Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 286

CONSERVATISM IN INTRAPLATE PSHA STUDIES

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ABSTRACT

When conducting probabilistic seismic hazard studies for seismic design, it is conventional, in addition to trying to cover the range of epistemic uncertainties, to opt consciously for decisions that tend towards the conservative, for obvious safety-related reasons. In hazard mapping studies, however, this constraint does not apply, since it is generally considered bad practice to take seismic design parameters from a map. Specifically, it can be shown that seismic hazard maps cannot be equally conservative over the whole area; therefore there is not really any reason to make them conservative at all. For intraplate areas, for instance, a typical problem relates to locations in proximity to past isolated damaging earthquakes. Whether one treats these as stationary events or as floating within a structural source zone is likely to depend on the purpose of the study. It was a project requirement in a recent hazard mapping study in the UK to treat the analysis in a non-conservative way; the resulting PGA values proved to be considerably lower than those obtained in previous studies. This naturally led to a desire to understand the reason for such a drop, of the order of a factor of three in some places. In this paper, the differences between a consciously conservative analysis and a non-conservative analysis are broken down into components to examine the impact of ground motion model, seismic stationarity, minimum magnitude, source model design and other factors contributing to the difference between the value that might appear on a map, compared to what might be found in a report intended for engineering design. It is shown that no single factor is dominant, and a combination of design decisions contribute to the difference in values.

Introduction

In 2006, the British Standards Institute (BSI) commissioned a new set of seismic hazard maps of the UK to inform the British National Annexe of Eurocode 8 (see Booth 2008). It was a specific part of the brief for this project that the model developed for the study should aim at realistic decision-taking without regard for conservatism. The results, when they appeared (Musson and Sargeant 2007), occasioned some surprise at the general lowness of the values; for the 475-year

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return period, only small parts of Wales showed PGA values in excess of 0.04 g, whereas in the SESAME map of seismic hazard in Europe (Giardini et al. 2003), 0.04 g is exceeded over the whole of Wales, and much of England and Scotland. This naturally invited speculation as to the reasons for the reduction, which is even greater when comparison is made with various commissioned site-specific studies. (Unfortunately, since such studies are never published, they cannot easily be cited, and this paper is restricted to referring to them anonymously).

The explanation of the differences is instructive. Some components relate to general developments in PSHA practice, particularly the development of new ground motion models; there is a large contrast between what was available to the SESAME project and what was available to Musson and Sargeant (2007) – even if some of the more recent models had to be accessed in draft form at the time. Other influences relate specifically to conservative and non-conservative decision-making.

It is worth stating at the outset that hazard maps can never be equally conservative over the whole area, therefore it is inappropriate to try and make them conservative at all (Musson and Henni 2001). An example is given by Reiter (1990) of two nuclear power plants in the same part of the USA, where the hazard computation turned on the issue of whether a particular geological feature was or was not seismogenic. Assuming it was, increased the hazard at plant A and reduced it at plant B. Assuming it wasn't, decreased the hazard at plant A and increased it at plant B. In the interests of conservatism, the logical course of action is to take the more pessimistic assumption depending on which plant is under study. But a hazard model for a map has to do for both sites, and for all others in the area. It cannot be conservative everywhere. This is a very good reason why the practice of reading design values off a seismic hazard map is bad (Page and Basham 1985). The same could also be said about handy seismic hazard calculators, web-enabled or otherwise, in which the user is encouraged to type in co-ordinates and calculate hazard from some generic model.

Contributors to conservatism

The following issues are identified as the principal factors in making a PSHA study conservative or non-conservative. They are presented here in alphabetical order. It is assumed that hazard is being computed in terms of PGA, but the factors apply equally to other physical ground motion parameters.

Component definition

This is simply how one chooses to define PGA. Early ground motion models used in the UK (e.g. Principia 1982, Ambraseys and Bommer 1991) took PGA to be the larger of two components. Most modern ground motion models define PGA as the geometric mean of two components, or something similar (Akkar and Bommer 2007). The reason for using the geometric mean is that this provides a more stable measure (Campbell 1981). Switching definition immediately changes the PGA by about 15%. Principia (1981) do use conservatism as a justification for preferring the maximum component definition, but ultimately it is a technical issue.

