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Deaggregating the differences between seismic hazard assessments at a single site.

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ABSTRACT:
In the last few years four probabilistic seismic hazard assessments (PSHA) of Adelaide have resulted 500 year PGA of 0.059, 0.067, 0.109 and 0.141(g). The differences between the first three are readily accounted for by choice of GMPE, how faults are included and differences in recurrence estimation, with each of these having a similar level of importance.
As no GMPEs exist for the Mt Lofty and Flingers Ranges the choices of GMPEs were all based on geological analogies. The choice of what GMPEs to include was more important than the actual weightings of the selected GMPEs.
At a return period of 500 years the inclusion of faults was not necessarily highly significant. The choice of whether the faults behaved with Characteristic or Gutenberg-Richter recurrence statistics had the highest impact on the hazard with the choice of slip rate the next most important. A low slip rate Characteristic fault, while increasing the hazard for longer return periods (i.e. ≥2500 years), results in only a minor increase at 500 years, with a high slip rate Characteristic fault resulting in a moderate increase at 500 years.
The magnitude frequency distribution b-value for the four studies were 1.043, 0.88, 0.915 and 0.724. For the same activity in the magnitude range of 3.0 to 3.5, the activity level at M 6.0 is an order of magnitude higher for a b-value of 0.724 compared to a b-value of 1.043. This increase in activity rate of larger earthquakes significantly increases the hazard.

The average PGA of the first three studies is 0.078±0.022 g. This range is reflecting the intrinsic uncertainty in calculating PSHAs where many of the inputs are poorly constrained. The results for the highest hazard level PSHA study (i.e. 0.141g) can be explained by a combination of their use of a low b-value (i.e. 0.724) and a fault model that is now considered to give an excessively high hazard.

INTRODUCTION

The multiple probabilistic seismic hazard assessments (PSHA) of Adelaide over the last few years, by Leonard et al. (2013), Somerville and Skarlatoudis (2013), Hoult et al. (2013) and Gibson and Dimas (2009) have produced 500 year average return period (ARP) PGA values of 0.059, 0.067, 0.109 and 0.141 respectively. Table 1 summarizes the four recently published estimates of the 500 year PGA hazard in Adelaide. As the sites are all within a couple of kilometer, we consider then to be essentially for the same site. Note they all used similar values of Vs30 so variation in Vs30 is not investigate here. In these four studies 3 different source zonation models, 3 different fault source models, 4 different estimates of recurrence statistics, 4 different combinations of ground motion prediction equations (GMPE) and 3 different computer programs have been used to estimate the PSHA. Given this diverse range of inputs and the inherent uncertainties in each of the inputs a range in the resulting hazards is expected. However a factor of 2.4 (between the lowest and highest) is higher than would normally be expected. Here we investigate the sources of these differences.

Table 1 summary of the four PSHAs of Adelaide undertaken in the last few years

Model	**Authors**	**GMPE**	**Vs30 m/s**	**PGA (g)**
AUS5	Gibson et al.	Chiou and Young 2008 (CY08) 1.0	1000	0.141
AUS5	Hoult et al.	CY08 0.5, AS08 0.25, CB08 0.25;	760	0.109
GA2013	Leonard et al.	AB06 0.25 CY08 0.25 S09 0.25 A12 0.25	760	0.059
RF2013	Somerville et al.	A12 0.3 S09 0.3 NGA-W 0.4	820-1000	0.062

RECURRENCE STATISTICS ESTIMATION

The catalogue we used is the one built by Gary Gibson(GGCat) from which we extracted the earthquakes in the Kanmantoo (also known as the Mt Lofty Ranges) source zone and used these to investigate the effect of recurrence estimation. The recurrence was estimated using three techniques; Least Squared regression (LR), Maximum Likelihood (ML) and modified Least Squares (MLS). Each technique gives an $A_{2.5}$ of 0.713 earthquakes per year per 10000 km^2. Their b is 0.724, 0.960 and 0.972 respectively. The AUS5 model used in the New Royal Adelaide Hospital study (NRAH), (Gibson and Dimas 2009, Figure 13), used a Least Squares regression and Brown and Gibson (2004) in the original AUS5 model used ML, though b was estimated from the combined Kanmantoo, Kangaroo Island and Spencer zones. The various a and b value are summarized in Table 2.

Table 2 the sensitivity of the b-value on regression technique for the Kanmantoo source zone.

