinkley PSHA. It was thought that the backbone approach would require significant additional work, mainly associated with the higher level of detail needed for the selection of the most appropriate GMPE for the region and for the calibration of the scaling of the selected GMPE required to account for the uncertainty on, for example, the median stress drop of UK earthquakes. It was also thought that the number of selected GMPEs for the project (five) from different geographical regions (including a GMPE from the UK itself), combined with the alternative V_S-kappa adjustments to their median predictions (upper, middle and lower adjustment factors), accounted for the epistemic uncertainty (also see Median Ground Motion Logic Tree sub-section below).

4.1.1. Approach to Selection of GMPEs

A critical review and comparison of an initial list of GMPEs was carried out to identify a final set of suitable candidate GMPEs for the Hinkley PSHA. At the first stage of the selection process over 400 potential candidate GMPEs were identified from the online compendium of Douglas (2014). This was reduced to a shortlist of 12 GMPEs by applying selection criteria based on recommendations by Cotton et al. (2006) and Bommer et al. (2010). Consideration was also given to selection criteria used in previous high-level seismic hazard studies [e.g., PEGASOS Refinement Project (Renault 2014); GEM Global GMPEs project (Douglas et al. 2012; Stewart et al. 2015)]. An assessment of the 12 preliminary-selected GMPEs was carried out by comparing the ground-motion predictions from the various models, as well as comparisons against ground-motion instrumental and intensity data retrieved as part of this project. Due to limitations of the instrumental and intensity data, comparisons against observations provided only limited, qualitative, guidance for the selection of the final suite of candidate GMPEs. For this reason, quantitative methods for the assessment of the match between ground-motion predictions from the GMPEs and instrumental data (e.g., Scherbaum et al. 2004, 2009) were not applied.

The selection of the final suite of candidate GMPEs was done through an expert judgement assessment by the GMM team based on a set of criteria that considered a range of pertinent technical issues, including the comparisons of the ground-motion predictions from the various models amongst themselves and against the ground-motion data, and project-specific factors. Based on this process, five GMPEs were selected for the prediction of the median ground-motion:

- Atkinson and Boore (2006, 2011) [AB0611] – model for ‘hard rock’ (V_{S30} > 2,000 m/s);
- Bindi et al. (2014a, b) [BETAL14] – model using R_{JB} and V_{S30};
- Boore et al. (2014) [BOOREETAL14] – base model (i.e., without regional factors);

- Cauzzi et al. (2015) [CETAL15] – considering the period-dependent reference V_{S30};
- Rietbrock et al. (2013) [RETAL13d] – magnitude-dependent stress drop model.

These models were subsequently adjusted to predict median ground-motions compatible with the ground conditions at the reference velocity horizon level defined for the HPC site (i.e., V_S-kappa adjustments) and to address incompatibility issues between dependent parameters of the various GMPEs, specifically style-of-faulting.

For the exploration of the space occupied by the suite of GMPEs methods such as the Sammon's map approach (Scherbaum et al. 2010; Scherbaum and Kuehn 2011) were considered. However, in view of project constraints, a full application of the Sammon's map technique and related visualization methods were considered beyond the scope of the study. Instead, a model-based approach was implemented for the weighting of the alternative GMPEs using the arguments for and against the various selected GMPEs considered during the GMPEs selection process.

The GMM team's degree-of-confidence in the various selected GMPEs resulting from this process was relatively uniform, which resulted on an a priori assessment of equal weights. However, it was decided to assign lower weights to the stochastic models in view of the important contributions to the hazard expected from the close-in sources, as they are known to be poorly constrained at short distances. The weight subtracted from the stochastic models was redistributed equally between the BETAL14 and BOOREETAL14 models, which were considered the overall best-behaved GMPEs in the selection. The CETAL15 equation thus is assigned a lower weight than the other two empirical GMPEs. This reflects the fact that CETAL15 is considered less well constrained than the BETAL14 and BOOREETAL14 models. Additionally, the underlying database of CETAL15 has not been subjected to the same level of scrutiny as the NGA-West 2 and RESORCE databases used by Boore et al. (2014) and Bindi et al. (2014a,b).

The final weighting scheme for the GMPE is shown in the Median Ground Motion logic tree in Figure 6.

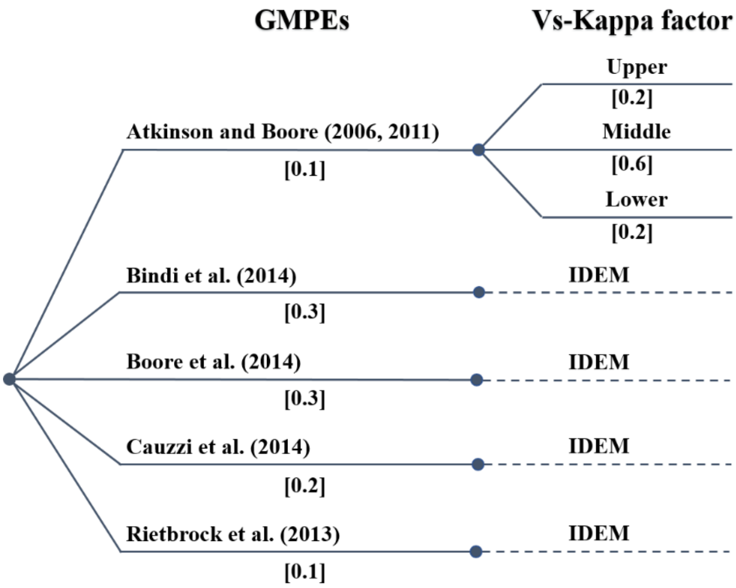

Fig. 6 Median ground-motion logic tree for the Hinkley PSHA. Numbers in square brackets are the weights assigned to each alternative branch

4.1.2. V_S-kappa Adjustment Factors

Following the selection of the final suite of GMPEs, the median predictions of each GMPE had to be adjusted to account for differences between the host region for which the GMPE was derived and the target location corresponding to the study site. This host-to-target adjustment involved quantifying, for the host and target regions, the effects of the shallow crustal shear-wave velocity (V_S) and the high-frequency crustal attenuation, termed "kappa".

The calculation of the V_S-kappa adjustment required four inputs to be defined:

- Average V_S profiles of the host ($V_{S\text{-host}}$) and target ($V_{S\text{-target}}$) locations; and
- Average kappa in the host ($\text{kappa}_{\text{host}}$) and target ($\text{kappa}_{\text{target}}$) locations.

For the two stochastic models (i.e. AB0611 and RETAL13d) $V_{S\text{-host}}$ profiles were evaluated using information provided by the developers of these models. For the three empirical models (BETAL14, BOOREETAL14 and CETAL15), $V_{S\text{-host}}$ profiles were derived using the generic V_S profiles of Cotton et al. (2006) for a V_{S30} value of 1,000 m/s.

For each GMPE, $\text{kappa}_{\text{host}}$ values were estimated using an approach involving generation of Fourier amplitude spectra for a scenario earthquake obtained from disaggregation using inverse random vibration theory (IRVT, Al Atik et al. 2014). The sensitivity of the kappa value to the earthquake magnitude and distance and to the fitted frequency range was investigated in some detail. It was found that for some GMPEs the kappa values depended quite significantly on magnitude and distance. Rather than propagate this additional computational load through the hazard calculation (which would also make checking of the calculations more difficult) and because some of the kappa values obtained from the inversion for some scenarios were unphysical, a single scenario was chosen based on controlling earthquake scenarios obtained from preliminary seismic hazard calculations for the HPC site for the high-frequency range, where the V_S-kappa adjustment factors are more important.

The $V_{S\text{-target}}$ profile was developed based on information obtained from a variety of sources, including: shallow borehole seismic data (down to approximately 120 m) available from the various historical ground investigation campaigns at the site, published velocity data from the 1 km deep Burton Row borehole (located 13 km ENE of the Hinkley Point site and which penetrates the same geological sequence), two crustal velocity models derived for the HPC site by SHWP (1987) using recordings from the Hinkley Point microseismic network, and the published deep crustal velocity model of Hardwick (2008) from local earthquake tomography.

A single $V_{S\text{-target}}$ profile was ultimately defined using a curve-fitting approach based on the method of Cotton et al. (2006). Whilst the shear-wave velocity at the Hinkley Point reference velocity horizon has a value of 1,000 m/s, the V_{S30} of the target V_S profile was 1,077 m/s.

Considerable efforts were expended trying to define a $\text{kappa}_{\text{target}}$ based on data available from the Hinkley Point microseismic network installed and operated by the SHWP from 1985 to 1994. However, the kappa values obtained for most stations examined were found to be compromised by potential site effects. The few ‘unaffected’ kappa values from the remaining stations were subsequently considered to be less relevant, due to the proposed definition of the reference velocity horizon at some depth beneath the site. Estimating $\text{kappa}_{\text{target}}$ from the microseismic data was, therefore, not considered possible for the study. These few surface kappa estimates could have been combined with the low-strain damping used in the site response analyses to derive estimates of kappa at the reference velocity horizon but this was not attempted in view of the large dispersion in the estimates.

