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TABLE OF CONTENTS

LIST OF ABBREVIATIONS

ALARP	As Low As Reasonably Practicable
ANS	American Nuclear Society
ASCE	American Society of Civil Engineers
BGS	British Geological Survey
BDBA	Beyond Design Basis Analysis
CAV	Cumulative Absolute Velocity
CEGB	Central Electricity Generating Board
CF	Capable Faulting
CoP	Codes of Practice
DBE	Design Basis Event/Earthquake
DBA	Design Basis Analysis
EPP	Expert Panel Paper
EPRI	Electric Power Research Institute
FAS	Fourier Amplitude Spectrum
GDA	Generic Design Assessment
GMM	Ground Motion Model
GMPE	Ground Motion Prediction Equation
IAEA	International Atomic Energy Agency
NRA	Nuclear Regulation Authority of Japan
OBE	Operating Basis Earthquake
ONR	Office for Nuclear Regulation
PGA	Peak Ground Acceleration
PML	Principia Mechanica Ltd
PSA	Probabilistic Safety Analysis
PSHA	Probabilistic Seismic Hazard Analysis
RGP	Relevant Good Practice
RVT	Random Vibration Theory
SAA	Severe Accident Analysis
SAP	Safety Assessment Principle(s)
SHWP	Seismic Hazard Working Party
SQUG	Seismic Qualification Utility Group
SSC	Structure, System and Component
SSM	Seismic Source Model
SSI	Soil-Structure Interaction
SSHAC	Senior Seismic Hazard Analysis Committee
SSSI	Structure-Soil-Structure Interaction
TAG	Technical Assessment Guide(s) (ONR)

USNRC	US Nuclear Regulatory Commission
UHS	Uniform Hazard Spectrum
URS	Uniform Risk Spectrum
WENRA	Western European Nuclear Regulators Association

GLOSSARY

Term	Description
Accelerograph	An instrument that records the acceleration of the ground during an earthquake, also commonly called an accelerometer. The recording is often called an accelerogram.
Capable fault	A fault that has a significant potential for displacement at or near the ground surface.
Convergence zone	A zone where tectonic plates collide, typified by earthquakes, mountain formation, and volcanic activity.
Cyclic mobility	Cyclic mobility is a liquefaction phenomenon, triggered by cyclic loading, occurring in soil deposits with static shear stresses lower than the soil strength. Deformations due to cyclic mobility develop incrementally because of static and dynamic stresses that exist during an earthquake, for example lateral spreading along Motagua River, Guatemala earthquake 1976. Lateral spreading, a common result of cyclic mobility, can occur on gently sloping and on flat ground close to rivers and lakes.
Epicentre	The point on the Earth's surface directly above the hypocentre of an earthquake.
Focal depth	The depth of an earthquake hypocentre.
Fourier Amplitude Spectrum	Expresses the frequency content of a dynamic motion, by showing how the amplitude of the component sinusoids of the motion vary with frequency.
Glacial isostatic adjustment	The response of the solid Earth to mass redistribution during a glacial cycle. The movement of water over the surface of the Earth, both as water and as ice, during a glacial cycle acts as a load and the Earth deforms in response to this force; subsiding under the load of an ice sheet or full oceanic basin, and rebounding once the ice sheets melt or water is removed from the oceanic basin. (see isostasy)
Gutenberg-Richter relationship	The relationship between the magnitude and number of earthquakes in a given region and time period generally takes an exponential form that is referred to as the Gutenberg-Richter law.
Hydraulic fracturing	Hydraulic fracturing or 'fracking' involves the injection of water, sand and chemicals at high pressure into boreholes. The water opens up cracks in the rock, and the sand grains lodge into the spaces and keep them open, allowing the released gas to flow out of the rocks.
Hypocentre	The calculated location of the focus of an earthquake. The focus is the point where earthquake rupture or fault movement originates.
Isostasy	Refers to a concept whereby deformation takes place in the Earth's crust in response to an applied load, in an attempt to return the Earth to a state of equilibrium.
Liquefaction	A process by which water-saturated sediment temporarily loses strength and acts as a fluid when subject to vibratory motion. This effect can be caused by earthquake shaking.
Mid-Atlantic ridge	The Mid Atlantic Ridge, like other ocean ridge systems, has developed as a consequence of the divergent motion between the Eurasian and North American, and African and South American Plates.
Moment magnitude	Moment is a physical quantity proportional to the slip on the fault times the area of the fault surface that slips; it is related to the total energy released in an earthquake. The moment can be estimated from seismograms (and also from geodetic measurements). The moment is then converted into a number similar to other earthquake magnitudes scales by a standard formula. The result is called the moment magnitude. The moment magnitude provides an estimate of earthquake size that is valid over the complete range of sizes, a characteristic that is lacking in other magnitude scales. Moment magnitude (Mw) = 2/3log(Mo) - 6.06 Where Mo = seismic moment (see seismic moment)
Palaeoseismological	Palaeoseismoloigcal data is based on palaeoseismology, the study old earthquakes. Primary evidence includes clues that are created by the movement

	on the fault during the earthquake such as fault scarps, offset or folded layers of sediment and soil. Secondary evidence includes clues produced by the shaking during the earthquake such as sand blows, rockfalls, landslides, and damaged trees.
Peak ground acceleration	Peak ground acceleration (PGA) is the maximum ground acceleration that occurred during earthquake shaking at a location and is equal to the amplitude of the largest absolute acceleration recorded on an accelerogram at a site during a particular earthquake.
Random Vibration Theory	The most common technique for site-response simulations is equivalent-linear analysis using time-series input motions. A potential alternative is random-vibration theory (RVT), which uses the same equivalent-linear wave-propagation approach, but allows for the calculation of the mean response with only one simulation. RVT-based site-response analyses are commonly used for site-response calculations that are incorporated into probabilistic seismic-hazard analysis.
Seismic moment	Seismic moment (Mo) = μ x rupture area x slip length, where μ is the shear modulus of the crust (approximately 3×10^{10} N/m)
Seismograph	A seismograph, or seismometer, is an instrument used to detect and record earthquakes. Generally, it consists of a mass attached to a fixed base by a spring. During an earthquake, the base moves and the mass does not.
Seismometer	See seismograph
Senior Seismic Hazard Analysis Committee (SSHAC)	A committee of academic and industry experts in seismic hazard analysis, established by the USNRC. This committee developed an approach to seismic hazard analysis that specifically accounted for epistemic uncertainty and the inclusion of expert judgment to resolve aspects where available data, etc. permitted more than one credible technical interpretation. The basic objective of SSHAC is to identify the centre, the body and the range of technically-defensible interpretations of the available data, methods and models relevant to the assessment of seismic hazard at the site.
Soil-Structure Interaction	The process in which the response of the soil influences the motion of the structure and vice versa.
Strain	Strain is the small change in relative length and volume of the Earth's crust associated with deformation of the earth by tectonic stresses or by the passage of seismic waves.
Structure–Soil-Structure (SSSI) Interaction	During an earthquake the dynamic response of one structure can affect the response of a neighbouring structure, resulting in structure-soil-structure interaction.
Time history	The time history is the sequence of values of any time-varying quantity (such as a ground motion measurement) measured at a set of fixed times.
Uniform hazard spectrum	The hazard is calculated separately for a range of structural natural frequencies, using the same source zone model and a regionally-valid spectral attenuation model. From this, a response spectrum that reflects the structural effects real levels of the hazard at the site at all natural frequencies can constructed. This is also known as a Uniform Hazard Response Spectrum (UHRS). This type of response spectrum is seen to more accurately predict structural response than one where the hazard is only calculated for say the PGA (or high frequency) point on the spectrum, which is then used to anchor an assumed spectral shape for other natural frequencies.

1 INTRODUCTION

1. This annex provides guidance on the main features of earthquake or seismic hazard considered relevant to nuclear safety on nuclear licensed and authorised sites. It applies the general principles set out in the head Technical Assessment Guide (TAG) 13 document [1] and provides guidance to inspectors in the application of the Safety Assessment Principles (SAPs) [2] to the assessment of seismic hazards. Seismic hazards are considered to include; ground shaking, surface fault rupture (capable faulting (CF)), the potential triggering of tsunamis from fault movement, liquefaction, landslides and other related geotechnical hazards. The scope also extends into other areas such as Soil-Structure Interaction (SSI) and plant response. This annex is supported by one Expert Panel Paper (EPP) [3], however due to the connection with tsunami parts of Annex 3 (Coastal Flood Hazards) [4], and its supporting EPP [5], are also relevant.

1.1 Historical Development of Seismic Hazard Analysis in the UK Nuclear Industry

2. A large amount of seismic design and analysis work has been undertaken in the UK nuclear industry since the 1970s. This work has become part of the fabric of nuclear safety development in the UK. The work has never been comprehensively reported into the public domain (most of it cannot be referenced for reasons of commercial ownership), yet features of it have informed how the regulatory approach to seismic hazards (and to external hazards generally) has developed. A brief overview is provided in Appendix A of this annex that provides a context within which the development of nuclear safety in relation to seismic hazard in the UK should be seen and also introduces and provides some background on some terms that are referred to in this annex.

