

Earthquake Hazard at Newcastle

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Abstract

This paper compares past and current earthquake hazard estimates for Newcastle computed using a range of earthquake recurrence models, and several ground motion models. It compares the resulting earthquake hazard estimates.

Estimates are all for soft bedrock motion, or $V_{s30} = 760$ m/s where relevant. There are at least eight phenomena associated with site response, and these vary significantly over short distances. Dhu and Jones (2002) described aspects of site response in Newcastle at high resolution.

The results show a wide variation in ground motion recurrence values, with the 475-year PGA varying over a factor of ten, from 0.025 g to over 0.3 g for Newcastle. This range includes some extreme assumptions that may not be appropriate, and most results are in the range 0.12 g to 0.16 g when considering earthquakes from magnitude 5.0, or 0.13 g to 0.19 g for earthquakes from magnitude 4.0.

The minimum magnitude chosen for the calculation has a significant effect on the value, especially for models with low levels of seismicity. Restricting the minimum magnitude helps eliminate high-frequency, short-duration motion from small to moderate nearby earthquakes that may give strong high frequency amplitudes (PGA), but do not cause structural damage. The effect of ground motion depends on amplitude, frequency content and duration of motion. Many earthquake codes assume a minimum magnitude of about 4.0, while most earthquake hazard studies for large well-engineered structures like dams use a value of about 5.0 or higher. Most ground motion models are unreliable for magnitudes less than 4.0.

The earthquake recurrence model used can be of low resolution, distributing earthquake activity widely, and giving low to moderate hazard with little variation. At the other extreme, models assuming that future earthquake activity only occurs where known past earthquakes occurred will give a wide range in hazard from place to place.

Between these extremes are models with source zones of dimension tens to hundreds of kilometres (such as AUS5), and smoothed historical seismicity models. Addition of high-resolution features, particularly active fault sources, gives hazard that varies widely over relatively short distances for locations near to the faults.

A choice of modern “Next Generation Attenuation” (NGA) ground motion models gives less variation in hazard results than is found when using a choice of older ground motion models, and the NGA models provide better results at extremes of small and large earthquakes, near and far earthquakes, and short and long periods of ground motion.

1. INTRODUCTION

In the 1890's and early part of the 20th Century, Australia's earthquake capital was Flinders Island. In 1954 Adelaide became the earthquake capital, followed by Meckering in 1968, and Newcastle in 1989. The last significant damaging earthquake dominates our thinking, especially if we experienced it either first-hand, or through the news media at the time. However, large and damaging earthquakes usually occur unexpectedly, both in time and place, especially in stable continental regions.

It is an anomaly that most earthquake hazard consulting studies are produced for major infrastructure (dams, mines, petroleum and gas facilities) that are in rural regions, and few site-specific studies are undertaken for cities. Newcastle has a significant history of earthquakes by Australian standards, much of which was not appreciated until after the Newcastle earthquake, and a study of historical activity in the region produced by Hunter (1991).

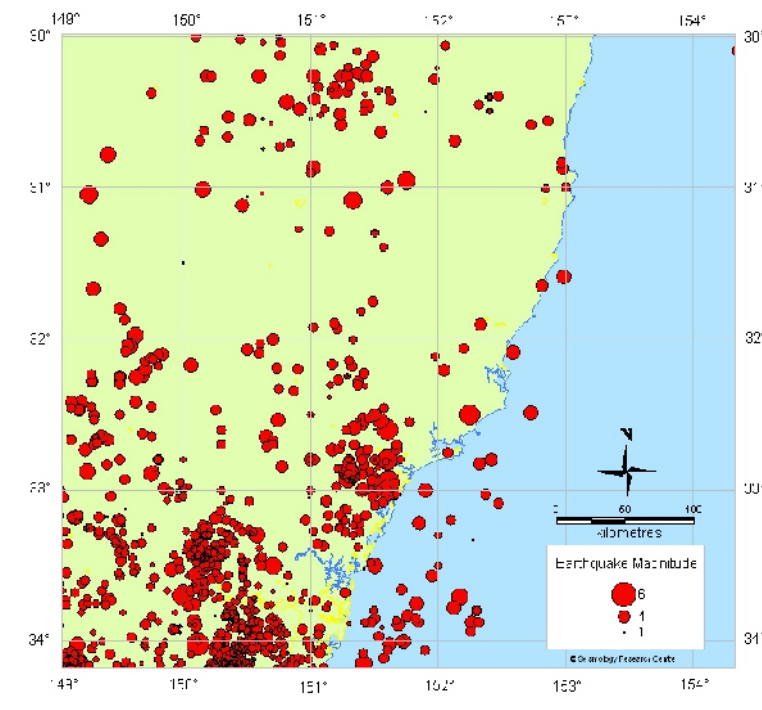


Figure 1: Earthquakes in the Newcastle region.

The estimation of hazard in the Newcastle region has several complications that produce significant uncertainties. The seismograph network in the region is less dense than about other large eastern Australian cities, so earthquake location precision is usually poor. Newcastle is a coal-mining region, and without a local network it is difficult to distinguish large coal blasts from earthquakes, and some earthquakes may be induced by mining. While early catalogues often included blasts as earthquakes, modern catalogues probably exclude earthquakes under the assumption that they are blasts.

One of the most difficult aspects of hazard studies at Newcastle is consideration of temporal clustering. The region has experienced more earthquakes over the past 170 years than would be expected from the long-term geological deformation in the region. Temporal clustering is expected in any region, but is particularly obvious in stable continental regions, where moderate and large events may be separated by long periods of quiescence. In active regions, large earthquakes may be experienced at intervals of tens or hundreds of years, while in stable continental regions they will occur at intervals of tens to hundreds of thousands of years.

