**ONR Expert Panel on Natural Hazards**

***NS-TAST-GD-013 Annex 1 Reference Paper:***

**Analysis of Seismic Hazards for Nuclear Sites**

*Expert Panel Paper No:* *GEN-SH-EP-2016-1*

Sub-Panel on Seismic Hazards

October 2018

***For more information contact:***

*Office for Nuclear Regulation*

*Building 4, Redgrave Court*

*Merton Road*

*Bootle L20 7HS*

*Email:* contact@onr.gov.uk

**TABLE OF CONTENTS**

[LIST OF ABBREVIATIONS 3](#_Toc522022882)

[Acknowledgements 4](#_Toc522022883)

[1 INTRODUCTION 5](#_Toc522022884)

[2 Seismic hazards and their assessment 6](#_Toc522022885)

[2.1 Earthquakes and Seismic Hazard 6](#_Toc522022886)

[2.2 Surface rupture 8](#_Toc522022887)

[2.3 Ground shaking 8](#_Toc522022888)

[2.4 Liquefaction 9](#_Toc522022889)

[2.5 Landslides and slope instability 10](#_Toc522022890)

[2.6 Tsunamis 10](#_Toc522022891)

[3 management of uncertainties 11](#_Toc522022892)

[3.1 Classification of uncertainties 11](#_Toc522022893)

[3.2 Characterisation of epistemic uncertainties 11](#_Toc522022894)

[3.3 Logic trees 12](#_Toc522022895)

[4 databases for seismic hazard assessments 15](#_Toc522022896)

[4.1 Data compilation and data collection 15](#_Toc522022897)

[4.2 Previous seismic hazard studies 16](#_Toc522022898)

[4.3 Geological data 16](#_Toc522022899)

[4.4 Instrumental earthquake catalogues 17](#_Toc522022900)

[4.5 Historical earthquake catalogues 17](#_Toc522022901)

[4.6 Ground-motion recordings 18](#_Toc522022902)

[4.7 Ground-motion prediction equations 18](#_Toc522022903)

[4.8 Dynamic site characteristics 18](#_Toc522022904)

[5 Capable Faulting 21](#_Toc522022905)

[5.1 Evaluation of capable fault hazard 21](#_Toc522022906)

[5.2 Methodology 22](#_Toc522022907)

[6 input models for psha 24](#_Toc522022908)

[6.1 Homogenised earthquake catalogue 24](#_Toc522022909)

[6.2 Seismic source model and recurrence relationships 24](#_Toc522022910)

[6.3 Reference horizon for hazard calculations 27](#_Toc522022911)

[6.4 Ground-motion prediction model 27](#_Toc522022912)

[6.5 Logic trees for PSHA inputs 28](#_Toc522022913)

[7 PSHA Calculations and Site Response Analyses 29](#_Toc522022914)

[7.1 Selection and qualification of PSHA software 29](#_Toc522022915)

[7.2 Limits on integrations in PSHA 29](#_Toc522022916)

[7.3 Quality Assurance on hazard calculations 30](#_Toc522022917)

[7.4 Site response analyses 30](#_Toc522022918)

[7.5 Incorporating site response into hazard estimates 32](#_Toc522022919)

[7.6 Long-period ground motions 33](#_Toc522022920)

[8 Outputs from a Site-specific PSHA 34](#_Toc522022921)

[8.1 Seismic hazard curves: means and fractiles 34](#_Toc522022922)

[8.2 Uniform hazard response spectra 34](#_Toc522022923)

[8.3 Disaggregation 34](#_Toc522022924)

[8.4 Acceleration time-histories 36](#_Toc522022925)

[9 Hazard Assessment for Induced Seismicity 37](#_Toc522022926)

[9.1 Causes of induced and triggered seismicity 37](#_Toc522022927)

[9.2 Adapting PSHA for induced earthquakes 37](#_Toc522022928)

[10 references 39](#_Toc522022929)

LIST OF ABBREVIATIONS

AFE Annual Frequency of Exceedance

ANS American Nuclear Society

BGS British Geological Survey

EPRI Electrical Power Research Institute

GMC Ground Motion Characterisation

GMPE Ground Motion Prediction Equation

G-R Gutenburg-Richter

IAEA International Atomic Energy Agency

IPR Independent Peer Review

ONR Office for Nuclear Regulation

PFDHA Probabilistic Fault Displacement Hazard Analysis

PGA Peak Ground Acceleration

PSA Probabilistic Safety Analysis

PSHA Probabilistic Seismic Hazard Analysis

SSC Seismic Source Characterisation

SSHAC Senior Seismic Hazard Analysis Committee

TAG Technical Assessment Guide

UHRS Uniform Hazard Response Spectrum

USNRC United States Nuclear Regulatory Commission

*a* Activity rate of earthquakes

*b* Slope of Gutenberg-Richter recurrence relationship

M Magnitude

**M** Moment magnitude

Mmax Maximum magnitude in PSHA integrations

Mmin Minimum magnitude in PSHA integrations

R Source-to-site distance

V/H Vertical-to-horizontal ratio (of response spectral ordinates)

VS Shear-wave velocity

VS30 Time-averaged shear-wave velocity over upper 30 m

ε Number of logarithm standard deviation in GMPE

κ Kappa (high-frequency damping parameter)

Acknowledgements

This document was drafted by members of the ONR Expert Panel on Natural Hazards – Sub-Panel on Seismic Hazards (Julian J Bommer, Robert E Holdsworth, Ian G Main and Jean B Savy). The document was also reviewed and additional input provided by several staff members of the Office for Nuclear Regulation and also by Alice B Walker, who serves as Technical Secretary to the ONR Expert Panel. Detailed reviews were provided by Brian Baptie and Ilaria Mosca of the British Geological Survey, which greatly helped to improve the document. Additional feedback was also provided by the US Nuclear Regulatory Commission.

Comments were also received from various external stakeholders through an organised stakeholder event. All these comments are gratefully acknowledged.

1. INTRODUCTION
2. A key element of developing a safety case for nuclear plant at a nuclear licensed site is the demonstration that the plant is adequately protected against external hazards, including those related to meteorological and geological processes. An indispensable component of this process is the characterisation and quantification of the external hazards that can credibly challenge nuclear safety at the site. Guidance for Inspectors on the assessment of site-specific studies to quantify the threat from external hazards at nuclear sites is provided in *Nuclear Safety Technical Assessment Guide NS-TAST-GD-013*, generally referred to as TAG 13 (ONR, 2018a).
3. Annex 1 of TAG 13 (ONR, 2018b) is focused specifically on seismic hazards and their analysis for nuclear sites in the UK. The purpose of this document is to provide additional detail on the analysis of seismic hazards. Annex 1 of TAG 13 is specifically intended to provide guidance to Inspectors carrying out assessment of earthquake hazard studies for nuclear sites, but the document also explicitly acknowledges that “*ONR can assess the analysis, but inspectors may need to seek expert assistance in reviewing the technical aspects*.” The present document is intended to provide guidance to such experts called upon to assist Inspectors with assessments of seismic hazard studies for nuclear sites in the UK. It also provides an overview of the seismic hazard analysis process for inspectors needing a deeper understanding of how earthquake hazard is analysed. We note that research in seismic hazard assessment is continually advancing and consequently this document, which will be periodically updated, can only ever be a snapshot of the state-of-the-practice at a given moment in time. As such, the papers cited and approaches presented should be considered only as illustrative examples rather than any form of prescription or template to be followed. The reader will also note the document does not cite many examples from the UK for similar reasons: the intention throughout is to communicate general principles rather than to propose any specific models or methods.
4. Seismic hazards and their assessment
5. This section provides an overview of the hazards arising from earthquakes and discusses how each of these may be quantified for the nuclear sites. This is only intended as a high-level introduction and only the assessment of ground shaking and surface rupture hazards are expanded upon in subsequent sections.
	1. Earthquakes and Seismic Hazard
6. An earthquake is a release of strain energy from the Earth’s crust caused by the abrupt displacement along a geological fault. If the fault rupture extends to the ground surface, the relative displacements can pose a significant direct threat to any structure straddling the fault trace. The assessment of surface rupture hazard is discussed in Section 2.2. Figure 1 illustrates the main features of earthquake processes and the resulting hazards—or potentially damaging consequences—that these can generate. Probabilistic seismic hazard assessments aim to estimate the annual frequency or probability of different measures of the specific effect, such as the amplitude of the ground acceleration. In the context of probabilistic hazard analysis, the term hazard is understood as the annual exceedance frequency of a specific value of an earthquake effect at the site.



**Figure 1**

Earthquake processes and resulting hazards (Bommer and Boore, 2004). Ellipses represent features of the natural environment and rectangles the potentially harmful effects of earthquakes.

1. The primary hazard associated with earthquakes is the strong shaking of the ground associated with the passage of seismic waves, which may be modified and amplified by soil layers at the surface. The amount of energy released from the earthquake source is reflected in the magnitude, which is determined from analysis of seismograms recorded on sensitive instruments. Such recordings are also analysed to estimate the location of the point at which the fault rupture initiates, which is referred to as the focus or hypocentre; it is located by the focal depth (below the ground surface) and the geographical coordinates of the epicentre (the point on the Earth’s surface directly above the hypocentre). A simplified schematic diagram illustrating the radiation and propagation of seismic energy from the earthquake source to the site of interest is shown in Figure 2. The amplitude and duration of the radiated motion will increase with the magnitude of the earthquake and may also be influenced by the style of faulting (normal, reverse or strike-slip). The amplitude of the ground shaking decreases with increasing distance from the earthquake source, due to geometric spreading of the wave front and attenuation (dissipation and scattering of the seismic energy). The nature of the motion may be strongly modified by the near-surface geo-materials at the site. An impedance contrast created by softer layers overlying harder rock will generally lead to amplification of the motion in certain frequency ranges; sedimentary basins can also lead to 2D and 3D amplification effects. Ground shaking hazard is discussed in Section 2.3.



**Figure 2**

Diagram depicting the release of seismic energy at the earthquake source (fault rupture), its propagation as seismic waves along a travel path to the site and then its transmittal into structures.

