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# UK seismic hazard assessments for strategic facilities: a short history

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***ABSTRACT*** The UK is a country with only low to moderate seismicity, and the long intervals between significant earthquakes in Britain results in people forgetting they occur. As a result, seismic hazard was only thought of for the first time in Britain in 1976. For ordinary construction, it is true that seismic hazard can be considered insignificant in the UK, but for strategic facilities, especially those with a high consequence of failure, such as nuclear power plants (NPPs), seismic hazard is important. This paper traces the history of such studies, with emphasis on those for the nuclear industry. The UK seismological community saw major investment from the nuclear industry after 1980. There was a cessation of NPP construction in Britain after 1995, but in recent years steps have been taken towards a resumption of NPP building, which will see a need for new seismic hazard studies.

**Key words:** seismic hazard, nuclear power plants, UK.

## 1. Introduction

There is a widespread misapprehension that Britain is a country without earthquakes; and before the 1970s, this notion extended to the UK engineering community. This was despite the fact that the first commercial nuclear power plant (NPP) in the UK commenced operation in 1956. Memory is short, and the fact that significant earthquakes in the UK are uncommon means that they are easily forgotten. Earthquakes strongly felt in London get far more media attention than those elsewhere (and this was as true in the 16$^{th}$ century as it is today), and the last earthquake widely felt in London was back in 1938 (Neilson *et al.*, 1984; Musson, 1994).

## 2. Early seismic hazard studies in the UK

Around the mid 1970s, awareness dawned that even in a low seismicity country like the UK, earthquakes still occur, and can be sufficiently large (albeit rarely) to be significant for high-consequence structures. The first structure in the UK, so far as I am aware, that was built with potential earthquake hazard in mind, was the Kessock Bridge near Inverness, and here the impetus was the belief that the Great Glen Fault, which the bridge spans, is still an active strike-slip feature [which is open to doubt: Musson (2007)]. At that date the last study of historical earthquakes in the UK was that of Davison (1924). The report on local seismicity compiled for the Kessock Bridge was therefore the first work on historical seismicity in the UK in 50 years (Browitt *et al.,* 1976), the previous one being the British earthquake catalogue of Davison (1924).

Browitt *et al*. (1976) seems also to have been the first published study in the UK in which historical earthquakes were critically revaluated from original source data. The study reproduced verbatim historical accounts from original newspaper descriptions, and assessed epicentral intensity values using both the Modifed Mercalli (1956) and Medvedev-Sponheur-Karník scales, and felt areas, and gave approximate magnitudes, but how these were derived is not discussed. The study makes the point that earthquakes in the mountainous north of Scotland have tended to "migrate" to settled regions; in other words, the population distribution affects the distribution of felt reports and this has caused misperceptions as to where the epicentres lay.

The companion hazard report by Burton and Browitt (1976) made an informal estimate of the 100-year event as 5.2 *mb*, and the 250-year event as 5.6 *mb*, these values taken from a rather approximate magnitude-frequency equation for the whole Inverness region. The authors then selected some strong ground motion records from California that were considered comparable to what might be expected at Inverness. This can be viewed as quasi-deterministic in nature.

At about the same time, Lilwall of the Institute of Geological Sciences [(IGS) now British Geological Survey (BGS)] was working on an attempt to prepare a numerate version of Davison's (1924) catalogue, updated to the present day. This catalogue was the basis of Lilwall's (1976) hazard map of Great Britain, the first quantitative assessment of seismic hazard in the UK. Lilwall's catalogue never progressed beyond a working file, and, as it did not refer back to original sources, incorporated many errors due to Davison's (1924) faulty compilation (to give Davison his due, he was a mathematics schoolmaster, not a historian).

