The British Dam Society

The 2020 national seismic hazard maps for the United Kingdom

I MOSCA, British Geological Survey
S SARGEANT, British Geological Survey
B BAPTIE, British Geological Survey
R M W MUSSON, University of Edinburgh
T PHARAOH, British Geological Survey

SYNOPSIS The 2020 seismic hazard maps for the United Kingdom (UK) update the previous national maps published in 2007 and are intended for use with the National Annex for the revised edition of Eurocode 8. The 2020 national seismic hazard model uses an up-to-date earthquake catalogue for the British Isles, for which the completeness periods have been reassessed. It also uses a modified version of the 2007 source model and incorporates some advances in ground motion modelling since 2007, including host-to-target adjustments for the ground motion models selected in the logic tree. For the first time, the national maps for the UK are provided for not only peak ground acceleration but also spectral acceleration at 0.2s and 1.0s for 5% damping on rock and the return periods of 95, 475, 1100, and 2475 years. The maps confirm that seismic hazard is generally low in the UK and is slightly higher in North Wales, the England-Wales border region, and western Scotland. We disseminate the updated seismic hazard maps via a dedicated webpage, downloadable data, models and outputs, interactive mapping tools, linkages with professional bodies and industry, as well as public seminars, webcasts, and attendance in scientific conferences.

INTRODUCTION

We have developed a new national seismic hazard model (NSHM) and accompanying national hazard maps (Mosca et al., 2020, 2022) for the United Kingdom (UK), an intraplate region with low levels of seismicity. The 2020 seismic hazard maps update the previous maps published by Musson and Sargeant (2007; hereafter referred to as MS07). The key changes between the 2007 and 2020 NSHMs are the following:

- The earthquake catalogue has been extended from June 2007 to 31 August 2018. Data from the earthquake catalogue of Manchuel et al. (2018) for France and the International Seismological Centre Bulletin database (ISC, 2021) have been used to improve data completeness in the English Channel, Northern France, and the North Sea.
- All magnitudes have been converted to Mw using the relation of Grünthal et al. (2009). This is an update of Grünthal and Wahlström (2003), which was used by MS07.
- The catalogue analysis, including the assessment of completeness and declustering, uses transparent and reproducible approaches.

- The seismic source characterisation (SSC) model, including the zone geometry, the maximum magnitude, and the computation of the earthquake recurrence parameters, has been modified with respect to MS07.
- A new ground motion characterisation (GMC) model that accounts for advances in ground motion modelling since 2007 has been used. This includes host-to-target adjustments (HTTAs) for the selected ground motion prediction equations (GMPEs) in the GMC model.
- The national seismic hazard maps have been computed for a larger area, which also includes the Shetland Islands, than in MS07.
- The national maps describe the hazard in terms of spectral acceleration at 0.2s ($SA_{0.2\,s}$) and 1.0s ($SA_{1.0\,s}$) to meet the requirements of Eurocode 8 and the drafting of a National Annex for the revised edition of Eurocode 8: Design of structures for earthquake resistance.

Engineers from the British Standards National (BSI) committee B/525/8 for Structures in Seismic Regions (the committee responsible for the UK input to Eurocode 8) guided the design requirements for the seismic hazard maps. This ensures that the 2020 maps are used to guide the application of the revision of the Eurocode 8 in the UK calibrating the design seismic requirements to the seismicity levels of the country. Although the UK is a low seismicity region and the design seismic action is not required for standard residential and commercial buildings, design seismic action is recommended for buildings with high economic, social, and environmental consequences (e.g. chemical power plants and dams) where the exceedance of the regional hazard at a specific site is above a certain threshold (Booth et al. 2008; BS NA EN 1998-1 2008).

SEISMO-TECTONIC CONTEXT

The UK lies in the northwest part of the Eurasian plate at the northeast margin of the North Atlantic Ocean, approximately 1,500km northeast of the Mid-Atlantic Ridge and around 2,000km north of the plate boundary between Africa and Eurasia. As a result of this geographic position, the UK is characterised by low levels of earthquake activity (Figure 1; e.g. Musson, 2012a). Evidence for this comes from observations of earthquake activity dating back several hundred years, which suggests that although there are many accounts of earthquakes felt by people, damaging earthquakes are rare. The observed seismic activity in the British Isles provides evidence of ongoing local crustal deformation. However, the nature of the crustal strain field and its relation to the observed distribution of earthquake activity is still not clearly understood due to very low strain rates in the region. Tectonic stresses generated at the Mid-Atlantic Ridge due to forces acting perpendicular to the spreading ridge, as well as strains resulting from the collision of Africa with Europe, are expected to result in a uniform stress field with approximately NW–SE-oriented compression and NE–SW-oriented extension (e.g. Gölke and Coblentz, 1996; Heidbach et al., 2016). This stress field will result in the tectonic loading of existing fault structures.

