Earthquake Clusters, Small Earthquakes and Their Treatment for Hazard Estimation

Gary Gibson and Amy Brown
RMIT University, Melbourne
Seismology Research Centre, Bundoora

AUTHORS

Gary Gibson wrote his first earthquake location program during 1971, and has been trying to learn more about earthquakes since then. He is particularly interested in seismograph networks and their applications, earthquake hazard analysis and the relationship between earthquakes and dams.

Amy Brown studied Geological Engineering at RMIT, and has been working in earthquake hazard analysis at the Seismology Research Centre for several years. She is working on a revised earthquake hazard map of Australia that is more heavily based on regional geology than previous seismicity based maps.

ABSTRACT

In earthquake hazard studies, several arbitrary decisions relating to small, non-damaging earthquakes may significantly affect results. These relate to:

- declustering of the earthquake catalogue.
- the choice of return period which effects the character of design ground motion and the shape of the response spectrum, particularly in areas of low seismicity.
- the choice of the minimum magnitude earthquake used in the ground motion recurrence computation.

Australia has a large proportion of its earthquakes in shallow space-time clusters. Declustering an earthquake catalogue where events are highly clustered, infrequent and shallow leads to lower estimates of short-term hazard, but higher estimates of long-term hazard.

Because small earthquakes do little damage to structures, ground motion recurrence estimates for structural purposes should either take their spectral content into account, or exclude them from peak motion calculations.

Clusters of small earthquakes provide useful geological constraints for hazard estimates by delineating active faults.

EARTHQUAKE CLUSTERS, SMALL EARTHQUAKES AND THEIR TREATMENT FOR HAZARD ESTIMATION

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INTRODUCTION

In earthquake hazard studies, there are several arbitrary decisions relating to small, non-damaging earthquakes that may significantly affect the results. These include:

- the definition of dependent events (foreshocks and aftershocks) as used to decluster the earthquake catalogue.

- the arbitrary choice of the return period (or annual probability of exceedance) can have a dramatic effect on the character of design ground motion, and the shape of the response spectrum. This is particularly so in areas of low seismicity where a short return period will emphasise motion from small earthquakes.

- the choice of the minimum magnitude earthquake used in the ground motion recurrence computation. When attenuation functions are extrapolated outside of the magnitude and distance range of the data used in their derivation, there can be significant effects on hazard estimates that depend on the form of the functions.

CLUSTERS

Australia has an unusually high proportion of earthquakes within clusters. In some areas more than 90% of catalogue events may be included in foreshock-mainshock-aftershock sequences or swarms. Swarms may involve hundreds of events, and often occur at very shallow depths within one or two kilometres of the surface. Although foreshocks and aftershocks can cause some damage, most earthquake damage is caused by the largest event in each sequence. Seismicity studies should consider the recurrence of sequences rather than individual events, and total moment rather than individual magnitudes.

Small shallow earthquakes can give very high peak ground accelerations (PGA). Although these may have the potential to cause non-structural damage to nearby buildings, earthquakes smaller than about magnitude 4 to 5, whether they are foreshocks, mainshocks or aftershocks, rarely cause damage to engineered structures.

Declustering an earthquake catalogue means removing dependent events, including foreshocks, aftershocks, and swarm events (except for the largest event in each swarm). The number of events removed is affected by the definition of dependent event.

Typically, events that are within a given time interval and a given distance of a larger event are regarded as dependent. This time interval and distance may vary with magnitude. The chosen values are arbitrary. For example, a dependent event may be defined as being within three weeks and 20 kilometres of a larger event.

In Australia, aftershocks may last for a very long period. For example, aftershocks of the Tennant Creek earthquakes of 22 January 1988 are continuing almost 12 years later. The Burragorang earthquake of 9 March 1973 was followed by aftershocks that lasted for more than a year.

The decluster interval chosen should perhaps be some small proportion of the return period of a larger earthquake *at the particular location*. A value of about one thousandth of the return period of the largest magnitude in the sequence may be appropriate. The cluster distance could be related to the rupture length for this event.