## 3. Seismic hazard and the UK nuclear industry

It was now very apparent that British seismicity needed to be addressed by the nuclear industry, and a lead in this was taken by the then Central Electricity Generating Board (CEGB), and also the Nuclear Installations Inspectorate [(NII) now Office of Nuclear Regulation (ONR)], part of the Health and Safety Executive (HSE), to whom by law regulatory oversight is given under the provisions of the Nuclear Installations Act of 1965. As a result, a large amount of investigation into UK seismicity was undertaken, principally by two consultancies (PML, 1982; SML, 1982), Imperial College London (Ambraseys and Melville, 1983), and BGS (Burton *et al.,* 1984 and references therein). In addition, funding was secured to expand the UK seismic monitoring network, which in the 1970s amounted only to a handful of stations in the Scottish Midlands (LOWNET), which were hardly suitable for detecting earthquakes in the south of England. Interest in seismicity was also taken by the offshore oil and gas industries, in connection with hydrocarbon development in the North Sea. This later led to several studies of general offshore hazard, notably Musson *et al*. (1997) and EQE (2002), both of which included hazard maps for the UK territorial waters. Hazard studies have also been undertaken from time to time for individual offshore sites, though it is not practical to compile a list of all these.

One interesting fact about the development of seismic hazard analysis in the UK at this early period is that there was never any interest in the deterministic method popular in Europe, based on maximum observed intensity. Right from the outset, aside from the Kessock Bridge study, hazard was conceived in probabilistic terms, either from a Cornell-like approach or from extreme value methods [which is what Lilwall (1976) employed]. Even in Burton and Browitt (1976), hazard is tied to earthquake recurrence intervals, even if no probabilistic methodology is applied.

The only other method used for hazard calculation has been a stochastic approach, introduced by BGS in the mid 1990s, and even this gives identical results to the Cornell (1968) method given the same input (Musson, 2012), and is fully probabilistic in nature.

The earliest hazard calculation specifically intended to be relevant to the nuclear industry was made by Irving (1979), who used a single uniform source covering the whole country to come up with a "typical" UK hazard value of 0.25 g peak ground acceleration (*PGA*) for a 10,000 year return period, a result that was later to be much used for mental "anchoring".

In an update, Irving (1982) divided the UK into ten source zones. Remarkably, this was done on a purely geographical basis, with no reference to anything beyond what common parlance would consider to be different regions. Irving's rationale seems to have been that where one draws zone boundaries is immaterial, because one simply proceeds to assess the seismicity rates that pertain to any zone. "Without recourse to tectonic regionalization it can be concluded … that the rough regional boundaries … can be used to rank regions in order of their seismic density per unit area …" (Irving, 1982). It does not seem to have occurred to Irving that, if the regions are not homogeneous with respect to earthquake generation, then the probabilistic seismic hazard analysis (PSHA) method is invalid.

Early hazard software used for site-specific analysis was EQRISK (McGuire, 1976), used by the consultancy Principia Mechanica Ltd. (PML), who made calculations of seismic hazard for various nuclear sites in the early 1980s (Woo, 2013: pers. comm.). In BGS an extreme value hazard program developed by Makropoulos (1978) was employed. An example of its use is found in Burton *et al*. (1981), calculating hazard for a hydrocarbon facility in the NE of Scotland. When the use of extreme value methods was discontinued, SEISRISK III (Bender and Perkins, 1987) was used for a while in BGS, later replaced by in-house software for stochastic simulation hazard estimation.

Spectral hazard for most UK NPPs was dealt with by anchoring standard spectral shapes to a computed *PGA* hazard amplitude. These were established in the 1980s and became entrenched through familiarity and regulatory acceptance, despite the fact that they were initially developed using very few records, and not updated as far more data became available. The development, use, and weaknesses of these standard spectra are reviewed in depth by Bommer *et al*. (2011).

While seismic hazard was not considered in the design basis of early nuclear plants in the UK, those designed after the early 1980s specifically included seismic loading as part of their design. For those built before this time, considerable effort has been expended to qualify the structures, plant and equipment. This included significant retrofitting of structures, systems and components (Weightman, 2011).

## 4. The Seismic Hazard Working Party

During the 1980s and 1990s, the majority of site-specific hazard studies for NPPs were undertaken by a group of consultants led by Mallard of the CEGB, and including staff from PML (before it ceased trading in the UK) and Soil Mechanics Ltd. (SML). The Seismic Hazard Working Party (SHWP), as they were called, developed a consistent set of working practices for PSHA based around a rewritten version of EQRISK (McGuire, 1976) called PRISK, developed by Woo, which included the ability to implement a logic tree structure for handling epistemic uncertainty.