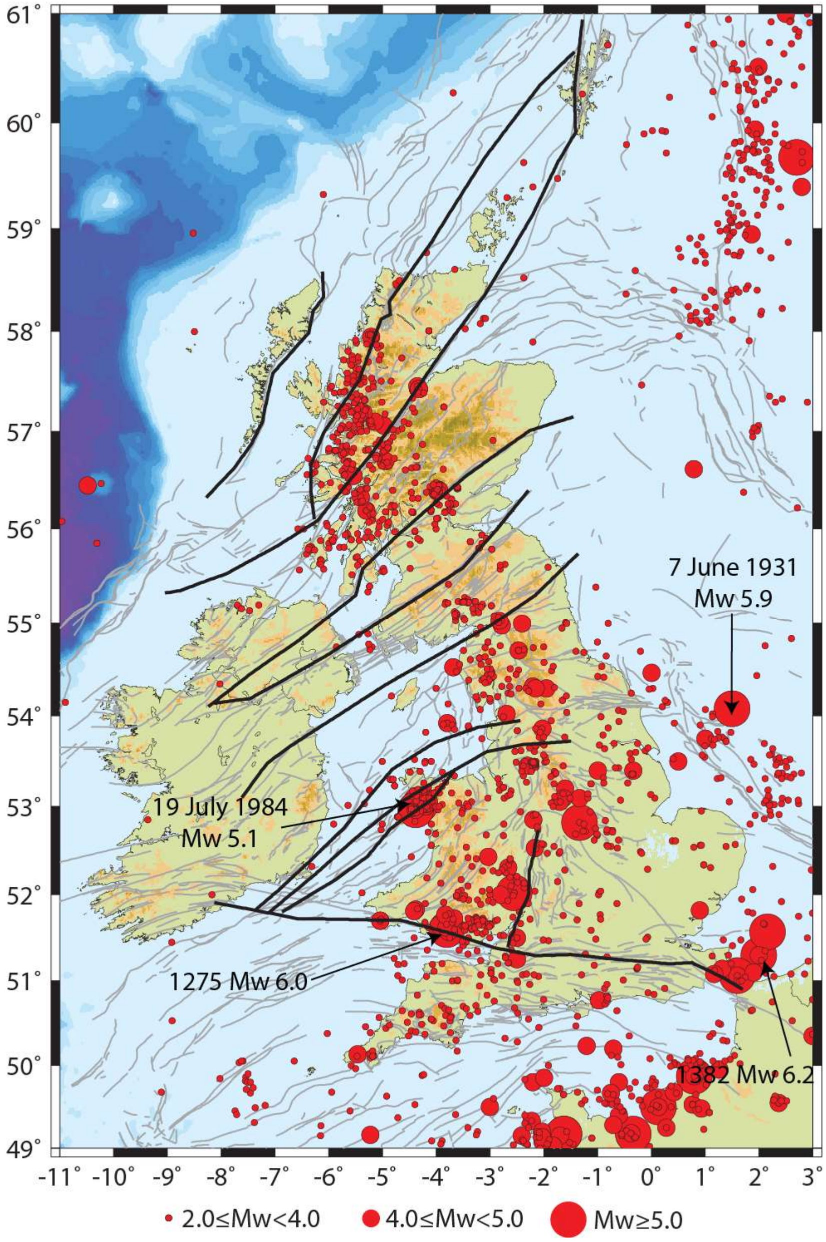

Figure 1. Seismotectonic map for the British Isles. Faults (thin grey lines) and major tectonic structures (bold dark grey lines) are from the British Geological Survey DigMapGB series. Red circles show earthquakes and are scaled by magnitude.