Earthquake Magnitude Recurrence Central Victoria

Maximum Likelihood Fit - All Earthquakes
Ao = 74.58, b = 0.84, magnitudes 1.9 to 7.5

Maximum Likelihood Fit - Declustered
Ao = 23.07, b = 0.71, magnitudes 1.9 to 7.5

– – – 1960-01-01 to 1998-06-30 - All Earthquakes
1435 events from magnitude 0.0

– – – 1960-01-01 to 1998-06-30 - Declustered
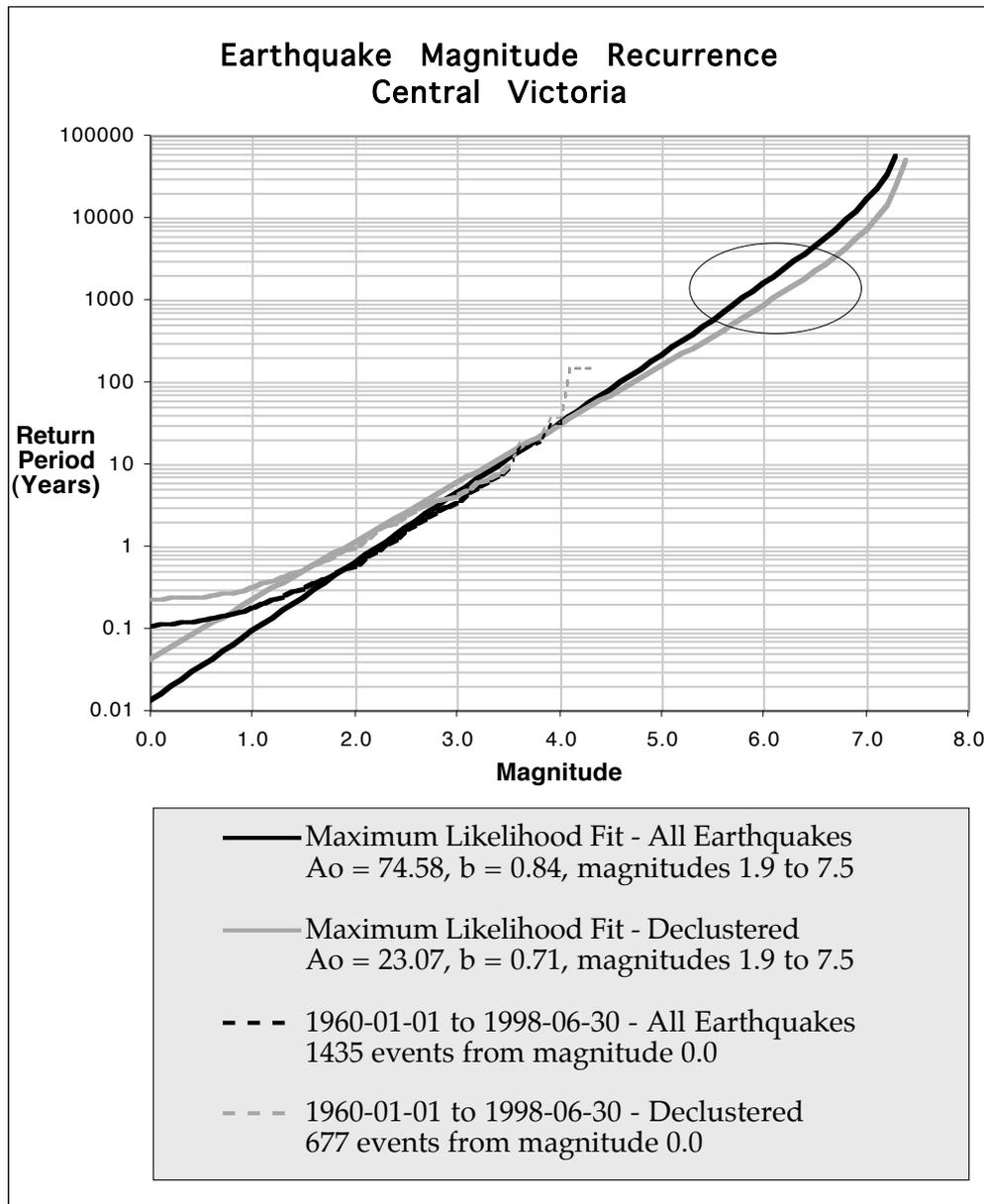677 events from magnitude 0.0

Figure 1: The effect of declustering on an earthquake hazard study in Central Victoria. A dependent event was defined as being within three weeks and 20 km of a larger event. The 1000 year earthquake magnitude for the declustered data is 6.1 compared with 5.7 for a fit using all events.