Depth

When using ground motion models that rely on hypocentral or rupture distance, the typical focal depths of earthquakes has an influence on the hazard. Earlier studies of seismic hazard in the UK tended to use depth distributions that were conservatively biased towards depths in the 5-10 km range. From the UK earthquake catalogue (Musson 1994), depths of 10-15 km are more common, and it is shown in Musson (2007) that there is some correlation between magnitude and depth. Events larger than 4 Mw with depths as shallow as 5 km are rare. Using ground motion models based on Joyner-Boore distance, depth has no effect; though one can argue that hypocentral/rupture distance is more suitable when dealing with small earthquakes (Musson and Sargeant 2007). Using only Joyner-Boore distance regardless of rupture size may be a factor in observing magnitude-dependent sigma (Musson 2009).

Faulting

The issue of the proper treatment of faults in intraplate PSHA is vexed, and a full discussion is outside the scope of the present paper (but see Musson 2005, Musson et al 2008). To put it simply, how does one handle the case where a historical earthquake is recorded close to a site of interest? In practice, this may vary depending on whether the event is close to a mapped fault. If it is, and can reasonably be attributed to that fault, then the fault is called "active" and modelled explicitly. This is not really correct. Assuming the earthquake to be accurately located, if it didn't occur on a mapped fault it occurred on an unmapped fault, and faults don't change their dangerousness at the moment someone maps them – even in California, as the seismicity of the last few decades has shown, unmapped faults can be just as dangerous as mapped ones.

The real issue, for intraplate earthquakes, is whether a historical earthquake indicates the presence of a structure that is a repeating source of earthquakes, or whether it is a background event that can occur anywhere in a structural region with the same probability. It is quite likely, in an intraplate case, that one has no geological or seismological evidence on which to base an answer to this question. Therefore the main basis for the decision will be made with respect to the purpose of the study and the appropriate level of conservatism needed. Thus, for a study calculating site hazard for a critical facility close to the epicentre, one would be inclined to assume a fixed source (conservative), whereas for a hazard map, valid for all locations, one would be inclined to assume a background event with the potential to strike in many places.

This can lead to substantial changes in hazard for site values compared to those plotted on a map, the size of the change being dependent on what one assumes about the activity of the fault, notional or otherwise. For instance, in 1884, a damaging earthquake occurred near the town of Colchester, Essex, in an area of otherwise very low seismicity. In the model of Musson and Sargeant (2007), this is treated as a background event in a large homogenous zone representing the English Concealed Caledonides, and the local 2,500 year PGA is less than 0.04 g. For a critical facility sited at Colchester, one would be inclined to introduce a notional stationary fault source, capable of repeating the 1884 earthquake, possibly in a larger version (the historical magnitude was around 4.5 Mw) at some estimated annual probability. The actual geology is heavily overlain with glacial deposits. Depending of the nature of the assumptions one made, the likely effect would be to increase the PGA by 50% for the 2,500 year return period, and by progressively larger amounts at longer return periods, e.g. by double or more than double for 10,000 years.

Nor is it an answer to add the notional fault to the hazard map model, as one would then have to do the same for every other earthquake, and end up with a map that simply recapitulated historical seismicity in a stationary manner – which would be obviously incorrect.

Ground motion model

Choice of ground motion models is an obvious area for conservatism in PSHA. In NW Europe, due to the lack of local strong motion data, it has always been necessary to import a model from elsewhere. There is not even a clear indication as to whether one should look for models from active European (or even Californian) conditions, or non-empirical models designed for areas such as Eastern North America; general practice in the past has been to take the former approach. In Musson and Sargeant (2007), the decision was made by a steering panel representing all interested parties in UK seismic hazard to use two models, one selected from the NGA project (Campbell and Bozorgnia 2006), and Bommer et al (2007) – both of these were in draft at the time of the project (Booth 2007). One could easily make more onerous choices; for instance, of the NGA models, Chiou and Youngs (2008) tends to be more conservative than Campbell and Bozorgnia (2006, 2008). Also, the model of Principia (1982), used for many early studies in the UK, tends to be on the conservative side.