2 HAZARD INFORMATION

4. An earthquake is an abrupt release of strain energy stored in the Earth's crust typically due to the sudden rupture of a geological fault followed by time-limited movement of the fault. These days the size of an earthquake is usually defined in terms of the moment magnitude scale, which is directly related to the seismic moment and therefore the factors that produce the rupture of the fault. Other magnitude scales may sometimes be used and can be related to the moment magnitude. The origin of an earthquake is defined in space by the location of the hypocentre, being the point at which the fault rupture initiates, which is uniquely defined by the focal depth (below the Earth's surface) and the coordinates of the epicentre, which is the projection of the hypocentre up to the surface. The time, location and magnitude of individual future earthquakes are highly uncertain and cannot be predicted with current technology, whereas long-term patterns of seismicity can be inferred from the earthquake record for a given region. However, any projections based on such observations are inevitably associated with considerable uncertainty, which must be accounted for in the assessment of the hazard, see [1] Section 5.8.10. Seismic hazards are described in more detail in the following subsections.

2.1 Hazard Description – (SAPs EHA.1, EHA.9)

5. The head TAG 13 document introduces the notion of primary, secondary, and correlated hazards and consequential hazards and effects (Ref. [1] Section 5.2). Earthquakes present challenges to nuclear safety via a number of primary, secondary and consequential hazards. Table 1 provides a list (not comprehensive) of primary, secondary and consequential site hazards associated with earthquake activity.

6. The various seismic hazards are briefly described below. Where additional information is necessary this sub-section is supported by Section 2 in Ref. [3].

2.1.1 Strong ground motion – *(primary hazard)*

7. The primary hazard due to earthquakes and the main cause of damage to structures and plant is strong shaking of the ground caused by the passage of seismic waves radiating from the earthquake source. The nature and amplitude of the shaking depends on several factors including the magnitude of the earthquake, the style-of-faulting (ie normal, reverse or strike-slip), the source-to-site distance, and the nature of the near-surface geotechnical profile at the site (eg the shaking can be extensively modified by soft soil layers at the site). Strong ground motion is usually recorded on accelerographs, although seismometers are also widely used in ground-motion studies. The outputs from these instruments are time-histories of ground acceleration. These time-histories can be processed to generate an acceleration response spectrum. The response spectrum shows the maximum absolute acceleration[1] experienced by single-degree-of-freedom oscillators of different natural vibration frequencies (and for a specified level of damping) under the action of a given ground motion. Accelerographs generally record the ground motion in three mutually orthogonal directions, two horizontal and one vertical, and parameters such as peak ground acceleration (PGA) and the response spectrum can be defined for both vertical and horizontal components. It is important that the treatment of the two horizontal components (for which several options, including the larger spectral ordinate at each frequency or the geometric mean of the two values, are available) is clearly defined. The characterisation of strong ground motion is usually carried out via a Probabilistic Seismic Hazard Analysis (PSHA).

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[1] Generally the absolute acceleration spectra are calculated, from which compatible spectra of pseudo-relative velocity and pseudo-relative displacement can be derived. The term relative refers to the movement of the mass relative to the base, and the term absolute refers to the movement of the mass relative to the base plus the movement of the base.

8. *Very low-frequency strong ground motion*: In some cases the response of nuclear plant at very low frequencies (usually <1Hz) may be significant enough that low frequency ground motion emanating from very distant sources needs to be considered by the PSHA. This is particularly relevant if these low frequencies coincide with the dynamic characteristics of the site such that the near surface geology would amplify these ground motions. Examples of structures, systems and components (SSCs) that exhibit low natural frequencies include sloshing in tanks and ponds, ship lifts, crane hook loads, and base isolated structures. Further discussion is given in [3] Section 7.6.

9. Example Consequential Hazards:

- *Internal hazard initiated faults*: Strong ground motion may (and in practice is likely to) initiate fault sequences that cause secondary hazards to occur on plant. Examples include the initiation of fires, internal floods, dropped loads, and failure of non-safety-related plant in ways that might cause it to fall onto or otherwise interact with safety-related plant eg impact from collapse of adjacent structures or secondary structural items such as walkways, stairs etc.

2.1.2 Surface-fault rupture (capable faulting) – *(primary hazard)*

10. Strong ground motion is caused by abrupt slip along geological faults. The dimensions of the fault rupture and of the slip grow with the magnitude of the earthquake. If the fault rupture extends to the ground surface then the relative displacements, whether vertical or horizontal, can present a serious threat to any structure or facility that traverses the fault trace. It should also be noted that creep-based surface fault rupture with no associated ground shaking or sudden movement can occur in certain parts of the world. Although surface rupture has not been associated with known UK earthquakes, the possibility exists and may be considered an exclusionary criterion for new nuclear sites.

11. In addition to the risk posed by primary faulting on the site the inspector should also be aware that strong ground motion or activity, on a primary fault structure, perhaps located away from the site could in principle give rise to sympathetic displacements on secondary faults that may be located on or close to the site, however this has not been directly observed in the UK.

12. While surface-fault rupture is identified here as a separate geo-hazard from strong ground motion, both arise from abrupt slip along geological faults therefore it is recognised that the analysis of these hazards should be very closely linked.

13. Example Secondary Hazards:

- *Surface displacement*: The realisation of surface rupture as a hazard is an offset surface displacement on the site.

14. Example Consequential Hazards:

- As for strong ground shaking (see paragraph 9).

2.1.3 Tsunami – *(secondary hazard)*

15. Tsunamis are very long period waves (30 minutes or more) caused by sudden movement of the seabed either by fault-surface displacements or submarine landslide. They typically travel at several hundred metres per second from their point of origin, and since the rate of energy loss is typically proportional to the inverse of the wavelength (which is usually very large) tsunamis dissipate very little energy. For this reason, tsunamis may affect UK coastlines over transoceanic distances and from a variety of potential source zones, please refer to Annex 3 [4] and associated EPP [5] Sections 2.7 & 8 for further details of these. On arrival at a coastline, the reduction of

water depth leads to a drastic reduction in the velocity of the wave with an accompanying increase of amplitude. The most damaging tsunamis are often trough-led waves, meaning that on arrival at the coastline the initial evidence is usually a substantial reduction and retreat of water, followed by a large peak and a substantial movement of water inland beyond the normal high-tide mark.

16. Example Consequential Hazards:

- Refer to Ref. [4] Table 1.

2.1.4 Geotechnical hazards – *(secondary hazard)*

17. Strong ground motion can trigger consequential hazards that may pose additional threats to structures and plant. Slopes[2], whether natural or man-made, may become unstable under the action of ground motion. Saturated, cohesionless soil, for example loose sands, may lose shear strength during ground shaking and undergo cyclic mobility (intermittent movement) or continuous movement via liquefaction. These effects can lead to settlements, sand boils, and, in the presence of a free face, lateral spreading[3].

18. Example Consequential Hazards:

- Loss of structure, system or component (SSC) function.
- Loss of buried essential services

2.2 Issues Affecting Earthquake Occurrence in the UK and Surrounding Region – (SAP EHA.9)

19. Recent and ongoing crustal movements in the UK and the UK continental shelf, including those inducing earthquakes, are related to stress generating mechanisms operating over a broad range of scales. The UK lies in the interior of the Eurasian continental plate and is located approximately equidistant from the northern end of the Mid-Atlantic ridge to the NW and the Eurasia-Africa convergence zone to the SE. Over the last six to eight million years, the interaction of these far-field plate boundaries has generated a first order NW-SE compressional stress regime. However, in the last two million years, the relatively simple plate tectonic stress regime has been perturbed by second-order stresses generated by loading and unloading of the crust by British and Fennoscandian ice sheets. These glacial isostatic adjustments are thought to influence deformation not only within the limits of the former ice sheets, but also for several hundred kilometres beyond the former ice margins.

20. The intraplate location of the UK and the UK Continental Shelf mean that it is a region of low tectonic activity. Historical and instrumental seismicity records point to a complex pattern of earthquakes that is neither purely random nor uniform (they are definitely random, but statistical patterns can be observed). There appears to be a poor correlation between seismicity and well documented ancient structures (eg faults) mapped at the surface in the UK. There is no compelling evidence for temporal clustering of UK earthquakes, other than aftershock sequences that are clearly apparent for some significant UK events. Thus significant earthquakes in the UK that might challenge nuclear safety are assumed to follow a Poisson process or model, implying events occur randomly with no memory of the time, size or location of the preceding event. In the UK, seismic hazard studies have shown that the Gutenberg-Richter relationship is generally appropriate.

21. Earthquakes can also be caused by anthropogenic activities such as mining, the impounding of deep reservoirs, hydraulic fracturing, conventional hydrocarbon

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[2] The “slope” can be within a subterranean failure plane, not necessarily on the surface.

[3] Lateral spreading occurs when shear resistance is lost in a buried liquefied layer and when a slope towards a free face is present (river, sea shore, etc.) the overlying layers simply slide *en masse*.

extraction and waste water disposal, or geothermal heat extraction that requires hydraulic fracturing; see [3] Section 4.8.

2.3 Hazard Data Sources – (SAP EHA.2, EHA.9, EHA.12, AV.3, AV.7)

22. A site-specific seismic hazard analysis for major nuclear facilities requires the compilation of all available information that may be pertinent to the geological and seismological characterisation of the region around the site within which earthquakes might produce ground shaking and / or surface breaking rupture of consequence at the site.

23. A fundamental requirement for a site-specific analysis of seismic hazard is a catalogue of earthquakes that have occurred in the region around the site, for which [6] indicates a radius of at least 300km should be considered. If the Licensee opts for a lesser value this would expect to be justified.

24. In order to provide additional constraint on the models developed for seismic hazard at the site, and to reduce the associated uncertainty, it will frequently be advisable to also collect new data and in most cases, measurements of dynamic characteristics of the surface geology would be expected as a matter of course.

25. A brief overview of data sources is given below, but more detail regarding some of these data required for a site-specific analysis of seismic hazards is given in [3] Section 4.