Excluding cluster events from a Cornell-McGuire probabilistic earthquake hazard study may suggest that declustering would reduce the apparent hazard in the area. However, as shown in figure 1, declustering lowers the relative number of small to large earthquakes (the b value). After extrapolation to the long return periods for larger earthquakes, this leads to a *higher* apparent hazard than when clustered events were included. Declustering also increases the apparent uncertainty in the estimates of the activity rate and b value because of the reduced number of events.

EFFECTS OF SMALL EARTHQUAKES

Earthquake hazard depends on the amplitude, frequency content and duration of the ground motion. Earthquake magnitude affects all three factors significantly. The distance from the earthquake affects amplitude, but has relatively little affect on frequency content and duration.

Earthquakes smaller than about magnitude 4 rarely do any damage to structures. Ground motion recurrence estimates for structural purposes should either take their spectral content fully into account, or exclude small events from ground motion calculations. In stable continental regions, where events are infrequent and very shallow, inclusion of small events can give estimates of PGA that are high and misleadingly conservative.

Clusters provide useful geological constraints for hazard estimates by delineating active faults. Modern portable digital seismograph systems in dense arrays, with high sample rates and precision timing, can locate cluster events to within 100 metres or better in both epicentre and depth. It may then been possible to associate the activity with a particular fault, previously known or unknown. A nearby active fault will significantly increase hazard estimates.

ATTENUATION FUNCTIONS

The shape of the response spectrum of earthquake ground motion varies significantly with magnitude and distance. Figure 2 shows response spectra for the attenuation function given by Sadigh and others, 1997. The magnitude and distance ranges of the data used to derive the function are emphasised.

Small earthquakes produce relatively little low frequency motion, so the gradient of the spectrum up to peak response increases significantly with decreasing magnitude. The frequency at which the peak response acceleration occurs also increases with decreasing magnitude.

The proportion of high frequency motion relative to low decreases with distance, because high frequency motion is attenuated with distance at a greater rate than low frequency motion.

For distances that are small relative to the rupture dimension (up to 10 km for M 6.0), there is relatively little variation of spectral acceleration, and thus little variation in spectral shape. Of course, by definition, the low frequency spectral displacement will increase a little with increasing magnitude for nearby events.
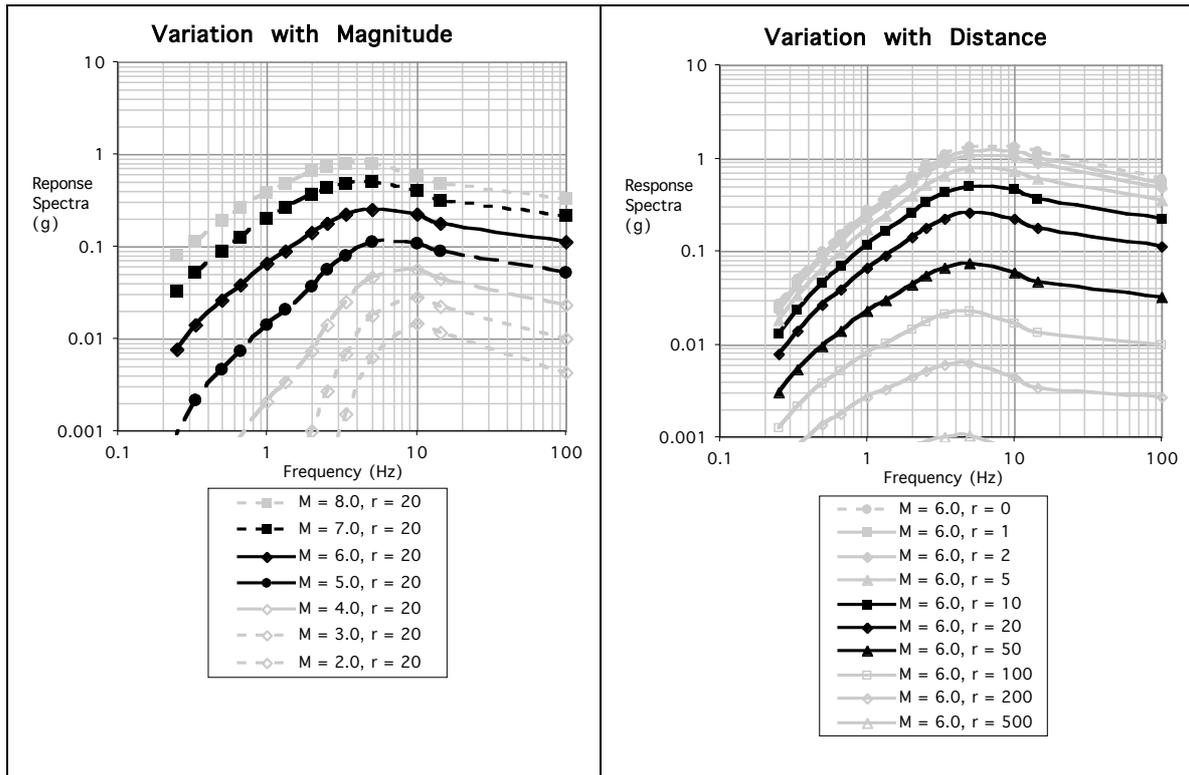
Figure 2: Sadigh 1997 attenuation for horizontal motion, 5% damping, and rock sites. The solid black lines show magnitude and distance ranges best constrained by the data. The response spectral acceleration at 100 Hz is numerically equal to the PGA.