Maximum magnitude

This is another parameter where obviously one can take a conservative or non-conservative line. There is no good evidence for any earthquake with Mw much above 5.0 ever occurring onshore in the UK, so there is a case for designing a source model that caps onshore seismicity at, say, 5.5 Mw (see for instance, Ambraseys and Jackson 1985). On the other hand, one can point to palaeoseismic evidence for stronger earthquakes, around 6.5 Mw, in Belgium (Camelbeeck and Meghraoui 1996), and it would be unsafe to assume this could not happen across the English Channel. So a conservative choice of maximum magnitude would be more likely to be around 7.0 Mw. In practice, because of the low probability of such events, maximum magnitude tends not to be a sensitive parameter, but it could be if one were to assume a very low b-value.

Minimum magnitude

Also referred to as lower bound magnitude (LBM). This is an arbitrary cut-off of modelled seismicity at smaller magnitudes in PSHA computations. Small earthquakes can produce high accelerations, but due to their short durations, these are considered "not of engineering significance". A full discussion of the topic is beyond the scope of this paper. Common values generally range between 4.0 Mw and 5.0 Mw (Benjamin 1989). The lower the value adopted, the higher the hazard result will be, though the degree of this effect varies depending on the nature of the ground motion model. The value selected may not be chosen on grounds of conservatism, but nevertheless has an effect.

Zone model

This category is something of a final catch-all. Obviously, there are many different ways in which the geometry of seismic source models can be drawn (and if using a zoneless approach, many different ways in which smoothing parameters can be defined). Decisions made may have differing effects on differing sites. For instance, consider a model designed for hazard mapping containing two adjacent zones, the eastern one of which contains more earthquakes. An analyst using this as the starting point for a site study for a location in the western zone, might elect to merge the two zones, which is a conservative decision for the western part of the model (but obviously not for the eastern part). Or short of merging them, might move the boundary between the two zones further west to bring the seismicity closer to the site. Either way, these are consciously conservative decisions with respect to the site under question, which can have no counterpart in the decisions taken for a generic model.

These seven factors are likely to contribute to conservatism in a wide range of PSHA studies, with the possible exception of the component definition, since the use of the geometric mean is now more or less a standard in contemporary methodological practice. It is not very likely that a modern analyst will consciously decide to use the older definition as a conservative choice, whereas there is no avoiding the need to make a choice of ground motion models.

Magnitude conversion

However, there is a further factor that is relevant at least to the UK case, and which, while not strictly an instance of conservative decision-making, has an effect that can't be ignored in comparing hazard studies.

If one looks at all the seismological literature relating to the seismicity of NW Europe in the last 30 years, one will find three magnitude scales. Local magnitude, ML, is the scale of preference for most of the regional seismic monitoring agencies. Moment magnitude, Mw, is only gradually replacing it, but is the scale of preference for modern ground motion models. Surface-wave magnitude (Ms) was used in older ground motion models (e.g. Ambraseys and Bommer 1991) and some earthquake catalogues (e.g. Ove Arup 1993), and therefore in many of the older seismic hazard studies.

To compare studies, therefore, one needs to make some sort of conversion between scales. For ML to Mw, a very well-constrained formula exists by Grünthal and Wahlström (2003), which agrees with purely UK data. For ML to Ms, an empirical relation by Marrow (1992) converts between these two scales specifically for UK data. For Ms to Mw, conversions by Ambraseys (1995), Scordilis (2006) and others are all in good agreement. The problem is that these three do not agree with one another (Fig.1). For example, an event of 4.4 ML converts to 4.1 Ms and 4.0 Mw – but 4.1 Ms converts to 4.8 Mw, 0.8 units higher. Since the ML to Ms and ML to Mw equations are consistent with or derived from local data, the problem evidently lies with the Ms to Mw conversion, which is imported. It is found by Bungum et al (2003), and confirmed by Grünthal and Wahlström (2003) that for NW Europe, Ms ≈ Mw. There are very few UK earthquakes for which both native Ms and native Mw are available; for those that exist, the semi-equality is reasonable (and in fact Mw is slightly lower than Ms).

