Introduction

Assessing seismic hazard is difficult enough even in active seismic areas with a long written history and a strong paleoseismology program, given the short period of instrumental recording, and the general lack of site-specific strong motion data. Making such assessments in areas of low seismicity with sparse populations is even more difficult. PSHA is not difficult to do, the difficulty is in justifying the results in a court of law.

Modern PSHA studies use a Cornell (1968) method within a decision tree structure allowing almost infinite flexibility in decision making for a hazard analyst. Infinite in the sense that any model of the source, the recurrence relation (a and b values), the maximum (and minimum) magnitude, the ground motion or spectral amplitude prediction equation, and site foundations that cannot be shown to be inapplicable should be given some weight in the hazard assessment process. A section of a typical decision tree model is shown below.

The process and results are strongly reliant on the particular expert group convened to do the study. Geologists with a strict biblical interpretation of Earth formation or an Earth-expansion model of tectonics would not normally be included in such an expert group - the mean results of any consequent analysis would be meaningless if they were. Such people are generally not given a place at the experts’ table or their views are given zero weight. The moral for clients is to choose their experts carefully. But even the most knowledgeable ‘experts’ estimate the weighting factors with an informed guess - there is no magic formula (see Bommer and others, 2004).

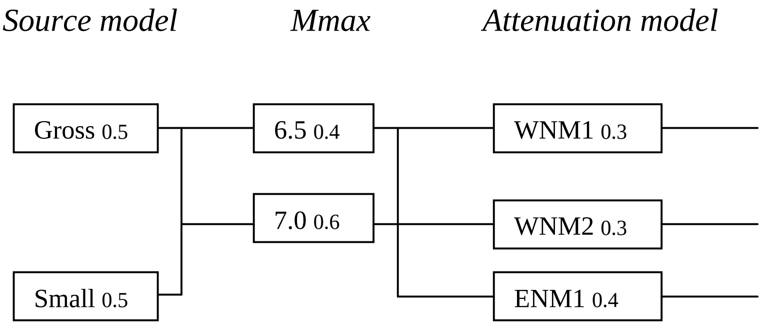

Figure 1 Part of a logic tree with input choices and weights

Some common practices that might be difficult to defend in a law court are discussed below.

The Source Choosing to assign earthquakes either to a few broad source zone areas or multiple small sources with or without active faults, or some combination of these can result in dramatically different estimates of hazard. Factors such as the site-fault distance and the relative weighting of faults and area sources are critical, especially when near-source effects are considered, as they must be in New Zealand or California. A good example is the Alpine Fault that dominates hazard calculations in the South Island despite the lack of a single large shallow earthquake on it in historical times. Compare the current hazard map of New Zealand (Stirling and others, 2002) using seismicity and paleoseismicity with the earlier maps (Smith,

1976) that were based mainly on historic seismicity. Which model best represents reality, in the short term and in the long term (see comments by Clark this volume)?

In Australia where the very existence of active faults is a topic of scientific debate, all views have some adherents. Most would accept that earthquakes preferentially occur on faults, and that there are many mapped faults at any scale so which, if not all, of a set of faults are the active ones? Take the example of the Snowy Mountains region in NSW where the decision can be critical for dam owners since river courses are controlled by joints and faults. In an elastic crust, how could just one or two of these faults move without overstressing an intersecting or adjoining fault? A model with dense faults and with earthquake foci distributed throughout their depth range may give very similar hazard estimates to one with no faults and uniform seismicity.

Figure 2 Mapped faults in the Snowy Mountains region NSW (from Bock & Denham, 1983)

Source variable*s* that are usually not modeled are the direction of slip, the faulting style and duration of slip. The source can make a large difference to the duration of shaking: a reverse or thrust fault initiating at the centre of a fault will stop in half the time of a strike-slip fault with the same earthquake magnitude initiating at one end. The duration of shaking may have a dramatic effect on damage though the response spectrum of both events may be identical. Normal, strike-slip and reverse faults are presumed to have different spectral amplitudes but data do not clearly reflect this view, another source of uncertainty for the decision tree.

The likely direction of slip on a strike-slip fault with respect to any site is unknown prior to an earthquake. Sarma (1976) many years ago modeled the ground motion along a strike-slip fault and showed that at the origin and end points the amplitude and frequency of ground shaking are dramatically different due just to the Doppler frequency shift, and different at each end to sites orthogonal to and near the centre of the fault. Field evidence and strong motion data highlighting this effect were seen at Kobe Japan in 1996 and much earlier in California during the 1966 Parkfield event.

It should be no surprise that the scatter in observed peak ground motions is so high.