1. In situations where the near-surface deposits include saturated cohesionless soils (sands), the shaking can lead to liquefaction. This secondary hazard is discussed in Section 2.4. The ground shaking can also trigger instability in natural and man-made slopes, as discussed in Section 2.5.
2. Another secondary earthquake hazard is tsunamis, which are caused by the sudden displacement of large bodies of water within the ocean. These displacements may be caused by fault ruptures or by landslides triggered by ground shaking, as discussed in Section 2.6.
3. A comprehensive earthquake hazard assessment for a nuclear site must consider all of these hazards, which are briefly discussed in the following sections.
4. Recent and present day crustal movements in the UK and United Kingdom Continental Shelf – including earthquakes – are related to stress generating mechanisms operating over a broad spectrum of scales (Stewart and Firth, 2004; Baptie, 2010). The British Isles lie in the interior of the Eurasian continental plate, located approximately equidistant from the Mid-Atlantic ridge to the northwest and the Eurasia-Africa collision zone to the southeast. Over the last 6 to 8 million years, the interaction of these far-field plate boundaries has generated a first order NW-SE compressional stress regime. In the most recent 2 million years, the relatively simple plate tectonic stress regime has been perturbed by second-order stresses generated by loading/unloading of the crust by British and Fennoscandian ice sheets. These glacial isostatic adjustments are thought to influence deformation over a region that extends for several hundred kilometres beyond the former ice sheet margins, leading to a relative increase in sea level in the south of UK. More locally, third-order stresses may additionally be imposed by topography, fault movements and, particularly in the southern North Sea, by processes related to movement of salt deposits buried at depth (halokinesis).
5. As well as naturally occurring earthquakes, it may be necessary to consider the potential hazard due to induced seismicity, which is discussed in Section 9.
	1. Surface rupture
6. As indicated in Figure 1, the abrupt slip along a geological fault that causes an earthquake may result in displacements—vertical and/or horizontal—at the ground surface if the rupture extends to Earth’s surface. The amplitude of these displacements along so-called capable faults and the extent of the area that they affect both grow exponentially with the magnitude of the earthquake. The surface displacements can pose a very serious threat to any structure or facility that is traversed by the fault trace. While some facilities, such as pipelines—including the trans-Alaskan oil pipeline that was tested by the **M**7.9 Denali earthquake in November 2002 (Nyman et al., 2014)—may be designed to withstand surface rupture displacements, it is not anticipated that new nuclear sites would be developed in the UK if surface rupture hazard was assessed to provide a credible threat to nuclear safety.
7. Unambiguous evidence of significant surface rupture has not been observed in the UK (however, see Ringrose, 1989, for possible examples), but it is still necessary to demonstrate that the hazard from surface rupture is very low if it is to be screened out for a site; the approach to the analysis of this hazard is discussed in Section 5.
	1. Ground shaking
8. The primary effect of earthquakes and the main cause of earthquake damage to structures and plants is strong shaking of the ground caused by the passage of seismic waves radiating from seismic sources. Insight into the nature of ground shaking is obtained from instrumental recordings (from accelerographs or seismographs), which are recordings of the ground acceleration (usually in two orthogonal directions in the horizontal plane and the vertical direction) against time, sometimes called time-histories. The horizontal motion is generally treated separately from the vertical and is usually more important since structures are generally designed with appreciable strength in the vertical direction to resist gravity loads. The most common parameter used to characterise earthquake ground shaking is the maximum absolute amplitude of the trace (time-history), referred to as peak ground acceleration or PGA. In nuclear engineering, the mostly widely used characterisation of the ground shaking is the response spectrum of absolute acceleration, which shows the maximum acceleration experienced by single-degree-of-freedom oscillators of different natural frequency of vibration (and a particular level of damping) when subject to a particular ground shaking. Whether referring to horizontal PGA or horizontal response spectral acceleration, there are several options for how to treat the two horizontal components of each recording, including the larger of the two and their geometric mean. There is no basis to identify any particular definition of the horizontal component of motion as superior; the only criterion is that the definition used to characterise the ground shaking must be consistent with the way that seismic actions are applied in the structural analyses and the derivation of fragility functions for structures and components.
9. For seismic hazard analysis, equations are required that predict values of the selected ground-motion parameter as a function of parameters that characterise the earthquake source, the travel path from the source to the site, and the nature of the site itself. Such equations are discussed in Sections 4.7 and 6.4, and their integration into a site-specific hazard assessment is described in Sections 7 and 8.
10. The potential for earthquake ground motion to cause damage may not depend solely on the amplitude of the accelerations and the frequency content (the two features that are represented in the response spectrum), but also on the total energy content of the motion and the duration of the ground shaking. Such parameters need to be correctly represented when acceleration time-histories are prepared for dynamic analyses (Section 8.4).
	1. Liquefaction
11. Liquefaction is a phenomenon that occurs in saturated sandy soils that involves the transfer of overburden stress from the soil skeleton to the pore fluid, with the commensurate increase in fluid pressure and reduction in effective vertical stress between adjacent soil particles. For earthquake-induced liquefaction, this transfer is due to the contractive tendencies of the soil skeleton during earthquake shaking. If the driving dynamic shear stresses then exceed the residual shear strength of the soil matrix, a situation referred to as flow liquefaction can occur that may result in bearing capacity failure, slope instability or—in the presence of a free-face such as a river bank and sea wall—lateral spreading. Deformations may also occur even if the pore pressure does not reach the total vertical stress levels if there is a partial transfer of the overburden stress to the pore fluid; this is known as cyclic mobility.
12. There are two basic elements to the assessment of liquefaction hazard. The first is the characterisation of the soil in terms of its susceptibility to liquefaction triggering. The second factor is the strength of the seismic shaking, which for liquefaction will include both the amplitude of the motion and the duration or number of cycles. For this reason, the characterisation of the shaking hazard is a prerequisite for the analysis of liquefaction hazard.
13. If the potential for liquefaction to occur at the site is identified, the response will normally be to mitigate the hazard through appropriate engineering measures such as drainage, ground improvement or even removal of the potentially liquefiable deposits. Engineering the hazard out in this way to the point where it is no longer credible means that it can be screened from subsequent plant safety analyses. As with surface rupture, therefore, there is no need to develop a design basis.
	1. Landslides and slope instability
14. Both natural and man-made slopes (including those behind retaining structures) may experience instability under severe ground shaking, particularly if this occurs during a period of intense precipitation that raises the groundwater table. As with liquefaction, the assessment of the potential for slope instability involves both characterisation of the slope strength and of the intensity of the ground shaking, emphasising once again the importance of the ground shaking hazard assessment. One important difference, however, is that whereas liquefaction hazard assessment is likely to be limited to the area within the nuclear site, the potential of external landslides to reach the site—including the cooling water intake, which could result from both submarine and coastal landslides—may need to be considered. In either case, rather than establishing any design basis for the plant, or any of its components, the response would generally be to incorporate appropriate engineering measures to mitigate or eliminate the hazard. These may include slope stabilisation works and external defences against landslides originating outside the site.
	1. Tsunamis
15. Tsunamis are very-long period sea waves that travel in the open ocean at high speed but decelerate on arrival to shallow coastal waters with a consequent increase in wave height. The most destructive tsunamis are trough led waves, meaning that on arrival at the coastline they are evidenced by a substantial retreat of water, followed by a substantial movement of water inland, beyond the normal high tide mark that can result in great destruction through wave impact as well as serious flooding. Significant tsunamis are generally associated with earthquakes of magnitude 7 or greater, particularly mega-thrusts along subduction zones. The effects of tsunami on nuclear power plants was vividly illustrated by the Fukushima Daiichi accident following the **M**9 Tohoku earthquake of March 2011.
16. Tsunamis may be triggered by a variety of causes but among the most common are earthquakes that cause uplift or subsidence of the sea floor, and submarine landslides, with the latter often initiated by earthquakes. Tsunami hazard will be treated as part of the assessment of flooding hazard for a nuclear site, but those conducting the seismic hazard assessment may be asked to provide input in the form of characterisation of earthquake-related tsunamigenic triggers (ONR Expert Panel on Natural Hazards, 2018).
17. management of uncertainties
18. Fundamental to the assessment of seismic hazard at a site is the gathering of all relevant data that can assist in the characterisation of earthquakes that might affect the site and the way that seismic waves will propagate to the ground surface at the site. The next section (Section 4) is entirely devoted to the databases that need to be assembled in order to conduct a robust assessment of seismic hazard. However, it is important to be aware from the outset that the nature of the data will inevitably and always be such that almost none of the inputs to the seismic hazard calculations can be uniquely and unambiguously defined. Therefore, from the perspective of regulatory assurance, it is essential that these uncertainties are identified, quantified and incorporated into the seismic hazard assessment. An understanding of the nature of uncertainties is useful when the databases are being assembled and interpreted.
	1. Classification of uncertainties
19. Definitions and classifications of uncertainties vary amongst different disciplines, as do the lexicons of terms used to describe uncertainties. In seismic hazard assessment, a distinction is generally made between randomness and uncertainty. To emphasise the difference between the two, randomness is often referred to as *aleatory variability* and uncertainty is qualified as being *epistemic uncertainty*. Aleatory variability is the inherent randomness in earthquake processes, which includes the location and timing of future earthquakes of different magnitudes and the amplitude of ground-motions for a given combination of parameters such as magnitude and distance. The precise origin of aleatory variability is open to discussion since it may in part be genuinely irreducible randomness. The observed variability may also be apparent randomness with respect to the models used to represent the phenomenon as a result of crude parameterisation (simple metrics to represent complex processes and some elements of the process not represented at all). The essence of probabilistic seismic hazard analysis (PSHA) is to integrate over distributions of random variables that represent the aleatory variability.
20. Epistemic uncertainty reflects lack of knowledge, both about earthquake processes in general and about earthquake occurrence and ground motion in the specific region under study. One of the key challenges in conducting a site-specific seismic hazard analysis is to adequately characterise epistemic uncertainties.
	1. Characterisation of epistemic uncertainties
21. Epistemic uncertainty in seismic hazard analysis arises for two main reasons. Firstly, the available data regarding earthquake occurrence, ground motions and dynamic site response are such that there will be many predictive models that could arise from interpretation of the data, each technically defensible. Secondly, the hazard calculations will inevitably consider scenarios that represent extrapolations beyond the limits of the data. In an environment such as the UK where earthquakes are relatively infrequent and the extent of seismic data is consequently rather limited, both of these will apply, particularly during the extrapolation to larger magnitudes. One may consider that an option for addressing this issue would be to adopt models derived in more data-rich regions. However, this simply replaces the original epistemic uncertainty with that associated with the non-trivial and potentially contentious assumption that the host (overseas) and target (UK) regions are analogous. Models may also be considered from regions that are tectonically or seismically analogous to the UK, but by definition such reasons would be expected to suffer from the same problems of limited data as the UK.
22. Whereas the distributions characterising aleatory variability are generally derived, at least in part, from the available data, by definition epistemic uncertainty cannot be measured by statistical analysis of available data. The quantification of epistemic uncertainty involves expert judgement, which is not to be confused with opinion: the distinction is that a judgement must demonstrate a line of reasoning from evidence to claim. Given the complexity of the processes being quantified, the often wide range of defensible interpretations of the available data, and the value of technical challenge and defence, it is widely accepted that the likelihood of adequately capturing epistemic uncertainties is greater when multiple experts are involved in making such judgements. However, experience in multiple-expert hazard analyses has demonstrated that clear guidelines are needed to ensure a common basis for the making of expert judgements. There also needs to be an appropriate degree of interaction among the experts and proper review of the technical bases for their judgements. Relevant good practice at this time for nuclear facilities is represented by the guidelines proposed by a group known as the Senior Seismic Hazard Analysis Committee (SSHAC; Budnitz et al., 1997), created by USNRC, EPRI and the US Department of Energy. The SSHAC guidelines specify four study levels of increasing complexity from Level 1 to Level 4, with the increasing numbers of participants, costs and schedule compensated by greater likelihood of regulatory assurance. For new build nuclear sites in the US, SSHAC Level 3 and 4 hazard studies are generally considered to be appropriate, although SSHAC Level 4 studies are considered very expensive for the extra benefit they provide and in recent years there has been a move towards Level 3 studies. Detailed guidance on the practical implementation of these procedures to PSHA for nuclear sites is provided in USNRC (2012) and USNRC (2017a).
23. The basic objective of the SSHAC guidelines is stated as being to represent “*the centre, the body and the range of technically-defensible interpretations*” of the available data, methods and models. In simple terms, the centre of the distribution may be thought of as the best-estimate model suggested by the available data and current science, and the body of the distribution by the alternative models arising from alternative interpretations of the data. The range refers to the possible limits on the models that lie beyond the data. Regardless of whether or not the SSHAC process is formally adopted, there are elements of the process that would be expected in any site-specific hazard assessment for a nuclear site:
* Due consideration of all available data, methods and models that may have an influence on the seismic hazard at the site, including engagement with members of the broader technical community in order to obtain greater understanding of key datasets or proposed models.
* Construction of a suitable representation of the distribution on each model element or parameter value that represents the current state of knowledge and the associated epistemic uncertainty.
* Clear documentation of the technical basis for all the decisions that underpin the final model.
* Independent peer review (IPR) of the study, including clear and conclusive resolution of all concerns, questions and objections raised.
1. One of the distinguishing features of the SSHAC Level 3 and 4 processes is that the independent reviewers—referred to as the Participatory Peer Review Panel —undertake both technical and process reviews. The latter is achieved through their presence, as observers, at workshops and some working meetings that are organised as part of the project. In a similar way, ONR is better able to assess the quality of a site-specific hazard study if Inspectors and members of ONR Expert Panels are offered the opportunity to observe some elements of the process, including interactions between those conducting the study and the IPR.
	1. Logic trees
2. Logic trees are universally used in current PSHA practice to represent epistemic uncertainties. The tool was first proposed for application to PSHA by Kulkarni et al. (1984) and many subsequent publications have discussed the details of constructing and applying logic trees in PSHA. The basic idea is that for each input to the PSHA calculations—those that define the seismic source boundaries, the recurrence relationships, and the ground-motion prediction models—a node is established with branches representing the alternative models or parameter values. Each branch is assigned a weight reflecting the relative confidence of the hazard analyst in each model or parameter value; these weights must sum to unity since the branches are intended to be collectively exhaustive and also because they are subsequently treated as probabilities in the calculation of the mean hazard and the fractiles (or confidence levels) on the hazard (Figure 3).



**Figure 3**

Illustrative example of a simple logic tree from a PSHA. The red symbols below each branch indicate the weights that sum to unity at each node. The subsequent branches are only shown for one branch at each node; the full implementation of this logic tree would involve 135 combinations for which the PSHA calculations would need to be performed. The weights associated with each of these 135 hazard curves is the product of the branch weights along the path followed through the logic tree, and these weights also sum to unity.