Seismicity in the British Isles is concentrated in a north-south band along the length of Britain, mainly along the western flank. This band gets wider moving south. The northeast of Britain, the northwest Atlantic margin and Ireland all show an absence of notable seismicity (Figure 1). The geographical distribution of instrumentally recorded earthquakes from 1970 to the present generally follows the distribution of historical seismicity over the last 300 years but with a generally smaller magnitude. There are a few exceptions to the correlation between instrumental and historical seismicity, such as the historical earthquakes in the Dover Straits, SW Wales and around Inverness in NE Scotland, where there has been relatively little instrumentally recorded seismicity. This highlights the fact that instrumentally recorded seismicity is not a reliable indicator of earthquake activity either in the past or in the future.

In common with many regions of diffuse intraplate seismicity, it is difficult to unequivocally associate earthquakes in the entire study area with specific faults for the following reasons. Firstly, no earthquake recorded either historically or instrumentally has produced a surface rupture. Secondly, uncertainties in the epicentral location and depth of the earthquakes are typically several kilometres.

The largest earthquakes in the study area are the ∼6.0 Mw 1275 and ∼6.2 Mw 1382 events in South Wales and the Dover Strait (Figure 1), respectively, but their magnitude and location estimates are associated with large uncertainties. The largest instrumentally recorded earthquake in the UK catalogue occurred on 7 June 1931 (5.9 Mw) in the Dogger Bank area of the North Sea; whereas, the largest (4.9 Mw) onshore earthquake in the UK since 1970 occurred on 19 July 1984 near Yr Eifl on the Lleyn (or Llŷn) Peninsula in northwest Wales.

NATIONAL SEISMIC HAZARD MODEL

Figure 2 shows an overview of the logic trees used for both the SSC and GMC components of the 2020 NHSM.

The SSC model consists of a single seismic source model with 22 source zones, each of which is an area where seismicity has an equal probability of occurring anywhere within it. It draws heavily on previous regional source models, including MS07 and the 2013 European Seismic Hazard Model (ESHM13) of Woessner et al. (2015), with some additional modifications to account for recent developments in the understanding of tectonics in the UK. We used the maximum magnitude (Mmax) distribution proposed for the British Isles by Meletti et al. (2009) for the ESHM13 model. It consists of four values (6.5, 6.7, 6.9, and 7.1 Mw with weights of 0.5, 0.2, 0.2, and 0.1), which were applied to all zones. The distribution for the hypocentral depths is between 5km and 20km, with a modal depth of 15km, as proposed by MS07. Strike-slip faulting, with north-south or east-west fault planes, has the highest weight, in agreement with calculated fault plane solutions for instrumentally recorded earthquakes in the last 30 years (Baptie 2010). The expected frequency-magnitude distribution (FMD) for each seismic source zone is quantified using the Gutenberg-Richter frequency-magnitude law (Gutenberg and Richter, 1954). The results of the FMD are expressed by a 5×5 matrix of possible values for the recurrence parameters (i.e. the activity rate a and the b-value), determining 25 triplets of a and b and their weight to account for the uncertainty in these parameters.

The GMC model consists of five GMPEs that were considered to be applicable for the UK. Specifically, these are Atkinson and Boore (2006), Rietbrock et al. (2013), Bindi et al. (2014), Boore et al. (2014), and Cauzzi et al. (2015). Since the strong motion recordings for the UK consist only of weak motion recordings and contain few recordings at near source-to-site distances, the selection of the suite of the GMPEs for the GMC model, together with the assignment of their weights, combines: (1) the results from the comparison of the ground motion predictions computed from candidate GMPEs with the recorded ground motions in the UK using various statistical approach; (2) the outcome from a workshop involving key experts on ground motion modelling. We corrected the ground motion predictions from the five GMPEs for the HTTAs using the approach of Al Atik et al. (2014) to account for differences in site conditions between the host regions, for which the GMPEs were derived, and the target region (i.e. the UK). This process accounts for both the effects of elastic amplification due to shear wave velocity structure and near-surface attenuation at a site, which is described by the parameter κ_0.