Following a literature review of kappa estimates from UK earthquake data, it was decided to use the empirical relationship of Van Houtte et al. (2011) to provide a best-estimate $\text{kappa}_{\text{target}}$ derived from the target V_{S30} value of 1,077 m/s. To account for the epistemic uncertainty on the estimation of $\text{kappa}_{\text{target}}$, three logic tree branches were set up to cover upper bound, best-estimate and lower bound values (0.0342 s, 0.0197 s and 0.0114 s, respectively), where the upper and lower bounds were set equal to the best-estimate value ± 1 standard deviation defined by Van Houtte et al. (2011). Weights to each alternative $\mathrm{kappa}_{\mathrm{target}}$ branch were assigned following a three-point approximation to the normal distribution as shown in Figure 6. The best-estimate $\mathrm{kappa}_{\mathrm{target}}$ value (middle branch) estimated for HPC compared well with kappa estimates for rock sites in the UK provided by Rietbrock et al. (2013), Ottemöller et al. (2009) and Ottemöller and Sargeant (2010). The variation of the final adjustment factors with period for all five GMPEs and the three alternative $\mathrm{kappa}_{\mathrm{target}}$ values are shown in Figure 7.

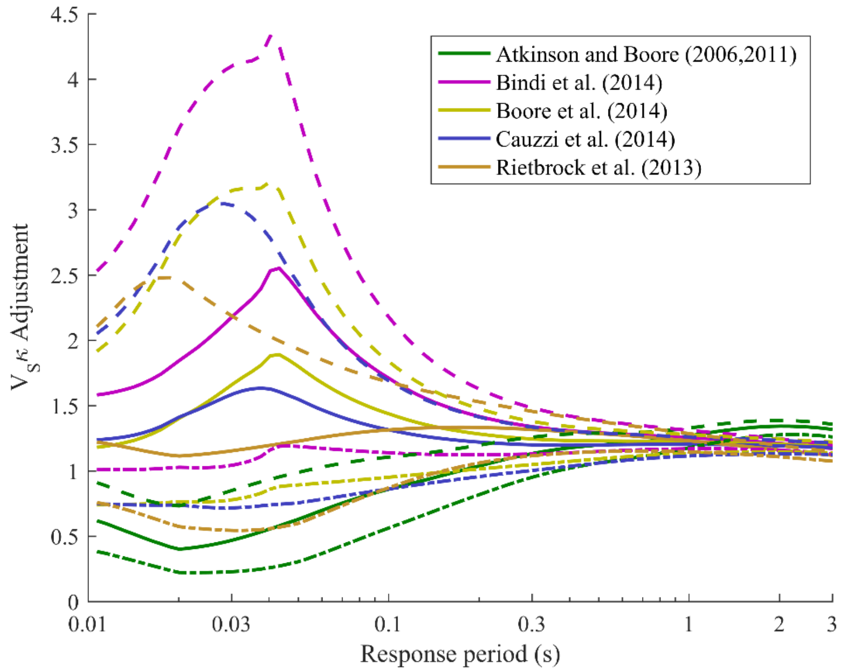

Fig. 7 V_S-kappa adjustment factors for application to response spectral acceleration from the host GMPEs for the target Vs profile and kappa values. Solid lines are for the middle target kappa, dashed lines correspond to the lower target kappa and the dash-dotted lines correspond to the upper target kappa

4.1.3. Median Ground Motion Logic Tree

The median ground-motion model for the Hinkley PSHA is then the result of combining the selected GMPEs and their corresponding V_S-kappa adjustment factors through the logic tree framework as represented in Figure 6. This median ground-motion model represents, in the view of the GMM team, the best ground-motion model for the specific region of interest (i.e., within 300 km of the HPC site).

Epistemic uncertainty in the median ground-motion model is captured by the two levels of logic-tree branches (i.e., GMPEs and V_S-kappa factors). The rigorous selection of the candidate GMPEs, along with the range of site-specific V_S-kappa adjustment factors, and corresponding weights, provides confidence that the median ground-motion model captures the range of likely ground-motion intensities (i.e., epistemic uncertainty) at the HPC site.

A comparison of the ground motions predicted by the five selected GMPEs against the magnitude-dependent model of Rietbrock et al. (2013), modified to account for a variation in the median stress parameter of $\pm 1\sigma(\log_{10}[\Delta\sigma])$ (i.e., 4 to 25.1 MPa, with a median of 10 MPa), shows that the suite of selected GMPEs adequately captures the epistemic uncertainty regarding the appropriate value of the stress parameter for the UK (see Figure 8). Previous studies present evidence that stress parameter increases with magnitude hence it could be argued that the upper bound of potential stress parameters for large UK earthquakes could be higher than the 25.1 MPa assumed in Figure 8. This figure shows, however, that the GMPE of Atkinson and Boore (2006, 2011) would still envelope the adjusted Rietbrock et al. (2013) GMPE at short structural periods even for higher median stress parameters.

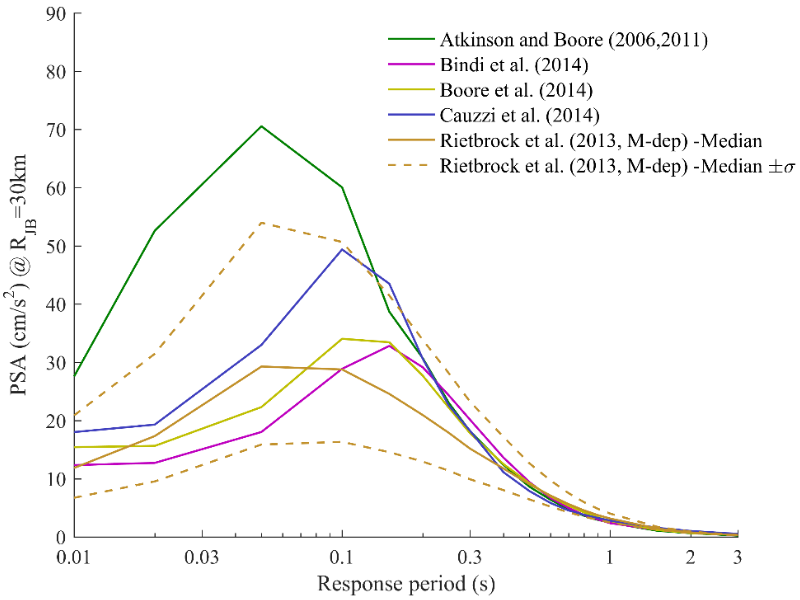

Fig. 8 Comparison of the response spectra for R_{JB} = 30 km and **M** 5.0 from the finally selected GMPEs, the Rietbrock et al. (2013) magnitude-dependent model for median stress parameter (10 MPa) and the median ± 1 logarithmic standard deviation of the stress parameter (i.e., 4 and 25.1 MPa)

The level of uncertainty implicit in the adjustment factors developed for the Hinkley PSHA was estimated and compared against uncertainty values reported for similar studies [i.e., Thyspunt project (Rodriguez-Marek et al. 2014); and Hanford project (Coppersmith et al. 2014)]. Uncertainty levels implicit in the Hinkley PSHA V_S-kappa adjustment factors for periods below 0.1 sec were found to be midway between the Thyspunt and Hanford uncertainty levels, for periods above 0.1 s Hinkley PSHA and Hanford uncertainty levels were found to be similar (see Figure 9). The intrinsic uncertainty captured in the V_S-kappa adjustment factors presented in Figure 9 was computed similarly to Rodriguez-Marek et al. (2014) as the weighted sample standard deviation of the logarithmic V_S-kappa adjustment factors shown in Figure 7.