Study	**Regression Technique**	$A_{2.5}$	b
This Study	LR	0.713	0.724
	ML	0.713	0.960
	MLS	0.713	0.972
AUS5 (NRAH)	LR	0.719	0.724
AUS5 (Original)	ML	0.719	0.880

At the magnitude of completeness of M2.5 all the techniques give identical results. However the variation in slope (b) gives activity rates at M5.5 of 480×10^{-5}, 165×10^{-5}, 94×10^{-5} and 87×10^{-5}, for

b = 0.724, 0.88, 0.96 and 0.972 respectively. This change in activity results in a large change in hazard. For example, setting $A_{2.5}$ = 0.713 and using b = 0.724 & 0.96 ($A_{5.6}$ = 406x10^{-5} and 75x10^{-5}) gives PGA hazards in Adelaide of 0.14 and 0.025 (g) respectively. The factor of 5.4 difference in $A_{5.6}$ results in a difference in PGA of a factor of 5.5. This highlights the importance of accurate estimate of $A_{2.5}$ and particularly b, with a change of 0.1 in b typically changing the hazard by a factor of 2.

GROUND MOTION PREDICTION EQUATIONS

The hazard level is sensitive to the choice of GMPE. The four PSHA analyses we are comparing all used different GMPE models with seven individual GMPEs being used. To measure the sensitivity to the hazard to selection of GMPE(s) we used the Kanmantoo zone, fixing the recurrences rates to $A_{3.5}$=0.1 and b = 0.88. The five individual GMPEs returned a 500 year PGA which ranged from 0.0296 to 0.0589 (Table 2), a factor of 2. As expected, the four weighted combinations gave a smaller range of 0.304 to 0.0508, being a factor of 1.67. The average PGA of the four combinations is 0.04g±0.01at 500 years and 0.138g±0.005at 2500 years.

Table 3 the effect of GMPE on PGA

GMPE	PGA (g)	
	500 yr	**2500 yr**
Allen 2012	0.0304	0.1395
AB06_BC	0.0296	0.1089
AS08	0.0589	0.1741
CB08	0.0531	0.1443
S09_NC	0.0387	0.1223

GMPEs	PGA (g)	
	500 yr	**2500 yr**
GA2013	0.0364	0.1318
AUS4 Hoult	0.0508	0.1436
RF2013	0.0304	0.1395
AUS5 Gibson	0.0407	0.1388

FAULT MODELS

Over the last 30 years there have been extensive discussions on how faults should be incorporated into PSHA. The idea that the statistics describing faults behavior is better described as Characteristic rather than Gutenberg-Richter has been around for 30 years (Aki 1983, Schwartz and Coppersmith 1984, Youngs and Coppersmith 1985). In this model faults tend to rupture in large earthquakes which occupy 50% to 100% of the fault length, with very few small earthquakes occurring on the fault. The approach is mostly used to combine historical seismicity in the region with geologically derived slip-rates and/or recurrence intervals on individual faults. A review paper, Ben-Zion (2003), cites 20 studies covering many different regions which all fitted a Characteristic rather than a Gutenberg-Richter magnitude frequency distribution (MFD). The evidence is not clear cut with various papers arguing that many particular faults/earthquakes do not fit the Characteristic model (e.g. Kagan et al. 2012). One of the main objections to the Characteristic model is that it has, apparently, lead to researchers dividing long faults into subsections and so excluding the possibility of multiple segments rupturing in a single large earthquake (e.g. 2011 Tohoku earthquake - Kagan and Jackson 2013). Hecker et al. (2013) using a composite global data set of paleaoseismic observations found that the data is more consistent with a Characteristic than a Gutenberg-Richter model.

In several studies of the Flinders Ranges in recent years (Love 2013, Pilia et al. 2013) no correlation between instrumental seismicity and mapped faults has been identified. Similarly no clear relation between the faults in East Gippsland and seismicity has been identified (Sandiford et al. 2012; Brown and Gibson 2004) and there is little correlation between local seismicity and either the Darling Fault or the Lapstone Monocline (e.g. Leonard 2008). This is consistent with the Characteristic model rather than a Gutenberg-Richter model of fault seismicity. In PSHA the common practice is to combine Characteristic faults with G-R zone sources (e.g. California: Field et al., 2009, 2014, Working Group on California Earthquake Probabilities, 1995, 2003; Italy: Romeo, 2005; Central and Eastern US: Petersen et al., 2008, 2014). For both the Meers fault in Oklahoma and the Cheraw Fault in eastern Colorado a Characteristic fault model is adopted for the US national seismic hazard map (Petersen et al. 2014). In a study of the Flinders Ranges Somerville et al. (2008) used a Characteristic fault model. Based on this evidence we conclude that a Characteristic fault model is more appropriate to Australia than a Gutenberg-Richter model.
To test the impact of including faults in a PSHA for Adelaide, a set of faults was adopted and the Characteristic and Guternberg-Richter models tested. The Fault models adopted were initially based on the faults used in the NRAH PSHA report and then modified slightly based on the latest version of the Geoscience Australia Neotectonics Features database (Clark et al. 2014). None of the faults in the Mt Lofty Ranges is well constrained. Complications include, how long the faults have been active at the current rate, their dip, statistical sampling of random processes, whether the Active~Quiescent fault model (Crone and Machette, 1997; Crone et al., 1997; Crone et al. 2003, Clark et al. 2014) applies here and if so in which phase the fault is currently in.