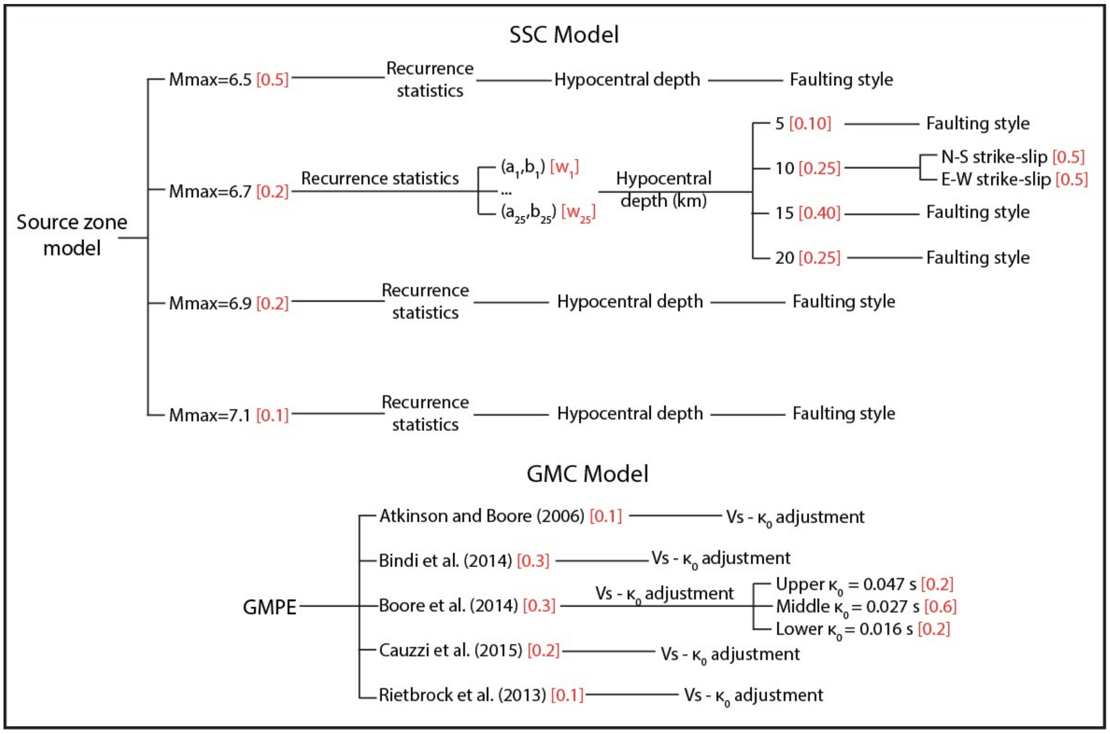

Figure 2. SSC and GMC logic tree for the NSHM for the UK .

NATIONAL SEISMIC HAZARD MAPS

We calculated the hazard using Monte Carlo-based probabilistic seismic hazard analysis (PSHA) to generate artificial catalogues by random sampling of the probability distributions in the SSC model (Musson, 2000). Musson (2012b) and Mosca (2019) show that the Monte Carlo-based approach is compatible with the Cornell-McGuire type approach for PSHA and provides the same output given the same initial model.

The minimum magnitude (Mmin) in a hazard calculation is defined as the threshold for potentially damaging earthquakes (e.g. Bommer and Crowley, 2017). Here, we used Mmin of 4.0 Mw to include the probability that the impulsive nature of small earthquakes and their high-frequency content could be potentially causing damage.

The hazard calculations were carried out for the region between 49°N - 61°N and 8.5°W - 2°E for a grid of 4141 points spaced 0.125° in latitude and 0.25° in longitude. We computed the hazard for peak ground acceleration (PGA), $SA_{0.2\ s}$, and $SA_{1.0\ s}$ with 5% damping for Vs30 (time-averaged shear wave velocity for the top 30 m) of 800 m/s and the return periods of 95, 475, 1100, and 2475 years. Figures 3 and 4 show the national hazard maps for return periods of 475 years (10% annual frequency of exceedance in 50 years) and 2475 years (2% annual frequency of exceedance in 50 years), respectively. For 475 years, PGA is less than 0.04g for most of the UK, except for North Wales and the England-Wales border region where the hazard reaches around 0.09g and 0.05g, respectively (left panel of Figure 3). A similar spatial variation is observed at 0.2s but the effects are more pronounced (central panel of Figure 3). At 1.0s, accelerations are smaller than 0.02g (right panel of Figure 3) but show less variation across the UK. For a return period of 2475 years, the Channel Islands, North Wales, the England-Wales border region through to North Central England, the Lake District and north-west Scotland are the areas of highest hazard for PGA and $SA_{0.2\ s}$ (Figure 4). The highest hazard values (0.25g for PGA and 0.47g for $SA_{0.2\ s}$) are observed around Snowdonia, in North Wales.