2. EARTHQUAKE HAZARD

An earthquake hazard study attempts to anticipate future earthquakes and their effects, considering time-scales longer than the experience of an individual. There are several earthquake hazards including surface rupture, liquefaction, triggered landslides, tsunamis, but most earthquake hazard studies emphasise recurrence of ground shaking by seismic waves.

Ground shaking hazard depends on the **amplitude** of ground motion (depending on the magnitude of the earthquake and its distance), the **frequency content** (also depending on the magnitude and distance), and its **duration** (depending mainly on the magnitude). It can be measured as displacement, velocity or acceleration, and peak values of these are often quoted, such as peak ground acceleration. These are poor measures of hazard because they do not consider frequency content or duration.

Fourier spectra of ground motion consider the frequency content, but do not give an indication of duration or resonance effects. Response spectra give the deformation of a damped harmonic oscillator (usually elastic), incorporating duration effects, so are the most useful measure of hazard for most engineering design.

Deterministic hazard studies usually consider rare large events that recur infrequently (for example, the maximum credible magnitude), while probabilistic studies consider the average return period (or annual probability of exceedence) of all earthquakes exceeding a given magnitude, or which produce seismic waves which exceed a given ground motion. A probabilistic study can be used to determine earthquake magnitudes appropriate for deterministic analysis, such as a time series analysis.

The most common probabilistic earthquake hazard assessment method is the Cornell method, which uses an earthquake recurrence model to anticipate the space, time and magnitude distribution of future earthquakes, as well as a ground motion model to anticipate the effects of these events. Ground motion recurrence probabilities are computed in a complex integration of the two models. Both earthquake recurrence and ground motion models have seen many developments over recent years.

2.1 Earthquake Recurrence Models

Earthquake recurrence models range from “flat-earth” models, which assume that spatial clustering will disappear in the long-term, and that earthquakes can occur anywhere in a specified region with similar probability.

At the other extreme, there are earthquake recurrence models that assume earthquakes will occur only in places where they have occurred in the past, either from known earthquakes or evidence of active faulting.

The authors of this paper prefer a hybrid model with significant geological input. In regions of low seismicity where temporal clustering gives long periods of quiescence, large earthquakes often occur in regions with little or no recent earthquake activity. In such regions it is particularly important to consider geological evidence of earthquake activity. Before the 12 May 1980 magnitude 8.0 earthquake, the Wenchuan region in Sichuan, China, experienced relatively few felt or damaging events over the past 1000 years, and few instrumentally located small events over the past 50 years. However, the local geology with steep topography displayed many aspects previous activity.

The earthquake activity in the Newcastle region is south of the north and east dipping Hunter-Mooki Fault System. It seems to be related to that fault, but in a way not yet understood.

2.2 Ground Motion Models

Ground motion models used in Australia have developed from the peak ground motion or intensity attenuation functions of Esteva and Rosenblueth, and Gaull, Michael-Leiba and Rynn in the 1960's and 70's. The first spectral functions (both Fourier and response spectra) used in Australia were by Trifunac in the 1970's and 80's. Significant models were published during 1997, including functions that could be used in eastern Australia, particularly by Sadigh et al. The first Next Generation Attenuation (or NGA) ground motion models were published in 2008, with significantly improved performance at extremes, small and large earthquakes, near and far earthquakes, short and especially long periods of ground motion. For the first time the ground motion models will now support displacement-based methods, and produce Acceleration-Displacement Response Spectra (ADRS).

The NGA functions provide some consideration of site response, particularly impedance amplification by soft surface sediments, but do not consider other site phenomena such as resonance or basin-edge effects.

3. EARTHQUAKE PGA RECURRENCE ESTIMATES FOR NEWCASTLE

3.1 Past Studies

Ground motion recurrence maps were published by McEwin et al, 1976, Standards Association of Australia (AS2121), 1979, Gaull, Michael-Leiba and Rynn, 1990, and Standards Australia (AS1170.4), 1993, Figure 2, A to D respectively.

The papers gave a variety of ground motion measures including peak ground acceleration, peak ground velocity, and Modified Mercalli intensity. None gave any spectral recurrence values. The maps covered a range of hazard criteria, so direct comparison requires conversions and assumptions

McEwin et al (1976) estimated the 50-year return period PGA, PGV and MM intensity. The authors warned that extrapolating 13 years of data to a 50 year return period was unreliable, and that large areas of Queensland and Western Australia could not be zoned. Only a small proportion of Australia was included above the minimum contour lines (0.1g, 50 mm/s, MMI 6 to 7, each with 50 year return period), and Newcastle was near these minimum contours.

The AS2121-1979 map was based on work by McCue (1973, 1975 and 1978), with new zones added in the Simpson Desert and Queensland. It used PGV with a zonation plot specifying four zones with increasing hazard – zones zero, A, 1 and 2, with zones 1 and 2 being comparable with regions of low hazard in more active regions. Newcastle was in zone zero, which had no lateral force requirement. The authors warned that data from events larger than magnitude 4.0 was complete across Australia only for the previous ten years, and that significant shaking could occur in any part of this zone in the future, and this did happen.

Gaull, Michael-Leiba and Rynn (1990) included large polygonal earthquake recurrence source zones, most being non-contiguous and delineating isolated regions of activity, and all within a wide background with sparse or no known seismicity. More than half of Australia lay in regions with ground motion above the minimum contour. The paper was published in 1990, but had been accepted for publication in October 1989, before the Newcastle earthquake. Newcastle was plotted with ground motion above the minimum contour for each of PGA, PGV and intensity.