This is not an issue of conservatism as such; given the evidence, it is not likely that one would specifically choose to apply Scordilis (2006) to convert UK Ms to Mw, just in order to be conservative. But this issue influences the whole discussion of comparisons. So for instance, it might be thought that the choice of 4.5 Mw as a minimum magnitude in Musson and Sargeant (2007) – the value recommended by the steering panel – was equally conservative as the 4.0 Ms used by numerous previous studies. In fact, it is less conservative, since it equates to 4.5 Ms.

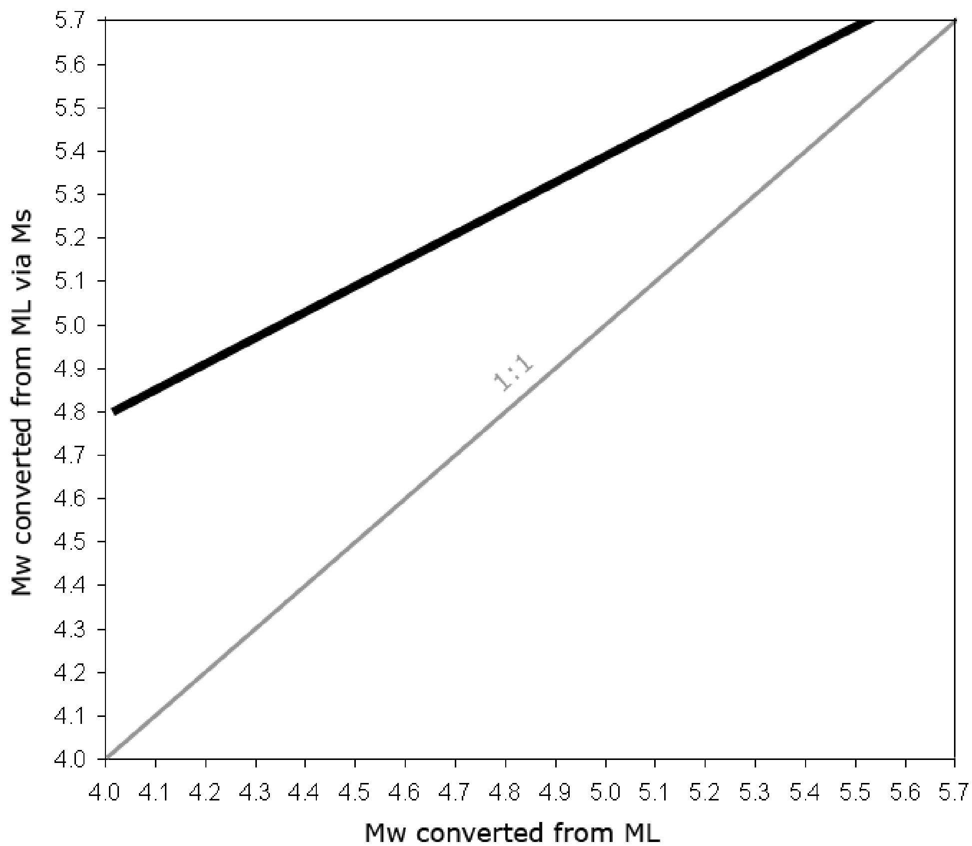

Figure 1. Discrepancy between Mw values when converted directly from ML or via Ms; 1:1 line shown for comparison.

It also illustrates the sensitivity of PSHA to issues that can easily be overlooked. Taking what appears to be a reliable conversion formula such as Scordilis (2006), and using it to convert an Ms-based earthquake catalogue such as that of Ove Arup (1993), and calculating hazard using modern ground motion models such as those from the NGA project, would be to increase all magnitude values in the computations by up to 0.8 of a degree, which would inflate the hazard undesirably.