1. The process of building a logic tree is generally conducted in two stages. The first involves the objective evaluation of all available data, methods and models for their potential applicability to the site and region in question. The second phase is the integration of those models judged to be credible into a logic tree with clearly defined branches, each with an associated weight. The documentation of the project should clearly describe both phases of the logic tree construction and fully justify the final logic tree structure in terms of both branches and weights.
2. Once the logic tree is set up, the hazard calculations are executed for all possible branch combinations, each of these yielding a hazard curve (annual frequency of exceedance, or AFE, plotted against spectral acceleration) to which a probability is attached; the probability obtained from the product of the branch weights. For any given level of response spectral acceleration, the statistics of the weighted AFEs are computed to obtain the mean hazard curve and the fractiles. The mean hazard curve will generally indicate greater accelerations at any AFE than the median hazard curve, and their separation—and the spread of the fractile curves—is indicative of the degree of epistemic uncertainty associated with the hazard analysis. The distribution of the uncertainty around the best estimate (usually interpreted as the mean) should be determined by both the defensible alternative interpretations of the available data and models, as well as by the limits of the data: extrapolation beyond the limits of the data must inevitably be accompanied by increased epistemic uncertainty. The same principles of collection of as much data as possible to reduce the epistemic uncertainty followed by efforts to then infer both best estimate models and the uncertainty that remains applies to all elements of the PSHA input. More specific details on the formulation of logic tree for PSHA are given in Section 6.5
3. The fractiles on the hazard estimates are required both to demonstrate that the Design Basis Earthquake response spectrum is sufficiently conservative and to provide the input required for seismic probabilistic safety analysis (PSA). The interpretation of the output from a PSHA conducted using logic trees and ONR expectations in this regard are discussed in Section 8.1.
4. databases for seismic hazard assessments
5. As explained in the previous section, an understanding of epistemic uncertainty is vital for a robust seismic hazard assessment, and it is very valuable to have in place procedures for the identification and quantification of such uncertainties. However, the epistemic uncertainties included in a logic tree for a site-specific PSHA should only reflect the uncertainty that remains after all reasonable efforts have been made to gather relevant data for the region and the site. This section discusses the databases that should be established for any PSHA for a nuclear site; excellent guidance on this topic is also given in IAEA Specific Safety Guide SSG-9 (IAEA, 2010).
	1. Data compilation and data collection
6. Before discussing the databases required for a site-specific PSHA, a distinction is made between the compilation of existing data and the collection of new data. All existing data related to the tectonics, geological structure and seismicity of the region, as well as data related to the geotechnical properties of the site, should be gathered as the starting point of the project. The evaluation of these data, possibly including hazard sensitivity analyses using simple preliminary models, may identify key gaps that should then inform a prioritised programme of new data collection. The extent of new data collection may have to respect constraints of budget, schedule and possibly the unavailability of data from commercial organisations, but the value of the exercise should be assessed in terms of the potential reduction of uncertainties as the quantity and/or quality of data increases. If few or no new data is collected, then this decision would need to be robustly justified and the subsequent PSHA should reflect the paucity of data as larger ranges of epistemic uncertainty and variability (see EPRI, 2013 for guidelines on minimum levels of uncertainty in the absence of new data collection). At the same time, new data collection activities should try to focus on those elements of the model that contribute most to the uncertainty in the final hazard estimates.
7. Many of the data types relevant to a PSHA—such as the earthquake catalogue and a database of ground-motion recordings—require the occurrence of earthquakes during the period of observation, which may render short-term deployment of seismic instruments ineffective. One element of the PSHA model where data collection can greatly reduce uncertainty without any dependence on seismic activity is the dynamic characterisation of the near-surface profile at the site. For this reason, and in view of the pronounced influence this can have on the surface motions at the site, collection of geotechnical data for the characterisation of the site should be considered indispensable (Section 4.8). Installation of seismic recording instruments, both at the surface and potentially also in boreholes, may be valuable for providing additional constraint on dynamic characteristics of the site (see paragraphs 54 and 93).
8. A final point to note here is the scale at which data compilation and collection should be conducted, which will clearly depend on the type of data, as noted in each section below. Whereas for the earthquake catalogue and high-level geological framework a radius around the site of at least 300 km should define the study area, clearly for the geotechnical information the focus would be primarily within the site perimeter and mainly on the area closest to, and below the nuclear island and other ancillary safety related structures. The guidelines of the IAEA (2010) define four areas for investigations: regional (300 km radius), near-regional (25 km radius), site vicinity (5 km) and site area (the site itself, typically 1 km2). Similar areas of investigation are defined in USNRC guidance (USNRC, 2007) but using slightly different terminology and radii from the site: site region (320 km), site vicinity (40 km), site area (8 km) and site location (1 km).
	1. Previous seismic hazard studies
9. For completeness, part of the process of conducting the study should be a review of any existing regional or national seismic hazard studies, such as that of Musson and Sargeant (2007). However, the scale at which such studies are conducted and the range of AFEs on which they focus means that the hazard estimates for the site itself are unlikely to be directly suitable for the safety analysis of high hazard facilities. Nevertheless the studies may serve as a baseline and may also provide useful insights into issues related to the tectonics of the region, the seismicity catalogue, and the selection of appropriate Ground Motion Prediction Equations (GMPEs).
10. Of greater relevance are previous site-specific studies, which in many cases will exist for adjacent sites with existing or decommissioned nuclear installations. These will generally be studies conducted by the Seismic Hazard Working Party, although as time progresses, other studies are being conducted and should be consulted if it is possible to gain access to them. For site-specific studies of the site, or a neighbouring location, it would be advisable to carry out a detailed gap analysis in the light of current best practice. All elements and datasets judged to be valid and relevant should be retained and used as appropriate, but there should be no imperative to retain or reproduce any element of the model only because of precedent. For the same reason, there may be no reason to take account of the actual hazard estimates from earlier studies and the results of the new site-specific study should be judged on their own merit rather than being compared with previous estimates. However, if the new results are substantially different, then some attempt should be made to identify the differences between the old and new models that give rise to divergence of hazard estimates.
	1. Geological data
11. The earthquake record can be extended back in time to the pre-historic era through the examination of faults exposed near the surface, a discipline known as palaeoseismology. The compilation of relevant geological data will provide a description of the geological features, such as fault locations, at site, regional and UK-wide scales. These data should also provide a history of the geological development relevant to the site over geological timescales (e.g. IAEA, 2015; ANS, 2008; ANS, 2015; USNRC, 2017b). It should begin with a desk-based study of regional setting, together with a summary of pre-existing data, published and unpublished research. In most cases, some new geological, geochronological and geophysical data collection and interpretation will also be required as part of the capable faulting assessment (see Section 5.2). Fault rocks and fracture fills associated with ancient fault zones located close to, or below a site, preserve an important record of processes that could occur along faults located at depth in the present day (e.g. Holdsworth et al., 2001). Furthermore, the near-surface character of faults is relevant to their potential mechanical strength and response to tectonic loading. Thus the geological characterisation of fault zones exposed at the surface in the vicinity of a nuclear facility is relevant to an assessment of both the PSHA and the capable faulting hazard. This should lead naturally to an overarching narrative between these two key components of a safety case (IAEA, 2015).
12. In general, however, geological data is unable to provide unequivocal evidence to support the occurrence of known earthquakes derived from the historical or instrumental record. This is because the known seismicity in the British Isles is too sparse for earthquakes to be positively located along particular faults mapped either at the surface, or imaged at depth using geophysical methods. Hence, the geological data will provide only a descriptive understanding of UK seismogenicity, rather than a quantitative one. This lack of correlation may change as our understanding and resolution of the three dimensional architecture of the British crust improve.
	1. Instrumental earthquake catalogues
13. In a region of relatively low seismic activity, such as the UK, seismic hazard assessments will be strongly influenced by models inferred from the catalogue of earthquake events in the region around the site (which might extend to a radius of about 300 km as per IAEA (2010), but particular attention should be paid to a smaller region around the site). An earthquake catalogue lists the basic source characteristics of an earthquake in a particular region, including the date and origin time (in UTC), the coordinates of the epicentre, the focal depth, and the magnitude; several values may be reported for the magnitude using different scales. An earthquake catalogue should be compiled for a sufficiently large region centred on the site, combining both instrumental and historical sources of information; the latter are discussed more in the next section. For the instrumental catalogue, the primary source of information will be the catalogue maintained by the British Geological Survey (BGS), but additional useful information may come from local networks as well as from seismological agencies in neighbouring countries of northwest Europe.
14. In order to be able to use the earthquake data effectively in subsequent interpretations and model building, it is important to establish for the catalogue the uncertainties in epicentral locations, focal depths and magnitudes estimates, all of which may vary as a function of time and location. It is important to note that the reported errors in epicentral coordinates and focal depths are based on residuals with respect to the velocity model used in the location procedure. As a result, the actual location errors may be much larger. Consideration should also be given to the development of the seismograph network over time and the likelihood of events being detected during different periods in order to inform the assessment of the catalogue completeness.
	1. Historical earthquake catalogues
15. Since earthquakes are associated with long-term geological processes, the period of reliable instrumental monitoring is generally too short to provide a stable indication of seismicity patterns. The earthquake record can and should be extended using historical accounts of earthquake effects, interpreted as macroseismic intensities and used to estimate locations and magnitudes of earthquake prior to the establishment of reliable and sensitive seismograph networks. Historical archives containing references to felt earthquakes may be used to estimate earthquake source parameters (time, location, magnitude) using the spatial variation of intensity. Earthquake intensity is a qualitative measure of the strength of shaking of an earthquake determined from the observed effects on people, objects and buildings. A number of intensity scales have been developed including the Modified Mercalli scale and the European Macroseismic Scale. These consist of increasing degrees of intensity, each designated by Roman numerals or integers. The Modified Mercalli intensity scale ranges from imperceptible shaking (I) to catastrophic destruction (XII). For a given earthquake, intensity is normally greatest at the epicentre and decreases with distance from this point, thus the spatial variation of intensity determined from historical accounts of earthquakes can be used to estimate an earthquake location and magnitude (e.g. Strasser et al., 2015).
16. Historical catalogues have been compiled for the UK as a whole—mainly by the BGS—and these should provide the starting point for compiling and extending the catalogue. However, it is generally found that concerted investigations of historical sources will often yield new data that can help to better quantify and constrain uncertainties. Interpretation of the historical data is a specialist discipline and one for which appropriate expertise should be sought.
17. As for the historical earthquake catalogue, careful consideration should be given to uncertainties in location and magnitude, and potentially event origin time as well. These uncertainties are likely to be appreciably larger than those associated with instrumentally-recorded earthquakes. Assessment of the completeness of the historical record for a given region in general terms—and particularly with regards to reports of other natural hazards such as meteorological events—can also be very useful for ascertaining the likely completeness, both spatial and temporal, as well as the quality of the earthquake catalogue. Due attention is needed here in order to ensure that an absence of evidence is not automatically interpreted as evidence of absence.
	1. Ground-motion recordings
18. Accelerograms of UK earthquake ground motions obtained by the recording network operated by the BGS can provide valuable insights and may form part of the database for a site-specific PSHA. However, these data is relatively sparse and also limited to recordings of small-to-moderate magnitude earthquakes. As a result, their usefulness may be limited in terms of constraining the uncertainty in ground-motion predictions for larger earthquakes. The Fourier spectra of the recordings may be inverted to estimate source and path parameters (e.g. Edwards et al., 2008; Ottemöller, 2010), which in turn may be used to generate stochastic prediction models (e.g. Rietbrock et al., 2013) or to adjust empirically-derived equations from other regions in order to render these applicable to the UK (e.g. Campbell, 2003). In both approaches, due allowance should be made for the uncertainty associated with extrapolation from the magnitude range of the data to the magnitudes considered in the PSHA calculations. The recordings may also be used to assess the performance of GMPEs in terms of prediction of UK motions, but the results of such tests using small-magnitude recordings should be applied with caution to larger earthquakes (e.g. Beauval et al., 2012).
19. Recordings directly from the site under study, or adjacent localities with similar surface geology, may provide very valuable insights into the dynamic properties of the site, as explained in Section 4.8.
	1. Ground-motion prediction equations
20. The starting point for constructing a GMPE logic tree may be the selection of a suite of existing GMPEs considered to be potentially applicable or adaptable to the UK and to the site under study. This should begin with an identification of all available GMPEs that may potentially be useable, rather than simply taking a selection of those models that have been used previously, or which are familiar to the hazard analyst. A useful global compendium of GMPEs for PGA and response spectral accelerations is maintained at [www.gmpe.org.uk](http://www.gmpe.org.uk).
21. Use of UK strong-motion data to guide the selection of GMPEs and rank the chosen equations is encouraged, but the uncertainty associated with extrapolating conclusions drawn from small-magnitude recordings to larger earthquakes, as discussed in the previous section, must be acknowledged and incorporated into the logic tree. The selection of GMPEs should also pay close attention to the boundary conditions of the PSHA calculations, especially in terms of the lower and upper limits of magnitude, the ranges of focal depth and source-to-site distance, and the site conditions for which the hazard calculations are to be performed. If the equation is not calibrated to the conditions encountered at the reference horizon for which the hazard calculations will be performed, suitable adjustments will need to be made and the uncertainty associated with such adjustments accounted for in the logic tree (see Section 6.4).
	1. Dynamic site characteristics
22. As seismic waves propagate to the ground surface, their amplitude and frequency are influenced by variations in the geological profile below the site. The most important effect, from the perspective of assessing seismic loads, is the amplification of the motions due to impedance contrasts at different depths below the site. Impedance contrasts arise from changes in the stiffness and density of materials; stiffness is most readily characterised by the shear-wave velocity, VS. The effects of impedance contrasts on the ground shaking are most pronounced when these are encountered close to the surface, which makes dynamic characterisation of the uppermost part of the profile at the site extremely important. The depth range over which this characterisation is needed will depend on the stratigraphic profile at the site, especially its overall stiffness, and the depth at which important impedance contrasts are encountered. The depth over which the dynamic properties are characterised should take account of the frequencies of interest in the motions: as a rule-of-thumb, the depth over which the profile will exert an influence may be estimated from 0.25 times the average VS over this interval divided by the lowest frequency of interest. This depth corresponds to a quarter wavelength of the lowest frequency of interest and indicates the depth to which amplification affects are likely to be significant.
23. The purpose of geotechnical site investigation in the context of seismic hazard assessment is usually to construct a model of horizontal layers below the site, with representative VS and density values assigned to each, together with variability estimates that reflect both the uncertainty in their determination and the lateral variations across the site (e.g. Bazzurro and Cornell, 2004a). The use of horizontal layers is predicated on the assumption that due to reductions in VS with decreasing depth below the surface, seismic waves are refracted into near-vertical propagation paths by the time they are approaching the surface; this assumption allows 1D vertical propagation to be used to model the wave arrivals at the surface.