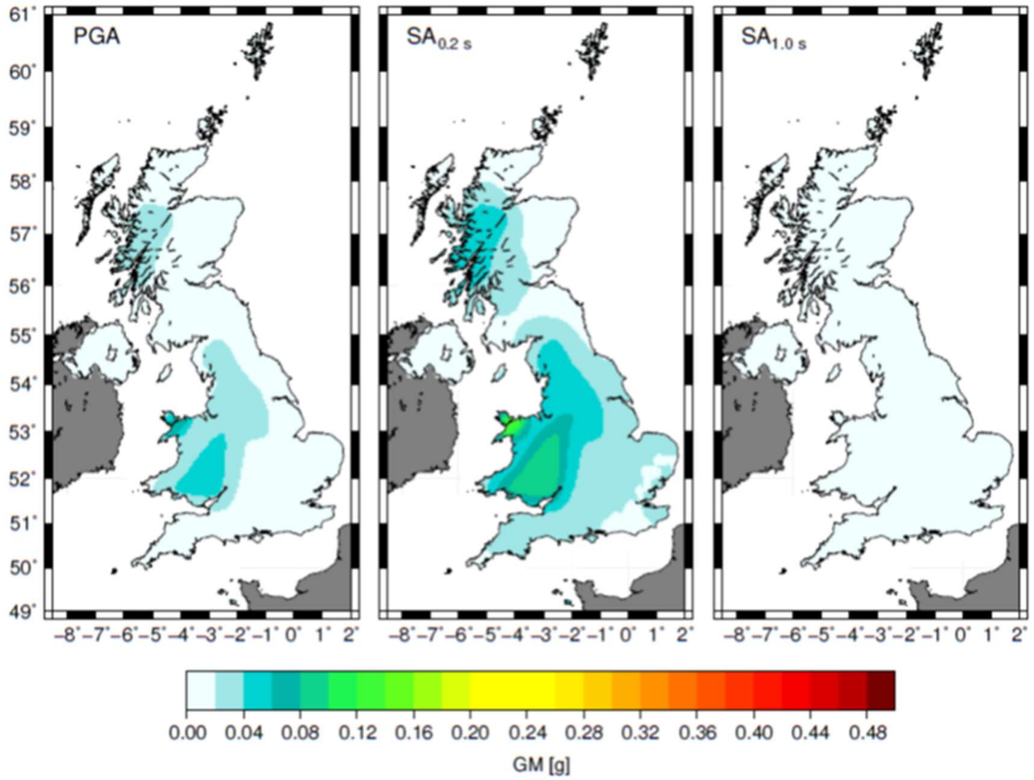

Figure 3. Hazard map for PGA, $SA_{0.2s}$, and $SA_{1.0s}$ at the 475-year return period.