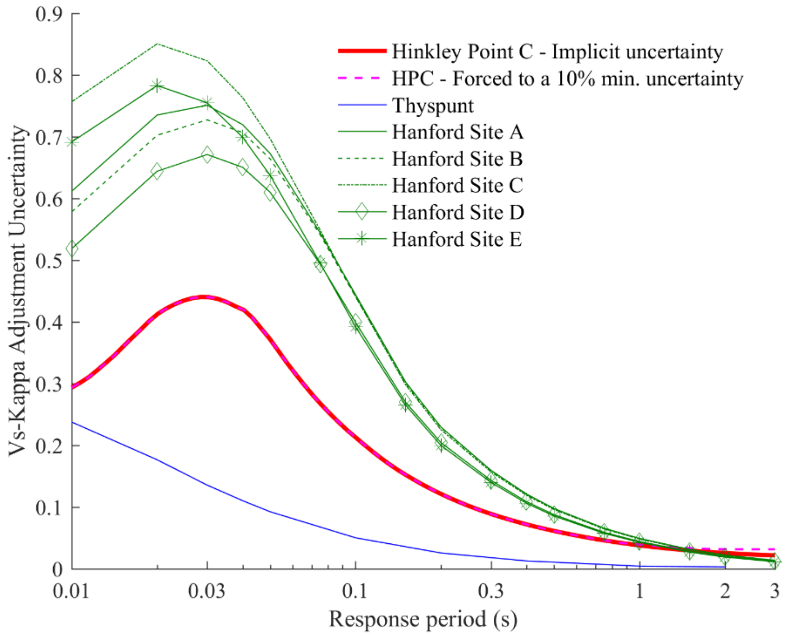

Fig. 9 Uncertainty implicit in the V_S-kappa adjustment factors for the HPC project compared to the equivalent values from the Thyspunt project (Rodriguez-Marek et al. 2014) and the Hanford project (Coppersmith et al. 2014). The dashed line for HPC corresponds to the case where the adjustment factors are forced to have a minimum spread of 10% around the best estimate value to account for unaccounted epistemic uncertainty on the target V_S profile. All values are given in terms of the natural logarithm

4.2. Sigma Model

The sigma model for the Hinkley PSHA was based on the single-station sigma (σ_{SS}) concept. The application of this concept within a PSHA for a nuclear power plant is presented by Rodriguez-Marek et al. (2014). The σ_{SS} model developed for the Hinkley PSHA considers separate models for the inter-event variability (τ) and the single-station intra-event variability (ϕ_{SS}), adjusted by a partially ergodic site-to-site variability term ($\delta\phi_{S2S}$) which accounts for epistemic uncertainty unaccounted for in the V_S-kappa adjustment factors, as well as the amplification factors considered in the site response. Both the ϕ_{SS} and τ models for the Hinkley PSHA were taken from models available in literature. $\delta\phi_{S2S}$ was calculated by forcing the uncertainty implicit in the V_S-kappa adjustment factors to remain above 10% across all response periods.

4.2.1. Tau Model

Following a comparison and assessment of eight tau (τ) models, the τ model of Abrahamson et al. (2014) was selected. To account for the epistemic uncertainty on whether the observed inter-event variability of the ground motion is magnitude-dependent or not, which is still an unresolved issue within the technical community, two alternative branches for the τ logic tree were considered. The first of the branches considered the magnitude-dependent (heteroscedastic) τ model of Abrahamson et al. (2014), while the second branch considered a magnitude-independent (homoscedastic) τ model, which was taken as the Abrahamson et al. (2014) τ model evaluated for **M** 6.0. The weights assigned to these alternative branches are discussed in the Sigma Logic Tree sub-section below.

A second level of branches in the τ model logic tree was considered to account for the epistemic uncertainty on the median τ predictions of each of the two alternative models (i.e., heteroscedastic and homoscedastic models). The second level of branches in the τ model logic tree considered upper and lower branches, in addition to the median branch, which were defined so as to envelope roughly the other examined τ models for magnitudes of less than $\mathbf{M} \leq 6.0$. For this second level of branches, weights were selected in accordance with the three-point representation of the normal distribution.

4.2.2. ϕ_{SS} Model

In a similar manner as for the τ model, various ϕ_{SS} models available in literature were assessed. Based on this assessment a ϕ_{SS} model logic tree for the Hinkley PSHA was developed considering the constant and magnitude-dependent models of Rodriguez-Marek et al. (2013). The first level of branches on the ϕ_{SS} logic tree considered the epistemic uncertainty on the magnitude-dependency of the intra-event variability of the ground motion (i.e., heteroscedastic and homoscedastic models). The heteroscedastic ϕ_{SS} model for the Hinkley PSHA was defined as a hybrid model consisting of taking the larger ϕ_{SS} estimate of the constant and magnitude-dependent models of Rodriguez-Marek et al. (2013). The homoscedastic ϕ_{SS} model was taken as the constant model of Rodriguez-Marek et al. (2013).

The second level of branches in the ϕ_{SS} logic tree addressed the epistemic uncertainty associated with the median estimates of the ϕ_{SS} models (i.e., heteroscedastic and homoscedastic) by including upper and lower branches. The upper and lower branches were constructed using the same dispersion in the median ϕ_{SS} prediction ($\phi_{SS,S}$) as estimated by

Rodriguez-Marek et al. (2014), which led to branches at 1.16 ϕ_{SS}, ϕ_{SS} and 0.84 ϕ_{SS}. Weights were assigned to each branch in accordance with the three-point representation of the normal distribution. It should be noted that the theoretically-more-appropriate chi-square distribution was used in some recent studies (e.g. Coppersmith et al., 2014).

4.2.3. Partially Ergodic Correction Term at Reference Horizon, $\delta\phi_{S2S}$

One of the requirements for the application of the single-station sigma concept is that epistemic uncertainty in the site term should be duly considered (Rodriguez-Marek et al. 2014; Coppersmith et al. 2014). This section deals more specifically with the site term at the reference velocity horizon, which in the Hinkley PSHA median GMM is represented by the suite of V_s-kappa adjustment factors presented earlier. The implicit uncertainty associated with this suite, shown in Figure 9, represents the total epistemic uncertainty captured in the V_s-kappa adjustment model, combining the epistemic uncertainty in the target kappa values, with the epistemic uncertainty captured by starting from a range of GMPEs, since all host-target combinations were considered. For HPC, the range of host kappas is very broad, ranging from very low values representative of CEUS to high values typical of active regions. It was therefore assessed that epistemic uncertainties were adequately captured in terms of the kappa contribution.

However, since the V_s-kappa adjustment considered a single target V_s profile, it was felt following discussions with Subject Experts that a correction factor to account for the epistemic uncertainty in this profile ought to be included in the site term at the reference horizon. Previous studies have found that the uncertainty relating to the selection of the target V_S profile accounts for up to 10% of the epistemic variability intrinsic to a suite of V_S-kappa adjustment factors (Biro and Renault 2012). Therefore, the adjustment factors at longer periods were modified such that the lower and upper adjustment factors for each GMPE deviated by at least 5% from the median adjustment factor, resulting in an overall minimum spread of 10%. The $\delta\Phi_{S2S}$ factor was then calculated based on the absolute difference between modified and original Vs-kappa adjustment factor uncertainty, and applied as a partially ergodic correction factor to the ϕ_{SS} term of the total ground-motion variability at the reference horizon as in Rodriguez-Marek et al. (2014).

4.2.4. Sigma Logic Tree

The total sigma logic tree considered alternative branches for heteroscedastic and homoscedastic variability in the first level of the logic tree. In the second level of the logic tree, upper and lower branches were considered in addition to the mean branch to account for epistemic uncertainty associated with the median predictions. The total-sigma upper, median and lower branches were constructed by combining upper-upper, median-median and lower-lower branches of the proposed ϕ_{SS} and the τ models, for the heteroscedastic and homoscedastic parts of the logic tree, independently. We chose this approach, the same as followed by Bommer et al. (2015), although different to that of Coppersmith et al. (2014) who combine the variances, to simplify the model. Combining upper-upper, median-median and lower-lower branches of the τ and ϕ_{SS} is deemed sufficiently equivalent to considering all combinations, and resampling the logic-tree accordingly, as both the center and the range of sigma values remain the same although a slightly wider range of epistemic uncertainty is modelled. The total single-station sigma (σ_{SS}) logic tree for the Hinkley PSHA is presented in Figure 10. The single-station sigma, σ_{SS}, for each branch of the logic tree in then calculated using the following equation:

$$\sigma_{SS} = \sqrt{\tau^2 + \phi_{SS}^2 + \delta\phi_{S2S}^2} \qquad (1)$$

Weights of 0.4 and 0.6 were assigned to the homoscedastic and heteroscedastic branches, respectively. This reflects the state-of-knowledge, with heteroscedastic between-event variability being often observed empirically and generally considered to be physically justifiable; however, doubt remains on whether this is a sampling issue or due to poorer-constrained parameters for smaller events (Al Atik 2014). For the second level of branches, weights of 0.2, 0.6 and 0.2 were adopted for the upper, median and lower branches, respectively, in line with the weights assigned to the branches of both the τ and ϕ_{SS} models.