Some consistent features of the SHWP methodology can be recognised: extensive geological and tectonic research and speculation; use of a single simplified seismic source model; adherence to $M_S$ (surface wave) as the only magnitude scale; use of a single model for strong ground motion; activity rates for sources modelled as a ten-point gamma distribution; and a regional *b* value with added small uncertainty. Ground motion was characterised as the larger of two horizontal components, rather than the geometric mean, which is the more common definition today. The lower bound magnitude used throughout was 4.0 $M_S$. The SHWP also placed emphasis on how expert opinion should be treated: a consensus view, made iteratively through open discussion. This open discussion, which would be used to derive logic tree weights, was to be guided by sensitivity of the hazard results to the weighting adopted, and the need for conservatism. This approach to consensus modelling anticipates in some ways current thinking on Senior Seismic Hazard Analysis Committee (SSHAC) methodology (USNRC, 2012).

The SHWP methodology used hardly changed from the mid 1980s to the late 1990s. A typical example study is SHWP (1987). One can see the logic, in that a completely consistent approach over fifteen years meant that there was never a question of an innovation in a later study casting doubt on the results of an earlier study. The disadvantage, however, was that no use could be made of developments in a fast-changing area of science. This particularly applies to ground motion modelling. The SHWP studies all used a single ground motion model for *PGA*, derived by PML (1982), augmented by a second model (PML, 1985) for earthquakes on modelled faults (it is not altogether clear why these should be treated separately) and a third (PML, 1988) for spectral acceleration.

The PML (1982) model was a product of its time, when worldwide resources of strong ground motion data were a fraction of what they are today, and understanding of ground motion behaviour was also far more limited. In a modern PSHA, a major effort would be made to express the epistemic uncertainty in ground motion, usually by employing a selection of models from the literature. In the early 1980s, it was reasonable to ignore epistemic uncertainty in ground motion models, given that PML were driven to developing the 1982 model for the lack of any suitable model they felt could import from elsewhere. By the late 1990s, however, so much progress had been made by the strong ground motion modelling community that ignoring all other studies was less defensible, especially given the inherent weaknesses of the PML (1982) model. Identified problems include, but are not limited to, the very limited data set on which it is based, and the use of a physically unrealistic formulation. If it were judged according to the criteria of Cotton *et al*. (2006), or more recently revised as Bommer *et al*. (2010), it would perform very badly, and would not be considered in any modern study.

To quote from a recent paper: "The shortcomings of the PML (1988) spectral prediction equations, when judged against the state-of-the-art in ground-motion prediction, are many and serious. However, it is an unusual quirk of the UK environment that GMPEs more than 20 years old are even considered fit for purpose, since in other regions of the world it is customary to update such equations as more data become available and as understanding of generation and propagation of seismic waves improves" (Bommer *et al*., 2011).

## 5. Site studies

The SHWP were the major contributors to seismic hazard analysis for nuclear sites in the UK, hence the value in discussing their methodology here. However, they were not the only contributors. Table 1 lists the various NPP sites in the UK, current and closed, and lists the seismic hazard studies done for each plant. The reports themselves are not referenced, as these are generally not obtainable, and sometimes not complete. The two UK Atomic Energy Authority sites at Dounreay and Winfrith are included, but not various civilian and military sites that handle nuclear materials but are not actually NPPs. In any case, such studies are often off the public record (similarly, it would be difficult to track the history of seismic hazard as conducted for dams, chemical plants, etc.). The sites named in Table 1 are shown on Fig. 1. Sites left blank in Table 1 were never the subject of major PSHA studies, though hazard calculations may have been made for them either by PML in the early 1980s, or in passing in other reports. In some cases, hazard projects for the NPP sites in Table 1 took place over several years, and more than one report was issued. In such cases, only the date of the final report is given here.

