A comparison of the seismicity of the UK and southeastern Australia

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Abstract In principle, the Global Seismic Hazard Assessment Program enabled, for the first time, the seismic hazard in areas of like tectonic setting to be compared. In practice, the formal process was not rigorously applied in some areas including Australia and the UK. We use modern and historical data, and strong motion information (intensity) to compare the seismicity of the UK where there is a 1000 yr long written history with a similar sized area in southeastern Australia with a 150 yr written history. These data are used to comment on the association of earthquakes and geological structure, to produce risk estimates for strategic areas within each of the two regions and to discuss the differences in engineering code requirements. If like-minded societies have a different response to risk assessment then the question *why* needs to be asked.

Introduction In an ideal world, people everywhere would face a similar level of risk from natural hazards by societies employing engineering solutions to mitigate their effects, reducing tem to a acceptable level; using building codes to make buildings less vulnerable to earthquakes and cyclones for example. To do this you would firstly have to quantify the hazard and then write and use a suitable loading (building) code with regulations specifying appropriate construction and foundation detailing.

The Global Seismic Hazard Assessment Program (GSHAP) initiated by the International Association for Seismology and the Physics of the Earth's Interior (IASPEI) for the United Nations 1990s *Decade for Natural Disaster Reduction* was the first attempt to map earthquake hazard worldwide using a standard methodology and format (Giardini and others, 1999). The mapping parameter chosen was peak ground acceleration (pga) on rock with a 10% probability of exceedence in 50 years. Comparing hazards and the way different societies cope with them is useful but the process actually used for GSHAP was crude in many cases; in the USA the standard methodology wasn't actually used. In Australia the then current hazard map was adopted with no special study; in the UK a new map was computed using a simplified version of the seismic model previously used in Musson and Winter (1996, 1997).

The parallel program initiated by the International Association for Earthquake Engineering (IAEE) to develop an international building code, the World Seismic Safety Initiative or WSSI, was unfortunately never finalised so the risks faced by different societies cannot be equated without a dedicated study.

We have taken two regions, Britain and southeastern Australia centred on Victoria, of similar size and with very similar cultural and legal backgrounds facing seemingly similar levels of earthquake hazard to see how each addresses the threat of earthquakes. Firstly we investigate the hazard in more detail, and then comment on the steps taken by their respective governments to ameliorate the risk.

History of earthquakes and of earthquake monitoring Seismographs were deployed relatively quickly in both the UK and southeastern Australia after their development late in the 19th century. However these early instruments were of little

use in recording useful ground shaking data from local earthquakes. That didn't happen in Australia until the late 1950s; in the UK high-gain, short-period instruments for studying local events were only set up around 1970 (Crampin, 1970). In both regions, instruments capable of measuring ground shaking for engineering purposes (accelerographs) were not installed until the 1990s.

In 2007, the British Geological Survey operates a monitoring network of 145 seismograph stations across the UK. Most of the stations consist of single, vertical component, short-period seismometers, although there are also a number of three-component seismometers and accelerometers. However, the network is increasingly being converted to broadband, with a reduction in the number of stations (Baptie, 2007). In Victoria there are currently 31 seismographs, mostly triaxial, and 9 accelerographs; fewer instruments but quieter sites.

The primary aim of the UK network is to develop a database of seismic activity for seismic hazard assessment and to provide a response to felt earthquakes. In addition, data are available for investigations of crustal and upper mantle structure and processes. In southeastern Australia most of the seismographs are dedicated to providing an alert service to owners of dams and other major infrastructure, and other roles are a secondary consideration.

On average, the UK network locates between 300 and 400 earthquakes per year and is capable of detecting all events greater than 2.0 ML (Richter local magnitude) in mainland Britain. In a typical year, around 40 events have magnitudes greater than ML 2.0 and about 20 are felt by local residents. In Victoria about 180 earthquakes are located in any year of which about 6 may be reported felt.

Where the earthquake databases differ is in the pre-instrumental written history, barely 100 years in southeastern Australia, over 1,000 years in the British Isles. Many earthquakes in each region's catalogue were located using intensity observations. The epicentre is usually assumed to be within the maximum intensity isoseismal, the focal depth estimated from the rate of change of intensity near the epicenter, and magnitude estimated in Australia from the radius of perceptibility (McCue, 1980).