2.3.1 Instrumental Data

26. The instrumental earthquake catalogue contains locations and magnitudes that are determined from seismograph recordings. The network of seismic monitoring in the UK is run by the British Geological Survey (BGS) and this is the primary source of instrumental earthquake information[4]. The accuracy of the instrumental catalogue may be enhanced through systematic re-analyses of the seismic data. The inspector should be aware that the monitoring network has limitations and these directly affect the uncertainty assigned to magnitudes and locations, particularly focal depth. Further information on the individual event uncertainties is available from the BGS and is discussed further in [3] Sections 4.4 & 4.6.

2.3.2 Historical Accounts / Records

27. The historical earthquake catalogue (ie pre-instrumentally recorded) should cover the longest period possible to obtain stable estimates of average recurrence intervals, for which reason it is general practice to interrogate descriptions of historical earthquake events and assign magnitude and locations. A source of such historical earthquake information in the UK is the BGS. A site-specific study would be expected to retrieve the BGS catalogue at least as a starting point[5]. The accuracy of this catalogue may be further enhanced by concerted historical investigations to provide greater constraint on the record of earthquakes within the region of study. The magnitudes and locations used to characterise historical events are not derived from instrumental measurements of physically quantifiable parameters, rather, observators' records and accounts of the event are used to infer intensity levels, from which an estimate of the magnitude and location can be made. The assessment of the uncertainties in both magnitude and location depend on expert judgements and are often much greater than instrumentally derived magnitudes and locations. The inspector should note that there may be a

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[4] It should be noted that seismological agencies from neighbouring countries and international agencies such as the International Seismological Centre may also be sources of data and these should be consulted where appropriate.

[5] Inspectors should be aware that other independent interpretations of UK macroseismic events are available – See Appendix A

subjective element to the estimation of these quantities. Further information on this is discussed in [3] Section 4.5.

2.3.3 Geological Data

28. Collecting relevant geological data provides a description of the geological features, such as surface and near surface fault locations, at site, regional and UK-wide scales. These data can also provide an overview history of the geological development relevant to the site over geological timescales. Together these provide a context within which the seismic hazard analysis is undertaken, and a rationale to support the various assumptions regarding earthquake occurrence and surface breaking rupture. Inspectors should note that geological data are not generally able to provide evidence to support the occurrence of known earthquakes derived from the historical or instrumental record. This is because in general the seismicity in the UK is too deep to enable earthquakes to be positively located on particular faults. Geological data therefore can only provide a qualitative understanding of UK seismogenicity, rather than a quantitative one.

29. The BGS holds the most complete database of faults in the UK at this time[6], but there is no database of active (potentially capable) faults or potentially active faults. There is a BGS database of historical and instrumental earthquakes, but no recognised database of palaeoseismological data exists in the UK and interpretation of that data is somewhat ambiguous and controversial, thereby not excluding the possibility of multiple scientifically valid interpretations.

2.3.4 Data from Site Seismological Investigation and Instrumentation

30. The nature of the near-surface geological conditions at a site can exert a strong influence on the characteristics of strong ground motion, and relevant site-characterisation data can be obtained from boreholes, geophysical surveys and site-based monitoring equipment (see also SAP ECE.5).

31. The dynamic characteristics of the site are primarily governed by the stiffness and damping of the near-surface soils and rocks. The most commonly used parameter to define the stiffness characteristics is the dynamic shear modulus which is derived from the in situ shear-wave velocity (V_S). Laboratory tests are often used to estimate dynamic shear modulus reduction and damping increase with increasing shear strain. There are a number of techniques for measuring the V_S distribution through the vertical soil profile under and across the site, see [3] Section 4.8. The value of V_S is the primary measure in determining whether site response and SSI analyses are needed; if so, the site response is usually considered as part of the PSHA, and the SSI forms part of the structural analysis to which the seismic hazard analysis defines the inputs. Inspectors should be aware that soil conditions can change rapidly across both the horizontal extent of the site and also with depth.

2.3.5 Data from Ground-Motion Records and Models

32. A key element of a site-specific seismic hazard analysis is a model for the prediction of ground-motion parameters, such as response spectral acceleration at specified oscillator frequencies, as a function of; earthquake magnitude, source-to-site distance, site characteristics and style of faulting. Such models are generally referred to as Ground-Motion Prediction Equations (GMPEs). Recent seismic hazard analyses for major nuclear plant indicate that no single GMPE is considered sufficient to capture the range of epistemic uncertainty in ground-motion predictions over the full magnitude range even in seismically-active regions with abundant local data. Therefore, for UK sites where strong ground motion data is limited, special care is needed in the

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[6] Inspectors should be aware that other sources of data are available from previous UK hazard studies – See Appendix A

selection and adjustment of GMPEs for a site-specific hazard analysis. See additional discussion in [3] Section 4.6.

2.3.6 Previous Seismic Hazard Studies

33. As part of the documentation of a site-specific seismic hazard assessment it would be expected that the Licensee or Prospective Licensee will conduct a detailed review and assessment of previous seismic hazard studies for the site, for any other sites in close proximity, as well as regional and national studies encompassing the site. These can provide useful information on seismic hazard at the site, depending on the pedigree of the study. However, inspectors should be aware that such studies may no longer represent relevant good practice (RGP) and should be used with caution.

34. Regional and national seismic hazard studies are also of interest to inform the site-specific analysis, but the usefulness of such studies may be limited for site-specific applications, since the seismic hazard maps they produce may be considered too coarse and approximate for site-specific use and the methodologies used differ and lack the conservatism expected for a nuclear facility.

2.3.7 Statistical data processing

35. All datasets compiled or collected for input to the site-specific hazard analysis require careful examination to ascertain the inherent uncertainties in the information. Examples could include the uncertainty associated with; geological dating results, the determination of epicentral locations & focal depths, and uncertainty about the magnitude estimates. Inspectors should seek assurance that data uncertainties have been properly characterised and accounted for in the seismic hazard analysis.

2.4 Notable Aspects of Plant Response to Seismic Hazards – (SAPs EQU.1, EAD.2, ELO.1, ELO.4, ECE.5, ECE.6, EMC.7, TAG 017 [3])

36. Strong ground motion is probably the most onerous external hazard to protect against because it constitutes a significant common cause hazard and can penetrate all areas of the site and plant. Mitigating its effects is one of the significant challenges for the design of plant with significant nuclear hazard potential. A feature of strong ground motion is that it can affect plant safety directly by imposing additional unexpected loads on components, thereby initiating secondary hazards, such as fire and internal flooding. In addition, the failure of SSCs that are not directly supporting nuclear safety can create consequential hazards for safety-related plant and equipment, so that the quantity of plant and equipment that must be seismically assessed is often much greater than just that with a direct safety function.

2.4.1 Overview

37. Protection and mitigation start at the plant and facility optioneering stage. For example, separation of buildings can reduce the possibility of earthquake induced accidents in one, propagating to the next. The structural layout of a facility or structure can directly affect its response to seismic excitation (for example by introducing, or avoiding, potential eccentricity and torsional effects). Attention to layout design can simplify access requirements needed if inspection / recovery or emergency arrangements actions have to be implemented following a seismic event (SAP EHF.1).

38. The load-resisting design of buildings, plant and equipment is normally covered by well-established design codes and standards.

39. Additional safety benefit is gained by employing the concepts of defence-in-depth (SAP EKP.3), and redundancy, diversity and segregation (SAP EDR.2), the last two of these are especially valuable in protecting against the common cause nature of seismic events.

40. Equipment qualification by experience [7] eg a Seismic Qualification Utility Group (SQUG)[7] type of approach is a recognised and valuable tool for use on existing plant systems and components subjected to seismic loads, and should include the adequacy of anchorages, bracing of electrical cabinets etc, additional support for extended structures like pipework using, for example, snubbers, and the potential for secondary hazards arising from the primary seismic event. Similarly, for new and replacement equipment, experienced based methods have been developed, albeit with limitations. Equipment qualification must include an assessment of the plant operating conditions before, during and after the seismic event ([7] & [8]). The application of such approaches requires suitably qualified and experienced personnel to undertake the work and robust peer review. Inspectors should ensure that processes are being applied in line with the SQUG expectations.

41. Strong ground motion is highly dynamic and can be subject to amplification in responding plant. It can also create situations where displacement rather than acceleration is the most significant response parameter, leading to pounding between adjacent buildings or plant items, if they are sited close together. Some plant elements can be isolated so as to alter their response to strong ground motion acceleration; however, this usually results in increased displacement response. Plant that has been "base isolated" by founding on rubber, elastomeric bearings, springs, friction-pendulum, or other methods requires special attention with respect to any connections they have with non-isolated plant, so that the behaviour under a seismic event and the potential for large relative displacements is properly understood and catered for. The inspector should note that beyond design basis displacements may be significant for such isolation systems.

2.4.2 Ageing and maintenance

42. Plant response and its ability to withstand strong ground motion can be significantly affected by physical changes induced by ageing and poor maintenance, therefore the impact of ageing and the adequate definition of examination, inspection, maintenance and testing should be included in any assessment. This is especially key on older facilities, but it should also be taken into account during the design or modification of plant. Specific attention should be taken to ensure that items such as base isolation systems or flexible fixtures, which contain materials whose properties are liable to change over time, are assessed and replaced as required.

2.4.3 Housekeeping

43. Finally, the potential for earthquake induced plant faults can be reduced by good housekeeping. Generally this involves securing or removal of equipment that might become a missile or secondary hazard to primary safety plant, or block access routes that are needed for safety significant operator actions. In some circumstances, temporary equipment may require seismic restraint to be provided at specified storage locations.