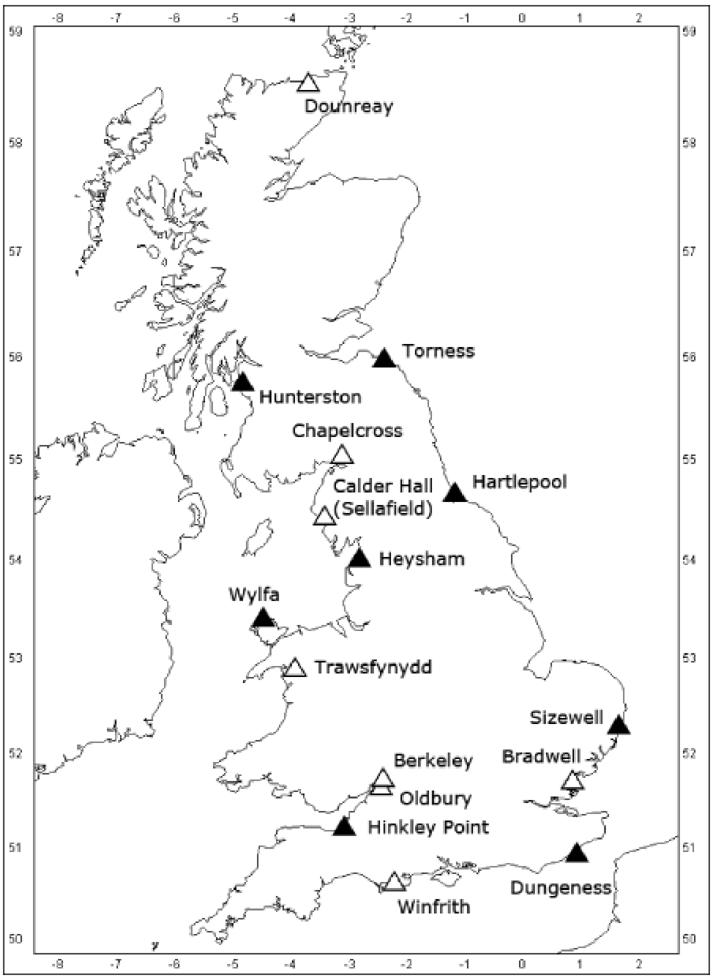


Fig. 1 - Locations of UK NPP sites (including closed sites, indicated by white triangles).

Table 1 - Seismic hazard studies undertaken for NPPs in the UK. The year indicated is year the last PSHA study concluded. A site is marked as currently operational if at least one reactor is still running.
Notes: 1. Sellafield is now a nuclear reprocessing site. The former NPP at Calder Hall, close by, is closed.

| Name of site | Study by | Year | Status |
|---|---|---|---|
| Berkeley | - | | Closed |
| Bradwell | SHWP | 1991 | Closed |
| Chapelcross | BGS & Halcrow | 1993 | Closed |
| Dounreay | Woo | 1994 | Closed |
| Dungeness | SHWP | 1995 | Operational |
| Hartlepool | SHWP | 1996 | Operational |
| Heysham | SHWP | 1996 | Operational |
| Hinkley Point | SHWP | 1991 | Operational |
| Hunterston | - | | Operational |
| Oldbury | - | | Closed |
| Sellafield1 | BGS | 1992 | Closed |
| | SHWP | 1998 | |
| Sizewell | SHWP | 1992 | |
| Torness | - | | Operational |
| Trawsfynydd | - | | Closed |
| Winfrith | - | | Closed |
| Wylfa | SHWP | 2001 | Operational |
| | BGS | 2001 | |

Studies have not been confined to ground shaking hazard; fault rupture has also been considered. While the threat to safety from strong ground motion can be countered with engineering measures, this is not possible with rupture hazard; therefore the presence of a capable fault on a site represents the one seismic concern that can render a site untenable for NPP development. A probabilistic approach to computing fault rupture hazard was pioneered by the SHWP as early as 1987 (Mallard and Woo, 1991).

## 6. Regulatory issues

The regulatory framework for nuclear facilities in the UK requires a formal and detailed safety case to be submitted for NPP sites before permission to construct or operate can be granted; such permissions are granted under the site license issued to the site owner/operator by ONR. The requirement for the site licensee (normally the operator) is to demonstrate that hazard at the site had been adequately characterised, and ONR has published guidance on what this means in its Safety Assessment Principles (SAP), the current edition being HSE (2006). The benchmark by which seismic hazard is measured is typically the *PGA* (with an associated response spectrum), conservatively defined with an annual probability of being exceeded of $10^{-4}$.