The Standards Australia (AS1170.4, 1993) map was produced after the Tennant Creek and Newcastle earthquakes, and was based on the Gaull et al (1990) map, together with results from site-specific hazard studies that had been undertaken over the previous ten years. Contouring was modified to emulate fully contiguous source zones, without a large separate background zone. Ground motion was given as a dimensionless “acceleration co-efficient” that was numerically equivalent to the 10% in 50 years (475 year return period) PGA. Newcastle was assigned a value of 0.11. Contouring was used to avoid significant changes at zone boundaries, and linear interpolation between contours was permitted. The contours did not reflect precise recurrence, but were an attempt to portray the broad underlying pattern of seismicity based on data available at the time. The map was drawn at low resolution, so did not incorporate the significant variations in hazard near to active faults.

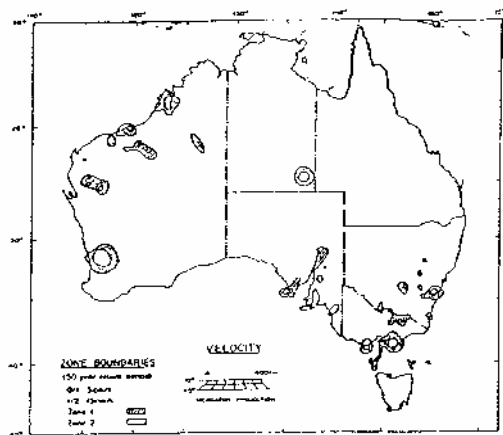


Figure A

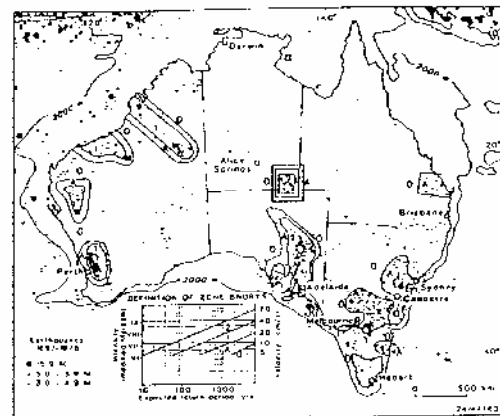


Figure B

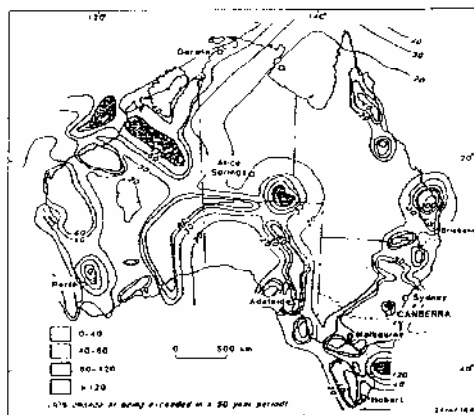


Figure C

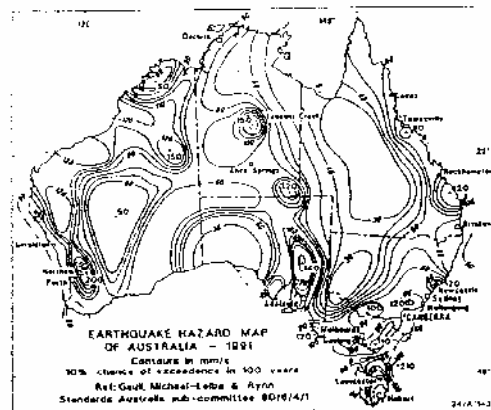


Figure D

Figure 2: Estimates Australian ground motion recurrence.

3.2 Dhu and Jones, 2002

Geoscience Australia conducted an extensive earthquake risk study of the Newcastle and Lake Macquarie region, which included detailed consideration of site response, plus a model of bedrock hazard. Ground motion was represented by PGA, and the hazard criterion used was 10% probability of exceedence in 50 years, with a result of 0.20 to 0.35 g at Newcastle. Two factors could have contributed to this high result.

The earthquake recurrence model was created from historical seismicity, which would concentrate anticipated activity in the same area.

The ground motion model used, Toro et al 1997, is from eastern and central North America, and is strongly influenced by records from the shield region of Canada, which give very high frequency motion, and thus high PGA values (see AUS5 value using Toro, Table 4). This function is probably more suitable for the shield region of central and Western Australia. Australia east of the Tasman Line has a much younger crust, dating from Palaeozoic, through Mesozoic and Tertiary, more comparable with California, so ground motion models from that region are more suitable, and will give lower PGA values for any given long period motion (or equivalently, for any given magnitude).

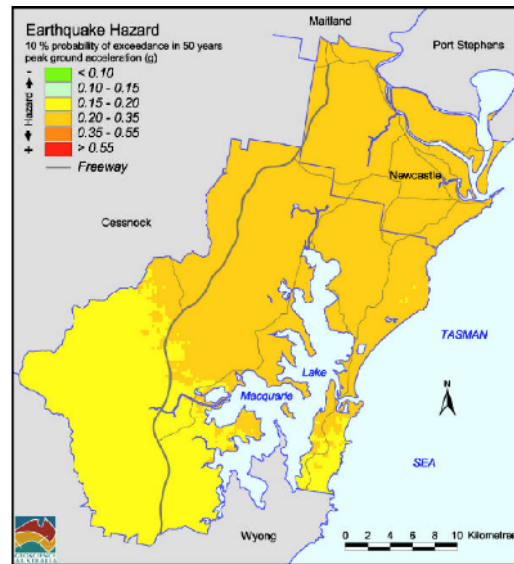


Figure 3: Earthquake hazard on rock in Newcastle, Dhu and Jones (2002).

4. NEW CALCULATIONS

4.1 Uniform Seismicity in a Large Polygonal Zone

In contrast to a model that restricts future activity to the location of past events, a model with large regions of uniform seismicity may be assumed. To illustrate this, a polygon has been drawn enclosing most of the earthquakes that have been declustered for this study (Figure 4).