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[7] The SQUG collects, evaluates, and facilitates the use of earthquake and testing experience data on behalf of its member companies. The group is organised under the auspices of the Electric Power Research Institute (EPRI).

3 SAFETY ANALYSIS – (SAP FA.1)

44. The sub-sections below reflect those in TAG 13 Section 5.1 [1] and provide advice to inspectors on the application of the general principles to seismic hazard specifically.

3.1 Hazard Identification, Characterisation and Screening – (SAPs EHA.1, EHA.19)

45. Regarding tsunami hazard, this is likely to be credible at all coastal nuclear sites, but is unlikely to be the dominating flooding hazard; see Annex 3 [4] and associated EPP [5].

3.1.1 Strong Ground Motion

46. Seismic hazard in terms of ground shaking is a non-discrete hazard. It is not anticipated that it will be screened out of the fault analysis for UK sites and therefore the seismic hazard analysis should develop inputs for seismically initiated faults for Design Basis Analysis (DBA), Probabilistic Safety Analysis (PSA) and Severe Accident Analysis (SAA) that have not been screened out as per the intent of SAP EHA.19.

3.1.2 Surface-Fault Rupture (Capable Faulting)

47. As noted in Section 2.1.2, the existence of a CF hazard at the site, understood as the potential for geological fault movements at the ground surface that could pose a threat to any SSC traversing the fault trace, has never been observed in the UK, although the possibility of it occurring cannot be automatically ruled out noting that absence of evidence is not evidence of absence. Clearly, if it did occur under safety-related nuclear plant, the consequences could be very significant. For this reason, if Licensees are seeking to screen out CF hazard from the fault analysis, inspectors should seek assurance that sufficient analysis of the hazard has been undertaken to confidently support such a claim. Therefore, as part of the CF study for the site the inspector should expect all known surface faults on-site to be characterised. However, to avoid prohibitive cost, a graded approach may be appropriate which is commensurate with the facility radiological hazard potential in accordance with as low as reasonably practicable (ALARP) principles.

48. Details of the sort of techniques that can be used to assess the potential for CF hazard to occur are given in [3] Section 5.

49. As noted in Section 2.1.2, surface rupture hazard is linked to ground shaking hazard by having a common causative mechanism, so the analyses for both should be consistent in terms of the data used by both analysis streams.

50. The treatment of CF in nuclear safety cases is complicated by the following factors:

- The consequences of significant surface relative displacement occurring under a major nuclear plant could be very severe.
- CF, in terms of surface movement, has never been observed in the UK following an earthquake event. Indeed, there has never been an unambiguous association in the UK between such an event and movement of a particular fault, even at depth.
- There is almost no credible quantitative data now, or likely to be available in the near future, that could support a detailed quantitative CF hazard analysis, without the use of large amounts of expert judgment.

51. The potentially severe consequential effects of CF hazard mean that the hazard cannot be screened out on the basis of low consequence. To screen out on frequency requires a high degree of confidence that significant surface displacement will only occur, if at all, at frequencies below 10^{-7}/yr, see [1] Section 5.3.1. The qualitative judgment of the informed technical community is that the latter condition holds true, but

the poor quality or absence of suitable data preclude, at this time, a quantitative calculation for screening to these low frequencies, see [1] Section 5.1.

52. If a Licensee elects not to screen out the hazard, a design basis has to be defined and a plant design to resist the deleterious effects of CF hazard has to be developed.

53. As noted above, the informed technical community in the UK is of the opinion that CF hazard is insignificant for UK sites and that the absence of good quality data prevents a quantitative demonstration of this judgement. The regulatory judgment at this time is that the technology currently available is not sufficiently mature to determine quantitatively whether at a particular site, CF hazard can be screened out as negligible and the overwhelming balance of expert judgement is that this is a reasonable position. The Office for Nuclear Regulation's (ONR) judgment is that CF hazard can be considered insignificant at a site if a thorough investigation of the site and immediate surroundings shows no evidence that CF has occurred in the current tectonic regime.

3.1.3 Consequential Hazards

54. As noted in Section 2.1.4, strong ground motion can lead to instability of both natural and man-made slopes, and also trigger cyclic mobility or liquefaction of saturated, cohesionless soils. For further information on assessing liquefaction and slope stability see [3] Sections 2.4 & 2.5. If these occur on-site, then there is the potential to initiate plant faults. It may be possible for these to be screened out of the fault analysis because they have no significant effect on nuclear safety. If not, the expectation would be for the site to be stabilised by engineered means so that such effects are very unlikely and on this basis, Licensees of both existing and new build sites are likely to screen out such hazards from the formal design basis fault analysis. However, these may still need to be considered for the beyond design basis event, PSA and SAA.

55. If these or other consequential hazards have associated faults that have the potential to make a significant contribution to the overall risks from the facility then these should be retained for DBA (SAP EHA.19).

3.2 Design Basis Analysis for Screened in Seismic Hazards – (SAPs FA.4 – FA.9)

56. The following sections assumes a design basis is required, for further information on this please refer to [1] Section 5.5.

3.2.1 Design basis events – (SAPs EHA.3, EHA.4, EHA.9)

Design Basis Earthquake Definition

57. The design basis ground motion for a site, often referred to as Design Basis Earthquake (DBE), is the fundamental input for deriving structural design loads and assessing plant effects as part of the DBA, see [1] Section 5.5 for more information on DBA.

58. Historically, a range of different approaches have been undertaken for the development of the DBE for UK Licensed sites, especially for sites where there was no requirement for seismic considerations at the time of construction. These approaches have been developed, as a result of the state of knowledge at the time of their derivation and of the level of risk posed by the site. Inspectors should exercise caution when examining the derivation of the design basis hazard in isolation from the totality of the safety case for such facilities. Instead, an appreciation of the manner in which the Licensee has demonstrated holistically that the risk from seismic events is ALARP is a more proportionate approach in line with good regulatory practice; see the guidance at [1] Section 2.

59. Inspectors should also be cognisant of the broad intent of the SAPs, namely that it is not the level of conservatism assigned to one element of the seismic analysis and

design process (in this case the definition of the seismic hazard), but the (overall) level of conservatism, applied to the process as a whole. The level of conservatism incorporated within the DBE, can be significantly enhanced or eroded downstream in the seismic analysis and design process. Therefore, the inspector should note the need for close liaison with related disciplines eg civil & mechanical engineering. This important consideration is discussed further in [1] Section 5.5.

60. With the above in mind the steps involved in developing a site-specific DBE for major nuclear hazard sites are outlined below.

61. *Step 1:* In order to meet the intent of EHA.3, EHA.4 and FA.5, the site-specific ground motion hazard corresponding to a range of annual frequencies of exceedance including 10^{-4}/yr, along with the full hazard uncertainty distribution, is expected to be derived via a PSHA study (see paragraphs 76 et seq below). This results in a set (or series) of Uniform Hazard Spectrum (UHS); further information on the PSHA outputs is discussed in paragraph 102.

62. *Step 2:* As per the intent of EHA.4, conservatism should be introduced in a way that preferably includes consideration of the uncertainty distribution associated with the 10^{-4}/yr UHS, along with the overall robustness and rigour applied to the underlying PSHA study, and its sensitivity to expert judgement[8]. The 84th percentile UHS provides a *starting point* for this consideration, inspectors should also note the more general guidance on this issue in [1] Section 5.5.1.[9]

63. In reviewing the level of conservatism proposed by the Licensee the inspector should also give consideration to the slope of the hazard curve around 10^{-4}/yr and how this propagates towards 10^{-5}/yr. Where the slope of the hazard curve at this point shallows rapidly (for a conventional graphical depiction of a hazard curve this indicates that hazard severity increases significantly for only modest reduction in hazard exceedance frequency), or where the hazard uncertainty increases significantly beyond this point, this *may* necessitate a higher level of conservatism to reflect the intent of SAP FA.5 and associated paragraph 629.

64. Once defined, the conservatively defined site-specific ground motion hazard can be viewed as the seismic demand spectrum. This is the site challenge discussed in [1] Section 2.3.

65. *Step 3:* The DBE is then developed so as to meet the conservatively defined site-specific ground motion hazard, this can be viewed as the seismic design spectrum.

66. Practice historically in the UK and many other countries indicates that the DBE is often defined by a standardised response spectral shape[10] scaled to a PGA value indicative of, or conservative to, the site or sites under consideration as defined by a PSHA. Traditionally these are piecewise linear spectra anchored to a median or mean PGA value. Whilst these may not be the preferred spectral shapes of seismic hazard analysts, they are an extremely useful tool in the design process, particular at the concept design stage, where the three zones of constant displacement, velocity and acceleration provide useful boundaries on potential design solutions.

67. This practice is also applied in the development of reference designs (usually site-independent) that have or may be subjected to Generic Design Assessment (GDA) or similar such processes in other countries. The shape of the spectrum chosen along

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[8] Licensees may also wish to take account of conservative assumptions in the plant design process (although this alone would not meet the intent of SAP EHA.4). If this is done, then the source of the conservatism should be clearly identified in Licensee safety submissions.

[9] There are other methods in existence such as that developed in the US defined in [14]. However such approaches have not so far been used for nuclear sites in the UK, so although not precluded in principle, Licensees should ensure that they provide equivalent levels of nuclear safety to those deriving from more conventional approaches.

with the anchor point is often driven by non-site-specific and sometimes non-safety factors and requires expert judgement as to its appropriateness. However, the inspector should ensure that such a DBE is shown to meet or exceed the seismic demand for the specific site as outlined in Step 2 above and be consistent with the intent of SAP EHA.4. See [1] Section 5.8.6.

