Estimating of the Rate of Deformation of Australia for the National Earthquake Hazard Map

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Abstract

One of the main outputs of the Earthquake Hazard project at Geoscience Australia is the national earthquake hazard map. The map is one of the key components of Australia's earthquake loading standard, AS1170.4. One of the important inputs to the map is the rate at which earthquakes occur in various parts of the continent. This is a function of the strain rate, or the rate of deformation, currently being experienced in different parts of Australia. This paper presents two contrasting methods of estimating the strain rate, and thus the seismicity, using the latest results from the seismology and geodynamic modelling programs within the project. The first method is based on a fairly traditional statistical analysis of an updated catalogue of Australian earthquakes. Strain rates, where measurable, were in the range of $10^{-16}s^{-1}$ to around $10^{-18}s^{-1}$ and were highly variable across the continent. By contrast, the second method uses a geodynamic numerical model of the Australian plate to determine its rate of deformation. This model predicted a somewhat more uniform strain rate of around $10^{-17}s^{-1}$ across the continent. The uniformity of the true distribution of long term strain rate in Australia is likely to be somewhere between these two extremes but is probably of about this magnitude. In addition, this presentation will also give an overview of how this kind of work could be incorporated into future versions of the national earthquake hazard map in both the short and long term.

Keywords: National seismic hazard map, strain rate, geodynamics, numerical modelling, earthquake recurrence, tectonics.

1. Introduction

There are three main inputs to calculating an earthquake hazard map:

1. the occurrence rate of earthquakes in an area
2. the distribution in earthquake magnitude between small and large events and
3. the level of ground shaking at a given distance from a given magnitude of earthquake

Geoscience Australia is presently in the process of drafting a short term (~2 year) and long term strategy for the future development of all these aspects of the national earthquake hazard map. The area is quite multi-disciplinary and involves research in many different areas of geology, geophysics and seismology.

In this paper, I will focus on the first input, estimating the rate of occurrence of earthquakes across Australia. One way of estimating this input is by measuring or modelling the strain rate across the continent. The strain rate measures the rate at which the continent is deforming with time. The faster the continent is deforming, the faster faults within the continent will be loaded to failure and thus the more frequently we can expect earthquakes (on average). Here I will present two ways of estimating this, the first from a seismic catalogue and the second from a geodynamic numerical model. Then I will discuss how these two methods could be incorporated into hazard maps in the future. The first, seismic catalogue based, map is an example of the sort of method Geoscience Australia envisages using for the national hazard map over the short to medium terms. The latter method, based on geodynamic modelling, is very much a long term project and is still essentially at the "proof of concept" stage of development.

2. Seismic Strain Rate

One way to estimate the rate of deformation is by using a catalogue of earthquakes to calculate the current rate and assuming that this rate will continue indefinitely into the future. Since this strain rate is determined primarily from an earthquake catalogue this is sometimes called the *seismic* strain rate in order to differentiate it from strain rates determined by other means. Typically the continent is broken up into source zones based on a combination of geology and seismicity (eg Gaull *et al* (1990), Brown & Gibson (2004) or Leonard (2008)). An alternative is to divide the continent into regular boxes or cells (eg 2 degrees by 2 degrees) and calculate the seismic strain rate or seismicity rate observed in each of them. An example of the latter method is shown in Figure 1 taken from Braun *et al*, 2009. The strain rate in this figure was found by making use of both Kostrov's formula relating seismic strain rate to cumulative seismic moment release (Kostrov, 1974) and the Gutenburg-Richter relationship (see Braun *et al*, 2009 for a detailed description of the method). For the particular map shown in Figure 1 the Gutenburg-Richter values a (the intercept of the Gutenburg-Richter relationship) and b (its slope) were found by linear least squares for all the earthquakes in each 2 x 2 degree cell. Cells with a correlation coefficient less than 0.95 were left blank. The catalogue used for this process was generated by combining Geoscience Australia's own catalogue with those of local and international networks. From this type of assessment both the rate and statistical distribution of earthquakes can be derived. From the strain rate, or equivalently the earthquake rate, we can calculate a hazard map once we have an appropriate ground motion attenuation model for the region.