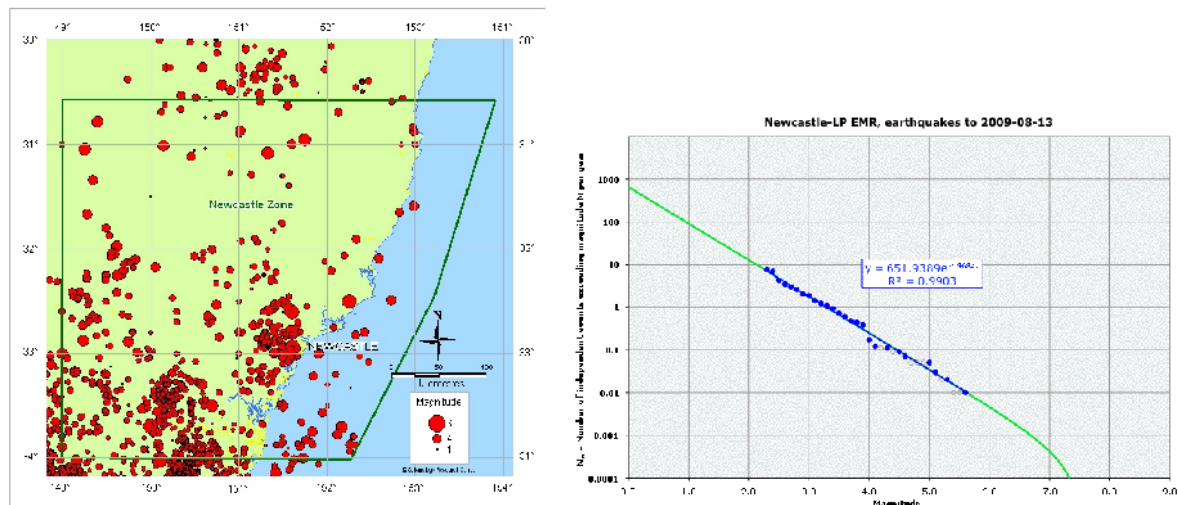


Figure 4: Large polygon zone, assuming eventual long-term uniform seismicity.

For this and the remaining models described, two minimum considered magnitudes of 4.0 (which usually relates best to past studies, and code values), and 5.0 (which may be more appropriate for large well-engineered structures). At this stage the seismicity is clearly spatially clustered and not uniform, but the model assumes that eventually future earthquakes will fill the gaps. Because of the size of the polygon, it includes 761 earthquakes, of which 577 were independent (not foreshocks or aftershocks). A total of 255 remained after relatively strict completeness criteria were applied (magnitude 5.0 from 1840 to 1910, 4.0 from 1910 to 1960, and 2.5 since 1960). The recurrence plot gives a good linear fit ($R^2 = 0.99$), but this does not necessarily mean that the model will reliably anticipate future activity.

Because this model smooths activity over a large region, it gives a low level of ground motion recurrence over the whole region. In this case the earthquakes that are within 4000 km² in the AUS5 model Newcastle zone are distributed over 150,000 km². This gives a 475-year PGA with minimum magnitude 4.0 of 0.049 g, and with minimum magnitude 5.0 of only 0.025 g.

4.2 AUS5 Model area source zones

The AUS5 source zones have been drawn using a 5-tier system (Brown & Gibson, 2004). Zones are defined by the geological and geophysical structure of the upper (seismogenic) crust, with consideration of seismicity distribution. Zone sizes are such that uniform seismicity can be assumed for each zone. Multiple zones are used to represent gradational seismicity.

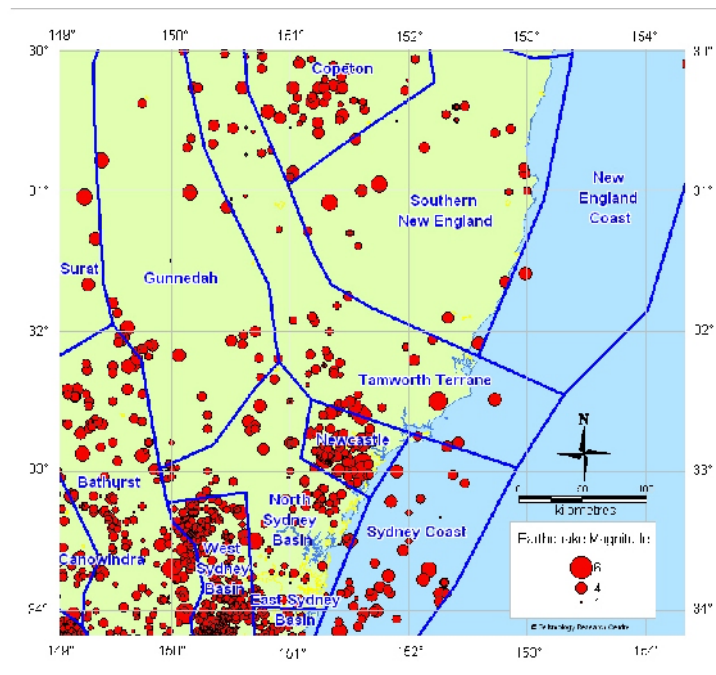


Figure 5: AUS5 area source zones about Newcastle.

The Newcastle area zone dominates the earthquake hazard for Newcastle (see Figure 9). Earthquakes in this zone can be smoothed over a wide area such as the large polygon model above, or they could be assumed to reflect the long-term activity. The AUS5 model takes a middle course, and assumes that above average activity does occur in the long-term, but not always at the rate that has been experienced over the past 180 years.