EARTHQUAKE HAZARD ESTIMATES

To illustrate the problems associated with indiscriminate use of small earthquakes in earthquake hazard estimates, a comparison was made of uniform hazard spectra computed using the EZ-FRISK program (Risk Engineering Inc, 1997) for return periods of 1,000 and 10,000 years, and for two modern spectral attenuation functions (figure 3).

One of the attenuation functions was produced by Toro, Abrahamson and Schneider (1997), using data from central and eastern USA. These are areas of low attenuation and high stress drop earthquakes, comparable with central and Western Australia. The other function is by Sadigh and others (1997), as used above. It was derived using data from western USA, which has higher attenuation and lower stress drop earthquakes. This gives lower high-frequency ground motion than the Toro function, and is more suitable for application in eastern Australia.

The same seismicity model was used for all calculations, with values typical of Victoria including a relatively low activity level, b value of 1.0, maximum credible magnitude of 7.5, and earthquake depths to 10 km. Spectra were computed for horizontal motion on bedrock, with probability of exceedance of 0.5 and damping of 5%.

For each of the attenuation functions and return periods, spectra were computed considering earthquakes from magnitude 1.0 to 7.5, from 3.0 to 7.5, and from 5.0 to 7.5.
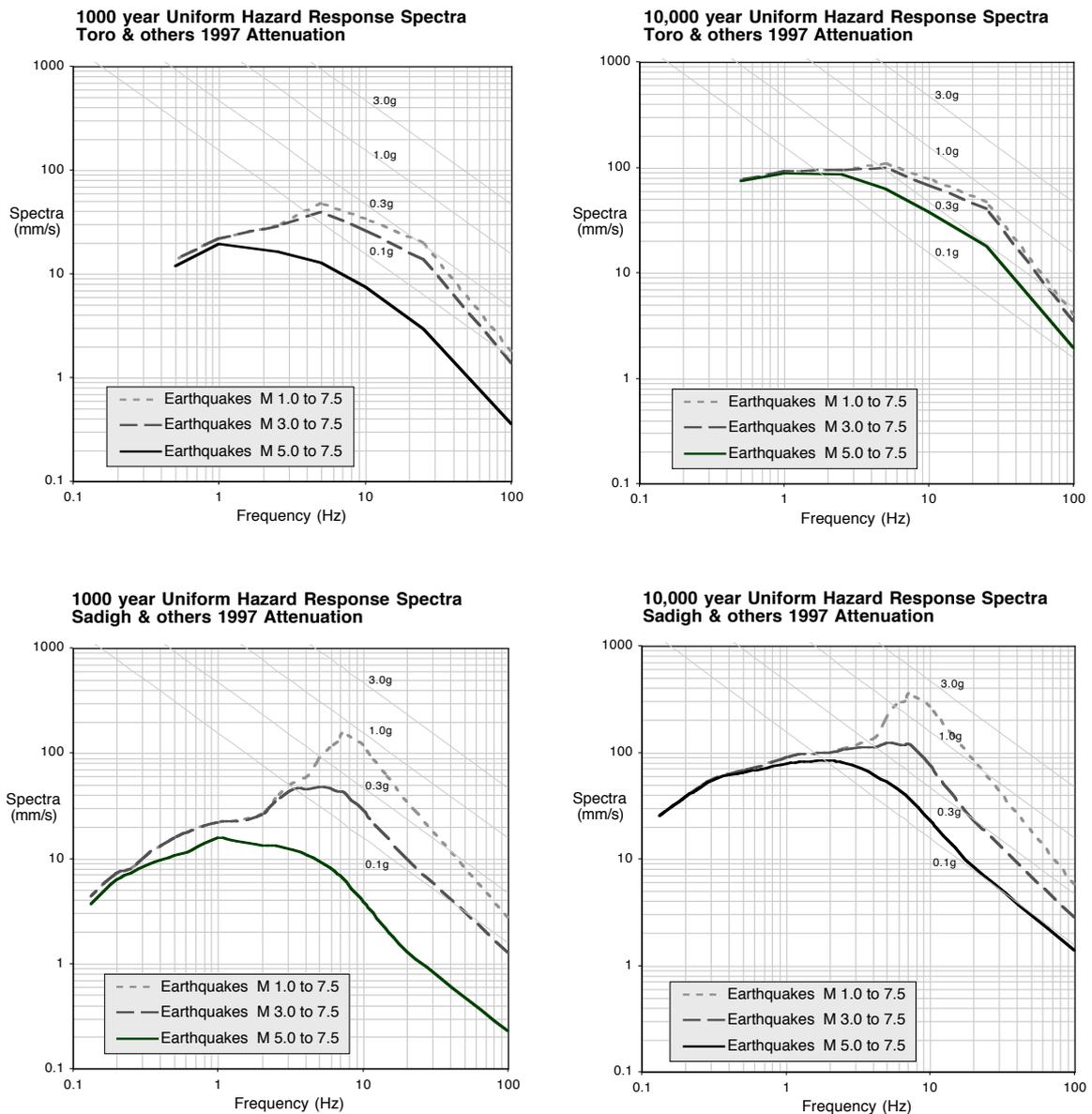
Figure 3: Comparison of uniform hazard spectra considering minimum magnitude, return periods of 1000 and 10,000 years, and two different attenuation functions, both extrapolated to earthquake magnitudes outside their range of validity. These are pseudo-velocity spectra, with spectral acceleration axes from 0.1 g to 3 g also plotted.

Both attenuation functions were derived using data that was predominantly in the magnitude range from 5 to 7, and the distance range from 10 to 100 km. Ideally, neither should be used outside these ranges.

However, earthquake hazard analyses are concerned about large nearby earthquakes, so extrapolation outside the empirically determined ranges is not unusual. This is often knowingly done when extrapolating to larger earthquakes. Extrapolating to smaller earthquakes can have significant and unexpected effects on hazard estimates.