68. In principle the DBE could be defined directly from the PSHA as the conservatively defined site-specific ground motion hazard[11]. The inspector should note that this approach implies that the seismic demand and seismic design spectra are equal indicating *potentially* lower (overall) margins (noting paragraph 59) than would be the case with standardised (slab-sided) response spectra, which often include relatively large margins at oscillator frequencies of engineering interest. This approach places greater reliance on the PSHA itself, therefore, the inspector should ensure that this is reflected in the quality and rigour of the PSHA methodology used to characterise the site-specific hazard, especially in terms of quantification and inclusion of uncertainties (see paragraph 81). Inspectors should also consider whether enhanced ONR assessment is necessary to confirm that the PSHA is suitable and robust. Should concerns arise, Licensees may elect to increase the levels of conservatism introduced in order to define the site demand spectrum (see paragraphs 62-64), especially at oscillator frequency ranges of engineering interest.

69. *Step 4:* Regardless of the approach taken to define the DBE, the inspector should ensure the Licensee has demonstrated that the minimum DBE level (discussed further below) is adequately met, subject to considerations of proportionality.

Minimum DBE Definition

70. RGP would indicate that nuclear power plants should be able to resist a minimum level of strong ground motion irrespective of the results derived from the PSHA. As noted above the Licensee is expected to demonstrate that their proposed DBE meets this minimum requirement.

71. With regard to the definition of this minimum requirement in the UK, the International Atomic Energy Agency (IAEA) in [6] and the Western European Nuclear Regulators Association (WENRA) in [9] identify this minimum as a *“horizontal free-field standardized response spectrum anchored to a PGA value of 0.1g”*. The current default spectrum that has traditionally been used in the UK is that defined by Principia Mechanica Ltd (PML) in 1981 [10]. However, this would not preclude the Licensee from proposing and / or developing another spectrum for use in the UK.

72. It is unlikely that site-specific ground shaking hazard below 0.1g would be appropriate for any site in the UK where a formal DBE is required, but Licensees whose arrangements call for multiple design bases might employ definitions less than this. In such cases, inspectors should confirm that the use of such low seismic design bases are consistent with the wider intent of the SAPs to ensure that plant operations are consistent with the risk ALARP principle.

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[10] Many standardised spectral shapes exist for varying site classifications. These are typically either vendor certified spectra, ie design spectra supplied by the reactor designer whose definitions are site independent as the intent is to envelope a range of site-specific response spectra, or they could also be a nationally agreed response spectra prescribed by regulatory authorities or reactor operators derived on the basis of country specific information. Some examples of these in common use are the EUR [26], USNRC Regulatory Guide 1.60 [30], PML [10], to name just a few. These are typically piece-wise linear shapes when plotted with log-log scales.

[11] A similar approach is permitted by the USNRC in Section 5.4 of [29]; however, despite the option being available for more than a decade, this does not appear to have been applied at any US nuclear site. Rather, the performance based Ground Motion Response Spectrum or Foundation Input Response Spectrum (FIRS) are typically used to underpin the site-independent standardised response spectrum known in the US as the Certified Seismic Design Response Spectrum [29].

73. It is also worthy of note that for plant with limited nuclear inventory or limited unmitigated dose potential, the design basis requirements can be reduced; see the TAG 13 Section 5.5.2 [1].

Operating Basis Earthquake

74. An operating basis level of ground motion, often referred to as Operating Basis Earthquake (OBE), is expected to be determined and substantiated for new facilities. This substantiation should satisfy SAP EHA.9 paragraph 254 such that "*no structure, system or component should be impaired by the repeated occurrence of ground motion at the OBE level*". In the case of existing facilities this OBE level is likely to be derived from assessments of the existing facility and its response to ground motion rather than from a particular hazard level.

75. The inspector should ensure that the Licensee has adequate arrangements in place to determine if the OBE or the DBE have been exceeded through judicious selection of quantitative measures. In addition the metrics chosen to determine whether a facility must be shut down following an earthquake should be carefully reviewed[12].

Probabilistic Seismic Hazard Analysis

76. RGP indicates that, for plants and sites with significant nuclear hazard, DBEs should be developed from, or underpinned by, the site-specific ground motion hazard derived from a PSHA. These studies derive hazard curves at a number of oscillator frequencies and present the uncertainties in terms of hazard curves at various confidence levels. From these suites of hazard curves the Uniform Hazard Spectra (UHS) can be constructed, and from disaggregation[13] significant earthquake scenarios, in terms of magnitude and source-to-site distance[14], can be identified for development of time history records. The vertical UHS is calculated either using direct vertical PSHA calculations or using a V / H factor to go from horizontal PSHA to vertical PSHA. More details on all important aspects of performing a PSHA are given in Ref. [3], and for further discussion on the outputs, see [3] Section 8.

77. The two fundamental inputs to a PSHA are a Seismic Source Model (SSM) and a Ground Motion Model (GMM). The SSM defines the characteristics of the seismic sources and the activity rates of earthquakes of different magnitudes within them. The GMM defines the ground motions at the site due to each earthquake scenario generated by the SSM. For further details on these see [3] Section 6.

78. M_{min} is a parameter applied in the PSHA calculations and is chosen as the level of magnitude below which ground motions would be insufficiently energetic to change the design of a well-engineered[15] facility[16]. Therefore, the Licensee is expected to justify that the ground motion effects from such events $< M_{min}$ on SSCs, have a negligible risk contribution. For a multi-facility site that may have differing levels of robustness the Licensee is expected to justify the value of M_{min} selected is appropriate. The inspector should be aware that other criteria such as cumulative absolute velocity (CAV) filters

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[12] The use of standardised cumulative average velocity in conjunction with response spectral acceleration and velocity are example of metrics used in other parts of the world.

[13] 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, see *[3]* Section 8.3.

[14] Various distance metrics may be relevant here depending on the GMPEs selected. The shortest distance from a site to the fault rupture surface or the shortest distance from a site to the surface projection of the fault rupture surface are just two commonly used examples.

[15] The term well engineered facility here refers to SSCs which have been designed and installed to RGP in terms of adherence to normal design standards and practices. If these standards also include some basic level of seismic provisions, this would aid in supporting the choice of a more elevated level for M_{min}.

[16] The computation of the hazard curves typically excludes events of a magnitude less than M_{min} from the integration.

have been proposed as an alternative to M_{min}. Further details on these, M_{min}, and limits on other input parameters are provided in [3] Section 7.2.

79. The estimation of the ground shaking hazard should also take full account of any features of the site that could modify the amplitude or frequency of the seismic waves propagating to the surface. Among the factors that can exert an influence on ground motions are topographical features, although for a nuclear site it is only likely that sub-surface contours (eg basin effects), would need to be considered. The most important local site effects will be associated with the near-surface soil profile as defined by changes in shear-wave velocity, density and damping with depth. The impedance contrasts created by such changes can lead to amplification or attenuation of the motions, which vary with frequency. In the case where the soil / rock profile varies significantly across the site it may be necessary to evaluate the site response associated with subsurface conditions localised to the specific building. From this site response analysis soil column properties are then derived that can be used to develop models and deterministic inputs for any required SSI analysis. For further information on-site response analysis refer to [3] Section 7.4.

80. There are very many factors that need to be considered when undertaking a PSHA, but one of the most significant is the handling of epistemic uncertainty. This is the uncertainty that arises when experts make decisions based on limited supporting information or data, resulting in alternative models, each technically defensible. The methods used to handle epistemic uncertainty can be extended to treat cases where there is no supporting information or data. The management of this issue forms a major part of the modern PSHA formalism, and guidelines have been developed in the US, originally by the Senior Seismic Hazard Analysis Committee (SSHAC) and latterly by others [11] & [12] (this concept is referred to as participatory peer review by the IAEA in [6]). These guidelines have been applied on many projects for nuclear sites (and other critical facilities) around the world.

81. For a modern PSHA the implementation of a structured decision-making process where the decisions are subject to technical challenge is considered to be RGP. The SSHAC guidelines may form a basis for this as noted above, although other possible alternatives are not precluded. For new-build sites the process applied is expected to be comparable to at least that of an enhanced SSHAC Level 2 study. However, the inspector should keep in mind that the process is site-specific and should be augmented proportionately to acknowledge aspects of the study that are either highly uncertain or particularly controversial, and that have a strong influence on the hazard results[17]. The inspector should keep in mind that the rigour applied to this process should be appropriate to the nuclear hazard potential posed by the facility, and how it is to be used in developing the DBE (see paragraphs 64-67). The inspector should ensure that these points are clarified clearly at the outset of the project. For further information on uncertainty analysis refer to [3] Section 3.

82. Although the consideration of long-period ground motion from distant sources outside the bounds of the PSHA is not precluded, if such an approach is taken the inspector should ensure that similar levels of rigour have been applied to such a study. Where there is an overlap in terms of frequencies with the PSHA, the results are expected to be compared to ensure consistency in the site-specific ground motion hazard definition.

83. Undertaking a PSHA project for a major nuclear site is time consuming and generally requires a team of technical experts to undertake the analysis for the Licensee. ONR

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[17] Some of the enhanced features could include, for example, a workshop with external subject matter experts on a particular topic distinguished by importance, uncertainty or controversy. Ideally, the hazard analysts would pose questions and engage in discussions with these resource or proponent experts in the context of the workshop and in the presence of the independent peer reviewers. Additional examples of enhancements can be found in NUREG-2213 [11].

can assess the analysis, but inspectors may need to seek expert assistance in reviewing the technical aspects.