24. The key activity in the geotechnical site characterisation for seismic hazard analysis is the measurement of VS profiles below the site. There are numerous techniques that can be used for such measurements, each having different advantages and shortcomings in terms of cost, ease of execution, depth of penetration, and degree of resolution near the surface and at depth (e.g. Pitilakis and Anastasiadis, 1999). The use of more measurement techniques, especially those performed in deep boreholes, and their application at more locations across the site, can both be expected to yield appreciable reductions in uncertainty in the final VS profiles. Such measurements are strongly encouraged given that this is one important source of epistemic uncertainty that can be reduced without requiring new earthquakes to occur. Any decision to exclude VS measurements at the site would need to be very robustly defended by the Licensee and, if only a limited programme of measurements are undertaken, then the additional epistemic uncertainty needs to be reflected in the study, for example in greater variability in the profiles used for site response analyses (EPRI, 2013).
25. In addition to the values of VS and density assigned to each layer, site response analyses also require curves relating the stiffness and damping of the layers to the induced shear strain. The sum of low strain damping values in the soil layers should be consistent with the site kappa (see paragraph 54). Laboratory testing—using techniques such as resonant column and cyclic triaxial tests—can be conducted to constrain these important characteristics, or at least to confirm the applicability of adopted relationships for damping and stiffness degradation (e.g. Darendeli, 2001). If such tests are performed, particular care may be required to obtain undisturbed soil samples; evidence would be required that both the field sampling and laboratory testing have been conducted by suitably qualified and experienced specialists. Multiple sets of modulus reduction and damping curves may need to be used to capture epistemic uncertainty.
26. Considerable value can be obtained from the installation of seismic recording instruments at the site in terms of *in situ* measurements that can provide insights into the dynamic characteristics of the site, especially if these include borehole-installed instruments (e.g. Trampert et al., 1993). Clearly the chances of benefiting from such instrumentation are enhanced through installation at the earliest time possible and also by setting the gain sufficiently high. Site-specific recordings are particularly useful for the estimation of the high-frequency damping parameter, kappa, which is particularly important at harder (rock) sites. Kappa is a parameter that reflects the diminishing effect of the uppermost part of the crustal profile on high frequency radiation due to material damping, scattering and potentially other effects (e.g. Knetidou et al., 2015); this is discussed further in Section 7.4. For this purpose it is important to ensure that the instruments have sufficiently high-frequency response (often not the case with typical ‘broadband’ seismographs). If the site response is to be calculated with respect to motions at a buried rock horizon, instrumentation of that rock—either at a nearby outcrop or in a borehole—could yield very valuable data. If borehole instruments at rock level are installed, additional instruments at the surface could then provide data for independent verification of the linear amplification factors calculated from the site response analyses. Site-specific recordings, especially from three-component instruments that allow calculation of the horizontal-to-vertical spectral ratios, can also be very useful for estimating the fundamental site frequency.
27. Capable Faulting
28. Capable faulting or surface rupture is considered a credible hazard in the UK, but is generally accepted as having a very low probability of occurrence at any given location. It is likely therefore that Licensees will seek to screen out this hazard on the basis of low probability; it is important to emphasise that this may be a qualitative argument, demonstrating that there is evidence for surface rupture at the site being very unlikely, rather than a quantitative estimation of the actual probability of surface rupture. This section outlines the geological processes that lead to surface ruptures, how this hazard may be evaluated and the methodologies that should be used in order to allow capable faulting to be screened out from further consideration.
29. The existence of a capable faulting hazard at the site is understood as the potential for geological fault movements and associated deformation at the ground surface that could pose a threat to any structure, component or system traversing the fault trace. Such faults are most often seismogenic, but could in theory form due to gradual creep (IAEA, 2015; ANS, 2015). If such aseismic movement occurs at a sufficient rate, it too has the potential to create a surface break and cause significant damage to a nuclear facility; creeping faults are therefore potentially capable. Unambiguous evidence of significant surface rupture has not been observed in the UK (however, see Ringrose, 1989, for possible examples, although these are not universally accepted, see Stewart and Firth 2004). It is still necessary to demonstrate that the hazard from surface rupture is very low if it is to be screened out for a site; the approach to the analysis of this hazard is discussed in Section 5.
	1. Evaluation of capable fault hazard
30. Faults that pass under the site at, or near the surface are of primary concern, but others close to the site may cause sympathetic movement of faults under the site near to, or at, the surface (IAEA, 2010; IAEA, 2015; ANS, 2015; USNRC, 2017b). The BGS holds the most complete database of faults in the UK (onshore and offshore), but there is no generally available database of active (potentially capable) faults or potentially active faults. There is a BGS database of historical and instrumental earthquakes, but no centralised database of palaeoseismological data exists – and interpretation of that data is somewhat ambiguous and controversial.
31. There are likely to be uncertainties in mapping faults close to the site. Licensees should consider these uncertainties and make conservative judgments regarding which near-field (close to) faults to consider within a capable faulting analysis.
32. The adequacy of a capable faulting safety argument for any site will be primarily judged on three key criteria: First, whether all existing knowledge and appropriate types of information and data, relevant to the likelihood of capable faulting in the UK, have been included and evaluated in the analysis. Second, whether there has been an appropriate gathering of new data. Third, whether an appropriate range of analytical methods and techniques have been used to obtain those data and to assess the potential for damaging ground rupture.
33. Probabilistic approaches to estimating the hazard of surface faulting have been developed (e.g. Youngs et al., 2003) and are referred to as probabilistic fault displacement hazard analysis, or PFDHA. However, these approaches are not described in any detail herein for the simple reason that for new build nuclear sites in the UK, Licensees would be expected to make the case for screening out this hazard rather than presenting a design basis for surface fault displacement. However, it is noted that PFDHA has been developed and applied (e.g. Petersen et al., 2011; Li et al., 2015; ANS, 2015), and these may be adopted if required.
	1. Methodology
34. In order to eliminate capable faulting as a credible threat to a nuclear installation, a comprehensive and up-to-date description of the surface and sub-surface geology and geological history are required over a range of scales from regional to site-specific (e.g. IAEA, 2010; IAEA, 2015; ANS, 2015; USNRC, 2017b).
35. The desk-based compilation of regional geological setting and existing geological and geophysical data compiled as part of the PSHA analysis should be used as a starting point for any study. In most cases, new geological data collection and interpretation will then also be required. Surface geological mapping and interpretations may be carried out using appropriate remote sensing data combined, where appropriate, with field-based structural and lab-based microstructural characterisation of exposed rock formations, fault and fracture systems. Subsurface investigations might include use of geophysical surveys (aeromagnetics, gravity, seismic reflection/refraction) and borehole analyses, including logging and description of any core materials collected. An assessment of the current in-situ stress regime is desirable, together with a simple slip-tendency analysis (e.g. Morris et al., 1996; Yukutake et al., 2015) using all available fracture orientation data from the site in order to identify specific fracture orientations that may be more favourable for slip. It may also be useful to include a study of the relationships (if any) between known geological faults and (micro-) earthquake locations at depth.
36. Collectively, these data should be integrated to build a three dimensional model of faults in the crust below and in the vicinity of the site. This model can then be used to develop a hierarchy of on-site faults based on their potential capability. It is considered good practice that each fault should have a fault data sheet, which describes its characteristics and evidence of activity.
37. For those faults judged to be potentially most capable, i.e. large faults with repeated fault movement histories, faults favourably oriented for slip in the current stress field, or faults rich in phyllosilicates (minerals with potentially lower friction coefficients, e.g. Moore and Lockner 2004), it may be necessary to undertake additional lab based studies. These could include radiometric age dating of past fault movements using appropriate methods and/or experimental testing to measure the frictional strength of specific fault rocks.
38. A range of radiometric age dating methods can be used to constrain the absolute age(s) of fault movement including: K-Ar and Ar-Ar dating of authigenic illites in fault gouge (e.g. Hnat and van der Pluijm, 2014; Viola et al.*,* 2016); U-Th and U-Pb dating of carbonate mineralisation (e.g. Nuriel et al., 2012; Roberts and Walker 2016) and Re-Os dating of fracture-hosted base metal sulphide mineralisation (e.g. Dichiarante et al. 2016). All such radiometric dating studies will need to be supported by detailed field and microstructural observations which show that the natural fault rocks and mineral fills are synchronous with fault movement. In the case of reactivated faults, the K-Ar ages of the <0.1 μm (or finer) illite fraction in fault gouge should give the age of the latest episode of deformation recorded by the fault rock, provided there is no microstructural or isotopic evidence for still later disturbance due to brittle deformation (without associated illite growth). This illustrates the importance of a full microstructural characterisation of fault zones in any geological assessment for the purposes of PSHA and capable faulting.
39. A logical argument should be developed that integrates the evidence determined from each of the methodologies used in order to provide a coherent evidence based case. Since surface rupture hazard is usually linked to ground shaking hazard by having a common causative mechanism, the analyses and resulting narratives for both should be consistent. The criteria used for deciding whether a fault is capable or not should be clear from the analysis, including the reasons and provenance for making these choices. It is important to include a discussion of the limitations of the investigations carried out and how these uncertainties will need to be considered when using the results. In keeping with the intent of PSHA methodology generally, especially given the high degree of uncertainty attached to making judgements about this hazard, it is considered good practice for Licensees to include an independent peer review by appropriate experts.
40. input models for psha
41. This section follows from the development of databases described in Section 4 and describes the derivation of models for the seismic source characterisation (SSC) and ground motion characterisation (GMC) that are the fundamental inputs to PSHA calculations. A simplified diagram illustrating the basic inputs to a PSHA are illustrated schematically in Figure 4.
	1. Homogenised earthquake catalogue
42. Once a catalogue is compiled, it is necessary to homogenise the magnitudes (which for historical earthquakes will be inferred from intensities) so that the size of all events is reported on a common scale. In selecting the final magnitude scale, consideration should be given to the magnitude scales used in the GMPEs since it is essential that the two are consistent; it is more common to adjust the magnitude scale of the earthquake catalogue to that used in the GMPEs rather than vice versa. Due consideration must be given to the selection of appropriate relationships between magnitude scales to make these adjustments, and the variability in these empirical relationships must be accounted for as well (see Section 6.2).
43. Since PSHA, based on the Cornell (1968) formulation, sums the contributions of several earthquake scenarios to obtain the total annual exceedance frequency of given levels of ground motion, there is an implicit assumption that all earthquake events in the catalogue are independent. This assumption necessitates the removal of foreshocks and aftershocks before recurrence parameters are calculated, for which an appropriate de-clustering procedure should be applied to the earthquake catalogue. If there are induced earthquakes in the catalogue, these will generally be removed as well; the hazard such events pose to the site are more likely to be dealt with separately (Section 9).
44. The final stage of compiling an earthquake catalogue for the PSHA study is to assess the periods over which the catalogue is complete for different thresholds of magnitude. Clear procedures and criteria should be presented for assessing these incompleteness intervals—which impact directly on the estimated recurrence rates—and the uncertainty associated with the assessment of the completeness should also be evaluated and included in the logic tree.
	1. Seismic source model and recurrence relationships
45. A seismic source model defines the locations and average recurrence intervals of earthquakes of different magnitudes that could affect the site under study. Within a given region, earthquakes of different magnitudes are generally distributed according to Gutenberg-Richter (G-R) recurrence relationship, which defines a linear relationship between magnitude and the logarithm of the average annual rate of earthquakes of a given magnitude and greater. Such a relationship that defines that average rate of occurrence of earthquakes of different sizes is the cornerstone of probabilistic seismic hazard analysis. The G-R relationship is defined by two parameters: the activity, *a*, and the gradient given by the *b*-value: log(N) = *a* – *b*M, where N is the number of earthquake of magnitude M or greater per year in the region of interest. In general, *b*-values are expected to be close to 1; significant deviations from this value will require explanation. Alternative recurrence models are discussed in Main (1996).
46. For relatively stable regions such as the UK, the association of observed seismicity with mapped geological faults is generally difficult and as a consequence seismic source models will usually be dominated by diffuse seismicity. However, geological investigations are expected to identify geological faults in the broad region around the site (Section 4.3) as well as in greater detail close to the site to address capable faulting hazard (Section 5). If geological faults are identified within or close to the site (or even more remote if the dimensions of the structure are large), unless evidence can be provided for their having no significant seismogenic potential, these may need to be included as explicit seismic sources within the PSHA with appropriate ranges of uncertainty on their recurrence characteristics and maximum magnitude.
47. Diffuse seismicity may be represented by source zones (polygons, or similar, within which earthquakes have uniform probability of occurrence) or using approaches based on the spatial distribution of the earthquake catalogue itself, subject to some degree of spatial smoothing (e.g. Frankel, 1995; Woo, 1996; Lapajne et al., 2003). When using the latter approach, it is important to demonstrate that the possible spatial incompleteness of the observed earthquake catalogue has been duly taken into account. With areal sources, clear justification (geological, geophysical and seismological) for the boundaries must be provided, particularly for any configuration of zones that maintains a concentration of earthquake activity remote from the site under study. Where the location of a source boundary has a significant bearing on the hazard results, the location of that boundary should be varied in the logic tree formulation.
48. Within each source zone, the earthquake activity will likely (although not always) be defined by G-R recurrence relationships determined from the observed earthquake data, taking account of the completeness intervals for each magnitude level and also for the propagation of variability in any magnitude conversion relationships that have been applied (e.g. Musson, 2012a). Since the cumulative recurrence rates at different magnitudes are not independent from one another, it is not mathematically correct to estimate the *a*- and *b*-values of the recurrence relationship by least squares regression; a maximum likelihood fitting technique (e.g. Weichert, 1980) should be used. Many PSHA studies now employ a penalised maximum likelihood estimate of recurrence parameters, which is particularly well suited to seismic sources zones with limited seismicity (e.g. Johnston et al., 1994).
49. The G-R recurrence relationship must be truncated at an upper limit, generally referred to as the maximum magnitude, Mmax, which represents the largest event considered physically possible for a given seismic source zone. The value of Mmax is inevitably associated with large epistemic uncertainty for areal seismic source zones and this should be reflected in the logic tree formulation; clear justification should be given for the distribution of Mmax values chosen and the weights assigned to each one.
50. In those cases where one or more potentially seismogenic geological faults are clearly identified in proximity to the site, these should be modelled as separate seismic sources. For such sources, consideration should be given to the use of characteristic (Youngs and Coppersmith, 1985) rather than G-R recurrence models. The slip rates should preferably be inferred from palaeoseismological data, where possible; such observations may also be supplemented with geodetic measurements of crustal deformation rates (e.g. Ward, 1994), recognising that modern geodetic measurements have to be considered as short-term observations of processes occurring on geological timescales. With or without such data, the assigned slip rates should clearly reflect the uncertainty in the average slip rates on each fault. Mmax values for fault sources may be inferred from empirical relationships between earthquake magnitude and rupture dimensions (e.g. Stirling et al., 2013), but the uncertainty in selecting appropriate relationships and variability in such empirical relationships must be taken into account. A useful exercise is to estimate the total seismic moment budget implied by each of the SSC models to ensure that this is consistent with the crustal deformation rates. A similar exercise can check that the implied catalogues are consistent with the seismicity data (Musson, 2012b). Careful consideration should be given to avoiding duplication of earthquakes on fault sources and in the area sources within which the faults are located.