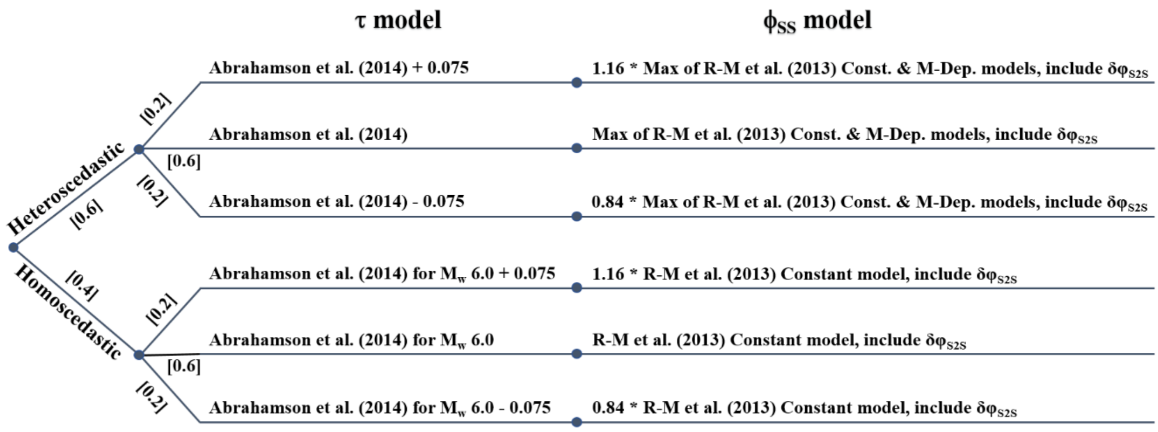

Fig. 10 Total sigma logic tree for the Hinkley PSHA. Numbers in square brackets are weights assigned to each alternative branch

5. Seismic Hazard at Reference Velocity Horizon

This section presents a summary of the methodology implemented to perform the hazard calculations for the Hinkley PSHA and the resulting hazard estimates at the reference velocity horizon. The latter formed part of the input data required for the site-response analysis, and were considered representative of both the onshore and offshore domains.

5.1. Seismic Hazard Methodology

Seismic hazard calculations were undertaken using the standard Cornell-McGuire approach (Cornell 1968; McGuire 1976), including explicit treatment of the epistemic uncertainty, using the logic-tree framework (Kulkarni et al. 1984), and aleatory variability of the ground motion.

The main seismic hazard calculations were performed using the software CRISIS2015 v1.0 (Ordaz et al. 2015). In addition to CRISIS2015 v1.0, the OpenQuake engine (OQ-engine, Pagani et al. 2013) was used as an alternative software to perform cross-checking calculations on a selected sub-set of the final hazard calculations as part of the QA process, following the approach of Bommer et al. (2013). Both programs include most of the modern features expected in seismic hazard software packages such as disaggregation analysis, leaky source boundaries and virtual fault ruptures.

Epistemic uncertainty was incorporated in the hazard calculations through the implementation of the logic tree framework. CRISIS2015 allows for the use of logic trees; however, for the Hinkley PSHA it was not possible to evaluate the logic tree using CRISIS2015 due to the very large number of branches. Output files of the hazard calculations at the end tip of each branch of the logic tree were compiled separately for each source zone, with logic tree calculations carried out at the post-processing stage using Matlab codes developed specifically for this project.

Hazard results were calculated for selected percentiles ranging from the 5th to the 95th, in addition to the mean estimates. Hazard estimates were calculated for a total of 12 spectral ordinates [i.e., PGA and 5% damped pseudo-spectral accelerations (PSA) at 0.025, 0.05, 0.10, 0.15, 0.20, 0.30, 0.40, 0.50, 1.00, 2.00 and 3.00 s]. Hazard results at the reference velocity horizon were provided in terms of hazard curves, and uniform hazard spectra (UHS), disaggregated results, controlling earthquake scenarios and scenario spectra for selected return periods.

Disaggregated results were only provided for PGA and PSA at 0.1, 0.2, 0.4 and 1.0 s. Disaggregated results for PGA were provided as it is common practice to provide a full set of results for this parameter. Disaggregated results for the remaining oscillator periods were relevant for the derivation of disaggregated results representative of the high-frequency (HF; 5 to 10 Hz) and low-frequency (LF; 1 to 2.5 Hz) ranges in accordance with the U.S. NRC Regulatory Guideline 1.208 (USNRC 2007). HF and LF range disaggregated results were then used to define the controlling scenarios for the development of the scenario spectra to be used in the site-response analysis.

5.2. Hazard Results at Reference Velocity Horizon

The mean UHS and response spectra for selected percentiles, for the reference velocity horizon, corresponding to the design return period of 10,000 years (annual frequency of exceedance, AFoE, of 10^{-4}) are presented in Figure 11.

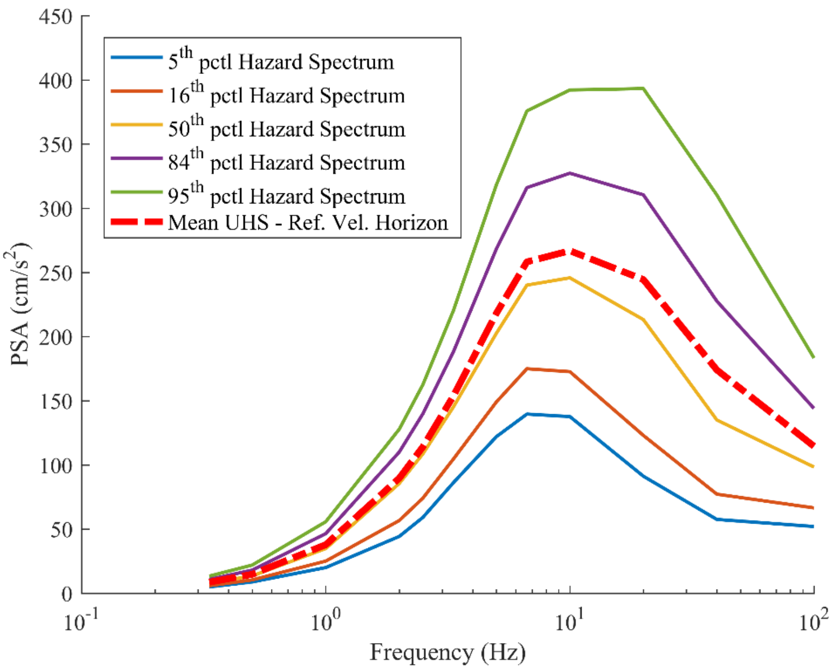

Fig. 11 10^{-4} AFoE mean UHS and hazard spectra for selected percentiles for the reference velocity horizon

Disaggregated results in terms of magnitude and distance were produced for AFoEs ranging from 10^{-3} to 10^{-6} for the LF and HF ranges in order to estimate the controlling scenarios to be used as input for the derivation of the scenario spectra required for the site-response analysis. LF- and HF-range disaggregated results for the AFoE of 10^{-4} are presented in Figure 12 in terms of magnitude and distance.

In addition to the controlling scenarios for the LF and HF ranges, USNRC (2007) recommends that for the LF range, when contributions to the hazard from events with distances ≥ 100 km are equal to or exceed 5% of the total hazard, controlling scenarios considering only contributions from events in that range of distances should be assessed. This condition was met only in the disaggregated results for the AFoE of 10^{-3}. A summary of the controlling scenarios in terms of magnitude and distance is presented in Table 1.

Unscaled scenario spectra to be used as input to the site-response analysis were derived for each of the controlling scenarios presented in Table 1. The scenario spectra were obtained as the weighted mean of the median response spectra obtained for each of the GMPEs, including their alternative V_S-kappa adjustment factors, in the ground-motion logic tree.

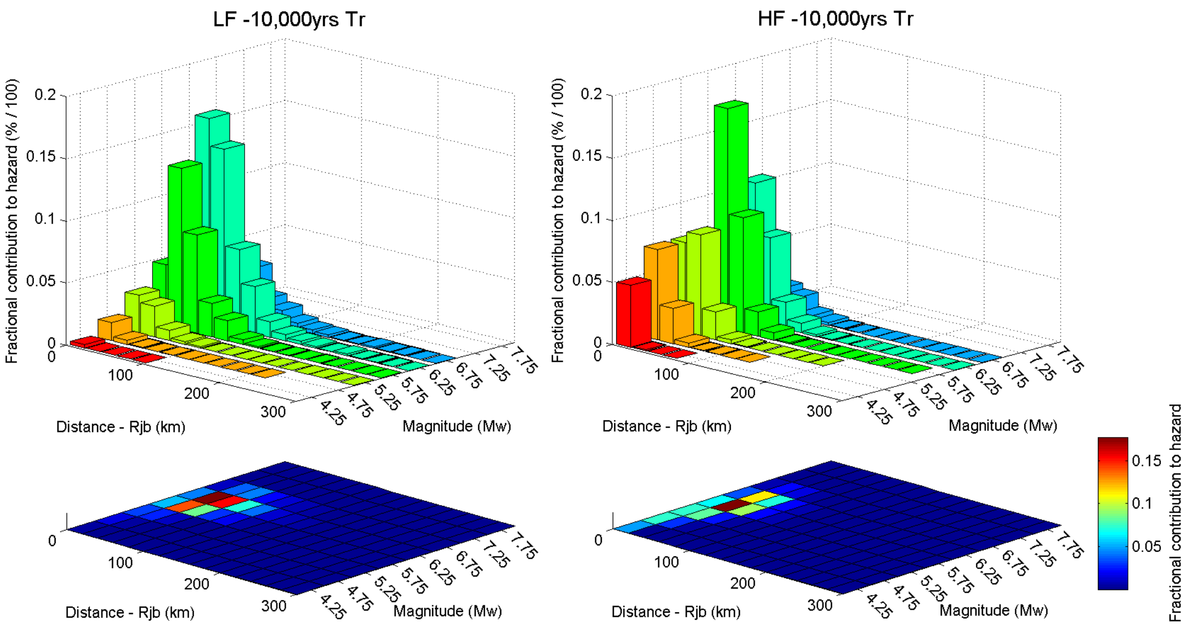

Fig. 12 Disaggregated results by magnitude-distance bins with an AFoE of 10^{-4} for the low-frequency (LF) range (left) and the high-frequency (HF) range (right)