As can be seen from Figure 2, strain rates in the regions with enough earthquakes to make a measurement vary from $10^{-16}s^{-1}$ to around $10^{-18}s^{-1}$. The higher rates are naturally in regions which have been previously identified as the most active in recent times (cf Leonard, 2008). The details of maps such as that shown in Figure 1 depend on the exact assumptions used to derive them. For example details such as the maximum magnitude chosen, the analysis technique (eg least squares versus maximum likelihood see Weichert (1980) and Bender, (1983) for a discussion of the effects of the choice of technique), the size of the cells, the temporal length of the catalogue used, the presence or absence of aftershocks can all affect the map to some degree. However, no matter what the technique, the broad scale patterns seen in Figure 2 are normally reproduced. For some more examples of effect of different assumptions or techniques on maps like that shown in Figure 1 see Braun *et al*, 2009.

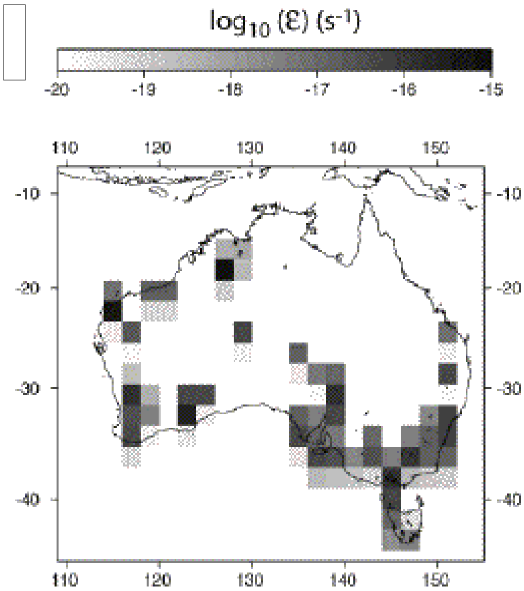

Figure 1 Seismic strain rate as predicted from the distribution and magnitude of earthquakes observed over the 1970-2007 period assuming a maximum earthquake magnitude, Mmax, of 7, aftershocks removed and a 2 deg by 2 deg binning of the data (from Braun *et al*, 2009).

One of the disadvantages of this method is that the catalogue is considerably shorter than the average length of time between major earthquakes in any region of Australia. This can mean that there are often simply not enough earthquakes within an area to estimate the strain rate reliably. In the example shown in Figure 1 these areas are shaded white (ie are blank) either because there weren't enough earthquakes in the cell or because the correlation co-efficient for the Gutenburg-Richter relationship in that area was too low. These areas unfortunately cover the majority of Australia. The other problem is that it is possible that the observed rate of earthquakes for each box is much higher or lower than its long term mean. This means that the seismic hazard estimated from this data could be much higher or lower than its actual long term value and could explain much of the variability in strain rate shown in Figure 1. Hazard maps derived from this type of approach often have "bull's eyes" of elevated hazard in regions which by chance have had a lot of seismic activity within the time frame of the catalogue.

3. Geodynamic Strain Rate

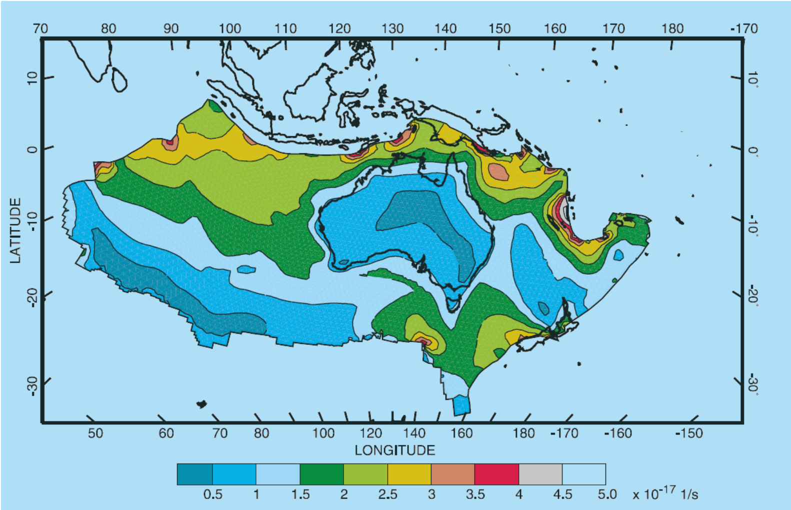

Figure 2. Geodynamic strain rate in the preferred model of Burbidge (2004).