Relative contributions to conservatism

There is no absolute guide to which factors contribute most to the overall conservatism of the results. Some factors combine in different ways – for instance, as mentioned above, maximum magnitude is a more sensitive parameter when low b-values are used (large earthquakes are relatively common) and not at all sensitive when b-values are high (large magnitudes are very improbable). The effect of including an explicitly-modelled fault depends largely on what parameters are assigned to it, including the logic-tree probability that it even exists.

As an illustrative guide to one possible case, a site was chosen in the NW of England for which a commercial unpublished hazard model, dating from the early 1990s, was privately available. For a return period of 10,000 years, the site-specific model (the target) gives a PGA of 0.24 g. Using the Musson and Sargeant (2007) model, one obtains 0.07 g for the same site, a third of the value. To track the contributions of different factors, the Musson and Sargeant (2007) model was gradually amended, step by step, until it matched the site-specific model, and the progressive change noted. The results are shown in Table 1.

Table 1. Progressive changes to PGA result for a sample site

	PGA (g)	**Increase**	**% of total difference**
Starting value	0.07		
Changing component definition	0.08	0.01	6
Changing ground motion model	0.10	0.02	12
Fixing magnitude conversion	0.13	0.03	18
Lowering Mmin	0.15	0.02	13
Adding notional fault	0.18	0.03	17
Raising Mmax	0.19	0.01	3
Using shallower depths	0.21	0.02	14
Changing zone model	0.24	0.03	17

The magnitude conversion issue is included here as a factor; the Musson and Sargeant (2007) model is couched in Mw, whereas the ground motion model in the target study used Ms. The change to the original ground motion model was done in two stages: firstly, the ground motion model was changed to that used in the target study, using Ambraseys (1995) to handle Ms to Mw conversion. This increased the PGA by 12% of the difference between starting and finishing values. Then the conversion was fixed to Ms=Mw, which added another 18%. (The reason why the hazard increases here when the conversion is fixed is because, in order to match the older model, Mw has to be converted to Ms, which is the reverse of the usual conversion). If the correct magnitude conversion were applied at the same time as the change in ground motion model (i.e. in one step rather than two) the difference in ground motion model would account for 30% of the total difference, in accord with received wisdom that epistemic uncertainty in ground motion models is one of the major factors in determining PSHA results. However, if one treated the magnitude conversion as an epistemic uncertainty, this would be the largest single contributor in this example.

The contribution of the fault added in the target study, to accommodate a historical earthquake near the site, is obviously restricted to this case only. The parameters attributed to the fault could have been more conservative still, which would have increased the impact. The same goes for differences in the zone model; this refers not only to the geometry of the zones, but also the computation of activity rates for each zone. It is notable, though, that changing the minimum magnitude by only 0.5 degrees accounts for 13% of the total difference, compared with a mere 3% for differences to the maximum magnitude. Changing the depth model was also significant.

Conclusions

The publication of Musson and Sargeant (2007) provided an illustration of the effects of deliberately avoiding conservative decision-making in PSHA. The difference between the results of that study and previous site studies can be of the order of a factor of three; this difference is completely explicable, and does not depend on any one single factor. As might be expected, the choice of ground motion model is the single largest contributor, but only contributes about a third of the difference. Differences in the source model (including the addition of a local fault) contribute another third of the difference, which could be a greater proportion in other cases (e.g. if the fault was given greater activity). The rest of the difference is contributed by a collection of issues: definition of PGA, maximum and minimum magnitude, and the depth distribution.
Also significant is the fact that Musson and Sargeant (2007) used a catalogue expressed in Mw (converted from ML) and Mw-based ground motion models, making no use of Ms, and thus avoiding problems associated with the fact that Ms appears to scale differently in NW Europe compared to other regions.

Acknowledgments

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References

Akkar, S. and Bommer, J.J., 2007. Empirical prediction equations for peak ground velocity derived from strong-motion records from Europe and the Middle East Bulletin of the Seismological Society of America, 97, 511-530.

Ambraseys, N.N., 1988. Engineering Seismology Earthquake Engineering and Structural Dynamics, 17, 1-105.

Ambraseys, N.N., 1995. The prediction of earthquake peak ground acceleration in Europe Earthquake Engineering and Structural Dynamics, 24, 467-490.