The following observations may be made:

- Microearthquakes smaller than magnitude 3 give almost no contribution at frequencies less than about 4 Hz for either attenuation function. At higher frequencies they give a much higher contribution with the Sadigh function than for the Toro function, with a peak at about 8 Hz.

- The hazard contribution from earthquakes less than magnitude 5 decreases with increasing return period for both attenuation functions. This shows the significance of the arbitrary choice of return period in areas of low seismicity. For return periods of 1000 years or less, a large proportion of the ground motion is from small earthquakes, which have short duration and low hazard.

- The spectra computed using events larger than magnitude 5 are not significantly different for the two attenuation functions at either return period. As expected, the Toro function (for low attenuation, high stress drop) does give greater high frequency content and higher PGA values.

Provided appropriate minimum magnitudes are used, the two functions are both suitable for earthquake hazard studies. We suspect that the Sadigh function gives a more realistic representation of actual ground motion when extrapolated to smaller earthquakes, but would give overly conservative hazard estimates if appropriate minimum magnitudes were not applied.

CONCLUSIONS

Small earthquakes can be useful but misleading in earthquake hazard studies. Declustering an earthquake catalogue is the removal of dependent small earthquakes (foreshocks and aftershocks), and can lead to an *increase* in long term hazard estimates by reducing the relative number of small events to large (the b value).

Particularly in areas of low seismicity, the choice of a short return period can give excessive weight to motion from small non-damaging earthquakes. This can have a significant effect on the shape of computed response spectra.

Elastic response spectra do not adequately reflect the significance of ground motion duration, so earthquake hazard computations must consider minimum magnitudes.

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