Use of the Geometric Mean as the Input to Structural Analyses

84. Physically the seismic input motion is vectorial. It is measured as three orthogonal components, two horizontal and one vertical. In recent years it has become common for GMPEs to be developed using the geometric mean[18] of the measured horizontal components. The PSHA will generally be conducted using the GMPEs as published and thus yielding UHS in terms of geometric mean.

85. However, it does not follow that the DBE should be automatically specified in terms of the geometric mean. Depending on the structural analysis approach used, and the dynamic properties of the structures themselves, this definition may not be appropriate[19]. In many cases, hazard analysts can apply a correction to the geometric mean motion to obtain a ground motion parameter that is in accord with the design intent. Therefore, the inspector should check to ensure that appropriate adjustment to the DBE (if required) has been carried out so as to be compatible with the characteristics of the structures being analysed and the SSI or structural analysis methodology.

Time Histories

86. Dynamic analyses in the time domain[20] for site response and SSI analyses will generally require the generation of an ensemble of acceleration time-histories that appropriately represent a given target spectrum. The target spectrum itself depends on the type of analysis being undertaken and the overall analysis approach adopted.

87. Information available from the PSHA disaggregation regarding the contributions to the hazard at particular response frequencies from intervals of magnitude, distance and epsilon[21], are typically used to select real earthquake records that can then be modified to represent the required spectrum. Although the use of artificially generated records is not precluded, the inspector should note that RGP is progressively moving away from using these as evidenced by Refs. [13] & [14]. Many methods continue to be developed for scaling and manipulating recorded ground motion records, and artificially generating records. Therefore the inspector is advised to seek specialist advice. For further information see [3] Section 8.4.

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[18] An averaged horizontal spectral acceleration calculated frequency by frequency as the square root of the product of the spectral accelerations along orthogonal axes. It should be noted that other more sophisticated definitions have also been developed for use by GMPEs.

[19] Structures that have similar horizontal stiffness properties and therefore response frequencies irrespective of orientation, for example vertical tanks and cylindrical structures will be exposed to the maximum direction or peak component response.

[20] Time domain analyses are used to predict the structural response at small time increments throughout the duration of the ground motion record used (this allows analysis of geometric and material non-linear behaviour, component fatigue, plastic response, or impacts between components to be modelled). Whereas, frequency domain analyses in most cases use response spectra as an input and are generally used to model linear systems (however non-linearity can be represented albeit simplistically by behaviour factors); they are computationally more efficient than time domain analyses but in the case of modal analysis provide only the maximum response of the structure or system.

[21] Epsilon is a parameter associated with strong ground motion that is defined as the number of standard deviations that an observed logarithmic spectral acceleration differs from the median logarithmic spectral acceleration from a GMPE. The uses of this parameter are further discussed in [3] Section 8.4.

88. Inspectors should be aware that for Random Vibration Theory (RVT) based site response analysis time histories are not required[22]. However it is still necessary to specify the Fourier Amplitude Spectrum (FAS) and ground motion duration as inputs.

89. In the case of soft sites the inspector should be aware that using overly conservative time histories could result in increased non-linear soil response and greater energy dissipation, and hence a lower peak structural input that may not be conservative. Hence time histories that are a mean best fit against the target spectrum without undue conservatism or bias are preferred. As per SAPs ECE.14 and AV.6, sensitivity studies are expected to explore this where appropriate.

Soil-Structure Interaction (SSI) and Structure–Soil-Structure Interaction (SSSI)

90. For large nuclear facilities not founded directly on hard rock (the definition of which is suggested in [15] and discussed more comprehensively in [13] Section 5.1), the response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil. The SSI modifies the response of the facility and therefore is expected to be explicitly accounted for. It may also be necessary to consider the influence of surrounding structures via SSSI.

91. SSI is a complex technical area and inspectors may need to seek specialist advice when assessing the adequacy of SSI analyses.

92. SSI analyses are usually carried out using specialist software and the inspector should ensure that the software, the inputs and assumptions, and the results, are appropriately validated and verified as per the intent of SAPs AV.2, AV.3 ECE.14 and ECE.15. Sensitivity studies may be used to explore the result of changes in input parameters and assumptions (SAPs ECE.14 and AV.6). RGP for this area is largely defined by ASCE4 [13]. The inspector should note that there is a significant cross over with the civil engineering discipline area and guidance in [16] may also apply to this area.

93. The inspector should establish the Licensee's approach or strategy for the SSI and downstream seismic analysis and design process. The underlying principle is that the resultant actions (or loads) resulting from SSI analysis using the appropriate representation of the seismic demand ground motion should be met by the design capacity noting the principles in paragraph 59 and [16] regarding the need for appropriate overall margin.

94. The inspector should note that SSI effects include the rotation of the facility about its base, therefore the forces on the facility increase with the distance from the centre of rotation of the structure. This means it is necessary to make the comparison between the GDA reference design and the site-specific SSI at all key levels of the facility. Comparing just the basic input response spectra is only valid for hard rock sites where SSI does not occur.

95. With respect to the application of the input motion within SSI, the inspector should examine this area carefully and where necessary seek to establish quantitatively whether the process of transferring and developing the SSI input motion maintains the intent of paragraph 65. With this in mind the inspector should note specifically the challenges associated with deconvolution. Section 5 of [13] provides principles to be aware of in determining the appropriate input motion for SSI.

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[22] The RVT approach to site response analysis is often applied as part of the PSHA. RVT does not utilise time domain input motions, but rather initiates all computations with the input FAS (amplitude only, no phase information). Because RVT does not have the accompanying phase angles to the Fourier amplitudes, a time history of motion cannot be computed. Instead, extreme value statistics are used to compute peak time domain parameters of motion (eg PGA, spectral acceleration) from the Fourier amplitude information.

96. It is expected that the soil column properties used in SSI are compatible with those used in the site response analysis[23]. This applies whether the site response is embedded in the GMPEs used, or a separate site response analysis is used. Of particular significance is that the uncertainties are appropriate and that the full range of values is considered in the analysis, not just the mean value. As advised in [13], the SSI analysis can be either carried out deterministically or probabilistically, however whatever approach is taken, the soil profiles used should be appropriately verified[24].

97. The inspector should be aware that if time histories generated from standardised response spectra are used to perform the derivation of the basic foundation compliance functions for SSI analysis, then due to the built-in conservatism involved in their use, this could lead to excessive and inappropriate degradation of the soil profile through non-linear response. Related to this, inspectors should note that for sites with very soft soil profiles it is possible that a lesser seismic input (a higher probability of exceedance) will be more onerous because of the reduced degradation in the soil profile. This situation should be checked if large soil strains are being observed.

98. Inspectors should be aware an SSI analysis can generate inaccurate results if the depth of soil beneath the structure is not suitably accounted for. If an assumed bedrock approach is used then its depth should be justified such that the wave amplification / attenuation are properly accounted for.

99. Closely associated with SSI analysis is the effect on the foundation soil interface. The rocking of the structure leads to unsymmetrical foundation loads, which in soft soil conditions can lead to large variations in the strains in the soil and consequently the stiffness and damping value. Where necessary the inspector should ensure the modelling approach taken can handle uplift appropriately. If such a situation appears likely then a check on the bearing capacity of the soil should be carried out. There are two reasons that such checks should be performed. Firstly, the response of the facility will change with the changing stiffness and damping of the soil and should be treated by appropriate analysis. Secondly, that change could result in reduced bearing capacity and factor of safety against bearing failure. Since the foundation is itself an SSC, it should be considered as being subject to Design Basis requirements, namely the application of conservative loading functions. Clearly, the three dimensional effect needs to be accounted for when evaluating the effects of the bearing capacity.

100. The inspector should be aware that other SSI effects resulting from wave incoherence, non-vertically propagating waves and rotational components of input motion are discussed comprehensively within [13].

Tsunamigenic Earthquakes

101. As noted earlier (Section 2.1.3), earthquakes represent one potential source for the generation of tsunamis that can contribute to flooding hazard at the site. The seismic characterisation of the site may therefore need to include both nearby and remote sources of submarine earthquakes that could generate tsunamis that would produce run-up at the site. As noted above, earthquake-triggered submarine landslides and coastal landslides that could enter the sea may also need to be characterised as inputs to the probabilistic modelling of tsunami hazards. For all of these potential tsunami triggers, estimates of both their magnitude and likelihood are required. Further information on these areas is discussed in [5] Section 8.

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[23] Soil column properties typically include strain dependent shear modulus and material damping curves. As soil strains increase under dynamic motion, degradation can lead to a non-linear decrease in the shear modulus from its value under static loading conditions.

[24] A verification method required by the USNRC is a demonstration that the deterministic soil profiles produce ground surface response spectra that envelope the probabilistic building / facility specific response spectrum, outlined in paragraph 102 and termed the Performance Based Surface Response Spectrum in [13].

3.2.2 DBA inputs from the seismic hazard analysis

102. In order to underpin the DBA inputs, as per the intent of paragraphs 61 - 65 above the PSHA and site characterisation needs to deliver a number of outputs. These outputs are dependent on the nature of the site, the plant configuration, and the overall seismic analysis and design approach to be adopted. There are several possibilities and the inspector should ensure that the approach is well defined and the inputs are appropriate. Typically these outputs may consist of:

- *Reference horizon response spectra*: These are typically horizontal UHS determined at depth, often, but not always, well below the foundation level of the nuclear power plant, represented by competent rock whose response to strong ground motion is not affected by either superficial soil deposits and / or SSI effects. Modern seismic hazard analyses may calculate the hazard at such a depth and then convolve this to the desired levels (free-field or some target horizon such as foundation level) via site response analysis, taking care not to double count the site-to-site component of variability. For further information refer to Ref. [3] Section 6.3.