The introduction of both global and regional seismograph networks following the International Geophysical Year, 1957-58, greatly improved the detecting capability, and thus the number of earthquakes within the catalogue, and the accuracy of locations and magnitude estimation. Another change occurred in southeastern Australia when digital seismograph networks were installed from about 1976.

The largest earthquakes observed were of similar magnitude: in Victoria at Mt Hotham on 3 May 1966 and Offshore Cape Otway on 14 September 1965, both magnitude ML 5.7, and in the North Sea in 1931, magnitude ML 6.1. Neither Australian event caused damage because of their distance from urban areas (more than 100 km). The 1903 Warrnambool earthquake on the south coast of Victoria was the state's most damaging earthquake to 2007 though no lives were lost. The maximum intensity on the modified Mercalli scale was rated as 7, with shear failure of un-reinforced masonry walls, fall and rotation of stone filials on church steeples, liquefaction features such as sand-boils, and extensive damage to tombstones. Its magnitude, derived from the felt area, was 5.3 (McCue, 1978).

The North Sea earthquake of 7 June 1931, magnitude ML 6.1, had an offshore epicentre in the Dogger Bank area (120 km NE of Great Yarmouth). It is the largest known earthquake in the UK. It was felt over most of Britain, eastern Ireland, the

Netherlands, Belgium, northern France, parts of northwest Germany, Denmark and southwest Norway. Damage in Britain was reported from 71 different places, the strongest effects at Filey, where the top of a church spire was rotated. Bridlington, Beverley and Hull were also affected, most of the damage affecting chimneys and plaster. A factory roof is reported to have collapsed at Staines (Surrey) and rocks or cliff collapse occurred at Flamborough Head and Mundesley, Norfolk. The earthquake was reported felt by a number of vessels in the North Sea and a woman in Hull died of a heart attack, apparently as a result of the earthquake. The 19 July 1984 Lleyn event of North Wales, with a magnitude of 5.4 ML, was the largest onshore earthquake this century in the UK and was felt over an area of around 240,000 square kilometres. The earthquake occurred in the lower crust at a depth of approximately 22 km and was followed by many aftershocks. Detailed mapping of the aftershock distribution highlighted a plane orientated WNW-ESE and dipping steeply NNE. This represents the fault plane and corresponds well with one of the planes of the mainshock focal mechanism. There is, however, no surface fault or feature which corresponds to this plane.

The maximum intensity in the epicentral area was 6 EMS (European macroseismic scale) and damage consisted of widespread cracks in plaster and falls of some chimneys and weak plaster. High intensities of 5 and 6 EMS reported from Liverpool appear to be due to the state of repair of some of the buildings.

Isoseismal maps of the similar sized Warrnambool and Lleyn earthquakes are shown for comparison of felt areas and regions of highest intensity, but note the scales.