Recurrence relation The method of choosing *a* and *b* values is usually not a matter for popular discussion outside the seismologists' circle. Extreme-value methods so popular in early decades have given way to the classical recurrence relation even when the range of magnitudes used to define *a* and *b* does not extend up into the damaging magnitude class (magnitude 5 and above). Predicting the frequency of large earthquakes from the observed frequency of small earthquakes is not necessarily sensible and can have a dramatic influence on results. When *b* is extrapolated from a limited magnitude range extending from say 2 to 4, to an M_{max} of 7.5 or more, one should not expect a realistic ground motion prediction, but experts routinely do this.

Focal depths and source size Focal depth range is one parameter that has probably not been publicly aired sufficiently in discussion of engineering quantization of hazard in Australia. Many of the early estimates of earthquake hazard in Australia took a fixed focal depth of 5 or 10 km with markedly different hazard results though the difference would probably be smaller if events below magnitude 5 had been excluded. Other ploys are to distribute the foci over several focal depth slices, modeling the brittle crust as a kind of layered cake, and apportioning events at each depth. There is usually precious little data to select a focal depth model for most sites in Australia.

Earthquakes aren't point sources and the larger the magnitude the further they diverge from a point source (see the figure below where the surface fault was comparable in length with the crustal thickness in the region).

Figure 4 Part of the 35 km long Meckering Fault scarp, WA (Photo I B Everingham)

In Australia it is often suggested that the brittle zone probably extends down to 15 km or so, a magnitude 6.2 earthquake would then rupture the whole of the brittle zone to the surface. Most hazard estimation programs do not handle this well. In recent decades, well-constrained measurements of the focal depths of a few Australian earthquakes have shown that they extend well below 15 km, some down to 40 km, to the very base of the crust in at least two parts of the plate, for no obvious physical reason. Perhaps there is no non-brittle zone in the cold thick Australian crust or even in areas of southeastern Australia where the crust is thinner and the measured heat flow relatively high.

Attenuation The question of which of a myriad of so-called attenuation relations derived overseas is appropriate for Australia has resulted in at least three *best* but very different relations being generally adopted for use. As two of these were derived from Western US, mainly Californian, data and a third from Eastern US data they generate very different numerical ground motion predictions and hence hazard (depending purely on the weighting function adopted by the 'expert' committee). Such relations usually predict the mean or modal value, the scatter being given by a Gaussian distributed term unbounded at either end. This uncertainty in ground motion prediction is generally considered to cause the greatest scatter in the resulting analysis, at least at long return periods. A recent paper by Bommer and others (2004) discusses the choice of mean or modal value and the impact on results of the physically unrealistic tail of the distribution, out to several standard distributions from the mean. This is particularly true when considering very long return periods that may be considered appropriate for the assessment of acceptable risk to nuclear reactors, or large dams. Such studies may give completely unrealistic results leading to an overestimate of the hazard by incorporating physically unrealistic numerical values from the unbounded tail of the scatter term.

Questions of judgment

The magical 475 year return period being so widely used is hardly ever questioned, though that wasn't always the case (NZ used 50 years until recently and there was not such a difference in the numerical results as in Australia). Now under the new loading codes of Australia and New Zealand, owners get to choose the level of acceptable hazard they want with little guidance. They can use the 475 (or 500) yr RP, or 1000 yr, 2500 yr or perhaps even 50 yr return period as conversion factors are given in the draft code. But where is the societal guidance on which return period is appropriate, because there is no generally satisfactory definition of acceptable risk?

Earthquakes are perceived differently to floods or bushfires which are more frequent. This can lead to strange outcomes. Spillways of many dams in Southeast Australia have been upgraded in the last decade because of a change in definition of the acceptable design level flood event, but they were not upgraded at the same time for the equivalent return period earthquake loads!

Design parameter It is surprising that pga is still the most often quoted hazard parameter despite Ambraseys' (1973) demonstration, repeated many times since, that pga is unrelated to damage potential. For several years after the San Fernando earthquake of 1971, a peak of 1.25g in the accelerogram recorded on the abutment of Pacoima Dam was overlooked, the pga quoted as 1.09g. When the accelerogram was corrected there was no observable difference in the computed response spectrum (ie elastic simple harmonic oscillators saw no difference). In Australia, high pgas (up to 1g or $9.8 m/s^2$) have been measured during small earthquakes on several occasions, though these short duration earthquakes should cause little if any damage in modern structures designed for some earthquake load. These data ought to be incorporated into prediction equations rather than being ignored as they are at present because they could be significant for some mechanical components of structures.

Reducing the computed hazard assessment

An unwanted result of having large scatter in measured parameters or making allowance for unknown factors is a higher assessment of the hazard parameter – the design spectral amplitude is larger than it would otherwise be. The computed hazard can be reduced by minimizing the uncertainty in each input parameter wherever possible. Curiously, the choice of minimum magnitude is an overlooked but critical factor (Bender and Campbell, 1989); by removing the very frequent small events which are really of no engineering significance but which may contribute substantially to the hazard due to the scatter in the attenuation relation, one can substantially reduce the apparent hazard.