In stable continental regions, the recurrence interval greatly exceeds the duration of the earthquake catalogue, so it is inevitable that long-term recurrence calculations must take this

into consideration. The same applies for all zones that have experienced a recent moderate or large earthquake.

The north boundary of the Newcastle zone is defined by the Hunter Fault, a northeast dipping reverse fault, which lies along the south boundary of the Tamworth Terrane. Very few earthquakes have been recorded on this fault. To the northwest of the Newcastle zone, the Hunter Fault strikes just west of north and continues north as the Mooki Fault along the west boundary of the Tamworth Terrane.

The west boundary of the Newcastle zone was originally defined by the earthquake distribution, but it seems to be collinear with a southern extension of the Mooki Fault. This approximates the focal mechanism of the 1989 Newcastle earthquake (Gibson et al, 1990). Although a surface outcrop of the fault has not been identified, the hanging-wall uplift is consistent with the hills between Newcastle and Lake Macquarie. It is possible that the fault does not outcrop.

The uplift to the southwest of Newcastle and the high level of earthquake activity over the past 180 years, together suggest that the Newcastle zone has above average activity, although perhaps not as high as experienced over the past 180 years.

Although the west and south boundaries of the Newcastle zone were originally defined by seismicity alone, the original geometry has been retained until any relationships with the Hunter-Mooki Fault are clarified.

Figure 6: Newcastle zone earthquake history

There are only 24 independent events in the complete coverage region above the cyan line.

An earthquake of magnitude 5.3 on 1842-10-27 has an imprecise location just north of the Newcastle zone, in the adjacent Tamworth zone.

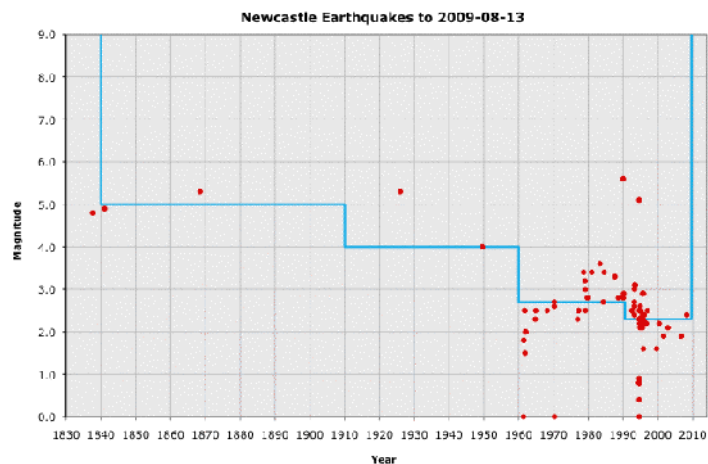
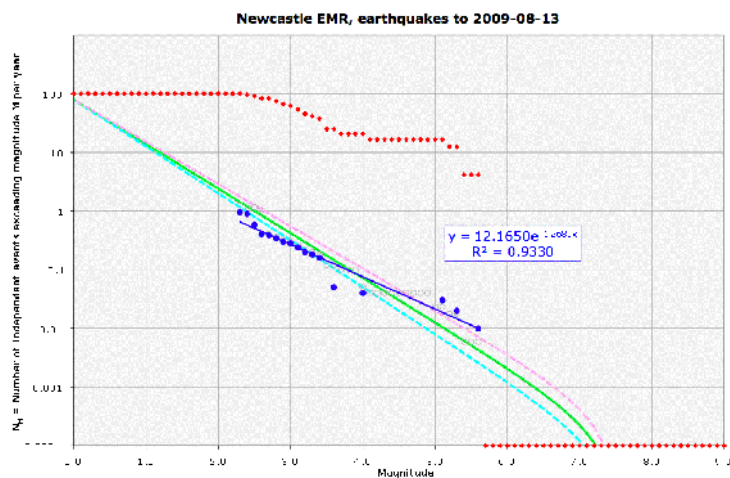


Figure 7: Newcastle zone earthquake magnitude recurrence.

The blue dots are the data, the blue line is the least squares fit with the fit values in the box

The green line is the adopted seismicity, while the pink and cyan lines indicate maximum and minimum hazards (1000-year magnitude from 6.0 to 6.6). The red dots show percent of data.

Constraint is very poor compared with the large polygon Newcastle-LP zone in Figure 4.



4.4 Area Source Zone Earthquake Recurrence Values

Only area source zones that were within 300 km of Newcastle were included.

Source Zone	Area (km ²)	A_0	b	M_{max}
Newcastle	3,859	207.308	0.75	7.5
Sydney Coast	25,910	59.94	0.93	7.5
Tamworth	32,870	8.930	0.80	7.5
North Sydney Basin	14,760	40.25	0.93	7.5
Southern New England	60,270	12.0	0.85	7.5
West Sydney Basin	8,266	140.0	0.77	7.5
Gunnedah	37,100	9.00	0.72	7.5
New England Coast	89,560	4.466	0.78	7.5
East Sydney Basin	3,303	160.0	0.93	7.5
Bathurst	26,240	165.0	0.93	7.5
Illawarra	4,851	59.940	0.93	7.5
Copeton	29,140	274.536	1.00	7.5
Canowindra	17,110	220.0	0.93	7.5
Surat Basin	231,600	18.940	0.834	7.5
Merimbula	30,410	160.0	0.93	7.5
Young	7,784	2100.0	1.00	7.5
Dalton	1,956	6000.0	1.00	7.5

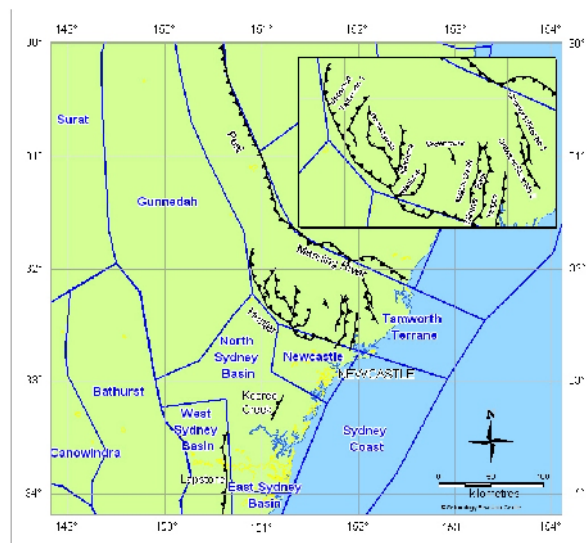
Table 1: Earthquake recurrence in area source zones.

