SEISMOLOGICAL CONTRIBUTIONS TO EARTHQUAKE LOADING CODES

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INTRODUCTION

The development of codes for the design of structures is probably the most productive way of mitigating earthquake risk. Risk is now normally defined as the product of hazard and vulnerability. Hazard is the study of the phenomena and its effects, and in the case of earthquakes is normally undertaken by seismologists. Vulnerability relates to the significance of earthquake effects on structures, particularly when these effects may cause damage or failure. Appropriate use of design and materials to minimise vulnerability is the basis of earthquake engineering.

The four key seismological inputs to earthquake loading codes are:

- The Hazard Zoning Map
- Design Spectrum for Rock Sites
- Site response, soil factors
- Performance or Return Period factors

BACKGROUND

Earthquake Hazards

Earthquake hazards include ground vibration, surface rupture, triggered landslides, and tsunami. By far the most important of these is ground vibration, and most building codes only consider this hazard.

Ground Vibration Hazard

The effect of ground vibration depends on *amplitude*, *frequency content* and *duration*:

- The *amplitude* is affected by magnitude and distance, represented by an attenuation function. The amplitude reduces with distance by geometric spreading (inverse square for body waves or inverse linear for surface waves), by absorption of energy within rock (especially soft or hot rock, and more pronounced in younger rock), and by scattering (in inhomogeneous rock). Attenuation is complicated by the earth’s structure, where reflections can lead to higher amplitudes at particular distances.
- The *frequency content* depends on magnitude. The motion from small earthquakes is at high frequencies, and the larger an earthquake the more low frequency motion is produced. Higher frequency motion is attenuated with distance more than low frequency motion, so there is proportionally more high frequency vibration near an earthquake, and distant earthquakes give only low frequency motion.
- The *duration* depends mainly on the magnitude. The duration of strong motion from earthquakes less than about magnitude 5 is less than a second. Nearby small events can give high peak ground accelerations, but rarely cause any structural damage.

Ground vibration can be represented:

- in the time domain by acceleration, velocity, displacement
- in the frequency domain by Fourier spectrum or response spectrum
- as a simple number or intensity determined empirically, or computed from the a time series and/or spectrum of the motion, such as the Arias intensity:

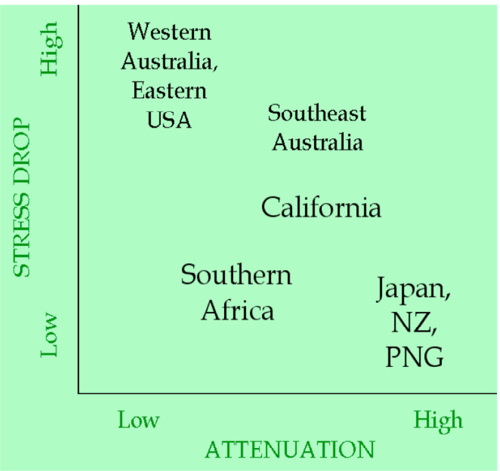
$$I_{ax} = \frac{\pi}{2g}\int_0^{t_D}[a_x(t)]^2 dt$$

Ground Motion Recurrence

Cornell Method
Seismotectonic Model
Active faults
Quantification of Source Zones
Attenuation Functions
Computation of ground motion recurrence

Australian Earthquakes

Australian earthquakes are predominantly on reverse faults due to horizontal compression. They are relatively shallow with few well-constrained depths greater than 20 km.



Levels of activity are low, rocks and faults are strong, and stress drops are high, giving above-average high frequency motion near the earthquake, and high accelerations.

Attenuation in the old rocks of central and Western Australia is low, while that in Eastern Australia is a little above average.

Minimum magnitude

There are many more small earthquakes than large. Typically, within a given area there are ten times as many events of magnitude 4 or larger than there are of magnitude 5 or larger. There are ten times as many again exceeding magnitude 3. The ratio varies from 10 depending on several factors, with low values in areas of high stress and low seismicity, but is usually in the range from 6 to 20. The logarithm to base 10 of this ratio is the seismicity b value, with a ratio of 10 corresponding to b = 1.0.
Small earthquakes rarely cause any damage. However, because there are so many small events, there is a high probability that small nearby events will give strong ground motion, particularly at high frequencies, and thus give high peak ground accelerations.

*** With modern attenuation functions, choice of minimum magnitude is highly significant, especially for high frequency motion and PGA. The acceleration coefficient in 1170.4 approximates the use of minimum magnitude 4.