Identifying active faults is very difficult in Australia where location uncertainty is often larger than the spacing of mapped faults and the uncertainty in the focal depth estimate is often greater than the thickness of the crust. Even in active interplate regions such as California and New Zealand active faults may not outcrop at the surface and must be inferred by mapping well-located (~ ±1 km) hypocenters.

The big contributor to hazard uncertainty is the attenuation relations. In Australia there are precious few site-specific strong motion records and the only way the influence of using overseas attenuation data can be removed is to install many more accelerographs throughout the country.

Codes of practice

Over the years assessments of hazard at any site have generally increased as more and better data have become available. Consider that once 0.1g was considered the rule of thumb for acceptable seismic design in California. In many parts of Australia no earthquake design is required for normal buildings, but that is not true for special structures. A high-hazard building near Melbourne was designed and built for a pga of 0.03g at a time when the Building Code of Australia did not require consideration of earthquake hazard. Now the building site has a rated 475 yr pga of 0.09 g according to the current hazard map of Australia. A safety review of the structure is currently underway, but is the 475 yr event an adequate event for such a structure? And if it isn’t what is?

In Australia and other countries, it seems almost immaterial what the hazard analysts derive, engineers on the code committee modify the force reduction factors introduced to compensate for overstrength or ductility, and the design forces remain unchanged.

The Building Codes Board warned members of the newly appointed loading code committee in 1994 that if the new draft contained any changes that would increase building costs it would not be called up into legislation! It is not as if the introduction and regular upgrading of codes worldwide had been accompanied by a steady reduction of damage and loss of life, the reverse is unfortunately true.

It would be useful to undertake a survey of the vulnerability of buildings in Australian cities. Of course the majority of buildings that predate or were not designed to AS2121-1979 or AS1170.4 -1993 would probably be more vulnerable now than when they were constructed. Existing buildings are not required to be brought up to the latest code requirements unless they undergo substantial structural modification. This class of building is at relatively high risk of being damaged when shaken by a moderate or larger earthquake as demonstrated in past damaging Australian earthquakes as small as that at Newcastle NSW in 1989.

So what of new buildings? There is a growing tendency for new buildings to be more and more asymmetric which we know is a retrograde step according to earthquake engineering principles as it introduces greater torsional forces in structures. New materials and forms are always being tested, if new structures fall down then the form is changed (the history of bridge design is a classic example) but damaging earthquakes in Australia are rare so most new structures are usually only subject to gravity and moderate wind forces.

One disturbing new development in Sydney is the construction of URM residential buildings up to 7 storeys in height, despite the code clearly limiting the height of such buildings to 4 storeys. How this came about is surely the problem for earthquake engineering in Australia, and it reduces to the lack of qualified regulators. The design engineers and architects of such structures should bear the responsibility in the first place, a prominent NZ consulting firm who apparently checked the design should also take some responsibility, but who is checking them? Up to the 1980s this task was done by governments but increasing privatisation and outsourcing of government business has seen this role palmed off to certified regulators with the result that there is no qualified higher engineering body overseeing the practice of earthquake engineering in Australia. Enforcing the codes is not the role of Standards Australia, nor of IEAust. Who then but the courts of justice are left to oversee this role?

The URM buildings already erected in contravention of the loading code will surely not be dismantled, but will others be built? This is not an isolated example, other cases in clear contravention of the code and earthquake engineering principles have been discussed from time to time in the AEES Newsletter including the amazing case of the AGSO building in Canberra.

This building has four interconnected wings, but for various reasons only one of the wings was strengthened to conform to Australian Standard AS1170.4 -1993 which was in press but not published at the time of construction. The other three wings were not similarly strengthened. Surely this building has become more vulnerable as the result of architects, structural engineers and the building owners having no knowledge of earthquake engineering principles. The regulator was obviously not qualified to judge.

Assessing hazard is an art that requires great judgment and experience. Ensuring that the codes are observed both in design and construction is also important and requires equal amounts of judgment and experience.

There seems to have been a diminution of the necessary skills in Australia over recent decades.

Reducing the assessed risk

Ways to reduce the computed risk include reducing the uncertainties in the hazard assessment by obtaining strong motion recordings of Australian earthquakes and using those records to obtain more appropriate spectra for the loading code. This approach requires the installation of more accelerographs throughout Australia, perhaps with a higher density in areas known for their past earthquake activity, if they are widely accepted to be the most likely sites of near-future seismic activity.

The other method is to restore the materials provisions to the Loading Code, turning it back into an Earthquake Code (like AS2121-1979), and then enforce its provisions.

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