**Figure 4**

Schematic illustration of the basic elements of PSHA. *Middle*: Four area source zones, one of which hosts the site; *Top*: Recurrence relationship for one of the source zones; *Bottom*: GMPEs for prediction of accelerations at the site for each earthquake scenario.

* 1. Reference horizon for hazard calculations
1. At an early stage of the PSHA project, the horizon at which the ground shaking hazard is to be estimated should be clearly identified, ensuring that this is consistent with the subsequent engineering analyses of the plant. The most appropriate elevation may often be the base of the nuclear containment since this is where the seismic loading is input to the critical structures although consideration also needs to be given to an appropriate horizon for inputs to dynamic soil-structure interaction analysis. Deconvolution of surface motions to a buried horizons has been common practice but the uncertainties associated with this procedure are such that its use is now generally discouraged.
2. However, even if the target horizon is at the foundation level of the nuclear island, it may be the case that the GMPEs are referenced to a deeper rock horizon. The reason is that generic factors for site amplification in GMPEs, conditioned on parameters such as VS30 (the time-averaged or harmonic mean shear-wave velocity over the uppermost 30 m at the site), are unlikely to accurately represent the dynamic characteristics of the specific near-surface profile at the site. In order to more faithfully capture the influence of the site geology on the amplitude and frequency characteristics of the motion, it is generally considered good practice to estimate the hazard at a horizon located at some depth—which is sufficiently stiff for linear behaviour to be assumed under a wide range of accelerations—and then to perform site response analyses to estimate the local amplification characteristics. Site response analyses and the combination of the site amplification factors with the hazard at the reference rock horizon are discussed in Sections 7.4 and 7.5.
	1. Ground-motion prediction model
3. GMPEs, sometimes referred to as attenuation relations, predict distributions of a specified ground-motion parameter—such as peak ground acceleration, PGA, or the spectral acceleration at a given oscillator frequency—as a function of explanatory variables such as magnitude, style-of-faulting, source-to-site distance, and classification of the site itself (most often by VS30). The distribution of the logarithmic values of the ground-motion parameter are defined by the median predictions obtained from the coefficients and variables of the equation, and the logarithmic standard deviation, generally referred to as sigma. The coefficients for the median predictions and the sigma value characterising the distribution of residuals are both indispensable elements of a GMPE.
4. The selection or generation of GMPEs for a stable region such as the UK is inevitably associated with large epistemic uncertainty since the indigenous database of strong-motion recordings is relatively small, lacking in near-source recordings and completely void of recordings from larger earthquakes. ONR therefore expects a logic tree structure for the GMPEs to capture and propagate the epistemic uncertainty associated with the ground-motion predictions, particularly at the larger magnitudes considered in the PSHA calculations. The selected GMPEs should capture alternative magnitude and distance models. An important issue to be borne in mind here is that the logic tree is intended to capture the range of possible ground-motion amplitudes for a given earthquake scenario (i.e. magnitude-distance combination). The population of the logic tree branches with large numbers of GMPEs from other regions may not necessarily result in a broad distribution of predicted ground-motion amplitudes; moreover, the range of predicted motions from GMPEs from other regions is unlikely to represent the full range of epistemic uncertainty on such predictions for the UK. Alternatives to simply populating the logic tree with a large number of imported GMPEs should therefore be carefully considered. Such alternatives may include the generation of stochastically-simulated models with a range of values on key parameters such as stress drop, or, similarly, the application of hybrid-empirical approaches with similar ranges for these key parameters—such as stress drop (source strength) and Q (path attenuation)—in the target region (i.e. the UK). The final logic tree structure should be justified, both with respect to the branch models and their weights, in terms of the resulting distribution of ground motions (e.g. Atkinson et al., 2014).
5. Particular attention should be given to the characteristics of the horizon at which the hazard is being estimated. If this is a deep rock layer with a high VS, it may well not be appropriate simply to set this value as the VS30 value in the GMPEs if the value lies outside the range of applicability of the equation. In such situations, it may be necessary to apply adjustments for host-to-target differences in both VS profiles and kappa (near-surface high-frequency damping; see Section 7.4) values (e.g. Van Houtte et al., 2011; Al Atik et al., 2014; Edwards et al., 2015; Knetidou et al., 2016). Additionally, if rock hazard is being combined with site-specific amplification functions, it may also be necessary to adjust the sigma term of the GMPEs, as explained in Section 7.5.
	1. Logic trees for PSHA inputs
6. The final logic tree should define all the alternative models and parameter values required to define the SSC and GMC models. Logic tree branches should only be assigned for elements of epistemic uncertainty and should aim to satisfy the criteria of being *mutually exclusive* and *collectively exhaustive*. Distributions of focal depths, for example, should not be represented by weighted branches at various depths, since this is an aleatory variable and should be integrated in the PSHA calculations. However, it would be appropriate to have branches representing alternative focal depth distributions if this is a significant source of uncertainty.
7. Due attention should be given to correlations among the recurrence parameters: for example, population of logic tree branches with pairs of *a*- and *b*-values rather than to develop separate nodes for these parameters. An advantage of the penalised maximum likelihood approach (see paragraph 74) is that it takes into account the correlation between the two parameters.
8. The logic trees representing the inputs to the PSHA calculations should initially be constructed to reflect the current state of knowledge regarding the seismicity of the region and the wave propagation characteristics of the site. The use of sensitivity analyses to justify the trimming of logic tree branches is discouraged since the removal of individual branches on the basis of modest influence on the hazard may overlook important effects of such branches in combination. Rather, the logic tree should be constructed to reflect the best estimates and associated epistemic uncertainty of each element of the PSHA input. If the final configuration is excessively cumbersome in terms of the total number of branch combinations, it is possible to re-sample the distributions at nodes with smaller numbers of branches that provide good approximations to the same distributions. For example, the distributions of implied recurrence rates can be re-sampled with a smaller number of branches (e.g. Stromeyer and Grünthal, 2015).
9. PSHA Calculations and Site Response Analyses
10. Once the complete logic trees for both the SSC and GMC models are assembled, the hazard calculations can be performed using appropriate computer codes. A PSHA code simulates all possible earthquake scenarios as defined by the seismic source model, each scenario corresponding to a magnitude, M (and associated recurrence rate) and distance, R (as determined by the location with respect to the site). The number of standard deviations above the mean logarithmic prediction from the GMPE required for a given scenario to generate the target ground-motion level at the site is also estimated, and the frequency of exceeding this value of ε determined from the standard normal distribution. The frequency associated with each M-R-ε combination is the product of the exceedance frequency of ε and the recurrence rate associated with the magnitude. Assuming all earthquake events to be independent, the frequencies of all M-R-ε scenarios causing the target acceleration at the site can be summed. Repeating the calculations for several acceleration levels, a hazard curve plotting AFE against acceleration can be plotted. This section discusses some of the issues related to execution of the hazard calculations and, when relevant, the combination of the hazard at the reference rock horizon with the site amplification factors for the overlying layers.
	1. Selection and qualification of PSHA software
11. There are numerous open-source, free and commercial software packages available for performing PSHA calculations. Some of these apply the direct integration approach as originally proposed by Cornell (1968) and subsequently extended (e.g. McGuire, 2008), whereas others use a Monte Carlo approach (e.g. Musson, 2002; Assatourians and Atkinson, 2013). ONR makes no specifications about which packages are suitable, but whatever software is used, it is important to provide independent verification of the calculations, preferably against well-established bench-marking exercises (e.g. Thomas et al., 2010). Hazard codes developed in-house may provide the greatest flexibility, but if such an approach is adopted, then it is particularly important to verify the performance of the software.
12. An important issue to consider is the ability of the software to correctly calculate source-to-site distance metrics for areal sources. A number of the earlier PSHA codes that are freely available and still in use only model the sources of individual earthquakes as points without any extension, whereas the dimensions of fault ruptures increase exponentially with increasing magnitude. For GMPEs using distance metrics defined relative to the fault rupture, such calculations require conversions or, preferably, the generation of virtual fault ruptures; if earthquakes are represented as points (hypocentres) within the source zones then the use of such GMPEs will result in systematic underestimation of the hazard (e.g. Monelli et al., 2014).
	1. Limits on integrations in PSHA
13. PSHA involves the integration over various random variables to calculate the annual frequency or probability of exceedance of a given ground-motion parameter at the site under study. The basic three random variables that are integrated in PSHA are the earthquake magnitude, M, the source-to-site distance, R, and epsilon, ε, which represents the number of standard deviations above or below the median predictions from the GMPEs. The range of values of M is defined by the maximum possible earthquake size in each source, Mmax, and the lower limit, Mmin, which is set on the basis of ground motions from smaller earthquakes being unable to generate motions that could be damaging to a well-engineered facility. The estimation of the upper limit, Mmax, will invariably be associated with appreciable epistemic uncertainty and therefore usually appears as a node in the SSC logic tree (Figure 3).
14. The definition of Mmin is unambiguously the level of magnitude below which ground motions—even if generated by an event directly below the site—would be insufficiently energetic to pose a threat to the facility[[1]](#footnote-1). The imposition of a lower magnitude limit in the PSHA integrations does, inevitably, lead to a reduction in the calculated hazard, but the premise behind the selection of this limit is that it has a negligible impact on the calculated risk to the facility being designed or analysed. In recent years, some studies have chosen to replace the Mmin limit with a filter on conditionally predicted ground motions to more explicitly exclude hazard contributions from scenarios that do not produce potentially-damaging motions, the most commonly-used parameter for this purpose being the cumulative absolute velocity or CAV (EPRI, 1989). There is, nonetheless, widespread misunderstanding regarding the definition and purpose of Mmin: it should never, for example, be determined by the completeness levels of the earthquake catalogue or the range of applicability of the selected GMPEs (Bommer & Crowley, 2017). The choice of the Mmin value selected for the PSHA should be well justified in the documentation of the hazard study, noting that this justification may be based on precedent from good practice. Values used in practice generally range from 4 to 5, with the upper limit being of particular relevance to nuclear applications (e.g. EPRI, 2005; USNRC, 2007). ONR will not accept values of Mmin greater than moment magnitude 5.0, which is also specified as an upper limit by IAEA (2010).
15. The range of values of R is determined by the geometry of seismic source zones, and would generally be expected to extend from zero (depending on the specific distance metric used) to an upper limit beyond which earthquakes make no appreciable contributions to the calculated hazard. In theory, ε is unbounded—since it corresponds to a log-normal distribution—but in practice it is usual to consider an upper limit on this variable for practical purposes. Any low truncation of this variable—for example at 3 standard deviations or fewer—would need to be robustly justified in the Licensee’s submission since studies have concluded that there is currently neither a physical nor a statistical basis for such low truncations (e.g. EPRI, 2006).
	1. Quality Assurance on hazard calculations
16. In addition to using a suitably qualified PSHA code (Section 7.1), it is important that the study documents Quality Assurance procedures followed to ensure that the hazard model was correctly implemented in the code. This is particularly important when the logic tree structure is complex. A number of activities can be undertaken towards this end, including verification of the implementation of individual elements of the model such as the predictions from the GMPEs, the source boundaries and the implied activity rates for earthquakes of different magnitudes.
	1. Site response analyses
17. As noted in Section 4.8, in order to accurately capture both the frequency-dependence of site amplification factors and any non-linearity in the soil response, ONR would generally expect the hazard calculations to be performed at a reference rock horizon—unless the site itself is a rock outcrop—and to then to combine these estimates of the shaking hazard with the amplification factors for the overlying layers. For this more rigorous approach of performing site response analyses using the measured VS profile and dynamic soil properties at the site, a key decision, as noted earlier, is the selection of an appropriate reference rock horizon that will serve as the base relative to which the site amplification functions will be calculated. In site response calculations, this horizon is treated as the top of an elastic half-space, which implies that it is an absorbing boundary (i.e. downward travelling waves are not reflected upwards by sharp impedance contrasts) and that the material behaves linearly (which requires sufficient stiffness, as reflected in the VS value, to respond linearly under the highest levels of acceleration considered). The choice of reference rock horizon must be fully explained and justified.
18. Once the top of the elastic half-space is defined, the next step is to ensure that the GMPEs are well calibrated to the conditions at this reference rock horizon, both in terms of VS30 and site kappa, the latter being a measure of the high-frequency damping over the topmost portion of the crust (e.g. Anderson and Hough, 1984; Laurendeau et al., 2013; Al Atik et al., 2014). If the GMPE has been imported from another region, adjustments may also need to be made for any differences in the crustal velocity profile between the host region where the equation was developed and the target region where the PSHA is being performed. However, if adjustments are made only for the differences in VS profiles, then transforming an equation for rock sites to very hard rock conditions at the reference horizon would result in de-amplification across the full frequency range, which is not realistic. Stiffer sites will have both higher VS values and lower kappa values. The consequence is that while response spectral ordinates at lower frequencies will be de-amplified, the high-frequency ordinates are likely to be increased as a result of the lower kappa (Figure 5).