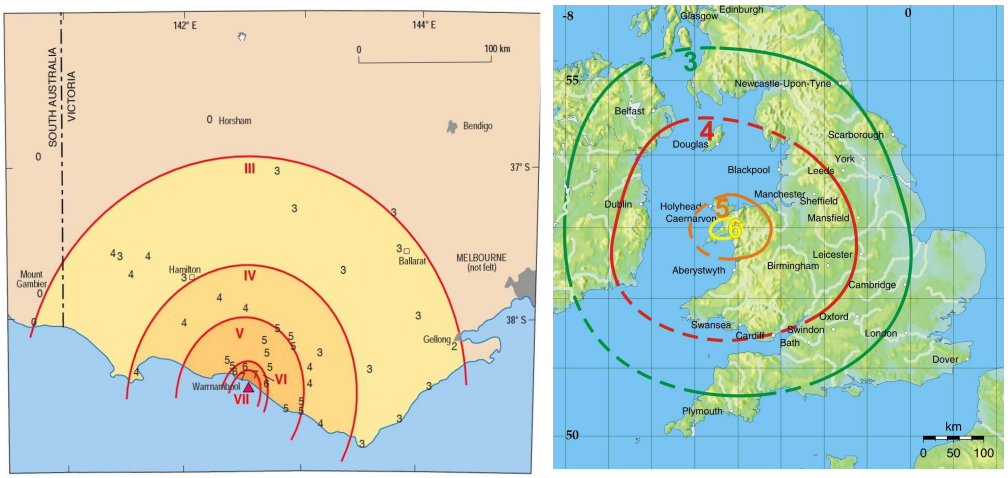

Figure 1 *Isoseismal maps of the Warrnambool Victoria earthquake, 14 July 1903, magnitude ML 5.3 and the 19 July 1984 Lleyn event of North Wales UK earthquake, magnitude ML 5.4*

There is no reason to suppose that larger earthquakes could not occur in either region. Magnitude 6+ earthquakes have occurred near the west and southeast borders of Victoria in the last 120 years. The Cadell Fault is a Recent fault scarp just north of the Victorian border, with significant offset in the past 30 000 years. Its mapped length is 40 km with a maximum displacement of more than 3 m, so the causative earthquake must have been about magnitude 7 (see Clark, 2007). This earthquake dammed and then redirected the Murray River to another course. Needless to say such an earthquake today in either the UK or Victoria would be very destructive. While there is no reliable palaeoseismic evidence for large earthquakes in the UK (Stewart et al., 2001), there is for Belgium (Camelbeeck and Meghraoui, 1996; Camelbeeck, 1999).

Seismicity

Southeastern Australia All earthquakes located in this region between 1900 and 2007 August 31 are shown in Figure 2 below. There are obviously more events in the east of the region than in the west, though one of the largest events plotted was in the far west of the map.