Ambraseys, N.N. and Jackson, D.D., 1985. Long-term seismicity in Britain. In: Earthquake engineering in Britain. Thomas Telford, London.

Ambraseys, N.N. and Bommer, J.J., 1991. The attenuation of ground accelerations in Europe Earthquake Engineering and Structural Dynamics, 20, 1179-1202.

Benjamin, J.R., 1989. Lower-bound magnitude for probabilistic seismic hazard assessment. EPRI, Mountain View.

Booth, E., 2007. Preparation of UK seismic hazard zoning map: Notes of project review meeting held at ICE HQ London, 26th April 2007. Privately circulated.

Booth, E., 2008. UK studies for the preparation of the UK National Annex to Eurocode 8. In: Proceedings of the conference Seismic risk in northern Europe, Liege, Belgium.

Bungum, H., Lindholm, C.D. and Dahle, A., 2003. Long-period ground-motions for large European earthquakes, 1905–1992, and comparisons with stochastic predictions Journal of Seismology, 7, 377-396.

Camelbeeck, T. and Meghraoui, M., 1996. Large earthquakes in northern Europe more likely than once thought EOS, 77, 405,409.

Campbell, K.W., 1981. Near-source attenuation of peak horizontal acceleration Bulletin of the Seismological Society of America, 71, 2039-2070.

Campbell, K.W. and Bozorgnia, Y., 2006. Campbell-Bozorgnia NGA empirical ground motion model for the average horizontal component of PGA, PGV and SA at selected spectral periods ranging from 0.01-10.0 seconds. Interim Report for USGS Review.

Campbell, K.W. and Bozorgnia, Y., 2008. NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s *Earthquake Spectra*, **24**, 139-172.

Chiou, B.S.-J. and Youngs, R.R., 2008. An NGA model for the average horizontal component of peak ground motion and response spectra *Earthquake Spectra*, **24**, 173-216.

Giardini, D., Jiménez, M.J. and Grünthal, G., 2003. European-Mediterranean seismic hazard map. ETH, Zurich.

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.

Marrow, P.C., 1992. UK earthquake magnitudes: a comparison of methods and published results. Global Seismology Report WL/92/36.

Musson, R.M.W., 1994. A catalogue of British earthquakes. Global Seismology Report WL/94/04.

Musson, R.M.W., 2005. Faulting and hazard in low seismicity areas. In: Stability and buffering capacity of the geosphere for long-term isolation of radioactive waste (OECD, ed. Nuclear Energy Agency, Paris.

Musson, R.M.W., 2007. British earthquakes Proceedings of the Geologists' Association, 118, 305-337.

Musson, R.M.W., 2009. Ground motion and probabilistic hazard Bulletin of Earthquake Engineering, 7, 575-589.

Musson, R.M.W. and Henni, P.H.O., 2001. Methodological considerations of probabilistic seismic hazard mapping Soil Dynamics and Earthquake Engineering, 21, 385-403.

Musson, R.M.W. and Sargeant, S.L., 2007. Eurocode 8 seismic hazard zoning maps for the UK. British Geological Survey Technical Report CR/07/125.

Musson, R.M.W., Sellami, S. and Brüstle, W., 2008. Preparing a seismic hazard model for Switzerland: The view from PEGASOS Expert Group 3 (EG1c) Swiss Journal of Geology, DOI 10.1007/s00015-008-1301-1.

Ove Arup, 1993. Earthquake hazard and risk in the UK. Dept. of Environment, London.

Page, R.A. and Basham, P.W., 1985. Earthquake hazards in the offshore environment. USGS Bulletin 1630.

Principia Mechanica Ltd, 1981. Seismic ground motions for UK design. Principia Mechanica Ltd, Cambridge.

Principia Mechanica Ltd, 1982. British earthquakes. Principia Mechanica Ltd, Cambridge.

Reiter, L., 1990. Earthquake hazard analysis. Columbia University Press, New York.

Scordilis, E.M., 2006. Empirical global relations converting Ms and mb to moment magnitude *Journal of Seismology*, **10**, 225-236.