4.3 AUS5 Model with faults

AUS5 can also include active faults, or faults assumed to be active, and when the fault seismicity can be quantified, this is normally subtracted from the zone seismicity. Without increasing the overall seismicity of the region, this can significantly increase hazard near the faults, and decrease it elsewhere.

Figure 8: AUS5 active faults in the Newcastle area.

In this case, most of the active faults are within the south end of the Tamworth zone, but not in the immediate vicinity of Newcastle, but this moves the earthquakes considered towards Newcastle, leading to a small increase in hazard estimates at Newcastle



Only faults that were within 150 kilometres of Newcastle were included in the calculations.

<i>Fault Name</i>	<i>Length (km)</i>	<i>Mmax</i>	<i>Rate, M5</i>	<i>Zone</i>
Williams River	36	7.1	0.000232	Tamworth
Targan	24	6.8	0.000156	Tamworth
Hunter	89	7.5	0.002311	Tamworth
Majors Creek	23	6.7	0.000149	Tamworth
Crawford River 2	19	6.5	0.000122	Tamworth
Karrakurra	23	6.7	0.000073	Tamworth
Crawford River 1	20	6.6	0.000128	Tamworth
Kooree Creek	17	6.5	0.000044	North Sydney
Webbers	19	6.6	0.000062	Tamworth
Brownmore	6	5.6	0.000050	Tamworth
Goorangoola	30	6.9	0.000193	Tamworth
Manning River	80	7.5	0.00026	Tamworth
Unnamed Tamworth 1	21	6.6	0.000068	Tamworth
Lapstone	57	7.5	0.00749	West Sydney
Peel	136	7.5	0.00236	Tamworth

Table 2: Earthquake recurrence in active fault sources.

4.5 Ground Motion Models

Ground motion recurrence was calculated using nine different ground motion models, five from the 1997 era, and four ‘Next Generation Attenuation’ models as published in 2008. The resulting PGA values are listed in Table 4. A soft bedrock site has been chosen where relevant, and $V_{s30} = 760$ m/s used for those functions that consider it. The NGA models use V_{s30} , the average shear wave velocity in the top 30 metres, to consider some aspects of site response such as impedance amplification, but not resonance effects.

<i>Ground Motion Model</i>	<i>Environment</i>
Sadigh, 1997	California
Abrahamson & Silva, 1997	California
Boore, Joyner & Fumal, 1997	Central California
Campbell, 1997, soft rock	California
Toro, 1997, midcontinent Mw	Central & Eastern North America
Chiou & Youngs, 2008, NGA	PEER-NGA database, mainly California
Boore & Atkinson, 2008, NGA	NGA flatfile, mainly California
Campbell & Bozorgnia, 2008, NGA	PEER-NGA database, mainly California
Abrahamson & Silva, 2008, NGA	Western USA shallow crustal

Table 3: Ground Motion Models.

4.6 Source Zone Contributions

Not surprisingly, in all cases most of the earthquake hazard computed using AUS5 at Newcastle was from the Newcastle area source zone. Those calculations including faults made little difference because the known faults were not in the immediate region about Newcastle, and were either small or too far away

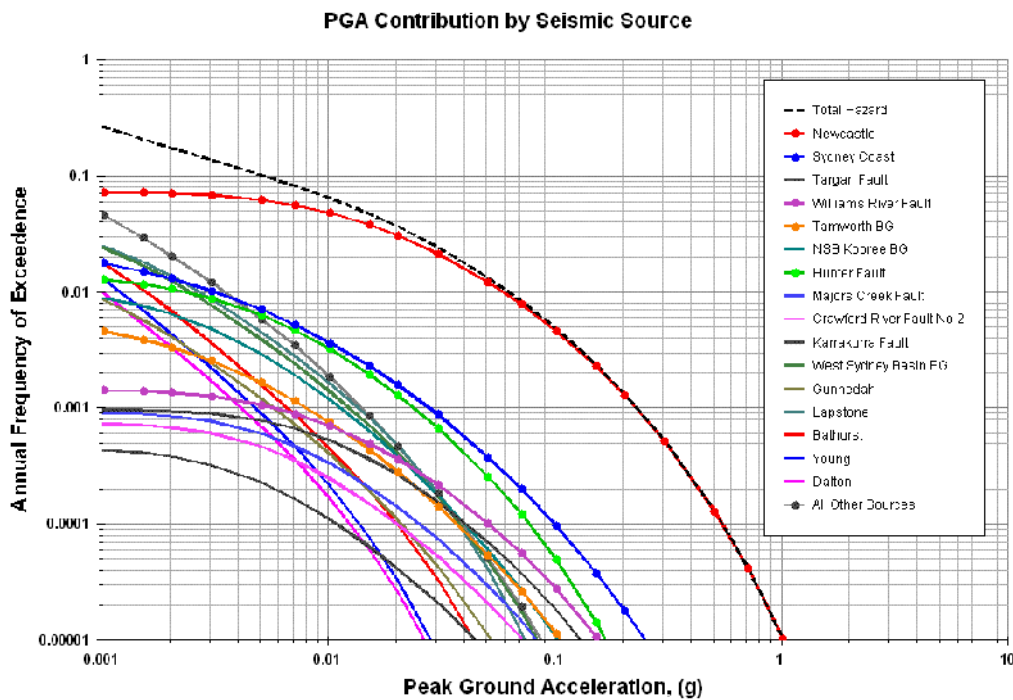


Figure 9: PGA contributions from source zones and faults.