The current Australian stress field is thought to have been in place since 3-4 Ma (Hillis et al. 2003, Sandiford et al. 2005) when the Oolong plateau collided with the Australian plate. Mueller et al 2014 found the orientation and level of stress in central Australia is sensitive to this distant event. As such we have adopted 4 Ma. It is thought that the faults in the Mt Lofty and Flinders Ranges are steeply dipping and we adopt 55°. As there is inadequate data to statistically sample the short and long term event rate or where within an Active~Quiescent fault model any the faults lie we have assumed that our estimate of the average slip-rate is the current rate.

CONSTRAINING SLIP-RATES

The Milendella and Willunga are the best constrained of the identified faults. The Willunga has 7±1 m of vertical offset in 0.12 Ma, 139 m in 1.7 Ma and 240 m in 15 Ma. This gives fault slip-rates of 60, 100 and 20 m/Ma respectively. These rates are not easily reconciled. Assuming 60 m/Ma for 4 Ma would require zero slip in the previous 11 Ma. One interpretation of the data, which implicitly assumes that there was a major change in the local stress field at 4 Ma, is to take the values of 45 m/Ma for 4 Ma and 5.5 m/Ma for 11 Ma. Another is to adopt the Active~Quiescent model and assume 200 m/Ma for 50 ka and a longterm average slip rate of 15 m/Ma. Similarly, the Milendella Fault has 30 m in 0.78 Ma and 160 m in 16 Ma. This gives fault slip-rates of 45 and 12 m/Ma respectively. One interpretation of this data is to take the values of 35 m/Ma for 4 Ma and 2.0 m/Ma for 12 Ma. Another is to adopt the Active~Quiescent model and assume 200 m/Ma for 50 ka and a long-term average slip rate of 10 m/Ma. For both these faults this analysis leads to a high slip-rate result and a low slip-rate result, with the low slip-rate result being similar to the AUS5 model (Brown 2004, Brown and Gibson 2004) and the NRAH PSHA report.

Based on the work of Sandiford et al (2005) and Clark and McPherson (2011), the most widely accepted model for faults in the Mt Lofty Ranges is that the range bounding faults are slipping more rapidly than the intra-range faults. We have assumed that the range bounding faults are slipping about four times faster than the intra-range faults. Table 3 summarizes faults and gives the high, low and AUS5 slip-rates on the various faults. The software used to model the hazard (EQRM), uses the formulation of Youngs and Coppersmith (1985) to generate the MFD, from the slip rate, Mmax and Mmin provided. For the zone source model, the Mmax in the Mt Lofty Ranges were reduced from 7.5 to 7.0. For the fault source model, the Mmax is calculated from the full fault length using the scaling relation of Leonard (2014).

Using the Kanmantoo source zone, with b=0.88, as the single background source zone we undertook two tests. The first compared various modes of including the high slip-rate characteristic fault source to the source zone. The second included the two fault slip rates as both Characteristic and Gutenberg-Richter faults using a single mode. Table 4 summarizes the results for these tests. The source zone alone produces a PGA of 0.0413 and adding the faults with Mmin set to 4.5, adds 0.0445 for a total PGA of 0.0857(g), an increase of 110%. Adding the faults with Mmin set to Mmax-1.5 adds 0.010 for a total of 0.0517(g) an increase of 20%. This highlights that even using the Characteristic model, at short return periods the hazard is still dominated by earthquakes in the range M4.5–5.9. In the second test the fault Mmin was set to 5.3 and Mmax of the Zone was set to 7.0, with the four permutations of high and low slip rate and Characteristic versus G_R tested. The Gutenberg-Richter faults always give much higher hazard levels than Characteristic faults and the hazard level is approximately linear with the slip-rate. In this case the high slip-rate Characteristic model gives a level similar to that of the low slip-rate G-R model.

In a recent study Clark and Leonard (2014) combined the GA13 zonation only hazard model and added in, as Characteristic, a new fault model they developed. They found a change in hazard for Adelaide from 0.061 to 0.115, an increase of 88%.

Table 3 the properties of the faults in the Mt Lofty Ranges.