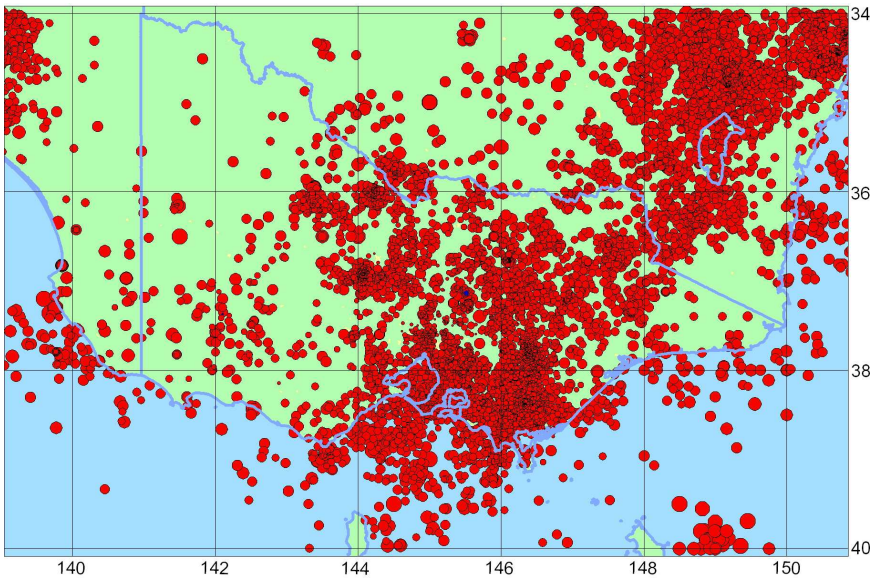

***Figure 2**: Earthquakes in southeastern Australia, 1900 to 2007.*

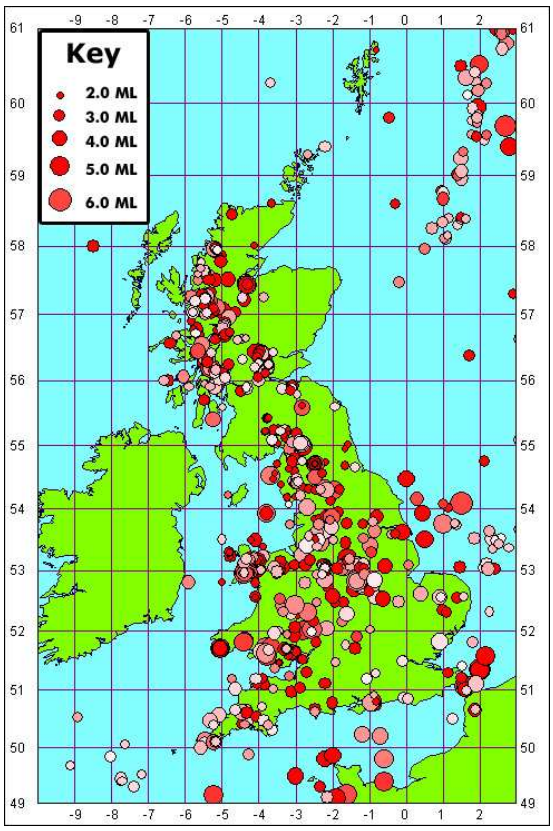

***Figure 3** Earthquakes in the UK to 2007.*

Focal depths All of the computed foci in southeastern Australia are in the upper crust, with a few as deep as 22 km (the transition zone above which deformation is assumed to be by brittle fracture and below it by plastic deformation). Allen et al (2004) demonstrated a variation in the character of seismicity of Victoria with depth, including a decreasing proportion of small to large magnitudes (*b-value*) with increasing depth. Many events occur at shallow depths, within about 4 kilometres of the surface, including shallow swarms that may be felt locally and many of the reservoir triggered earthquakes, plus possibly other induced or triggered events, but with few events larger than magnitude 4.0 to 4.5. Most larger earthquakes occur at depths from about 9 to 15 kilometres.

Onshore UK seismicity generally occurs within the seismogenic zone, to mid-crustal depths. However, the

activity on the Lleyn Peninsula following the 1984 mainshock and subsequent aftershock series occurred at depths of around 22 km, in the lower crust. Other well constrained deep activity has occurred in the Welsh Borders around Newtown, suggesting a lowering of this brittle-ductile transition zone. In contrast, shallower than average focal depths of around 6 km are obtained for Cornwall where radiogenic granites are responsible for the highest heat flow in the UK. Variation in the cut-off depth for crustal seismicity is thought to be due to a combination of heat flow and chemical/mineralogical differences (decreased quartz levels) in the crustal rocks.

Earthquake Recurrence

Recurrence relations describing the frequency of earthquakes in both southeastern Australia and the UK are shown in Figure 4 where the annual cumulative number of earthquakes per year is plotted against magnitude (normalised to the area of the UK map, 1.105 x 10^6km^2).

Southeast Australia (0.78 x 10^6 km^2): log Nc = 4.24 – 0.95 M
UK (1.105 x 10^6 km^2): log Nc = 3.59 – 1.01 M

The scatter about the linear line of best fit is quite large in both areas and the b-value is almost the same over much of the magnitude range (the curves are almost parallel). The southeastern Australian area includes large earthquakes (up to M6.5) in the volcanic zone to the west and the largest of an unusual swarm of earthquakes off northeast Tasmania in the 1880s.

The expected once-per-year earthquake in SE Australia is 4.3 compared with 3.6 in the UK, and the once-per-hundred year earthquakes are 6.3 and 5.6 respectively.