Figure 9 shows the contributions to PGA from AUS5 with faults when using NGA ground motion models. It is dominated by the contributions from the Newcastle zone, and all other zones make only very minor contributions to the hazard. Other zones contribute more to longer period motion, but hazard is still dominated by the Newcastle zone.

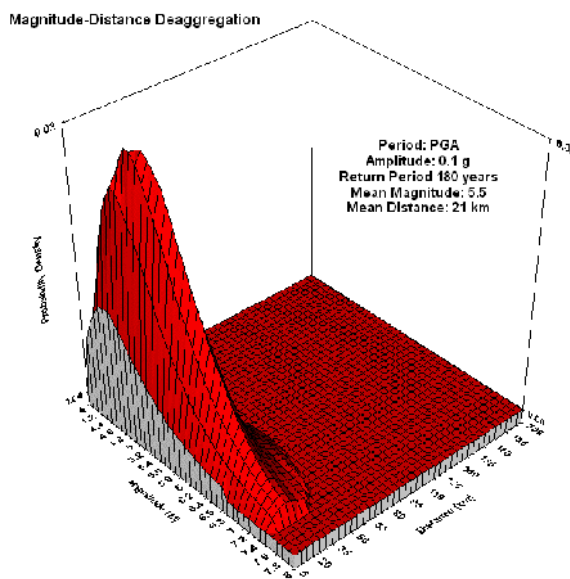


Figure 10: Magnitude-Distance deaggregation.

Using the AUS5 model, the vast majority of hazard at Newcastle is from earthquakes within 50 kilometres. This plot is for PGA motion with amplitude 0.1 g, where the mean magnitude and distance of 5.5 and 21 km are quite close to those of the 1989 December 27 earthquake.

RESULTS

<i>Earthquake Recurrence Model, Ground Motion Model</i>	<i>Magnitude 4.0 plus</i>	<i>Magnitude 5.0 plus</i>
McEwin, Underwood and Denham, 1976	Fifty year return period PGA ~0.10 g , PGV ~50 mm/s, and MM intensity 6 to 7.	
Earthquake Code AS2121-1979	500-year return period PGV less than 50 mm/s, zone zero.	
Gaull, Michael-Leiba and Rynn, 1990	10% in 50 year motion (475 year return period), PGA 0.045 g , PGV 40 mm/s, MMI 5 to 6.	
AS1170.4	10% in 50 year horizontal bedrock motion (475 year return period), PGA 0.11 g	
Dhu and Jones (2002), simulated earthquake model magnitudes 4.5 to 6.5. Toro et al (1997), Eastern North America.	10% in 50 year bedrock motion (475 year), PGA 0.20 to 0.35 g.	
Large polygon “flat earth” model Sadigh 1997.	0.049 g	0.025 g
AUS5 no faults, Sadigh 1997.	0.166 g	0.118 g
AUS5 with Faults for this and all below Sadigh 1997.	0.167 g	0.120 g
Abrahamson & Silva, 1997	0.138 g	0.119 g
Boore, Joyner & Fumal, 1997	0.159 g	0.123 g
Campbell, 1997, soft rock	0.151 g	0.111 g
Toro, 1997, midcontinental Mw	0.299 g	0.218 g
AUS5 with faults, NGA Chiou & Youngs 2008	0.184 g	0.159 g
AUS5 with faults, NGA Boore & Atkinson, 2008	0.124 g	0.107 g
AUS5 with faults, NGA Campbell & Bozorgnia 2008	0.134 g	0.117 g
AUS5 with faults, NGA Abrahamson & Silva, 2008	0.193 g	0.151 g

Table 4: Peak ground motion results for various earthquake and ground motion models.

Results show the significant effect of the minimum considered magnitude on the PGA recurrence. The effect is much less with longer period motion.

Earthquake recurrence models assuming wide uniform seismicity give much lower hazard for an active region like Newcastle, while models strongly based on known seismicity give high values. The AUS5 model and the Risk Frontiers smoothed seismicity lie between the extremes.

Compared with 1997 models, the 2008 NGA models are more consistent, behave better at extremes of magnitude, distance and frequency, and have smoother spectral shapes