THE HAZARD ZONING MAP

Zoning and Microzonation

One of the key parameters for any map is the scale. For earthquake hazard studies there are three key scales to consider:

1. The variation in seismicity over a large region, such as Australia. The variation in return period for an earthquake of any magnitude can vary by a factor of about 100 or more. This variation may occur over a distance of less than 300 kilometres, such as between Mildura and Adelaide. A contour map of Australian earthquake hazard will show such variation, but will not resolve individual active faults. A typical scale may be 1:20 million.
2. The variation of seismicity that is of significance to the earthquake hazard at a particular site, such as a dam or power station. In this case, the most significant activity is within 100 km, and any seismicity beyond about 300 km is too far to be significant. At this scale, any active faults should be delineated. The resolution at this scale is too high for an earthquake loading code. A typical scale may be 1: 1 million
3. Microzonation, or a scale where variations in site response is important. Site amplification can vary over distances of hundreds of metres due to variations in near-surface sedimentary cover. This high resolution scale is most relevant when considering the earthquake hazard over a limited area, such as a city. A typical map scale may be 1: 100,000.

At present, the large scale is relevant to loading codes and the two smaller scales to earthquake hazard studies of particular sites or areas.

Four stages in the development of the Australian earthquake hazard map are shown in ***Figure 1***.
A is McEwin et al 1976
B is AS2121
C is Gaull etal
D is AS1170.4

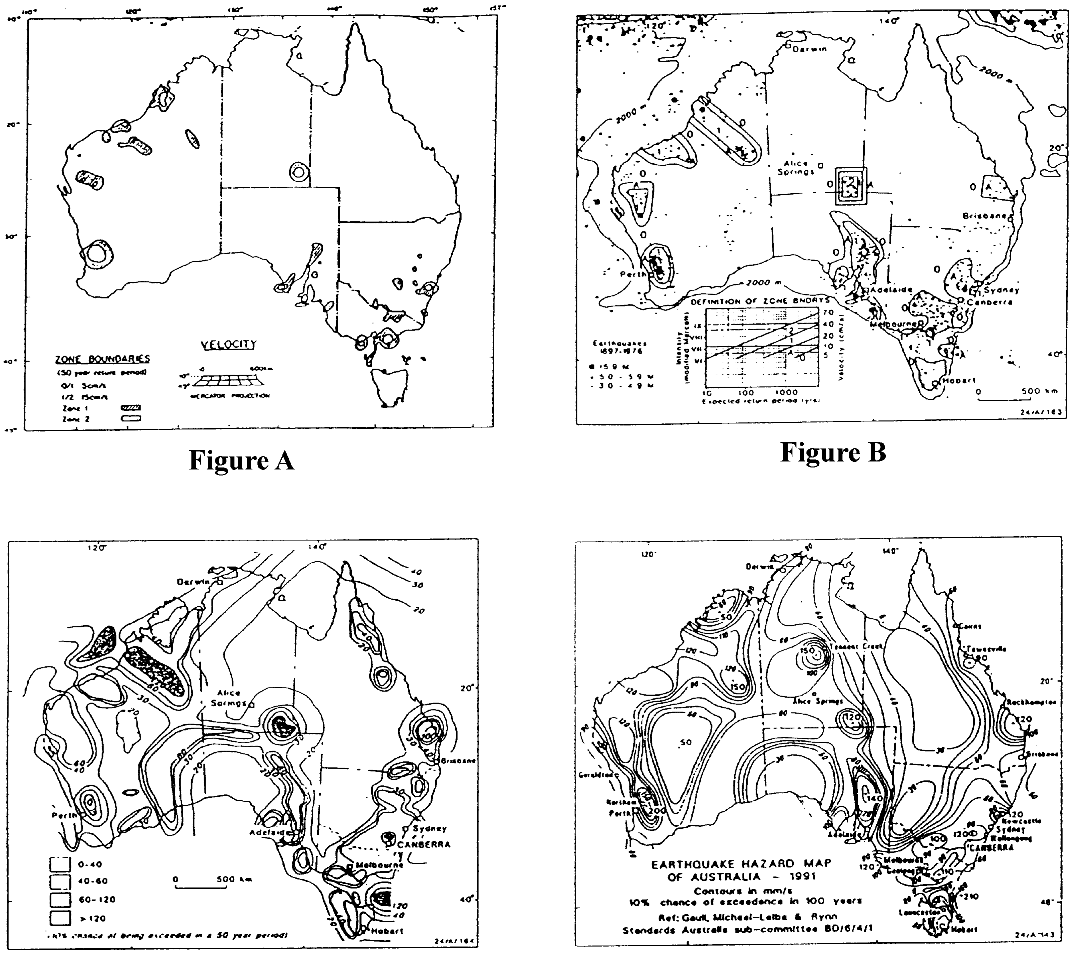


Figure A

Figure B

Figure C

Figure D

Figure 1: Australian hazard zoning maps, 1979 to 1993

Note the trend ……..

The working group for the new joint Loading Code considered four contenders for the hazard map:

Uniform Hazard There has been strong support over the years, mostly from engineering quarters for a single hazard rating across Australia. The basis was that there was no model to explain the earthquakes, they seemed to keep happening in different places, often outside existing source zone boundaries.