Table 1 Controlling earthquake scenarios for the various AFoE of interest, for the high-frequency (HF), low-frequency (LF) ranges, and for the low-frequency range considering events with distances ≥ 100km (LF100) when the contributions from that range of distances is equal to or greater than 5% (%LF100)

AFoE / Range	10^{-3}		10^{-4}		10^{-5}		10^{-6}	
	M_w	R_{jb}	M_w	R_{jb}	M_w	R_{jb}	M_w	R_{jb}
HF	5.50	43.9	5.66	31.4	5.75	21.8	5.82	14.7

LF	5.83	65.6	6.06	45.8	6.17	31.5	6.24	20.3
LF100	6.16	153.6	N/A		N/A		N/A	
%LF100	14		4		1		0.3	

6. Site Characterization

The geological characterization of the site required a large body of ground investigation reports to be reviewed for the existing and newly proposed NPPs at Hinkley Point, undertaken between the late 1960s and 2010. In addition to the historical campaigns, two single-station microtremor surveys were conducted in 2014 and 2015 as part of the Hinkley PSHA (BRGM 2014, 2015).

The site characterization focused on the soil and rock parameters required for the site response analysis, namely: shear-wave velocity, V_S and its variation with depth; dependency of the shear modulus, G, and damping ratio, D, on shear strain, γ_s for each individual geological unit, and saturated density, ρ_{sat}, for the different geological units. Separate assessments were made for the onshore and offshore domains of the site, although the current article focuses only on the onshore characterization. A more detailed description of the derivation of the dynamic soil and rock properties is presented in the companion paper by Lessi-Cheimariou et al. (2018).

The variation of V_S with depth was defined following a detailed review of data from the historical ground investigations and geophysical surveys. Significant differences were identified between V_S values from the cross-hole and down-hole techniques. The results from the cross-hole testing were strongly influenced by the presence of stiff limestone bands within the parent mudrock which caused an overestimation of V_S in the mudrock due to refraction of the seismic waves along the stiffer layers. More credence was ultimately given to the shear-wave velocities from the down-hole tests, resulting in the definition of the “Median 1” V_S profile and the corresponding variability, σ_{lnVs}, shown in Figure 13.

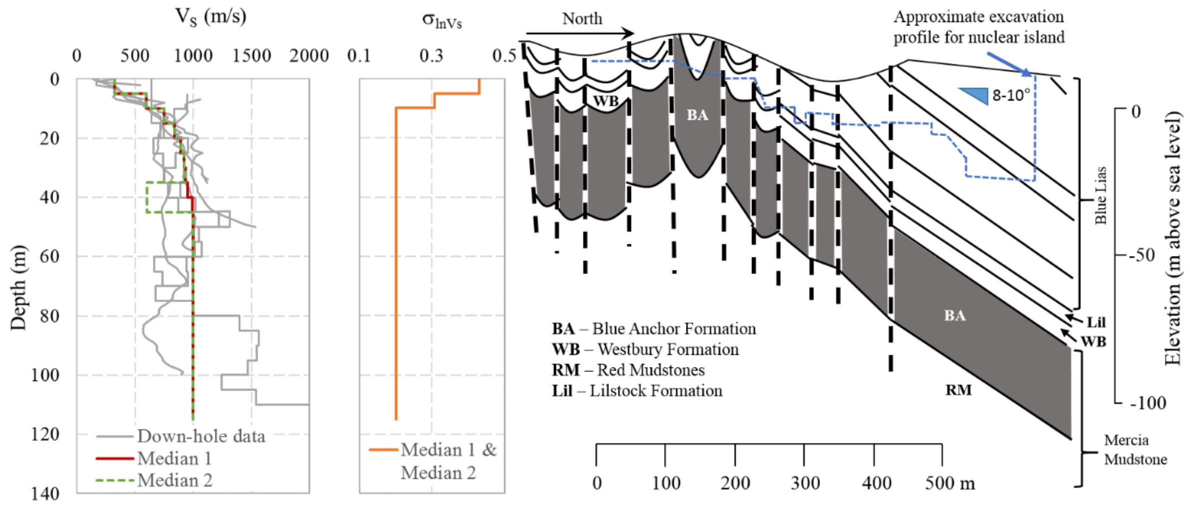

Fig. 13 Onshore model comprising two median V_S profiles, the proposed variability of the natural logarithm of the V_S (σ_{lnVs}) and the down-hole data used to derive the model. The shear-wave velocity reversal in Median 2 (green dashed line) at 35 m corresponds to the Westbury Formation (WB) in the central part of the site. Principal geological strata are shown in a typical north-south cross-section through the proposed nuclear island. The reference velocity horizon was defined at the top of the Blue Anchor Formation (BA)

The interpretation of the data from the two recent microtremor campaigns (BRGM 2014, 2015) consistently showed the presence of a 3.5 Hz peak in the horizontal-to-vertical spectral ratio for locations in the northern part of the site. Site response sensitivity analyses demonstrated that this characteristic peak was most likely associated with the presence of a shear-wave velocity reversal related to the Westbury Formation, which is encountered in this area of the site between about 35 m and 45 m depth. It was considered important to capture this feature in the site response analysis through the definition of a second V_S profile, “Median 2”, as shown in Figure 13. The same σ_{lnVs} established for Median 1 was used for Median 2.

As highlighted in the cross-section in Figure 13, the strata underlying the HPC site are dipping gently 8 to 10 degrees northwards. This presented a challenge for definition of a suitable reference velocity horizon, as the depth to any single geological unit varies from south to north across the nuclear island by approximately 70 m. On reviewing the strata present on site, the Blue Anchor Formation appeared to be the best candidate for the reference velocity horizon, based on the range of measured V_S within that unit, with a median shear-wave velocity of 1,000 m/s, and the need for the reference velocity horizon to be beneath the Westbury Formation, whose significance was highlighted by the microtremor investigation. The site response approach accounted for the variability in the range of measured V_S and the depth to the reference velocity horizon, as explained in the following section.

Due to a lack of reliable site-specific cyclic tests, non-linear properties of the mudstones were based on the earlier work of Nuclear Electric (NE 1995), also presented in Davis et al. (1996). They reinterpreted shear modulus degradation and damping curves from cyclic laboratory testing of soft rocks from other sites (Hara and Koyota 1977; Nishi et al. 1983; and Kim 1992) in the light of non-linear properties from monotonic in situ and laboratory testing of samples of mudstone from HPC. A distinction was made in the nonlinear properties between the shallower strata (<=25 m deep) and deeper strata (>25 m) in order to reflect the variations in lithology and the weathering of the rock at HPC.

7. Site Response Analysis

The site response analysis was performed as part of the partially non-ergodic PSHA to determine the median of the site term and its associated variability. The median site term, which expresses the average deviation of the ground motions at a site from the predictions of the GMPEs at the reference velocity horizon, can also be determined by statistical analysis of site-specific ground motions (Rodriguez-Marek et al. 2014), where suitable and sufficient records exist. Due to lack of site-specific records for the HPC site, the numerical site response approach, as described in the following sub-sections, was adopted for this study to estimate the site term. Separate analyses were performed for the onshore and offshore domains, although only results for the onshore domain are presented herein.