Fault	This study				AUS5		
			Slip (m/Myr)				
	Length (km)	**Mmax**	**High**	**Low**	**Length**	**Mmax**	**Slip**
Alma	89	7.5	20	4	-	-	-
Bremer	50	7.15	30	5	90	7.5	5
Clarendon	33/45	6.85	30	8	45	7.3	5
Clarendon Cent	20				19	6.6	5
Eden-Burnside Nth	33	6.85	30	8			
Eden-Burns Sth	30	6.78	50	10			
Eden-Burnside					46	7.3	5
Eden-Burnside Cent	30	6.9			19	6.9	5
Encounter Bay	65	7.34	-	-	34	7.1	3
Meadows	51	7.16	-	-	52	7.4	3
Milendella	58	7.26	40	5	-	-	-
Palmer	40	6.99	30	5	99	7.5	5
Para	44/54	7.1	40	9	54	7.5	4
Para Cent.	27				27	6.9	5
Tarlee/Williamstown	38	6.95	20	4	-		-
Willunga	58/82	7.26	40	6	82	7.5	3
Willunga Cent.	35	7.1			35	7.1	4

Table 4 sensitivity of model to Fault and Zone parameters.

Model	PGA Hazard (g)		Model	PGA Hazard (g)	
	500	**2500**		**500**	**2500**
Zone only, Mmax 7.0	0.0413	0.1407	L S/R Ch. Mmin 5.3	0.0433	0.1548
H S/R CH Mmin =4.5	0.0857	0.2753	L S/R GR Mmin 5.3	0.0558	0.2025
H S/R CH Mmin =Mmax-1.5	0.0517	0.1981	H S/R Ch. Mmin 5.3	0.0513	0.2031
H S/R CH Mmin =Mmax-1.0	0.0449	0.1674	H S/R GR Mmin 5.3	0.1186	0.3469

Discussion

Despite the quality of the catalogue in the Adelaide region, recurrence statistics, particularly the *b*, are subject to significant uncertainties (e.g. ±0.1) that results in variations in hazard of a factor of 2. Similarly there is no strong ground motion data from the Flinders and Mt Lofty Ranges with which to constrain or even quantitatively weight GMPEs. The current selection GMPEs give variations in hazard of a factor of 1.7. This is likely a conservative estimate as it does not include the possibility that the current “expert opinion” that the Mt Lofty Ranges earthquakes and crust are approximately like California is incorrect. Uncertainty in fault slip-rate can lead to a variation in hazard of a factor of 5 and uncertainty in model type leads to a variation in hazard of 7. Even assuming that the Characteristic model is correct still leaves an uncertainty of 5. These ranges are per source or GMPE or fault. As the hazard studies or Adelaide used multiple zone sources, multiple GMPEs and multiple faults the variation will be reduced. For random noise the error reduces by the $\sqrt{n}$, where n is the number of samples, in which case an increase by 2 in the number of inputs would reduce the uncertainty by a factor of 1.4. However none of the sources of uncertainty are likely random so applying this simple rule is unlikely to be fully valid.

Assuming that the total hazard function is of the form: Z = SZ*GMPE + FZ*GMPE, where SZ is the Source Zone Recurrence Model, FZ is the Fault Recurrence Model and Z is the Total Hazard. Using the standard formula for combining errors requires the error contribution of the two products be evaluated first then the errors combined. Rearranging gives Equation 1 and substituting the various estimates of hazard discussed above (ΔSR, ΔFR and ΔGMPE) and assuming a $\sqrt{n}$ reduction in them, give a total hazard and uncertainty of 0.08±0.08 (g). We consider this to be an upper estimate of the uncertainty.

$$\Delta Z^2 = Z^2 \left(SZ^2 \left(\left(\frac{\Delta SR}{SR}\right)^2 + \left(\frac{\Delta GMPE}{GMPE}\right)^2 \right) + FZ^2 \left(\left(\frac{\Delta FR}{FR}\right)^2 + \left(\frac{\Delta GMPE}{GMPE}\right)^2 \right) \right) \qquad 1$$

CONCLUSION

Even in Adelaide, which has amongst the best earthquake catalogues and probably the best constrained active faults in Australia, the earthquake hazard is subject to high uncertainties. The four PSHAs undertaken for Adelaide in recent years give a range of 0.059–0.141 g for PGA at 500 year ARP, which gives 0.10±0.04. The higher of these is now thought to perhaps overestimate the hazard from the faults. The average of the lower three studies is 0.084±0.025 (0.059 –0.109) g. Using the results of Clark and Leonard (2014) in place of GA13 gives 0.101±0.04 and 0.089±0.027 for the four and three models respectively. These ranges are reflecting the intrinsic uncertainty in calculating PSHAs where many of the inputs are poorly constrained. In this paper we have shown that the recurrence statistics, selection of GMPEs and fault models all have significant uncertainties. Our attempt to quantify these uncertainties gives higher value (i.e. 0.08±0.08 g) than that suggested by the ranges encompassing the three or four studies.

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