The seismic hazard "case" then normally forms a supporting reference to the wider safety case justifying nuclear safety of the activities for which permission is being sought. For a major seismic hazard study that would be expected to support permission to operate a NPP, ONR will assess the technical adequacy of the case using the SAP as a guide, and historically has taken advantage of independent expertise in the Earth sciences community to assist in this task.

For nuclear sites without operating nuclear reactors, a more pragmatic approach can be adopted subject to the overriding principle that risks generally, and those from seismic hazard specifically, are As Low As Reasonably Practicable (ALARP).

## 7. The future

After 1995, there was an end to new nuclear construction in the UK, and after a 2001 BGS assessment of seismic hazard for the Wylfa site in north Wales (opened 1971) no further major NPP seismic hazard assessments were completed. However, a government policy review in 2006 announced the resumption of NPP construction, and since then there has been extensive work on site selection (a mixture of previous NPP locations and new sites). ONR recently commissioned a report on capable faulting in the UK as a general set of guidelines, and founded a permanent panel of reviewers to provide guidance on future hazard assessments, in place of the ad hoc expert reviewing arrangements of the past. PSHA studies are currently in progress for the first new build sites to be considered, which will doubtless reflect advances in PSHA methodology since the last century. Although the SSHAC system developed in the USA (Budnitz *et al.*, 1997; USNRC, 2012) has not been officially adopted in a UK context, SSHAC terminology is now practically unavoidable in PSHA discourse. Projects underway could be classified as somewhere around Level 2 in SSHAC definitions.

As with many countries, the nuclear emergency in Japan following the Tohoku earthquake in 2011 provoked much reflection in the nuclear industry in the UK, notwithstanding the fact that the UK is in a totally different tectonic regime, and thus immune from large subduction earthquakes and attendant tsunamis (with the exception, perhaps, of distant effects of events such as the 1755 Lisbon tsunami). Also, the UK has no boiling water reactors (the type used at Fukushima). With the exception of Sizewell B, which is a pressurised water reactor, all UK NPPs use gas-cooled technology.

Immediately after the earthquake, the Secretary of State for Energy and Climate Change requested that Her Majesty's Chief Inspector of Nuclear Installations examine the circumstances of the Fukushima accident to see what lessons could be learnt to enhance the safety of the UK nuclear industry. The ONR report was published later the same year (Weightman, 2011).

Because the UK nuclear regulatory system is largely non-prescriptive, it is expected that the industry will take the prime responsibility for learning lessons, rather than relying on the Regulator to tell it what to do. The intention behind the ONR report was therefore to point out areas for review where lessons may be learnt to further improve safety, but with the industry taking ultimate responsibility for the safety of their nuclear facility designs and operations (Weightman, 2011). The major conclusion of this report was that the SAP approach to regulation used in the UK, goal-setting rather than deterministic and prescriptive, provided a "a robust, structured and comprehensive methodology for identifying design basis events" for the purposes of seismic safety in the UK. In addition, "the mandatory requirement for UK nuclear site licensees to perform periodic reviews of their safety cases and submit them to ONR to permit continued operation provides a robust means of ensuring that operational facilities are adequately improved in line with advances in technology and standards …" (Weightman, 2011).

In response to a request from the Council of the European Union, a specification for stress tests for nuclear power stations was developed, and the ONR directed that these test should be undertaken by the nuclear industry in the UK. The results of these tests were then collected and published in a second report the following year (Weightman, 2012). In this report, it is concluded that after one year, 58% of items raised in the tests remain open; thus, at the time of writing, these activities are still continuing. Of particular relevance to this paper, Stress Test Finding STF-2 states that "The nuclear industry should establish a research programme to review the Seismic Hazard Working Party (SHWP) methodology against the latest approaches. This should include a gap analysis comparing the SHWP methodology with more recent approaches such as those developed by the Senior Seismic Hazard Analysis Committee (SSHAC)" (Weightman, 2012). At the time of writing, this is still ongoing.

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