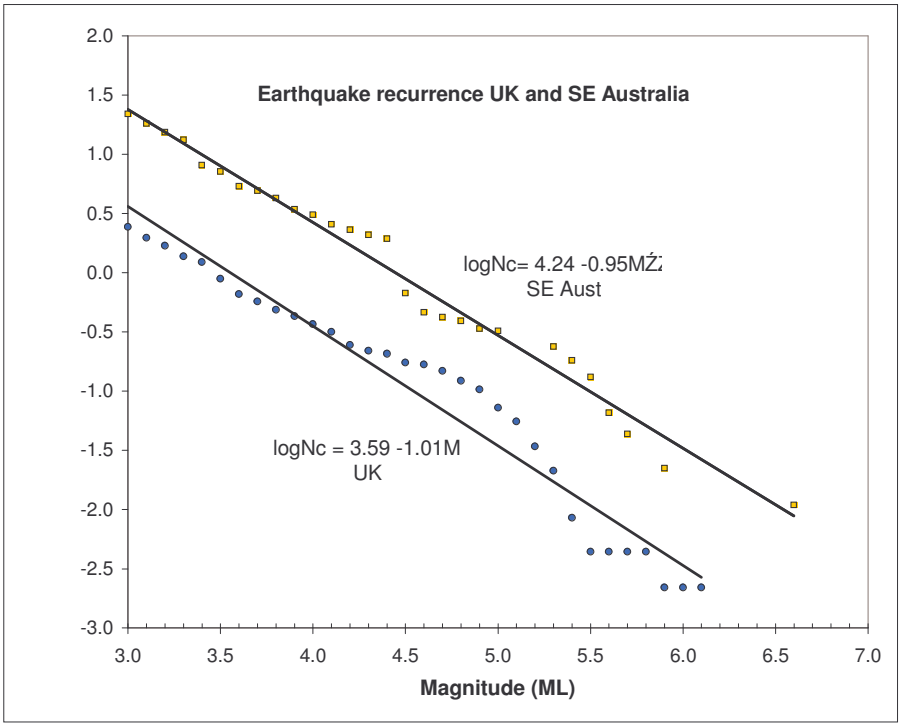

Figure 4. *Comparison of the cumulative annual frequency of earthquakes in the UK and southeastern Australia. The solid lines are the least squares fit to southeast Australia (upper) and UK (lower) annual earthquake numbers.*

Relation of earthquakes with structure (faults)

In areas of high seismicity and dense monitoring, for example along the San Andreas fault complex in California, where major faults can be mapped at the surface, the relationship between an earthquake and the associated fault movement can often be firmly established. Occasionally major earthquakes occur on previously unknown 'blind' faults or unmapped faults, even in California.

It is more difficult to identify the causative faults in areas of low seismicity, where long-term average fault slip rates can be similar to local erosion and sediment deposition rates. The length of the fault involved in generating small magnitude events need only be of the order of a few hundred metres and faults may show no related surface features. Location errors for the calculated hypocentre vary according to the magnitude of the event, the station density, and station distribution about the hypocentre. If the earthquake occurred offshore or near the coast, there is an asymmetrical distribution of the monitoring stations and correspondingly much greater location errors.

Onshore, surface geological maps are highly detailed for the UK showing an abundance of mapped faults. For a given epicentre, if surface fault density is high and location errors are large, the error 'circle' can encompass many possible causative faults. The causative fault may be listric in nature, shallowing with depth, and extrapolation between the focus at depth and any surface feature vertically above would not be relevant. Deeper earthquakes in the mid-lower crust may occur on faults that have no connection to the surface and, therefore, no related surface feature.

The seismicity distribution for mainland and offshore UK is neither random nor uniform in density, with more frequent and larger events occurring on the west coast. In Scotland, most of this activity is concentrated between Ullapool and Dunoon with centres near the Great Glen and clusters of activity at Comrie. North Wales, especially around Caernarvon and the Lleyn Peninsula, and the Welsh border area also show higher levels of seismicity. The NE of Scotland and the SE of England are, in contrast, areas of low seismicity, although examination of the historical record shows that NE Scotland, around Inverness, and SE England were both active. Areas such as Aberdeen and Caithness have, however, always been quiet. Offshore, in the North Sea, there is a clear correlation of epicentres with the major structures, the Viking and Central grabens, the Norwegian coastal region, and with the NE Atlantic passive margin. The major basin-bounding faults are, therefore, currently active, or at least, subject to current reactivation. The stuctural highs in this region are, in contrast, relatively aseismic, for example the West Shetland Platform and the Mid North Sea High.

As in the UK, Victoria has an excellent set of 1:250,000 scale geological maps covering all regions apart from those with Quaternary sediment cover. Many of the faults were initiated in the late Palaeozoic during a period of extreme east-west compression, giving a series of north-south striking reverse faults, some of which form major geological boundaries within the state. Following a period of extensional tectonics in the late Mesozoic and early Tertiary, a renewed period of compression began in the mid-Tertiary. Today, the maximum principal stress trends southeast-northwest in Gippsland in the southeast of the state, and east-west in the west and north. This stress direction facilitates rejuvenation of the Palaeozoic faults, many of which show late Tertiary and Quaternary movement, albeit at a very much lower level of activity than in the Palaeozoic when they were initially created.