Statistical studies of the pattern of past epicentres (McFadden and others, 2000) showed that, at a very high probability, this pattern was inconsistent with that expected from a random distribution of earthquakes and therefore the assumption of randomness could be rejected. Spreading the earthquakes across the whole country decreased the computed hazard for most Australian cities.

Coulomb model This is the first physically based model proposed to explain the Australian epicentre distribution (McCue and others, 1998). It was based on the distribution of regions with no earthquakes and these were explained as resulting from the known tectonic stress at Australian Plate boundaries generating preferentially oriented shear zones. The model was considered too radical and did not get the general support of the seismological community though accepted by many engineers so it too was rejected.

Picture??

Gibson/Brown model This model, a detailed source zone study based on regional geology, geophysics, and the distribution of past earthquakes. It is a generic seismological model including variations of seismic velocity and attenuation, as well as the seismicity parameters (Brown & Gibson, 2000). It was not completed in time for consideration by the zoning working group.

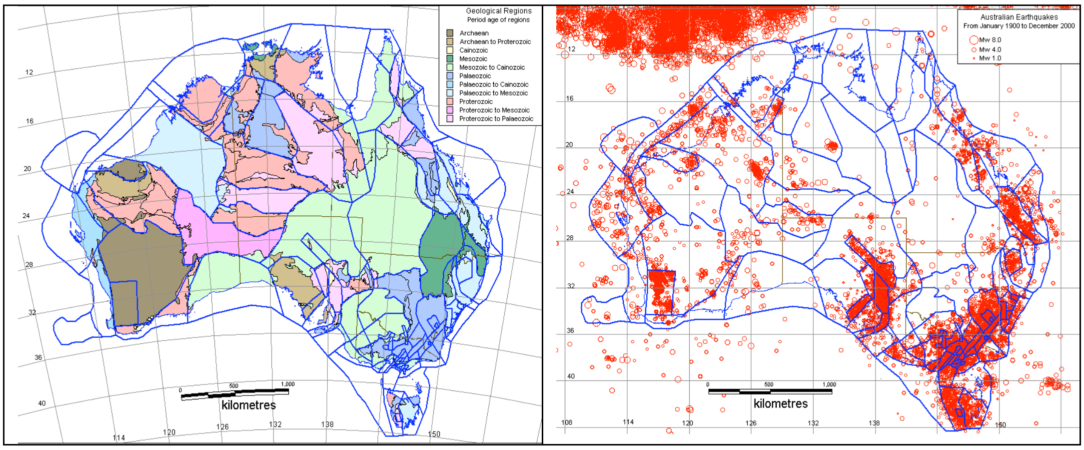


Figure 2: Source zones for the Gibson/Brown model AUS5

Existing model Based essentially on past epicentres grouped into broad source zones essentially independent of the geology the study by Gaull, Michael-Leiba and Rynn, 1990 was substantially modified for inclusion in AS1170.4 - 1993. With some minor modification to the 1993 contours caused by 'surprise' earthquakes such as the magnitude 6.3 Collier Bay event in 1997, this model was retained (McCue and others, 1998).

DESIGN SPECTRUM FOR ROCK SITES

***** Spectra vary with magnitude (figure). In Australia the 500 year event is quite small, so its spectrum is dominated by high frequency. No properly engineered structure should be affected by such a small event!!! In the long-term, the low frequency motion from less frequent larger earthquakes is more important.

The lack of accelerograms of large Australian earthquakes prevents the preparation of a truly Australian spectrum. Great uncertainty exists about the predicted amplitude of ground shaking, its frequency content and duration, and the variation with distance and azimuth (Brown and others, 2001). The joint urban monitoring program initiated after the 1989 Newcastle earthquake has provided a remarkable database of accelerograms in the cities, a good start but still restricted in the range of magnitude and distance (Examples – perhaps Boolarra event at SHY or MPDM).

Somerville and others (1998) devised a set of criteria for suitable rock accelerograms and collected appropriate records from international databases. The 38 components of 6 records from Europe and the US were chosen by tectonics, magnitude and distance range, and site geology. These data were normalised to a standard peak ground velocity and their median spectrum computed. This was fitted by a Newmark style spectrum with flat segments to acceleration, velocity and displacement in the high frequency, mid frequency and low frequency ranges. Appropriate corner frequencies were specified. This spectrum reflects the data, no contribution from infrequent major earthquakes (M>7), the most likely destructive Australian earthquake is a moderate magnitude 6 ± .5 event in the 20 to 30 km distance range. The data sets do not include events on major strike slip faults such as the San Andreas which have a different spectral shape to the high stress drop thrust events typical of Australian earthquakes.