**Figure 5**

Soft-rock to hard-rock amplification factors accounting for (a) VS only, (b) site kappa only, and (c) the combination of VS and κ0 (Knetidou and Abrahamson, 2016).

1. The calculation of the site amplification functions for the layers between the reference rock horizon and the target elevation may be performed in a number of ways, using either time-domain solution of 1D SH-wave propagation, or the random vibration theory approach (e.g. Stewart et al., 2014; Kottke and Rathje, 2013). The 1D assumption is generally invoked because as a result of the reducing velocity towards the ground surface, seismic waves will usually be refracted into near-vertical ray paths over the uppermost tens of metres. A choice must also be made between equivalent linear analyses and fully non-linear site response analyses. The choices should be explained and justified with respect to the specific characteristics of the site profile. The uncertainty in the VS profile should be characterised by a best estimate profile and associated variability, with the possibility of more than one best estimate being defined and the different profiles being treated as an epistemic uncertainty. Standard practice is to define the best estimate profile as the geometric mean VS of the available measurements at each depth and the associated variability as the standard deviation of the residuals of logarithms of VS. Using the variability estimated for the VS profile, the site response calculations should be performed using randomised velocity profile, generated with an appropriate layer-to-layer correlation function in order to avoid unrealistic velocity contrasts and inversions. The other properties of the layers (density, stiffness degradation and damping) may also be randomised. The randomisation allows the uncertainty and variability in the site profile to be captured and also avoids artificial resonances arising from the idealised layer model. Using randomised soil profiles and properties, as well as multiple loading levels at the top of the elastic half-space, the calculations yield both the median amplification functions and the associated variability. The input motions used in the site response analyses need to cover a range of values, especially those commensurate with the controlling earthquake scenarios identified from disaggregation of the hazard results at the target AFE.
	1. Incorporating site response into hazard estimates
2. There are numerous options for combining the calculated hazard at the reference rock horizon with the amplification functions discussed above. The most rigorous approach is when the rock hazard is fully convolved[[2]](#footnote-2) with the distribution of amplification factors—which allows faithful tracking of the calculated AFEs to the ground surface—including both the median amplification functions and their associated variability (e.g. Bazzurro and Cornell, 2004b; McGuire et al., 2001). A schematic overview of how reference rock hazard can be combined with probabilistic site amplification is presented in Figure 6. The convolution approach depicted in this figure is often referred to as Approach 3; it is also possible to embed the site amplification factors directly in the hazard integral. The latter approach has some advantages, particularly in terms of calculation of the hazard fractiles at the target horizon and also for cases where the site amplification factors are scenario dependent (e.g. Stafford et al., 2017).
3. Due attention must be given to the treatment of site-to-site variability, which is one of the components of sigma in empirical GMPEs. When this variability is captured through the site amplification calculations and incorporated into the surface hazard estimates through the convolution process, it needs to be removed from the sigma in the GMPEs used to calculate the rock hazard (e.g. Rodriguez-Marek et al., 2014).



**Figure 6**

Flowchart illustrating the calculation of hazard at a baserock horizon and its convolution with probabilistic site amplification factors (Rodriguez-Marek et al., 2014). The process illustrated involves calculating the hazard at a buried rock horizon through PSHA and then convolving the rock hazard estimates with probabilistic site response analyses in order to obtain the surface motions.

* 1. Long-period ground motions
1. Some structures and components at nuclear installations may be sensitive to long-period motions, including tanks and spent-fuel pools on reactor sites, and some large specialist plant items on some non-reactor sites. In the past this sometimes presented a challenge because GMPEs, based mainly on records from analogue accelerographs, had limited ranges of useable periods as a result of the need to apply filters to the recordings. Even in such circumstances, however, the final response spectra (see Section 8) could be extrapolated to longer periods with some confidence by first transforming the accelerations to displacements and then linearly extending the final portion of the resulting spectrum. This displacement spectrum would be expected to linearly increase in amplitude up to an oscillator period that is dependent primarily on the magnitude of the controlling earthquake (and the stress drop of the event as well), beyond which the displacements would be constant. The applicable acceleration spectrum can then be obtained by inverting the transformation.
2. Such approximate procedures are required less nowadays because GMPEs often provide coefficients for the prediction of spectral accelerations at longer response periods, as a result of using recordings from digital instruments.
3. If estimates of long-period motions are relevant to a nuclear installation, consideration should be given to motions that might arise from large-magnitude distant events, such as a repeat of the 1755 Lisbon earthquake. This should not require the development of a complete SSC model for such remote earthquakes so far beyond the normal distance ranges that would be considered in developing source models. It may be sufficient to compare predicted motions—at an appropriate exceedance level—for a scenario earthquake with the uniform hazard response spectrum from the PSHA to inform a judgement regarding the adequacy of the long-period portion of the site-specific spectrum.
4. Outputs from a Site-specific PSHA
5. This section briefly lists the minimum requirements for the presentation of outputs from a site-specific PSHA for a nuclear installation. The need for clear and complete documentation of all aspects of the model building and the hazard calculations, in addition to the specified outputs from the analysis, cannot be emphasised too strongly.
	1. Seismic hazard curves: means and fractiles
6. Within the framework of a logic tree formulation, the PSHA calculations will yield multiple seismic hazard curves (showing the AFE for various levels of a given ground-motion parameter), with one curve for each possible branch combination. The weight on each hazard curve is the product of the individual branch weights. The hazard curves should be presented in the form of the mean hazard—calculated as the weighted average of the AFEs at each ground-motion level—and the fractiles or confidence levels (including at least the 5th, 16th, 50th, 84th and 95th percentiles), all of which should be presented down to AFEs as low as 10-7, and in some circumstances even lower as indicated in IAEA SSG-9 (IAEA, 2010). The fractiles of the hazard estimates are required for two key reasons:
7. Seismic probabilistic safety analyses (PSA) require not only the mean hazard, but also the complete distribution of the confidence intervals as represented by the fractiles.
8. For substantiation of the site design basis ONR expects that the site-specific ground motion hazard should be expressed as uniform hazard response spectra (UHRS; see Section 8.2). For further information on the considerations necessary to develop an adequate design basis please refer to Annex 1 of TAG 13 (ONR, 2018b).
9. The hazard calculations should be performed for response spectral ordinates at several oscillator frequencies to ensure adequately clear definition of the response spectrum, particularly at the natural vibration frequencies of safety-critical structures and components.
	1. Uniform hazard response spectra
10. As noted in paragraph 103, the PSHA results should be presented in the form of UHRS at various AFEs (including 10-3, 10-4, 10-5, 10-6 and 10-7) at the mean and various percentiles including the 85th percentile level. The spectral ordinates should be for 5% of critical damping, although the spectra may additionally be shown for other damping ratios as well if these are relevant to the design of any structures or components. As noted in Section 2.3, the definition of the horizontal component of motion must be clearly specified.
11. If the vertical response spectrum is also required, this may be obtained by the application of appropriate vertical-to-horizontal spectral ratios (e.g. McGuire et al., 2001; Gülerce and Abrahamson, 2011; Akkar et al., 2014). Alternatively, the PSHA calculations may be repeated using GMPEs for the vertical component of motion but this approach can lead to horizontal and vertical response spectrum dominated by different magnitude-distance combinations.
	1. Disaggregation
12. Since PSHA is a process of integration over random variables, the process can be inverted through disaggregation to show the contributions from different sources and scenarios. ONR would expect to see mean hazard curves for several oscillator periods plotted together with the curves corresponding to individual seismic source zones in order to view the relative contributions. Similarly, additional plots should compare the mean hazard with hazard curves that would be obtained by assigning a weight of unity to individual branches (i.e. as if the PSHA were conducted using a single value of Mmax or a single GMPE) in order to explore sensitivities. Alternative representations of sensitivity, such as tornado plots showing the contributions of uncertainty on individual elements of the model to the overall uncertainty in the hazard (Figure 7), are also welcomed.



**Figure 7**

‘Tornado plot’ used to provide feedback to evaluator experts on the relative contributions to overall uncertainty in the PEGASOS project for PSHA at nuclear power plant sites in Switzerland (USNRC, 2012). Each horizontal bar shows the range of uncertainty associated with the logic tree branches related to a particular model parameter; the total uncertainty is indicated by the lowest bar. Such a plot shows the relative contributions to overall uncertainty, the dominant contributor in this case being the uncertainty in the median ground-motion predictions.