Spectra from AUS5 Model with pre-NGA and NGA ground motion

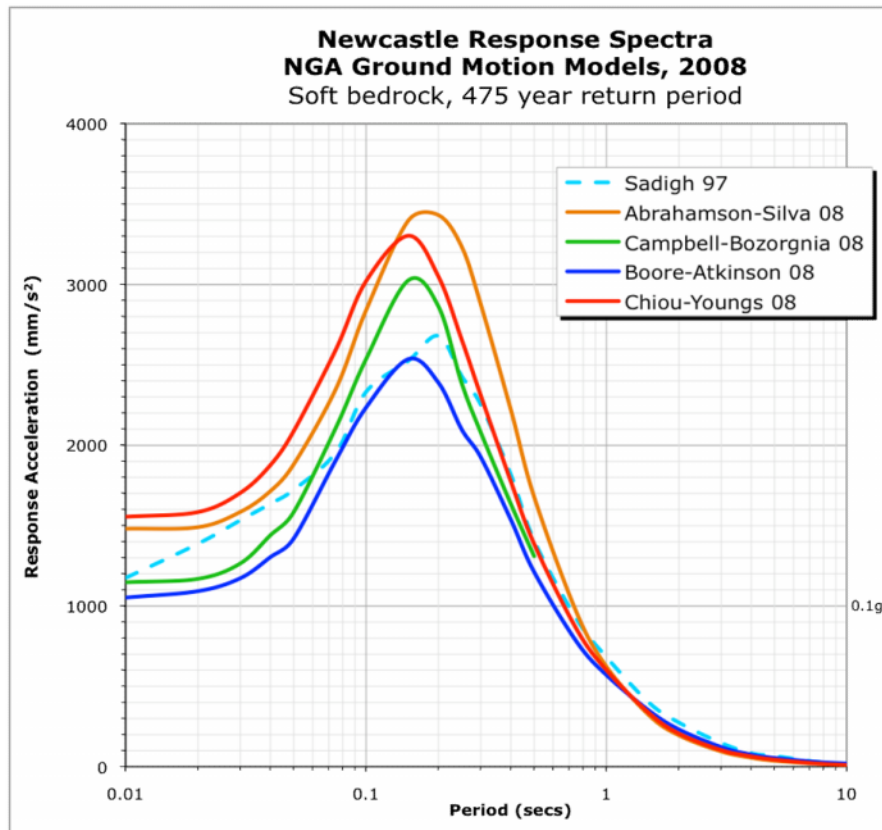
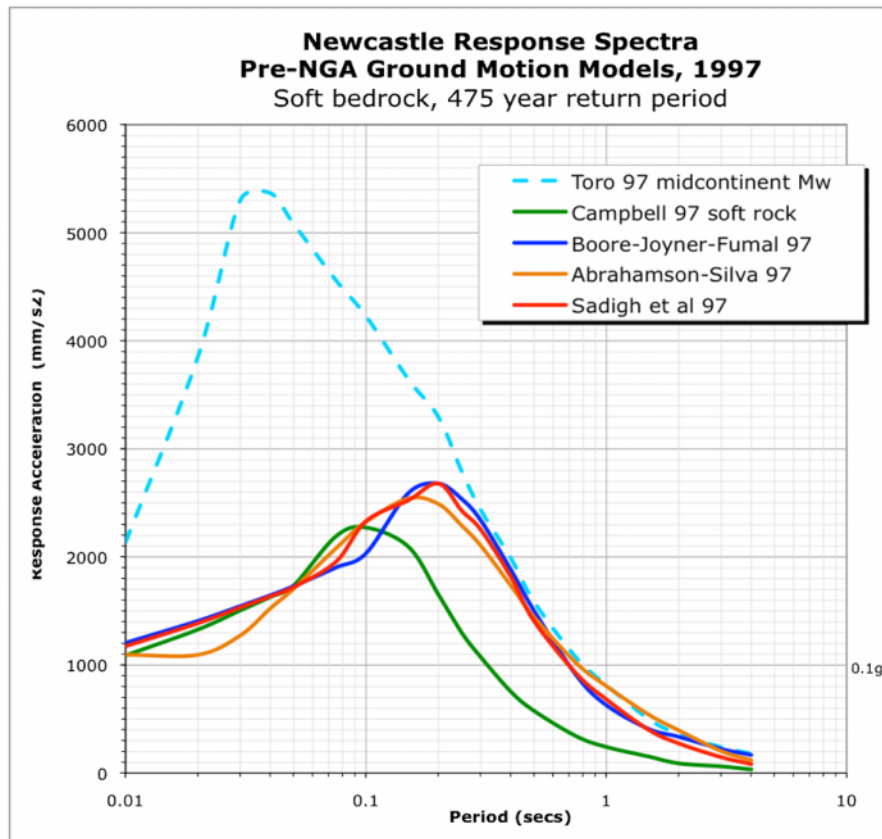


Figure 11: Newcastle uniform probability response spectra, log-linear.

Figure 11 shows that the NGA model spectra are much more consistent at long periods than the spectra from pre-NGA models. This is to be expected given that magnitudes are defined by long period motion or displacements, which are less affected by variation in attenuation than short period motion. NGA models consider motion to periods of 10 seconds, whereas pre-NGA models consider motion to only 2 or 4 second periods.

The variation in high frequency motion and PGA (PGA is numerically equal to response spectral acceleration at short periods, 0.01 second period here) is much greater in NGA models than in pre-NGA models, reflecting variations in earthquake focal mechanism. The Chiou and Youngs (2008) and Abrahamson-Silva (2008) NGA models represent higher stress earthquakes than the other NGA models, so give higher PGA values, and are more appropriate for Australia.

The Toro (1997) midcontinent model as shown in the pre-NGA figure is that used by Dhu and Jones (2002) for their model, resulting in the high values in Table 4.

The Sadigh (1997) pre-NGA model spectrum is repeated on the NGA plot, and shows the poor resolution of motion typical of pre-NGA models at all periods of motion. The short period spectra for the Sadigh model is only defined at 0.01 seconds (PGA), 0.07 seconds and 0.10 seconds, so interpolation at short periods can be misleading.

The pre-NGA models are defined at few periods, typically 8 to 13; while NGA spectra are defined at 22 or 23 periods, so give much smoother spectral curves.

The ground motion recurrence results for NGA models would be higher for values of V_{s30} less than 760 m/s, and lower for higher V_{s30} values.

CONCLUSIONS

This study of earthquake hazard in the Newcastle region shows a wide variation in the 475-year PGA depending on the assumptions made about the earthquake source scale and geometry, the minimum magnitude adopted, and the ground motion model used. It shows how carefully these input parameters must to be chosen.

Comparisons between the results of different earthquake hazard studies need to consider all of the assumptions made in each study. The purpose of hazard studies may differ, resulting in low or high values of ground motion recurrence for particular situations.

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