7.1. Method of Analysis

Site response analyses were performed in accordance with the recommendations of the USNRC Regulatory Guidelines (USNRC 2007) and the requirements for a partially non-ergodic PSHA (Rodriguez-Marek et al. 2014) using the software STRATA (Kottke et al. 2013). The analyses were performed using the best estimates of the site properties and incorporated the variability in the various site properties using Monte Carlo simulations and the following statistical models, which are integrated into STRATA (Kottke et al. 2013):

- The shear-wave velocity was varied based on the median V_S profile and the σ_{lnVs} using the Toro (1995) model. The principal assumption of the Toro (1995) model is that the shear-wave velocities are characterized by a log-normal distribution. Upper and lower bounds of ± 2.0 σ_{lnVs} around the median value were adopted to ensure that the realizations were not unrepresentative of the measured data and following the recommendations from EPRI (2013). The input and output $\sigma_{\ln Vs}$, from a total of 1,000 Monte Carlo simulations, were compared to ensure that the input variability was preserved by the simulated shear-wave velocity profiles, a good agreement was achieved between the input and resulting $\sigma_{\ln Vs}$.

- The generic layering model after Toro (1995) was used for generating layering within the soil/rock column, assuming a non-homogeneous Poisson process where the number of layer interfaces per meter varies with depth.
- The nonlinear properties were varied using the Darendeli (2001) model which assumes that both the shear modulus reduction and damping curves are normally distributed. The shear modulus reduction and damping curves were correlated using a correlation coefficient equal to -0.5, implying that a value of shear modulus reduction above the mean (higher stiffness) will be related with lower damping.
- The depth to reference velocity horizon was modelled using a uniform distribution to capture the influence of the shallow northward dip of the geological bedding. This introduces an averaging effect of the site response across the nuclear island footprint, which is considered a desirable outcome as the nuclear island will be resting on a monolithic concrete raft.

The input motions were defined based on the approach in USNRC (2007). The selection of other input parameters was based on the results of parametric analyses and empirical relationships as described before.

Equivalent linear (EQL) random vibration theory (RVT) site response analysis was performed. The use of EQL site response analysis was justified (e.g., Kaklamanos et al. 2013; Stewart et al. 2014) by the low strain response (~<0.1 %). It was also demonstrated that RVT site response analysis did not introduce a systematic bias in comparison to time-series site response analysis (Bard et al. 2004; Kottke and Rathje 2013; Lessi-Cheimariou et al. 2018) due to the site response concentrated at high frequencies. RVT site response analysis was preferred due to its computational efficiency and because input motion acceleration time histories do not need to be defined and selected. A total of 1,000 Monte Carlo simulations were performed for each scenario spectrum and median V_S profile considered. Amplification factors (AFs) of a representative subset of these 1,000 simulations, for the high-frequency scenario spectrum, 10^{-4} AFoE, and for both Median 1 and Median 2 V_S profiles, are shown in

Figure 14. It is noted that all site response analysis outputs were computed for a target velocity horizon (i.e. target foundation level) of 5 m below existing ground level, recognizing that the shallowest material will be removed during the construction. The V_{S30} representative of the target velocity horizon is 802 m/s.

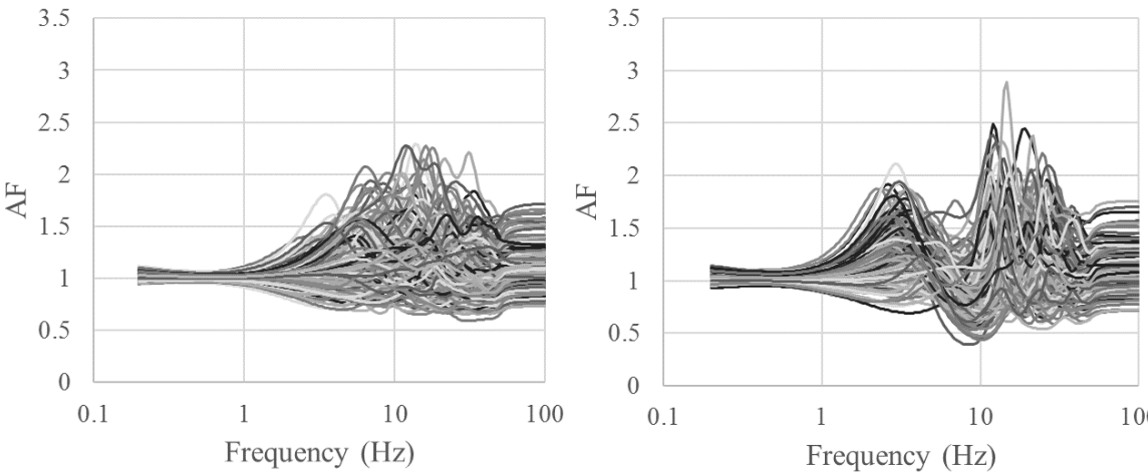

Fig. 14 Amplification factors for Median 1 (left) and Median 2 (right), high-frequency scenario spectrum, AFoE 10^{-4}

The results from the site response analysis were integrated with the hazard estimates at the reference velocity horizon using Convolution-Approach 3 (McGuire et al. 2001; Bazzurro and Cornell 2004), which have the advantage of computational and project organizational efficiency of treating the site response analysis as a post-processing step in the computations, thus decoupling the site response analysis from the bedrock hazard calculations.

A logic tree was developed to capture the epistemic uncertainty associated with the determination of the V_S model. A higher weight, 2/3, was assigned to Median 1 to reflect the fact that it was representative of the conditions across the entire site whilst a weight of 1/3 was assigned to Median 2 which was only representative of the ground conditions to the north of the site where the microtremor results indicated a characteristic 3.5 Hz peak. An additional level of branches for analysis with and without Monte Carlo simulations was proposed to address the issue of potential over-smoothing of the amplification factors, which can occur when Monte Carlo simulations are performed (Bard et al. 2004). Equal weights were assigned to these branches as there was no justification to give more credence to either type of analysis. In order to be able to implement the convolution approach for the analyses without any Monte Carlo simulations, the standard deviation was adopted from the corresponding analyses which included Monte Carlo simulations.

Seismic hazard curves for the 5th, 16th, 50th, 84th and 95th percentiles were calculated for the target horizon level using the approach recommended in EPRI (2013). This approach involves combining the site response logic-tree branches into a single composite distribution of logarithmic amplification factors (lnAF), with equivalent mean and variance, and is justified by the fact that all individual branch tips of the site response logic-tree are normal distributions of lnAF. An alternative implementation involving convolution of the reference horizon hazard with the individual site response logic-tree branches, and then recombining surface hazard branches was also explored, but found to be less robust numerically. In the particular case of HPC, the lnAF distribution shows very little departure from linearity, so the convolution with the combined lnAF distribution preserves the reference horizon percentiles as it is a monotonically increasing transformation (Pearson & Tukey, 1965).

7.2. Epistemic Uncertainty of the Site Term and $\delta\phi_{S2S}$

An assessment was carried out to ascertain whether the proposed site response model adequately captured the epistemic uncertainty of the AFs across the full range of response periods. From that assessment, it was considered necessary to apply correction factors to the computed values of σ_{lnAF} (standard deviation of the natural logarithm of the amplification factor from the site response analyses) at the longer periods, where this quantity was not well resolved owing to the onset of bandwidth limitation in the site response approach. This correction was applied to ensure a minimum floor level, equal to 0.1 natural logarithm units, for the logic-tree branches including Monte Carlo randomizations. For the branches without Monte Carlo randomizations, the σ_{lnAF} values of the equivalent Monte Carlo branches were adopted, since the principal purpose of removing the randomizations was to ensure that the median behavior was adequately captured and, therefore, did not impose constraints on the definition of the variability. Sensitivity analyses showed that the choice of the floor level value (within reasonable limits) had little impact on the surface hazard results, and thus the selected value of 0.1 was considered appropriate for all branches of the site response logic-tree.

8. Seismic Hazard at Target Horizon

Seismic hazard estimates at the target horizon (i.e., target foundation level) were provided in the form of hazard curves for the mean and the 5th, 16th, 50th, 84th and 95th percentiles for the 12 response periods of interest. In addition to this, mean UHS and response spectra for the selected percentiles were derived for a range of AFoE between 10^{-3} and 10^{-6}.

8.1. Onshore Results

Figure 15 presents a comparison of the PGA, PSA(0.2s) and PSA(1.0s) mean hazard curves for the target horizon and the reference velocity horizon along with hazard curves at target horizon for selected percentiles [i.e., 5th, 16th, 50th (median), 84th and 95th].

Figure 16 compares the 10^{-4} AFoE UHS and response spectra for the 5^{th}, 16^{th}, 50^{th}, 84^{th} and 95^{th} percentiles at target horizon against the HPC design spectrum. From this comparison, it is clear that the HPC design basis spectrum comfortably envelopes the 84^{th} percentile response spectra at the target horizon across the whole range of frequencies, with the exception of PSA at 40 Hz where the HPC design basis spectrum is only slightly higher than the 84^{th} percentile spectrum.