1. Additionally, disaggregation plots showing the contributions by M-R-ε bins to the hazard at different oscillator frequencies and AFEs are also required. Such plots are very important to illustrate the earthquakes dominating the hazard, which is also very useful information when defining acceleration time-histories for the use in dynamic structural or soil-structure analyses.
	1. Acceleration time-histories
2. For dynamic structural analyses, accelerograms are required, which should be broadly consistent with the response spectrum defined by the PSHA and also consistent with the characteristics of the dominant earthquake scenarios identified through disaggregation. There are benefits in ensuring that the generation of acceleration time-histories is well integrated with the PSHA study and, in this regard, it can be helpful to include this representation of the hazard within the scope of the IPR.
3. Whereas in the past it was common to use artificial accelerograms generated from filtered white noise to match a target response spectrum, it is now recognised that such records rarely possess the characteristics of real earthquake recordings and are not best suited for non-linear dynamic analyses. In view of the large databases of real earthquake accelerograms now available, it is considered preferable to use such recordings, which can be readily accessed from several Internet sites.
4. There is a vast technical literature now available on procedures to select and modify natural accelerograms for use in dynamic structural analyses and in site response calculations, and it is difficult to navigate through these often conflicting proposals. Nonetheless, some broad general principles can be established. The first step is always to identify the criteria for the selection of the accelerograms—which are often referred to as seed records—and it is generally found to be beneficial to search for records that approximately match the shape (rather than the amplitude) of the target response spectrum. The target response spectrum can be the UHRS but this is not ideal since it will often represent the envelope of contributions from several different earthquakes and/or seismic sources. A better procedure is to construct the target response spectrum for the dominant scenarios found from disaggregation of the hazard at the target AFE and at the dominant response frequency of the structure to be analysed. An additional refinement is to account for the decreasing period-to-period correlation with increasing separation of the response periods to generate a conditional mean spectrum (Baker and Cornell, 2006b).
5. Once the target spectrum is defined, records can be selected on the basis of similarity of the shape of the response spectrum as well as consideration of magnitude and distance, so that the recordings have durations that are consistent with the dominant earthquake scenario. The records then need to be linearly scaled so that their response spectral ordinates approximately match or exceed those of the target spectrum over a specified frequency range. Careful consideration needs to be given to the definition of the horizontal component of motion used in the GMPE and how it treats the two horizontal components from each recording. There is no general agreement on which is the best definition but what is vital is that the definition be consistent with how the resulting motions are used in structural analyses (e.g. Baker and Cornell, 2006a).
6. An additional refinement is to apply spectral matching techniques—most efficiently performed using wavelets (e.g. Al Atik and Abrahamson, 2010)—in order to match each record more closely to the target response spectrum. Stable estimates of structural response can be achieved with much smaller numbers of analyses using spectrally-matched records than with records that have been linearly scaled (e.g. Hancock et al., 2008).
7. Hazard Assessment for Induced Seismicity
8. The focus of the previous sections has been exclusively on the quantification of seismic hazard associated with natural (tectonic) earthquakes. At some sites, it may also be necessary to take account of earthquakes of anthropogenic origin.
	1. Causes of induced and triggered seismicity
9. Several human activities have been identified as leading to increased levels of seismicity including the impounding of deep reservoirs (e.g. Simpson et al., 1988) and with mining, among others (e.g. Klose, 2013). The topic of induced seismicity has attracted greater attention in recent years, particularly because of several cases of seismicity related to processes involving the high-pressure injection of fluids into the Earth’s crust, including waste-water disposal (Ellsworth, 2013), enhanced geothermal systems (Majer et al., 2007), and hydraulic fracturing for shale gas production (Davies et al*.,* 2013). In terms of a distinction between induced and triggered seismicity, triggered earthquakes are those where the stress change leading to the event is only a small fraction of the ambient level (in other words, the earthquake was incipient and its time of occurrence brought forward by the anthropogenic activity), whereas for induced seismicity, the stress change is comparable in magnitude to the ambient shear stress acting on a fault (McGarr et al., 2002). In operations that involve high-pressure injection of fluids, for example, small-magnitude earthquakes caused directly by hydraulic fracturing would be considered induced, whereas larger events caused by the injected fluid intersecting a critically-stressed pre-existing fault would be triggered.
10. Using the term induced seismicity to cover both triggered and induced events, the first task may be to distinguish such events from natural earthquakes whose location and time of occurrence are not influenced by any human activities. Suggested guidelines for separating natural and induced earthquakes are given by Dahm et al*.* (2013).
	1. Adapting PSHA for induced earthquakes
11. In seismic hazard assessment, earthquakes identified to be of anthropogenic origin, such as quarry blasts or mining events, are usually removed from the earthquake catalogue prior to the definition of source zones and associated recurrence relationships. However, for induced and triggered seismicity related to causes such as hydrocarbon production, enhanced geothermal systems and wastewater injection, the contribution to ground shaking may warrant consideration. Although it may be unlikely that a design basis ground motion due to induced seismicity would ever be defined for nuclear installations, a probabilistic assessment of the induced seismic hazard may be conducted to quantify the potential impact relative to the design basis due to natural seismicity. The response to such a comparison may be to suspend, relocate or otherwise modify the anthropogenic activity responsible for the earthquake activity, but this is outside the scope of this document.
12. There are, however, some important points to be made with regards to the application of PSHA to induced earthquakes, since there are important differences with natural seismicity that require special attention. These include the fact that induced seismicity can never be treated as a stationary process, which is a standard assumption in PSHA for natural earthquakes. A consensus approach to PSHA for induced seismicity has yet to be established, and it may be the case that different approaches will be required depending on the causative mechanism and the geological setting. However, some guidance may be obtained from studies that have attempted to extend classical PSHA to the non-stationary seismicity associated with anthropogenically-induced earthquakes (e.g. Convertito et al., 2012; Goertz-Allmann and Wiemer, 2013; Mena et al., 2013; Hakimhashemi et al., 2014; Bourne et al., 2015; Hutchings et al., 2015; Petersen et al*.*, 2018).
13. Among the challenges in quantifying the seismic hazard due to induced earthquakes is estimation of the largest possible magnitude, Mmax. For fluid injection processes, it has been suggested that the largest induced event can be related directly to the volume of injected fluid (McGarr, 2014). The possibility of triggered earthquakes, releasing tectonic strain energy from the crust rather than being limited by the causative process, must also be considered and for such events Mmax estimates are likely to be similar to those for tectonic earthquakes.
14. Another important difference is that focal depths of induced earthquakes will generally be much shallower than most natural earthquakes, which may challenge the applicability of any existing GMPEs derived from recordings of tectonic earthquakes. The challenges include issues related to the very short travel paths associated with these shallow events and the need to constrain the near-source distance saturation for such scenarios, as well as the possibility of depth-dependence of stress drops.
15. references

Akkar, S., Sandıkkaya, M.A. and Ay, B.Ö. (2014). Compatible ground-motion prediction equations for damping scaling factors and vertical-to-horizontal spectral amplitude ratios for the broader European region. *Bulletin of Earthquake Engineering* 12(1), pp.517-547.

Al Atik, L. and Abrahamson, N. (2010). An improved method for nonstationary spectral matching. *Earthquake Spectra* 26(3), pp.601-617.

Al Atik, A., Kottke, A., Abrahamson, N. and Hollenback, J. (2014). Kappa (κ) scaling of ground-motion prediction equations using an inverse random vibration theory approach. *Bulletin of the Seismological* Society of America, 104(1), pp.336-346.

Anderson, J.G. and Hough, S. (1984). A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies. *Bulletin of the Seismological Society of America* 74(5), pp.1969-1993.

ANS (2008). Criteria for Investigations of Nuclear Facility Sites for Seismic Hazard Assessments. ANSI/ANS-2.27-2008, American Nuclear Society, Le Grange Park, IL.

ANS (2015). Criteria for Assessing Tectonic Surface Fault Rupture and Deformation at Nuclear Facilities. ANSI/ANS-2.30-2015, American Nuclear Society, Le Grange Park, IL.

Assatourians, K. and Atkinson, G.M. (2013). EqHaz: An open-source probabilistic seismic-hazard code based on the Monte Carlo simulation approach*. Seismological Research Letters* 84, pp.516–524.

Atkinson, G.M., Bommer, J.J. and Abrahamson, N.A. (2014). Alternative approaches to modeling epistemic uncertainty in ground motion in probabilistic seismic-hazard analysis. *Seismological Research Letters,* 85(6), pp.1141-1144.

Baker, J.W. and Cornell, C.A. (2006a). Which spectral acceleration are you using? *Earthquake Spectra,* 22(2), pp.293-312.

Baker, J.W. and Cornell, C.A. (2006b). Spectral shape, epsilon and record selection. *Earthquake Engineering & Structural Dynamics,* 35, pp.1077–1095.

Baptie, B. (2010). Seismogenesis and state of stress in the UK. *Tectonophysics.* 482, pp.150-159, doi: 10.1016/j.tecto.2009.10.006

Bazzurro, P. and Cornell, C.A. (2004a). Ground-motion amplification in nonlinear soil sites with uncertain properties. *Bulletin of the Seismological Society of America,* 94, pp.2090-2109.

Bazzurro, P. and. Cornell, C.A. (2004b). Nonlinear soil-site effects in probabilistic seismic hazard analysis. *Bulletin of the Seismological Society of America,* 94, pp.2110-2123.

Beauval, C., Tasan, H., Laurandeau, A., Delavaud, E.,Cotton, F., Guéguen, P. and Kuehn, N. (2012). On the testing of ground-motion prediction equations against small-magnitude data. *Bulletin of the Seismological Society of America,* 102(5),pp.1994-2007.

Bommer, J.J. and Boore, D.M. (2004). Engineering Seismology. *In*: Encyclopaedia of Geology, Academic Press, Volume 1, pp.499-514.

Bommer, J.J. and Crowley, H. (2017). The purpose and definition of the minimum magnitude limit in PSHA calculations. *Seismological Research Letters,* 88(4), pp.1097-1106.

Bourne, S.J., Oates, S.J., Bommer, J.J., Dost, B., van Elk, J. and Doornhof, D. (2015). A Monte Carlo method for probabilistic seismic hazard assessment of induced seismicity due to conventional gas production. *Bulletin of the Seismological Society of America,* 105(3), pp.1721-1738.

Budnitz, R.J., Apostolakis, G., Boore, D.M., Cluff, L.S., Coppersmith, K.J., Cornell, C.A. and Morris, P.A. (1997). *Recommendations for probabilistic seismic hazard analysis: Guidance on uncertainty and the use of experts*. NUREG/CR-6372. Two volumes, US Nuclear Regulatory Commission, Washington D.C.

Campbell, K.W. (2003). Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America. *Bulletin of the Seismological Society of America,* 93(3), pp.1012-1033.

Convertito, V., Maercklin, N., Sharma, N. and Zoldo, A. (2012). From induced seismicity to direct time-dependent seismic hazard. *Bulletin of the Seismological Society of America,*102(6),pp*.*2563-2573*.*

Cornell, C.A. (1968). Engineering seismic risk analysis. *Bulletin of the Seismological Society of America,* 58(5), pp.1583-1606.

Dahm, T., Becker, D., Bschogg, M., Cesca, S., Dost, B., Fristschen, R., Hainzl, S., Klose, C.D., Kühn, D., Lasocki, S., Meier, T., Ohrnberger, M., Rivalta, E., Wegler, U. and Husen, S. (2013). Recommendation for the discrimination of human-related and natural seismicity. *Journal of Seismology,* 17(1), pp.197-202.

Darendeli, M.B. (2001). *Development of a New Family of Normalized Modulus Reduction and Material Damping Curves*. PhD Dissertation (supervisor: Prof. Kenneth H. Stokoe, II), Department of Civil Engineering. The University of Texas at Austin. August, 2001.

Davies, R., Foulger, G., Bindley, A. and Styles, P. (2013). Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons. *Marine and Petroleum Geology,* 45, pp.171-185.

Dichiarante, A.M., Holdsworth, R.E., Dempsey, E.D., Selby, D., McCaffrey, K.J.W., Michie, U.McL., Morgan, G. and. Bonniface, J. (2016). New structural and Re–Os geochronological evidence constraining the age of faulting and associated mineralization in the Devonian Orcadian Basin, Scotland. *Journal of the Geological Society,* 173, pp.457-473.

Edwards, B., Ktenidou, O-J.,Cotton, F. and Abrahamson, N. (2015). Epistemic uncertainty and limitations of the κ0 model for near-surface attenuation at hard rock sites. *Geophysical Journal International,* 202, pp.1627-1645.

Edwards, B., Rietbrock,A., Bommer, J.J. and Baptie, B. (2008). The acquisition of source, path and site effects from micro-earthquake recordings using Q tomography: applications to the UK. *Bulletin of the Seismological Society of America,* 98(4),pp*.*1915-1935.

Ellsworth, W.L. (2013). Injection-induced earthquakes. *Science,* 341, 142-143. DOI: 10.1126/science.1225942.

EPRI (1989). *Engineering Characterization of Small-Magnitude Earthquakes*. EPRI Report NP-6389, Electric Power Research Institute, Palo Alto, California,

EPRI (2005). *Use of Minimum CAV in Determining Effects of Small Magnitude Earthquakes on Seismic Hazard Analyses*. EPRI Report 1012965, Electric Power Research Institute and US Department of Energy.

EPRI (2006). *Program on Technology Innovation: Truncation of the Lognormal Distribution and Value of the Standard Deviation for Ground Motion Models in the central and Eastern United States*. EPRI Report 1013105, Technical Update, February 2006, Electric Power Research Institute, Palo Alto.

EPRI (2013). *Seismic Evaluation Guidance—Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic*. EPRI Report 1025287, February 2013, Electric Power Research Institute, Palo Alto.

Frankel, A. (1995). Mapping seismic hazard in the Central and Eastern United States. *Seismological Research Letters,* 66(4), pp.8-21.

Goertz-Allmann, B.P. and Wiemer, S. (2013). Geomechanical modelling of induced seismicity source parameters and implications for seismic hazard assessment. *Geophysics,* 78(1), KS25-KS39.

Gülerce, Z. and Abrahamson, N.A. (2011). Site-specific design spectra for vertical ground motion. *Earthquake Spectra,* 27(4), pp.1023−1047.

Hakimhashemi, A.H., Yoon, J.S., Heidbach, C., Zang, A. and Grünthal, G. (2014). Forward induced seismic hazard assessment: application to a synthetic earthquake catalogue from hydraulic simulation modelling. *Journal of Seismology,* 18, pp.671-680.

Hancock, J., Bommer, J.J. and Stafford, P.J. (2008). Numbers of scaled and matched accelerograms required for inelastic dynamic analyses. *Earthquake Engineering & Structural Engineering,* 37(14), pp.1585-1607.

Holdsworth, R.E.,Stewart, M., Imber, J. and Strachan, R.A. (2001). The structure and rheological evolution of reactivated continental fault zones: a review and case study. In: *Continental Reactivation* and *Reworking.* (Miller, J.A., Holdsworth, R.E., Buick, I.S. and Hand, M. [Eds])Special Publication of the Geological Society, London, 184**,** pp**.**115-137.

Hnat, J.S. and van der Pluijm, B.A. (2014). Fault gouge dating in the Southern Applachians, USA. *Bulletin of the Geological Society of America,* 126, pp.639-651. DOI:10.1130/B30905.1

Hutchings, L., Savy, J., Bachmann, C., Heidbach, O.,Miah, M., Lindsey, N., Singh, A. and Laboso, R. (2015). Examination of a site-specific, physics-based seismic hazard analysis applied to surrounding communities of The Geysers geothermal development area. *Proceedings, Geothermal Research Council*, Reno, Nevada.

IAEA (2010). Seismic hazards in site evaluation for nuclear installations. Specific Safety Guide no. SSG-9, International Atomic Energy Agency, Vienna, 80 pp.

IAEA (2015). The contribution of palaeoseismology to seismic hazard assessment in site evaluation for nuclear installations. IAEA-TECDOC-1767, International Atomic Energy Agency, Vienna, 193pp.

Johnston, A.C., Coppersmith, K.J., Kanter, L.R. and Cornell, C.A. (1994). *The Earthquakes of Stable Continental Regions*. Five vols. Final report for Electrical Power Research Institute (EPRI), Palo Alto, CA, EPRI TR-102261.