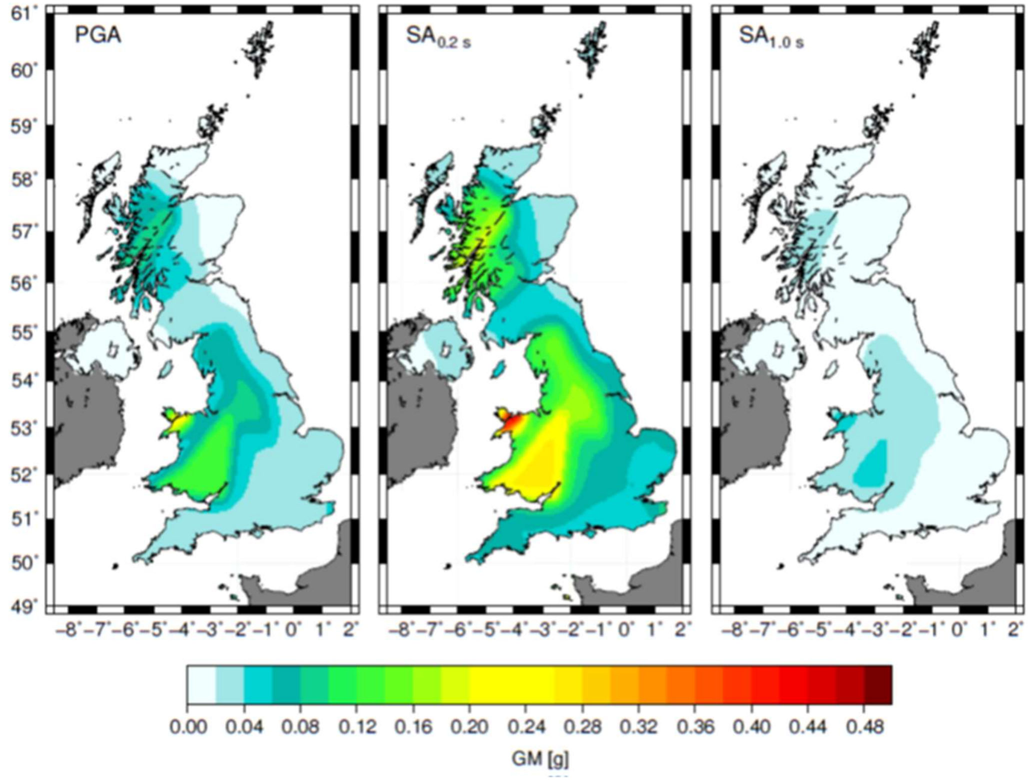

Figure 4. Hazard map for PGA, $SA_{0.2s}$, and $SA_{1.0s}$ at the 2475-year return period.

DISSEMINATION OF THE RESULTS

To increase the visibility of the 2020 NSHM for the UK and make it accessible and available to a wide range of users, we used various channels and tools.

The products of the NSHM are accessible to the public through a dedicated webpage (http://www.earthquakes.bgs.ac.uk/hazard/UKhazard.html) and an interactive mapping tool (https://www.bgs.ac.uk/map-viewers/geoindex-onshore/). The former allows users to download all elements of the NSHM model and the output files in text format. The latter allows users to view the hazard maps interactively, navigate to a specific area of interest, query the maps, and download the hazard values at a specific location or area of interest. It is the first time that the seismic hazard maps for the UK are interactively accessible to the public. Furthermore, accessible data to the public ensure the transparency of the hazard model.

To promote the work with end-users (e.g. the engineers' community in the UK), we communicated the results of this project to professional bodies, such as BSI committee B/525/8 and the Institution of Civil Engineers (ICE), and presented them in a public talk of the Society for Earthquake and Civil Engineering Dynamics (SECED). We also disseminated the 2020 national hazard maps on the BGS website (https://www.bgs.ac.uk/news/developing-new-seismic-hazard-maps-for-the-uk/) and the ICE website (https://www.ice.org.uk/news-and-insight/the-civil-engineer/november-2020/updated-seismic-hazard-maps-for-the-uk) and published them in a peer-reviewed journal (Mosca et al., 2022). Finally, we presented the outcomes of this project at a number of scientific conferences, e.g. the SECED conference in September 2019, the annual meeting of the Seismological Society of America in April 2021, the 3rd European Conference on Earthquake Engineering and Seismology in September 2022.

CONCLUSIONS

We have developed the 2020 seismic hazard model for the UK and accompanying hazard maps for PGA and spectral acceleration at different return periods using a Monte Carlo approach for PSHA and objective and reproducible data-driven analyses.

National hazard maps are only a first-order approximation of seismic hazard for engineering structures and help to identify regions of high seismic hazard to inform the need for site-specific risk assessments. The decisions to construct the seismic hazard model are not driven by the specific site of interest as it happens for site-specific PSHA but are taken uniformly across the region (e.g. Musson and Sargeant 2007; Gerstenberger et al. 2020). A site-specific assessment might be required if the hazard exceeds some given threshold at the site after the appropriate site conditions for the site are taken into account. Also, NSHMs usually do not consider the hazard for long (≥ 10,000 years) return periods that are important for highly critical structures, such as dams and LNG power plants. To compute the hazard for such long return periods, the effects of distant large earthquakes and the occurrence of earthquakes at very long recurrence intervals should be accounted for. The former requires computing the hazard at longer spectral periods, and the latter requires a detailed geological investigation in the area within 300km of the site to understand when these faults were last active (e.g., IAEA, 2022).

REFERENCES

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

Atkinson, GM, and Boore, D M (2006). Earthquake ground motion prediction equations for eastern North America. *Bulletin of the Seismological Society of America*, **96(6):** 2181–2205.

Baptie B (2010). Seism genesis and state of stress in the UK. *Tectonophysics*, **482(1-4):** 150-159.

Bindi D, Massa M, Luzi L, Ameri G, Pacor F, Puglia R and Augiera P (2014). Pan-European ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods up to 3.0 s using the RESORCE dataset. *Bulletin of Earthquake Engineering*, **12(1):** 391–430.