In the UK regulatory context, the design basis spectrum, commonly pre-defined at an early stage as part of the generic design assessment, is expected to envelope the 84^{th} percentile response spectra with an AFoE of 10^{-4} obtained from a site-specific PSHA. This is somewhat different to the approach in the US for the seismic design of nuclear facilities (ASCE/SEI 43-05), where the design response spectrum (DRS) for structures with seismic design category 5 (e.g., the nuclear island in a NPP would be classified as SDC-5) is obtained from the multiplication of the 10^{-4} AFoE UHS and a ‘design factor’ which is dependent on the slope of the seismic hazard curve for the target foundation level, of each response period available in the UHS, at around an AFoE of 10^{-4}. For the particular case of the HPC site, the 10^{-4} 84^{th} percentile response spectrum is slightly more conservative than the DRS derived in accordance with ASCE/SEI 43-05 (see Figure 16). However, this conclusion may not hold for other sites.

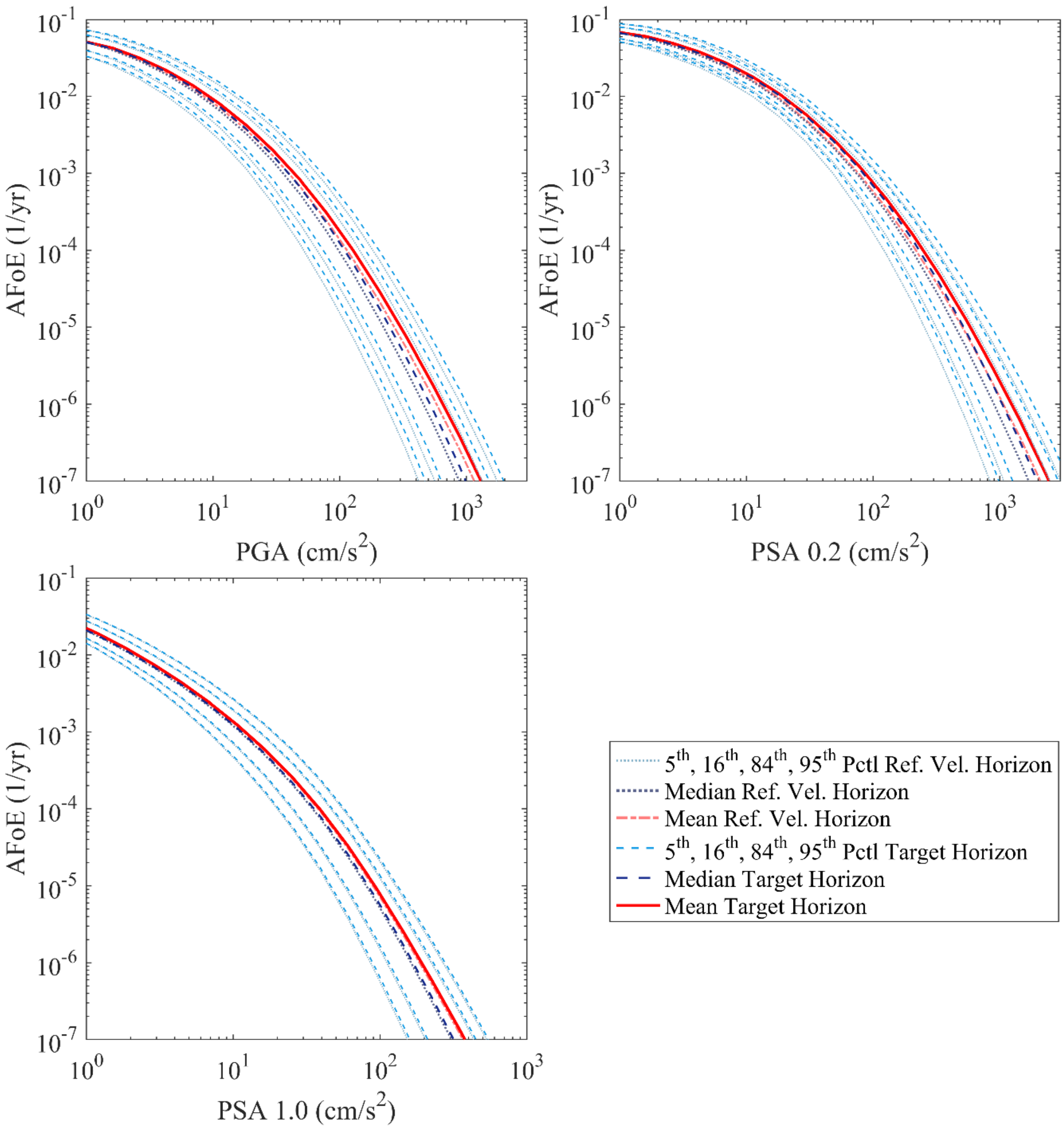

Fig. 15 Mean and 5th, 16th, 50th (median), 84th and 95th percentile hazard curves for the onshore target foundation level at the Hinkley Point site

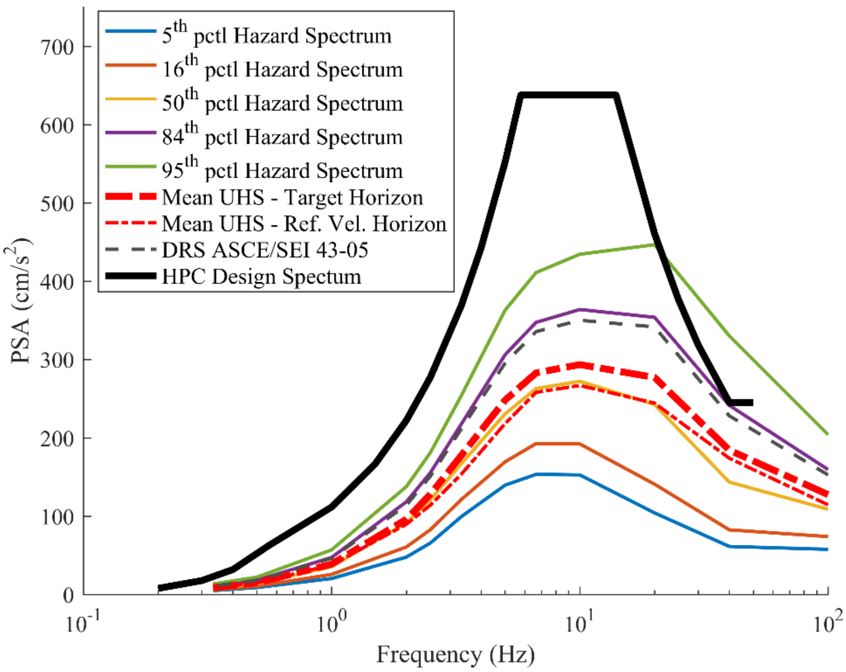

Fig. 16 10^{-4} AFoE mean UHS at target and reference velocity horizons, and 10^{-4} AFoE hazard spectra for selected percentiles at target horizon, compared against the HPC design spectrum

From Figure 16, it can also be observed that the level of 'conservatism' of the design basis spectrum is not uniform across the full range of frequencies of interest, with lower levels of conservatism at the high frequencies (> 20 Hz). The main reason for this lower level of conservatism in the HPC design basis spectrum is that it was derived using the piecewise linear design response spectra defined in the European Utility Requirements for Light Water Reactor Nuclear Power Plants (commonly referred as EUR spectra) whose origins date to the 1980s. The EUR spectra, therefore, do not incorporate recent developments in the understanding of the characterization of ground motion, which affects particularly the high frequency range of the spectrum. Similar observations have been made at other similar sites in the UK and the US. A more detailed discussion on the EUR spectrum is provided by Bommer et al. (2011) and Coatsworth (2015).

9. Assessing Epistemic Uncertainty

In PSHA the spread of the percentiles calculated using the full set of hazard curves from the logic tree represents the epistemic uncertainty in the results. The greater the spread of the percentiles, the higher the epistemic uncertainty. Assessing whether the level of epistemic uncertainty captured by the logic tree of a particular PSHA is adequate for the level and objectives of the study is not a trivial task as it implies quantification of the "unknown". To do this, first a metric to "measure" in a consistent manner the level of uncertainty captured in a PSHA needs to be specified; secondly, a criterion defining acceptable levels of epistemic uncertainty needs to be defined depending on the level of rigour and objectives of the PSHA study. Various metrics to measure the epistemic uncertainty captured in a PSHA are discussed by Douglas et al. (2014). However, to the knowledge of the authors of this paper, no criterion to define minimum acceptable levels of epistemic uncertainty in a PSHA has been proposed and developing a criterion may not even be possible due to the intrinsic "unknown" nature of epistemic uncertainty as discussed above. It should be noted that minimum levels of epistemic uncertainty associated with specific elements of the PSHA can be defined based on amount and quality of data available (e.g. EPRI 2013); however, the discussion presented in this section concerns the "overall" epistemic uncertainty captured by the PSHA study.