Klose, C.D. (2013). Mechanical and statistical evidence of the causality of human-made mass shifts on the Earth’s upper crust and the occurrence of earthquakes. *Journal of Seismology,* 17(1), pp.109-135.

Knetidou, O-J., Abrahamson, N.A., Drouet, S. and Cotton, F. (2015). Understanding the physics of kappa (κ): Insights from a downhole array. *Geophysical Journal International,* 203, pp. 678-691.

Knetidou, O-J. and Abrahamson, N.A. (2016). Empirical estimation of high-frequency ground motion on hard rock. *Seismological Research Letters,* 87(6), pp.1465-1478.

Kottke, A.R. and. Rathje, E.M. (2013). Comparison of time series and random-vibration theory site-response methods. *Bulletin of the Seismological Society of America,* 103(3), pp.2111-2127.

Kulkarni, R.B., Youngs, R.R. and Coppersmith, K.J. (1984). Assessment of confidence intervals for results of seismic hazard analysis. *Proceedings of the Eighth World Conference on Earthquake Engineering*, San Francisco, Volume 1, pp.263-270.

Lapajne, J., Motnikar, B.S. and Zupančič, P. (2003). Probabilistic seismic hazard assessment methodology for distributed seismicity. *Bulletin of the Seismological Society of* America, 93(6), pp. 2502-2515.

Laurendeau, A., Cotton, F., Ktenidou, O-J., Bonilla, L-F. and Hollender, F. (2013). Rock and stiff-soil site amplification: dependency on VS30 and kappa (κ0). *Bulletin of the Seismological Society of* America, 103(6), pp.3131-3148.

Li, F., Hsiao, E., Lifton, Z. and Hull, A. (2015). A simplified probabilistic fault displacement hazard analysis procedure: Application to the Seattle Fault Zone, Washington, USA. *Proceedings of 6th International Conference Earthquake Geotechnical Engineering*, 1-4 November, Christchurch, New Zealand.

Main, I. (1996). Statistical physics, seismogenesis, and seismic hazard. *Reviews of Geophysics,* 34, pp.433-462.

Majer, E., Nelson, J., Robertson-Tait, A., Savy, J. and Wong, I. (2012). *Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems*. DOE/EE-0662, US Department of Energy.

McGarr, A. (2014). Maximum magnitude earthquakes induced by fluid injection. *Journal of Geophysical Research: Solid Earth*, 119(2), pp.1008-1019. http://dx.doi.org/10.1002/2013JB010597

McGarr, A., Simpson, D. and Seeber, L. (2002). Case histories of induced and triggered seismicity. *International Handbook of Earthquake and Engineering Seismology*, *eds*. W.H.K. Lee, H. Kanamori, P.C. Jennings & C. Kisslinger, Academic Press, vol. 81A, pp.647-661.

McGuire, R.K. (2008). Probabilistic seismic hazard analysis: Early history. *Earthquake Engineering & Structural Dynamics,* 37, pp. 329-338.

McGuire, R.K., Silva, W.J. and Costantino, C.J. (2001). Technical basis for revision of regulatory guidance on design ground motions: Hazard- and risk-consistent ground motion spectra guidelines. NUREG/CR-6728, US Nuclear Regulatory Commission, Washington D.C.

Mena, B., Wiemer, S. and Bachmann, C. (2013). Building robust models to forecast induced seismicity related to geothermal reservoir enhancement. *Bulletin of the Seismological Society of America,*103(1), pp.383-393.

Monelli, D.,Pagani, M., Weatherill, G., Danciu, L. and Garcia, J. (2014). Modeling distributed seismicity for probabilistic seismic-hazard analysis: Implementation and insights with the OpenQuake engine. *Bulletin of the Seismological Society of America,* 104(4), pp.1636-1649.

Moore, D.E. & D.A. Lockner (2004). Crystallographic controls on the frictional behavior of dry and water-saturated sheet structure minerals. *Journal of Geophysical Research,* 109**,** B03401. DOI:10.1029/2003JB002582.

Morris, A., Ferrill, D.A. and Henderson, D.B. (1996). Slip tendency analysis and fault reactivation. *Geology,* 24(3), pp.275–278.

Musson, R. (2000). The use of Monte Carlo simulations for seismic hazard assessment in the U.K. *Annali di Geofisica,* 43, pp.1–9.

Musson, R.M.W. (2012a). The effect of magnitude uncertainty on earthquake activity rates. *Bulletin of the Seismological Society of America,* 102(6), pp.2771-2775.

Musson, R.M.W. (2012b). Objective assessment of source models for seismic hazard studies: with a worked example from UK data. *Bulletin of Earthquake Engineering,* 10(2), pp.367-378.

Musson, R.M.W. and Sargeant, S.L. (2007). *Eurocode 8 seismic hazard zoning maps for the UK*. Seismology and Geomagnetism Programme Technical Report CR/07/125, British Geological Survey, Keyworth, Nottingham, 70 pp.

Nuriel, P., Rosenbaum, G., Zhao, J.X., Feng,Y., Golding, S.D., Villemant, B. and Weinberger, R. (2012). U-Th dating of striated fault planes. *Geology*, 40, pp.647-650. DOI: 10.1130/G32970.1.

Nyman, D.J., Hall, W.J. and. Szymkowiak, V. (2014). Trans-Alaska pipeline seismic engineering legacy. *Proceedings of the 10th US National Conference on Earthquake Engineering*, 21-25 July 2014, Anchorage, Alaska.

ONR (2018a). NS-TAST-GD-013 Rev. 7, Nuclear Safety Assessment Technical Guide: External Hazards.

ONR (2018b). NS-TAST-GD-013 Annex 1, Rev. 1: Seismic Hazards.

ONR Expert Panel on Natural Hazards (2018). Analysis of Coastal Flood Hazards for Nuclear Sites, Expert Panel Paper No: GEN-MCFH-EP-2017-2.

Ottemöller, L. and Sargeant, S. (2010). Ground-motion differences between two moderate-size intraplate earthquakes in the United Kingdom. *Bulletin of the Seismological Society of America,* 100(4), pp.1823-1829.

Pitilakis, K.P. and Anastasiadis, A.J. (1999). Soil and site characterization for seismic response analysis. *Proceedings of the Eleventh European Conference on Earthquake Engineering: Invited Lectures*, A.A. Balkema, pp.65-90.

Petersen, M.D., Dawson,T.E., Chen, R. and Frankel, A.D. (2011). Fault displacement hazard for strike-slip faults. *Bulletin of the Seismological Society of America,* 101(2), pp.805-825.

Petersen, M.D., Mueller, C.S., Moschetti, M.P., Hoover, S.M., Rukstales, K.S., McNamara, D.E., Williams, R.A., Shumway, A.M., Powers, P.M., Earle, P.S., Llenos, A.L., Michael, A.J., Rubinstein, J.L., Norbeck, J.H. and Cochran, E.S. (2018). 2018 one-year seismic hazard forecast for the Central and Eastern United States from induced and natural earthquakes. *Seismological Research Letters*, 89(3), pp.1049-1061. DOI: 10.1785/0220180005.

Rietbrock, A., Strasser, F. and Edwards, B. (2013). A stochastic earthquake ground-motion model for the United Kingdom. *Bulletin of the Seismological Society of America,* 103(1), pp.57-77.

Ringrose, P.S. (1989). Recent fault movement and palaeoseismicity in Western Scotland. *Tectonophysics,* 163, pp.305-314.

Roberts, N.M.W. and Walker, R.J. (2016). U-Pb geochronology of calcite-mineralized faults: Absolute timing of rift-related fault events on the northeast Atlantic margin. *Geology,* 44**,** pp.531-534. DOI:10.1130/G37868.1.

Rodriguez-Marek, A., Rathje, E.M., Bommer, J.J., Scherbaum, F. and Stafford, P.J. (2014). Application of single-station sigma and site response characterization in a probabilistic seismic hazard analysis for a new nuclear site. *Bulletin of the Seismological Society of America,* 104(4),pp.1601-1619.

Simpson, D.W., Leith, W.S. and Scholz, C.H. (1988). Two types of reservoir-induced seismicity. *Bulletin of the Seismological Society of America,* 78(6), pp.2025-2040.

Stafford, P.J., Rodriguez-Marek, A., Edwards, B., Kruiver, P.P. and Bommer, J.J. (2017). Scenario dependence of linear site effect factors for short-period response spectral ordinates. *Bulletin of the Seismological Society of America,* 107(6), pp.2859-2872.

Stewart, I.S. and Firth, C.R. (2004). *Neotectonics of the United Kingdom: a review of existing information*. Contractors Report to NIREX by Neotectonics Research Centre, Department of Geography and Earth Sciences, Brunel University, 100pp.

Stewart, J.P., Afshari, K. and Hashash, Y.M.A. (2014). *Guidelines for performing hazard-consistent one-dimensional ground response analysis for ground motion prediction*. PEER Report 2014/16, Pacific Earthquake Engineering Research Center, University of California at Berkeley.

Stirling, M., Goded, T., Berryman, K. and Litchfield, N. (2013). Selection of earthquake scaling relationships for seismic-hazard analysis. *Bulletin of the Seismological Society of America,* 103(6), pp.2993-3011.

Strasser, F.O., Albini, P., Flint, N.S. and Beauval, C. (2015). Twentieth century seismicity of the Koffiefontein region (Free State, South Africa): consistent determination of earthquake catalogue parameters from mixed data types. *Journal of Seismology,* 19, pp.915-934.

Stromeyer, D. and Grünthal, G. (2015). Capturing the uncertainty of seismic activity rates in probabilistic seismic-hazard assessments. *Bulletin of the Seismological Society of America,* 105(2A), pp.580-589.

Thomas, P., Wong, I. and Abrahamson, N. (2010*). Verification of probabilistic seismic hazard analysis computer programs*. PEER Report 2010/106, Pacific Earthquake Engineering Research Center, UC Berkeley, California.

Trampert, J., Cara, M. and Frogneux, M. (1993). SH propagator matrix and QS estimates from borehole- and surface-recorded earthquake data. *Geophysical Journal International,* 112, pp.290-299.

USNRC (2007). *A performance-based approach to define the site-specific earthquake ground motion.* Regulatory Guide 1.208, US Nuclear Regulatory Commission, Washington D.C.

USNRC (2012). *Practical implementation guidelines for SSHAC Level 3 and 4 hazard studies.* NUREG-2117Revision 1, U.S. Nuclear Regulatory Commission, Washington, DC.

USNRC (2017a). *Practical implementation guidelines for SSHAC hazard studies.* NUREG-2213, U.S. Nuclear Regulatory Commission, Washington, DC.

USNRC (2017b). *Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants,* NUREG-0800, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, DC.

Van Houtte, C., Drouet, S. and Cotton, F. (2011). Analysis of the origins of *κ* (kappa) to compute hard rock to rock adjustment factors for GMPEs. *Bulletin of the Seismological Society of America,* 101(6), pp.2926-2941.

Viola, G., Scheiber, T., Fredin,O., Zwingmann, H., Margreth, A. and Knies, J. (2016). Deconvoluting complex structural histories archived in brittle fault zones. *Nature Communications,* 7, 13448. doi.org/10.1038/ncomms13448.

Ward, S.N. (1994). A multidisciplinary approach to seismic hazard in southern California. *Bulletin of the Seismological Society of America,* 84, pp.1293–1309.

Weichert, D.H. (1980). Estimation of the earthquake recurrence parameters for unequal observation periods for different magnitudes. *Bulletin of the Seismological Society of America,* 70(4), pp.1337-1346.

Woo, G. (1996) Kernel estimation methods for seismic hazard area source modelling. *Bulletin of the Seismological Society of America,* 86, pp.353-362.

Youngs, R.R., Arabasz, W., Anderson, R.E., Ramelli, A.R., Ake, J.P., Slemmons, D.B., McCalpin, J.P., Doser, D.I., Fridrich, C.J., Swan, F.H., Rogers, A.M., Yount, J.C., Anderson, L.W., Smith, K.D., Bruhn, R.L., Knuepfer, P.L.K., Smith, R.B., dePolo, C.M., O’Leary, D.W., Coppersmith, K.J., Pezzopane, S.K., Schwartz, D.P., Whitney, J.W., Olig, S.S. and Toro, G.R. (2003). A methodology for probabilistic fault displacement hazard analysis (PFDHA). *Earthquake Spectra,* 19(1), pp.191-219.

Youngs, R.R. and Coppersmith, K.J. (1985). Implications of fault slip rates and earthquake recurrence models to probabilistic seismic hazard estimates. *Bulletin of the Seismological Society of America,* 75(4), pp.939-964.

Yukutake, Y., Takeda, T. and Yoshida, A. (2015). The applicability of frictional reactivation theory to active faults in Japan based on slip tendency analysis. *Earth and Planetary Science Letters,* 411, pp.188-198.

1. Special care is needed when specifying this limit for nuclear sites where structures systems and components may be more susceptible to earthquake shaking. This may be the case, for example, for older existing facilities, for which the selected minimum magnitude requires particular justification. [↑](#footnote-ref-1)
2. Convolution in this sense is a mathematical process for combining (algebraically relating) probability distributions. [↑](#footnote-ref-2)