At the other extreme is the *geodynamic* strain rate determined from numerically modelling the rate of deformation across the plate. An example of the strain rate predicted using this method is shown in Figure 2 (from Burbidge, 2004). This strain rate is calculated by assuming the plate obeys a particular rheology and then applying tectonic forces to the margins and/or base to estimate the rate at which these forces cause the plate to deform. In the case of the model shown in Figure 2, the plate had an anelastic brittle/ductile rheology with laterally varying elevation and heat flow (Burbidge, 2004). The model's parameters were chosen to minimize the misfit against a variety of observations such as the direction of maximum principal stress in different parts of the plate or the rate of plate motion (eg from GPS measurements). This particular model predicts a fairly uniform strain rate of around $10^{-17}s^{-1}$ across the continent with a broad low running through the central Australia, southern Queensland and central NSW.

While this model used a large amount of observations to constrain it, more information from neotectonic studies can also be used to either constrain the model's inputs or its outputs. However, the model needs a much higher resolution before a direct comparison between the slip on a particular fault can be resolved. The map shown in Figure 2 primarily shows the rate of deformation expected over a large area.

The results could also be compared to statistical analysis of the history of earthquake across Australia. However it must be remembered that one reason for doing this analysis is that we expect that the rate of seismicity over the last few decades may not be representative of the long term rate due to relatively short length of the catalogue.

From a numerically determined geodynamic strain rate like the one shown in Figure 2 Kostrov's formula can then be used to estimate the seismic moment release rate across the area of interest. Given an earthquake relationship, like Gutenberg-Richter, this can be used to estimate a spatially varying earthquake occurrence rate and thus a seismic hazard map (once an appropriate ground motion prediction model is given). Thus is it is possible using this method to derive a seismic hazard map which does not rely on having a long earthquake catalogue.

Unlike a seismic strain rate map, this type of map is most appropriate for really long term seismic hazard assessments. If a historic catalogue is long enough then any strain rate map derived from a catalogue (Figure 1) should approach a geodynamic strain rate map like that shown in Figure 2 (if the latter model's predictions are accurate). However, given the very long recurrence times between major earthquakes in Australia, this would require a catalogue going back many thousands of years.

One of the main disadvantages of the geodynamic approach is that modelling of this sort is still in its infancy and it is only ever as accurate as the input data to the model and the assumptions used in the modelling. Also the resolution of these models is only ever as good as the resolution of the input data and is also limited by what is computationally feasible. Some of the uniformity in Figure 2 is likely to be due to the relatively coarse resolution of this model and its input. It is highly likely that clear neotectonic features like the Flinders Ranges represent areas of long term elevated strain rate but they are not reproduced in models like that shown in Figure 2. This is probably because of the relatively limited resolution of that model and possibly the assumptions used to derive it. The true, long term, distribution of strain rate is thus likely to be between the two models shown here (ie not as variable as Figure 1 but not a smooth as Figure 2) but is probably of about this magnitude.

4. Discussion: Hazard Maps in the future

So, what then is the most appropriate method for hazard maps? For shorter term hazard assessments, earthquake catalogue based maps based on seismic zones (eg Leonard, 2008), smooth seismicity models or some combination thereof (eg Petersen *et al*, 2008) may still be the most appropriate. They reflect the seismicity of the recent past and probably the near future. This is will remain the main type of hazard map produced, for example, for things like the earthquake design code in the short term (ie next few years). In the medium to long term, geodynamic numerical models, based on the observed patterns of neotectonic models, may be preferable as they represent the way seismic moment release is distributed across the whole continent over long periods of time. Future, higher resolution, geodynamic models are likely to be somewhat smoother in appearance than Figure 1 (ie no "bull's eyes" in areas of recent intense, but possibly short lived, areas of seismic activity), but not as smooth as the relatively coarse geodynamic model shown in Figure 2. Hazard maps of the future may end up using a blend of both approaches, perhaps with the tectonic methods weighted higher at the longer return periods than at the shorter ones. In the very long term, future hazard maps may rely entirely on high resolution numerical models thus avoiding the problem of a short seismic earthquake catalogue entirely. Similarly, the other aspects of earthquake hazard assessment (eg ground motion) may also increasingly rely more on physics based, rather than empirical, models as our understanding of earthquakes improves over time.

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