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

Boore D M, Stewart J P, Seyhan E and Atkinson GM (2014). NGA West 2 equations for predicting PGA, PGV, and 5%-damped PSA for shallow crustal earthquakes. *Earthquake Spectra*, **30(3):** 1057–1085.

Booth E D, Skipp B and Watt P (2008). Establishing the need for seismic design in the UK. *Research Enabling Fund, Report ICE-02*, Issue 2, 31/01/2008, Institution of Civil Engineers, London, United Kingdom.

BS NA EN 1998-1 (2008). *UK National Annex to Eurocode 8: Design of structures for earthquake resistance.* British Standard Institution, London, United Kingdom.

Cauzzi C, Faccioli E, Vanini M and Bianchini A (2015). Updated predictive equations for broadband (0.01–10s) horizontal response spectra and peak ground motions, based on a global dataset of digital acceleration records. *Bulletin of Earthquake Engineering*, **13:** 1587–1612.

Gerstenberger M C, Marzocchi W, Allen T, Pagani M, Adams J, Danciu L, Field E H, Fujiwara H, Luco N, Ma K-F, Meletti C and Petersen M D (2020). Probabilistic Seismic Hazard Analysis at Regional and National Scales: State of the Art and Future Challenges. *Review of Geophysics*, **58**: https://doi.org:10.1029/2019RG000653.

Gölke M and Coblentz D (1996). Origins of the European regional stress field. *Tectonophysics,* **266(1–4)**, 11–24.

Grünthal G and Wahlström R (2003). An Mw-based earthquake catalogue for central, northern and northwestern Europe using a hierarchy of magnitude conversions. *Journal of Seismology*, **7:** 507-531.

Grünthal G, Wahlström E and Stromeyer D (2009). The unified catalogue of earthquakes in central, northern, and northwestern Europe (CENEC)— updated and expanded to the last millennium. *Journal of Seismology*, **13:** 517-541.

Gutenberg B and Richter C (1954). *Seismicity of the Earth and Associated Phenomena*. Princeton University Press, New Jersey, USA

Heidbach O, Rajabi M, Reiter K, Ziegler M and the WSM Team (2016). World stress map database release 2016. *GFZ Data Services*.

IAEA (2022). Seismic Hazards in Site Evaluation for Nuclear Installations. *IAEA Specific Safety Guide Series No. SSG-9*, International Atomic Energy Agency, Vienna, Austria.

ISC (2021). *International Seismological Centre* (2021), http://www.isc.ac.uk/, https://doi.org/10.31905/D808B830 .

Manchuel K, Traversa P, Baumont D, Cara M, Nayman E and Durouchoux C (2018). The French seismic CATalogue (FCAT-17). *Bulletin of Earthquake Engineering*, **16:** 2227-2251.

Mosca I (2019). Comparing seismic hazard software: M3C vs. OpenQuake. *British Geological Survey Open Report OR/19/038.* British Geological Survey, Nottingham, United Kingdom.

Mosca I, Sargeant S, Baptie B, Musson R M W and Pharaoh T (2020). National seismic hazard maps for the UK: 2020 update. *British Geological Survey Open Report OR/20/053*, British Geological Survey, Nottingham, United Kingdom.

Mosca I, Sargeant S, Baptie B, Musson R M W and Pharaoh T (2022). The 2020 national seismic hazard model for the United Kingdom. *Bulletin of Earthquake Engineering*, **20:** 633–675.

Musson R M W (2000). The use of Monte Carlo simulations for seismic hazard assessment in the UK. *Annals of Geophysics*, **43:** 1-9.

Musson R M W (2012a). Interpreting intraplate tectonics for seismic hazard: a UK historical perspective. *Journal of Seismology*, **16:**261–273.

Musson R M W (2012b). PSHA validated by quasi-observational means. *Seismological Research Letters*, **83**: 130-134.

Musson R M W and Sargeant S (2007). Eurocode 8 seismic hazard zoning maps for the UK. *British Geological Survey Report CR/07/125*, British Geological Survey, Nottingham, United Kingdom.

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

Wöessner J, Giardini D and the SHARE Consortium (2015). Seismic hazard estimates for the Euro-Mediterranean region: A community-based probabilistic seismic hazard assessment. *Bulletin of Earthquake Engineering*, **13:** 3553-3596.