More rigorous PSHA studies, such as those related to the safety of nuclear facilities (equivalent to SSHAC Level 3 or 4), are expected to better capture the full range, body and center of the epistemic uncertainty than less rigorous PSHA studies, common for the design of conventional structures (equivalent to SSHAC Level 1 or 2), as more time and effort has been spent on constraining the 'unknowns'. More rigorous studies, by virtue of their greater investment in data collection, may allow a genuine reduction in epistemic uncertainty, which is in contrast to the apparently low (but actually underestimated) uncertainties shown by a narrow spread in hazard curves in less rigorous studies (e.g. Douglas et al., 2014).

A way to assess whether epistemic uncertainty has been adequately captured in a PSHA is through historical precedent, by comparing the distribution of selected percentiles at a given return period from the PSHA of interest against other PSHA studies with similar level of rigour and levels of seismic activity. Douglas et al. (2014) present a comparison of results from various published PSHA reporting mean, median and 16th (or 15th) and 84th (or 85th) percentiles for PGA for the 475- and 2,475-year return periods.

A similar approach to Douglas et al. (2014) was followed in this study, comparing the epistemic uncertainty captured in the Hinkley PSHA logic tree against data from previous studies providing hazard estimates for the Hinkley site [i.e., SHWP 1987; AMEC 2012; and Woessner et al. 2015 (SHARE Project)]. For each of these projects, empirical probability distribution functions (PDFs) were derived using the available percentiles, for AFoEs of 10^{-4} and 10^{-5}, for PGA and PSA at 0.2 s and 1.0 s. Figure 17 presents the comparison of the empirical PDFs (solid lines), and best fit to the log-normal distributions of the various percentiles (dashed lines), for PGA with an AFoE of 10^{-4}. Similar results were observed for an AFoE of 10^{-5} and for PSA at 0.2 s and 1.0 s; figures for these parameters and AFoE are not presented here because of space limitations.

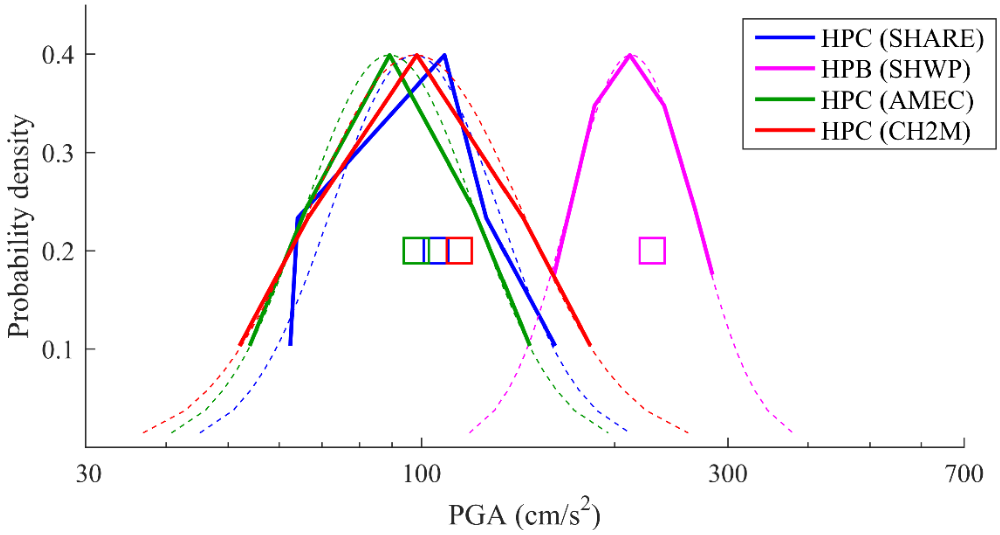

Fig. 17 Probability density functions derived from percentiles for PGA from various projects and for the Hinkley PSHA. Solid lines are empirical PDFs based on the percentiles available for each study; dashed lines are the best fit to the log-normal distribution of the percentiles; squares indicate the means

The SHWP (1987) study was the first of a series of site-specific studies undertaken for UK nuclear power plant sites in the late 1980s, early 1990s, which were considered state-of-the-art at the time and incorporated epistemic uncertainty through the use of the logic tree framework. However, one of the main limitations of the SHWP (1987) study, when compared to modern practice, is the use of single GMPE for the hazard evaluation. This is likely to be the reason for the much smaller spread in the SHWP results than the other studies, as the selection of the suite of GMPEs to be used in the hazard assessment has been found to be the largest contributor to epistemic uncertainty in PSHA (e.g., Stepp et al. 2001).

The AMEC (2012) study was carried out as a site-specific study for the HPC site with a more limited scope that the study presented in this paper, equivalent to a SSHAC Level 1 study, which was aimed at providing an early indication of the seismic hazard levels at the HPC site using more modern methods that the SHWP study, particularly regarding the use of modern GMPEs. The SHARE study, based on a European project aimed at providing a Euro-Mediterranean seismic hazard model and to establish new standards in PSHA practice, is the only non-site-specific study included here. Hazard results from the SHARE project for a specific location within the project area are available from their web page (http://www.efehr.org/en/home/).

The PDFs of the assessed ground motions from the independent studies by SHARE, AMEC and CH2M (this study) show considerable overlap. This lends confidence that the results obtained for the Hinkley PSHA are a good representation of the seismic hazard at this site and that the uncertainties have been appropriately captured. Although the results from the CH2M, AMEC and SHARE studies show similar levels of epistemic uncertainty, a higher level of confidence is associated with CH2M's empirical PDF due to the site-specific nature of the study, as opposed to the regional nature of the SHARE project and to the greater level of effort and rigour/formalism of CH2M's PSHA process compared to that of the AMEC study. The relation between the level of rigour and objectives of a study, and the level of confidence in their results is clearly summarized by Budnitz et al. (1997): "*there is nothing inherently 'wrong' with the calculated results that come from a modest hazard analysis conducted by a single contractor; nor does the use of multiple experts in a large-scale project guarantee that the hazard results are more defensible (particularly if done poorly). They are, however, more likely to capture accurately the scientific community's information*".

10. Conclusions

A state-of-the-art PSHA has been carried out for the HPC site with the objective of underpinning the HPC design basis spectrum and providing input to inform the probabilistic safety assessment elements for the Safety Case. This is the first time that a seismic hazard study for a NPP in the UK has successfully passed through the regulatory approval process since the work done by the SHWP in the 1980s and early 1990s for the existing fleet of UK nuclear power stations. The present study is consistent with international best practice and incorporated a number of key elements, summarised below.

A project-specific earthquake catalogue was developed, including archive search to collect data on known events and to identify previously undiscovered earthquakes. The seismicity model considered fourteen seismic sources, combined to form six alternative seismic source models in order to capture the main sources of epistemic uncertainty associated with the delineation of the source boundaries, and in particular with the location of the Variscan Front which demarcates the boundary between the higher levels of seismicity in South Wales and the lower levels observed south of the Bristol Channel.

Recurrence rates were determined for all the seismic source zones considering the doubly-truncated exponential Gutenberg-Richter model. To capture the epistemic uncertainties associated with earthquake recurrence, nine alternative combinations of the activity (a) rate and b-value parameters were defined for the host seismic source and the next two most hazard-significant seismic sources. Logic tree weights were source-specific as they were based on a maximum-likelihood fit to the data.

The ground-motion model was developed using separate models for the median ground-motion and aleatory variability. The median ground-motion model comprised a suite of five GMPEs adjusted to the site-specific conditions using V_S-kappa factors. A partially non-ergodic sigma model was adopted with separate components for the inter-event variability, and single-station intra-event variability, adjusted by a partially ergodic site-to-site variability term.

Site response analysis was performed using equivalent-linear random vibration theory with explicit incorporation of the variability in the ground properties using Monte Carlo simulations. The final PSHA results were obtained by convolution of the hazard at the reference rock horizon with the site amplification factors. The HPC design basis spectrum was shown to envelope the 84th percentile UHS across all frequencies with the exception of PSA at 40 Hz, where a marginal exceedance was observed.

The overall epistemic uncertainty captured by the logic tree was assessed and compared against results from earlier PSHA studies for the same site. The epistemic uncertainty was similar amongst all studies, except for SHWP (1987) which showed a lower level of epistemic uncertainty, attributed mainly to the use of a single GMPE in their study. Despite the similar levels of epistemic uncertainty captured by the most recent studies, a higher level of confidence is associated with the empirical PDF from the current study due to the greater level of effort on constraining the epistemic uncertainty and the greater rigour of the PSHA process.

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