The spectrum has been developed using real earthquake ground shaking recorded on rock in 'typical' Australian-type earthquakes. These data are preferred to those obtained using synthetic accelerograms or using synthetic spectral shapes when important parameters such as corner frequency, stress drop and duration or maximum magnitude are ignored or guessed and which incorporate no knowledge of Australian 'type' earthquakes.

SITE RESPONSE

Site Amplification

Site factor
Earthquake Magnitude
Liquefaction

Soil spectra

The lack of appropriate Australian data is lamentable. Only in the western US is there sufficient data to investigate the effects of soils on ground shaking though a significant set of isoseismal maps has been compiled for Australian earthquakes which provide some ground truth. It is a very neglected resource. The expected amplification does occur on soils relative to rock sites and may be predictable with sufficient knowledge of the foundation soil profile, engineering properties and likely earthquake. Effects seem to vary with azimuth in cities such as Perth.

For these reasons the spectral amplification factors proposed for the US NEHRP provisions (Crouse and McGuire, 1998) were adopted. These factors show amplification at all frequencies a degree of conservatism which will only be reduced with local data. They do not reflect the frequent observation of amplification in a narrow frequency range coincident with the natural frequency of the soil layer. This would be difficult to accommodate other than on a site-by-site basis because soils are rarely flat lying and buildings change their natural period as the shaking intensifies which may be worse for stiffer buildings than flexible buildings.

These factors were based on observations of real soil behaviour in real earthquakes and so are preferred to factors computed by linear, elastic wave propagation modelling.

Multiple Resonance

AS 1120 did it

PERFORMANCE OR RETURN PERIOD FACTORS

Choice of return period

Originally 500 years, or 10% in 50 years (corresponding to 475 year return period). In very active areas, this corresponds to a very large earthquake, often approaching the magnitude of the maximum credible earthquake. However, in areas of low seismicity the 500 year event is very small, and nothing like as large as the maximum credible magnitude

Overseas Practice

Fewer people have died during earthquakes in the US than in most other countries with high seismicity over the last 50 years, since earthquake codes have been widely introduced. They must be doing something right, not just formulating codes but enforcing their implementation. Seismic design criteria developed there in recent years for the IBC and which will be implemented throughout the US (Kircher, 1999) have a very different design philosophy than previous US codes for the Eastern US (EUS). EUS has infrequent earthquakes, comparable with Australia, just as New Zealand on the plate boundary with relatively frequent earthquakes is comparable with the Western US (WUS).

Previous practice in the US was to consider the ground shaking with a 10% probability of exceedance in 50 years, the same design earthquake was adopted in Australia. The down side was that, whilst in the Western US (read New Zealand), the maximum capable earthquake was not considered to be more than 50% larger than the design earthquake so that a structure might be still damaged but not collapse under the MCE, this was patently not true in the EUS (read Australia).

Large earthquakes have occurred in Australia and EUS, they are not as frequent as large earthquakes in New Zealand or WUS but if a long enough time period is taken, 5000 to 10 000 years then the ground motion expected from the largest earthquake in high and low hazard areas becomes similar. Of course, there are many more large earthquakes during this long period in the more active areas than in the stable regions.

US regulators have defined a new earthquake, the so-called Maximum Considered Earthquake (MCE) and suggested that all structures be designed for ground shaking corresponding to the MCE.

In probabilistic terms, this extends the design earthquake from 10% in 50 years to 2% in 50 years (or 500 year event to a 2500 year event). This according to Kircher better captures the rare events in regions of low or moderate seismicity *like Australia*.

Return Period as Another Loading Code Factor

A table has been prepared in the draft loading code to convert the 500 year PGA or spectral amplitude at a characteristic frequency, to PGA or spectral amplitude at a range of other return periods. This table was compiled by comparison of many hazard studies in Australia but particularly in Adelaide which is one of the best studied cities in Australia and a reasonable basis for calibration (Love, 199?).

Surprisingly this table was found to be very similar, effectively identical given the uncertainty and scatter, to the equivalent NZ table and the two were combined in the draft loading standard.

The table enables owners and design engineers to use a number of different combinations of building life and probability of exceedance. That is, alternatives to the usual 10% in 50 years may be specified if relevant. Care should be taken using the values out to 2500 years or beyond, and a special study should be undertaken for critical facilities rather than simple scaling of the spectrum.

CONCLUSION

The following are the main outstanding problems

- Spectra
- Return Period
- Site response
- Xxx, etc

Our new joint loading code is very analogous to the US code, balancing high hazard regions (parts of New Zealand) with low hazard regions (Australia and other parts of New Zealand) and we too should adopt this philosophy if public safety is the main criterion for code formulation, let us too do it right. It is a waste of time though if the codes are not enforced and if old pre-code buildings with no or little earthquake resistance, the majority of the building stock in Australia, are ignored, especially schools and hospitals.

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