- *Free-field ground surface response spectra*: These are horizontal and vertical UHS determined as free-field motions on the ground surface. This definition includes the effect of local soil response but not the effects of SSI. These UHS are derived from the global understanding of the as-built site soil profiles[25] above the reference horizon as determined from the site characterisation, and therefore, are unique to a particular site.

- *Foundation input response spectra*: This corresponds to the horizontal and vertical UHS determined as free-field outcrop spectra at the foundation level specific to the building being analysed. These UHS are derived from the global understanding of the site soil layers above the reference horizon as determined from the site characterisation, and therefore, are unique to a particular site. These can be used to verify that the soil columns to be used in a deterministic SSI analysis produce surface response spectra that envelope the free-field ground surface response spectra.

- *Building / facility specific response spectra*: For some sites that have large variations of dynamic properties perhaps spatially, and / or with depth, it may be necessary to evaluate the horizontal and vertical UHS associated with subsurface conditions localised to the specific building. Free-field ground surface motion would be developed on a probabilistic basis through site response analysis. The soil columns to be used in a deterministic SSI analysis can then be shown to produce ground surface response spectra that envelope these building specific response spectra.

- *Dynamic Geotechnical Parameters for inputs to SSI: From the site response analysis a* description of the soil column profile with iterated site-specific soil properties at the 10^{-4}/yr annual frequency of exceedance level, including the strain-dependent shear modulus, degradation curves and damping curves, and associated adopted variabilities.

103. The inputs for the DBA process can be defined as follows:

- *DBE definition:* A response spectrum that is underpinned by; the conservatively defined site-specific ground motion hazard, and the minimum DBE definition (see paragraphs 70 - 73), at an explicitly defined depth or horizon (see paragraphs 65 - 69).

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[25] The as-built soil profiles would include any made ground used to create the final site platform levels.

- *Time Histories:* For the analysis of SSC response, an ensemble of acceleration time-histories will be required, appropriately matched to the appropriate target spectrum as discussed in paragraphs 86 - 89 above.

- *SSI Inputs:* The location specific soil column properties for both horizontal and vertical site-specific ground motion for use in the SSI analysis as discussed in paragraph 96 above.

- *In-structure response spectra:* These are computed from a model of the structure and plant sufficiently well-defined so that design basis motions can be defined at important points within the major structures, for example, foundation slabs and floor levels. If pertinent, SSI effects should be included in this model. Such motions can then be used as inputs to analyse the seismic response of SSCs. The objective of deriving these design basis motions is that plant and equipment within the major structures can be designed directly from these, without further reference to the underlying design basis definitions. If what are regarded as secondary SSCs might affect the response of the primary SSC then it is expected that these are explicitly modelled in terms of mass and stiffness in the main building model.

3.2.3 Beyond design basis events & cliff-edge effects – (SAPs EHA.18, EHA.7, EHA.9)

104. In order for the Licensee to carry out beyond design basis analysis (BDBA) as intended by EHA.18 and EHA.7, the hazard arising from earthquakes should be derived for frequencies less than 10^{-4}/yr. The results are usually presented as hazard curves. The purposes of BDBA are explicitly outlined by EHA.18 paragraph 246 and covered in detail in [1] Section 5.5.3.

105. Inspectors should confirm (in conjunction with other disciplines) that the Licensee has:

- Confirmed the absence of cliff-edge effects just beyond the design basis from existing design basis seismically-initiated faults (in terms of radiological consequences)

- Identified the hazard level at which safety functions could be lost (ie determine the beyond design basis margin to failure)

- Provided an input (or support) to the seismic PSA to show that risk targets have been met, or at least that risk has been reduced ALARP.

- Ensured that safety is balanced so that seismic hazard does not make a disproportionate contribution to overall risk, although at very low frequencies consistent with severe accidents, this may not be feasible.

106. Inspectors should also confirm (in conjunction with other disciplines) that the Licensee has:

- Provided an input to SAA if appropriate.

- Identified the possibility of additional plant faults being initiated just beyond the design basis level.

107. The term “just beyond the design basis” should be interpreted as a higher hazard level (ie lower annual frequency) that provides a margin over the DBE level. This margin should, in a qualitative sense, account for the level of uncertainty in both the DBE definition and the plant response analysis, such that if the plant can still be shown to be robust at this level, there is high confidence that the design is adequate and the seismic risk arising from it has been reduced ALARP (SAP ERL.4).

108. By definition the BDB region stretches from the design basis to SSC failure. The inspector should ensure (in conjunction with other disciplines) that the SSC robustness reflects its radiological significance.

109. The hazard levels & proposed methodology to test the SSC responses for both cliff edge effects and beyond design basis capability should be proposed by the Licensee (refer to [1] Section 5.5.3).

3.3 Seismic Probabilistic Safety Analysis – (SAPs FA.10 – FA.14)

110. It is anticipated that earthquake-initiated faults will be included in the Seismic PSA plant model unless it can be shown that the consequential effect of such faults is not significant. Guidance regarding when a seismic PSA is considered appropriate is given in [1] Section 5.6 and specific guidance on Seismic PSA in [17]. The inspector should ensure that all credible earthquake-initiated fault sequences are accounted for, including those arising from surface rupture hazard if these have not been screened out, and that these have been modelled in the Seismic PSA by an appropriate process. The hazard analysis should deliver an appropriate mean hazard curve and associated uncertainty fractiles (confidence levels), and if necessary in some cases, a set of representative hazard curves of a selected number of branches of the final logic tree in order to preserve the correlation built-in between the values of ground-motion, so that the risk contribution from seismic hazard can be calculated as part of the site Seismic PSA.

111. Developing fragility data for the probabilistic analysis of plant response to earthquakes is a specialist area. Fragility curves for SSCs are typically generated from shake-table testing, calculation, or success / experience data. Fragility curves for major structural elements are often derived by calculation. Open literature, for example Ref. [7], provides a substantial amount of fragility data, especially for US nuclear structures and equipment. The regulatory assessment of fragility analysis lies primarily with the engineering disciplines within ONR covering the plant and equipment items to which the analysis refers.

3.3.1 PSA inputs from the seismic hazard analysis

112. The inspector should seek to ensure that sufficient input data are provided to facilitate the PSA process. For a major nuclear plant should include at least:

- Site-specific hazard curves covering a range of exceedance frequencies from at least 10^{-2}/yr – 10^{-6}/yr [26].

113. The hazard curve should be provided at a range of uncertainty fractiles including; the mean, 5%, 16%, median, 84%, 95% and others as necessary for the PSA, to give an indication of the uncertainty distribution associated with the site-specific hazard analysis.

3.4 Severe Accident Analysis – (SAPs FA.15, FA.16, FA.25)

114. Seismic Hazard is unique in that it affects both internal and external SSCs of a facility both on-site and off-site more or less simultaneously. This may result in initiation of other internal or external secondary hazards both off-site and on-site. It may be credible that the seismic hazard could lead to severe accident site conditions or plant scenarios that differ from those assumed for other reasons (eg severe internal plant faults). Therefore, the effects of earthquakes should be considered during the

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[26] As per [6] this value may need to be extremely low (eg 10^{-8}/yr) for seismic PSA studies where the nuclear plant has a very low core damage frequency in relation to non-seismic initiators. In such cases, care should be taken to assess the suitability and validity of the seismic source and ground motion models, along with the basis for the expert judgement, since uncertainties associated with these can significantly bias the hazard results.

development of an appropriate SAA for the site, see [1] Section 5.7 for guidance on SAA.

3.4.1 SAA inputs from the seismic hazard analysis

115. The inspector should seek to ensure that sufficient input data are provided to facilitate the SAA process as advised by the fault study discipline.

4 EMERGENCY PLANNING & ARRANGEMENTS (SAP AM.1)

116. The potential effects of seismic hazards should have been considered as part of the hazard identification and analysis process, as discussed in Section 3, and used to inform the site's emergency plan and arrangements under Licence Condition 11. If the response to seismic hazards is fully accounted for by the arrangements in place to cover other fault conditions, then this should be stated. If not, the arrangements should be revised as appropriate to take account of additional consequences that could arise from seismic events. Inspectors should consider the following issues:

a) Common cause effects: A consideration with seismic hazard (and major consequential hazards) is that they provide a common cause effect across the site, in other words several independent fault conditions may be created on the site simultaneously. The site's emergency arrangements should recognise this and be able to respond in a pragmatic way to this possibility.

b) Provision of post-earthquake information: Earthquake information in the UK is provided by the BGS. On-site and in-plant monitoring should also be available for this hazard, with indications provided to operators of the existence of on-site seismic effects that could cause damage to SSCs. There are currently no early warning systems for seismic events or tsunamis in the UK.

c) Off-site infrastructure: Severe ground shaking on-site implies severe ground shaking in the locality off-site. The emergency arrangements should recognise that the provision of both supplies and staff from off-site (as well as the ability to support the off-site response) may be hindered for the duration of, and following, an earthquake, and identify ways of mitigating the adverse effects on nuclear safety if this occurs.

d) Post-Fukushima Resilience Equipment: After the Fukushima accident following the Great Tohoku Earthquake in 2011, ONR recommended the establishment of off-site stores of emergency back-up and recovery equipment, capable of recovering basic safety functions following a severe external hazards event. The site's emergency arrangements should refer to such equipment where appropriate, and the type of equipment should be justified by the types of severe accidents that external hazards could generate.

e) Local Authority Off-site Plan: ONR regulates Local Authorities in respect of the adequacy of their off-site emergency plans. Such plans are based on what is considered to be a reasonably foreseeable radiation emergency as identified by the site operator and, if they consider seismic hazards at all, will likely concentrate on managing the infrastructure away from any nuclear licensed sites within their geographical area of responsibility. Inspectors (or relevant site inspectors) should consider the significance of natural external hazards and their potential for widespread common cause effects both on and off nuclear licensed sites. Inspectors should be aware that for natural hazards especially emergency response services, transport links and off-site power supplies, may not be available for some considerable time following an event.