Smaller approximately parallel faults occur between the larger faults, and most places within the state are within 10 to 20 kilometres of a significant mapped fault.

The dominance of reverse faulting means that earthquakes are offset from the surface outcrop of the fault under the upthrown block, for distances of 20 to 30 kilometres. The faults appear to be slightly listric, with dips near the surface being typically about 35° to 40°, and slightly shallower at depths to about 15 to 20 kilometres.

As in the UK, uncertainties in earthquake locations due to the limited seismograph network make it difficult to use earthquake locations to delineate faults. This is only possible when seismographs are in a dense network designed to precisely locate events, such as when recording reservoir triggered earthquakes, or aftershock sequences. However, when epicentres are distributed in a band along the upthrown side of the fault (relative to activity on the downthrown side), it may be possible to assume that the fault is at least partially responsible for the activity.

If the rate of geological deformation across a fault may be estimated over the late Tertiary or particularly within the Quaternary, then this may be compared with the seismicity along the fault. For example, the vertical offset across a reverse fault over geological time should be compatible with the seismicity parameters for the fault.

Traditionally it was believed that earthquakes occurred in temporally random clusters, often with foreshocks and usually with aftershocks. It was assumed that this occurred at all scales, so monitoring of small earthquakes on a fault or within a region would give a quantitative estimate of the recurrence of larger earthquakes.

Most modern models of seismicity now consider an earthquake cycle that involves a long period of stress accumulation between events that produces little earthquake activity. As high stress levels are approached, precursory and/or foreshock activity may occur before the mainshock. This is followed by aftershocks in or near to the main rupture, and possibly by adjustment events in the surrounding region, followed by another long period of quiescence as the stress accumulates again.

Monitoring activity during the quiescent period will usually not yield useful information regarding future activity. However, activity occurs on many scales, and regional seismograph monitoring analysed together with fault information may eventually allow development of a time-dependent seismo-tectonic model that will give a more reliable indication of future activity than the spatial distribution of earthquakes alone. In some cases it may be possible to detect precursory activity. About half of the Australian earthquakes with magnitude exceeding 6.0 show precursory activity in the year to ten years before the major event

Attenuation Earthquake hazard analysis requires knowledge of how the amplitude of ground shaking on representative rock or soil foundations attenuates with distance, and how frequency content varies. The amount of shaking at any point will vary with the magnitude of the earthquake, its depth, and the distance from the point to the epicentre or closest point on the rupturing fault.

Deriving a local attenuation functions for intensity is usually possible as there are often plenty of observational data available. But since strong ground motion recording instruments are a fairly recent development and still not widely used, finding empirical data for calculating acceleration or spectral attenuation is difficult. This is particularly the case for low-seismicity areas, where significant earthquakes are rare anyway.

Acceleration attenuation data are available in California, the Mediterranean, New Zealand and Japan. In places like Eastern North America, Northern Europe and Australia seismologists look to theoretical techniques to estimate attenuation, in order to circumvent the lack of hard data.

What little strong motion data has been obtained for the UK (and also northwest Europe) appears to show PGA values that are grossly overpredicted by published ground motion models (Musson et al., 1994, Free et al., 1998). A recent study by Bommer et al., (2007) shows that ground motion does not scale in a uniform way with magnitude, and the implications of this have yet to be fully taken into account in hazard studies in intraplate areas. There are also considerable problems in modelling strong ground motion from smaller earthquakes due to uncertainties in the metadata, and this can lead to exaggerated scatter in the resulting model (Bommer et al., 2007, Musson and Sargeant, 2007).