4.1 Emergency Arrangements Inputs from the Seismic Hazard Analysis

117. The inspector should seek to ensure that sufficient input data are provided to facilitate the development of adequate emergency plans both on-site and off-site where this is necessary and appropriate, see [1] Section 5.9. This may include representative seismic hazard levels to be assumed for emergency planning purposes[27].

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[27] The inspector should be aware that a number of earthquake intensity measures are in use to represent effective damage potential, the most common of which is CAV. This was developed in the US as a more useful measure of ground-shaking intensity than PGA. In the US, seismic monitoring devices on plant often are set to alarm during an earthquake event once a specified value of CAV is exceeded.

5 RELEVANT STANDARDS AND GOOD PRACTICE

118. Although RGP has been articulated throughout this document some of the important areas are repeated here to ensure clarity for the inspector. A brief overview is also provided of the important codes and standards that are applicable.

119. With respect to the definition of the DBE, for new build the use of a standardised spectrum constitutes RGP, although using the conservatively defined site-specific ground motion hazard directly is not precluded, but would be subject to further scrutiny. For existing sites the current position in the UK is complex with some sites having quite bespoke design bases.

120. However, regardless of the DBE adopted, the expectation is that this should demonstrably meet the conservatively defined site-specific ground motion hazard and the minimum DBE definition in [6] & [9]. Where (mainly for existing facilities) qualification of SSCs against such a DBE is not achievable then the inspector (in conjunction with other disciplines) should ensure that a risk ALARP position is achieved, further information on this is given in [16].

121. For the derivation of the site ground motion hazard a modern PSHA implementing a structured decision making process where the decisions are subject to technical challenge is considered to be RGP. The SSHAC guidelines [11] & [12] may form a basis for this, or as a possible alternative a robust peer review, such as the participatory peer review described by IAEA in [6], may be appropriate. The rigour applied to this process should be appropriate to the nuclear safety risk posed by the facility. It is expected that this hazard derivation will provide the appropriate information for input to the PSA and SAA.

122. Although CF has not been associated with known UK earthquakes, the possibility exists and may be considered an exclusionary criterion for new nuclear sites. Clearly, if it did occur under safety-related nuclear plant, the consequences could be very significant. Therefore in order for Licensees to screen out CF hazard from the fault analysis, inspectors should seek assurance that sufficient analysis of the hazard has been undertaken to confidently support such a claim. Therefore, as part of the CF study for the site the inspector should expect all known surface faults on-site to be characterised. However, to avoid prohibitive cost, a graded approach may be appropriate which is commensurate with the facility radiological hazard potential in accordance with ALARP principles.

5.1 Established & Interpretative Standards

123. It is expected that the Licensee will take advantage of the available guidance when planning and conducting its hazard analyses. A large body of RGP for this hazard has been, and continues to be, developed by organisations such as USNRC, IAEA, WENRA, AFCEN and NRA (Nuclear Regulation Authority of Japan). The guidance produced in the United States of America by the US Nuclear Regulatory Commission (USNRC) and standards organisations such as the American Society of Civil Engineers (ASCE) and the American Nuclear Society (ANS) is the most stringent. Noteworthy examples being the SSHAC guidelines [11] & [12] (discussed further in [3]) that are being applied in hazard studies by many countries with nuclear facilities, and the approach to external hazards PSA developed in ASME/ANS RA-S-1.2-2013 [18].

124. There are also codes of practice (CoP) specific to nuclear power plants that are commonly used by Licensee’s, examples of such are ASCE4-16 [13], ASCE43-05 [14], ANS/ANSI-2.27 [19], & 2.29 [20] along with guidance from other bodies such as the IAEA [6], [7], [8], [21], [22], [23], [24], and the US Electric Power Research Institute (EPRI) [25]. Some US utility companies have sponsored the development of specific codes that outline and describe the use of standardised design spectra, an example

being the EPR technical code [26]. Other examples relating more to design and analysis of structures can be found in [16].

125. The inspector should be aware that CoP are routinely reviewed and updated as research in the area becomes absorbed as best practice, however these revision cycles can take many years. An example of this was the revision to ASCE4 [13]. Therefore, the inspector cannot always rely solely on formally published CoP to define RGP. The extent to which Licensees should research such practice depends on the safety significance of the nuclear activities to which the practice is to be applied. Inspectors should seek assurance that the Licensees (and their contractors) of major nuclear plant have sufficient knowledge of world-wide practice to determine whether or not it applies to their plant.

126. In addition, a large number of non-nuclear specific CoP, particularly from seismically active countries, may contain guidance and principles that could be useful in specific instances. Refs. [27] & [28] are examples of such.

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TABLE 1 – EXAMPLE SEISMIC HAZARDS, AND ASSOCIATED PRIMARY, CORRELATED, SECONDARY AND CONSEQUENTIAL HAZARDS

Primary Hazard – (Design Basis Hazard Descriptor)	**Example correlated hazards that may occur in combination**	**Secondary Hazards**	**Consequential Hazards / Effects**
Strong Ground Motion	Surface Fault Rupture (Capable Faulting)	Tsunami Geotechnical Hazards: • Slope instability • Liquefaction & Cyclic Mobility • Lateral Spreading • Landslide Collapse of adjacent and secondary structures Permanent surface displacement	• For tsunami see Annex 3 Table 1 [4] • SSC damage • Initiation of Internal Hazards • Loss of containment
Surface Fault Rupture (Capable Faulting)	Strong Ground Motion		

APPENDIX A

Historical development of seismic hazard analysis in the UK nuclear industry

The first nuclear power station to be seismically designed in the UK for the Central Electricity Generating Board (CEGB) in the 1970s was Heysham 2. The CEGB and South of Scotland Electricity Board were at the time the two reactor operators in the UK. The CEGB planned to embark on a major new reactor build programme through the 1980s and 1990s and set in motion a programme of work to develop a general seismic design basis for the UK, supported by the development of design response spectra applicable to various ground conditions in the UK. This was followed by development of a site-specific methodology for the seismic hazard. Significant research was undertaken on a number of fronts:

- The collection and characterisation of historical earthquake data in the UK so that it could be used for seismic hazard analysis.
- The development of a methodology for analysing the seismic challenge at UK nuclear reactor sites.

The work progressed to the point of becoming an internally-consistent comprehensive methodology for the development of site-specific seismic design bases. Many of the features of a modern PSHA can claim to have seen early development work in these programmes:

- The analysis method was fully probabilistic akin to modern PSHA methods
- The method used the logic tree approach to incorporate epistemic uncertainty in the analysis.
- The programme of work first developed attenuation equations for expressing the hazard in terms of PGA, then later adopted the concept of UHS which at the time was referred to as Uniform Risk Spectrum (URS).
- The analysis method included an early expert elicitation technique to cover parameter uncertainty that could not be resolved by data analysis alone.

A number of major historical seismicity characterisations were undertaken for the UK and, at the time, led to the historical seismicity in the UK being amongst the best characterised anywhere in the world.

The UK general approach was applied to the design of Sizewell B, being the first of ten proposed PWR builds in the 1980. Subsequently the site-specific PSHA method was used to support the safety case. This was followed, by application, in a suitably abridged form to existing UK reactor sites and to Sellafield. All of this work was undertaken under contract for the CEGB by a number of specialists working as a collective group called the Seismic Hazard Working Party (SHWP). The primary aim was to develop a methodologically robust conservative estimate of the site-specific seismic challenge at an exceedance probability of 10^{-4}/yr. Although the method produced hazard curves down to exceedance probabilities of 10^{-6}/yr, and URS at various exceedance probabilities across this range, its primary focus was on developing the "conservative" best estimate UHS at 10^{-4}/yr.

The early design response spectra, developed by PML and known as PML spectra, were developed from a statistical analysis of world-wide (but mostly Californian) earthquake records as conservative enveloping spectra to be scaled on PGA. There were three standard spectral shapes, each applicable to different site conditions characterised by the near surface shear-wave velocity as *hard*, *medium* and *soft.* These spectra have the classical enveloping form with straight line elements on a log-log plot. At the time they were perceived to be very conservative especially in the constant displacement / low frequency region, although recent studies have shown that this assumption does not hold across the high-frequency range for hard sites.

With the subsequent introduction of UHS, the UK reactor and major nuclear chemical plant sites generally adopted the following approach: for new plant, relevant enveloping PML spectra anchored to a mean 10^{-4}/yr PGA were used as a conservative design basis; for existing plant, somewhat less conservative mean UHS 10^{-4}/yr spectra were used for analysis of its withstand capability. At the time these mean UHS were deemed to be adequately robust against the real site challenge because of the choice of values for the parameters in the PSHA.

The work of characterising the seismic challenge at each of the reactor sites was completed in 2001 (for Wylfa). The work undertaken by the SHWP and PML for nuclear facilities has never been comprehensively reported into the public domain, or even promulgated effectively to other parts of the UK nuclear industry; although comparable information is available that has been used for the offshore sector [A1]. Consequently, access to this work is limited to a few published papers that cover specific limited aspects. The most comprehensive review available publically was undertaken on behalf of ONR in 2003 [A2]. Other publically available reports that summarise various methodological aspects of the SHWP approach are at [A3], [A4], [A5], [A6] & [A7].

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