Earthquake hazard assessments The results of the GSHAP process can be compared in the two regions as a first approximation: the part of Southeast Australia considered here is entirely in the 0.8 – 1.6 m/s^2 rating whereas western England and Scotland and all of Wales is in the lower band, 0.4 – 0.8 m/s^2, eastern England and Scotland in the lower band again, 0.2 – 0.4 m/s^2 and all of Ireland in the 0 – 0.2 m/s^2 band. The GSHAP hazard rating for Southeast Australia varies from the upper range of "Low" to the lower range of "Moderate", while that in the UK covers the three levels of "Low". For a given recurrence interval, such as the 10% probability of exceedence in 50 years, the peak ground acceleration in Southeast Australia is higher by a factor of about 2 to 4.

Source models have evolved in both southeastern Australia and the UK since GSHAP. The original PSHA models (Cornell, 1968) are being extended to include Monte-Carlo type methods, and source models begin to include geological data from active faults, increasing the resolution of hazard. Results from these show that hazard may be more variable than originally expected and with greater extremes, though treating the uncertainty more formally with the Monte-Carlo methods usually does produce higher hazard assessments.

Monte-Carlo methods can also be used with conventional source zone models as a way of computing hazard in a quasi-observational way, rather than the Cornell (1968) approach, which relies on integration. This was done in the most recent hazard mapping study for the UK (Musson and Sargeant, 2007).

Earthquake monitoring and strong ground motion recording are required to refine our understanding of the level of seismic risk in both the UK and southeastern Australia. Although seismic hazard is low by world standards it is by no means negligible, particularly with respect to potentially hazardous installations and sensitive structures. The results help in assessment of the level of precautionary measures which should be taken to prevent damage and disruption to new buildings, constructions and installations which otherwise could prove hazardous to the population.

With the higher hazard assessments obtained using Monte Carlo methods and the large uncertainty in expected earthquake ground motion measurements, it is possible that the level of hazard in the UK and southeastern Australia may not be as different as GSHAP maps show.

Engineering practice After the magnitude 6.8 Meckering earthquake in Western Australia (Everingham and others, 1969), Australian engineers moved to introduce an earthquake building code throughout Australia (Bubb, 1999) following advice that earthquakes were possible throughout continental Australia. Subsequent monitoring and historical and paleoseismology studies (McCue 1990, Clark and McCue, 2003) have shown evidence of large, magnitude 6 or greater, earthquakes in each state though there are extensive regions with no observed large earthquakes.

The probability of a potentially destructive earthquake occurring in the UK or southeastern Australia in any year is about 1%. This can be expressed another way as; the return period of a magnitude 6 earthquake is about 100 years in southeastern Australia, and about 300 years in the UK. This is interpreted in Australia as evidence that building regulations should incorporate earthquake resistant design for all buildings throughout the region where the loading code site factor (S) exceeds 1, i.e. unless the building is on rock and has a low occupancy factor or low importance.

In the UK, only nuclear power stations are rigorously required to be designed and built to resist earthquakes. Why the difference? Are Australian lives more valuable than those in the UK? Perhaps it can be attributed to the fact that the unthinkable political reality has already occurred in Australia at Meckering WA in 1968 which showed engineers what damage a major earthquake was capable of wreaking, followed by the fatalities and extensive damage from the Newcastle earthquake of moderate magnitude 5.6 in December 1989. Not only could it happen, but it did, and it could happen anywhere in Australia, as the paleoseismic evidence shows.

Could it happen in Britain? If so the consequences do bear thinking about, because to do otherwise with all the evidence available would be political suicide. Up to now, the idea of enforcing earthquake regulations for non-nuclear-related structures has been considered politically unacceptable, due to the perception (not incorrect) that the likelihood of earthquake damage in the UK is rather low. No engineered building has ever been damaged in a British earthquake as yet. In contrast, the hazard from wind is high, given the damaging gales that the UK is subject to, and designing buildings against wind does give them lateral strength that is also useful in resisting earthquakes. Recently, though, the occurrence of a shallow magnitude 4.3 ML earthquake under the town of Folkestone, Kent, has given earthquakes in the UK more prominence – this was the first occasion on which a UK local authority has had to institute emergency procedures and evacuate unsafe buildings (Musson and Walker 2007). Of course this raises the question of what to do about existing buildings, but a suitable strengthening program could start quickly with schools and hospitals and post-emergency buildings.

Acknowledgment

The contribution of RMW Musson is published with the permission of the Executive Director of BGS (NERC).

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