Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

The seismic hazard of Australia - a venture into an uncertain future

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ABSTRACT: The seismic hazard of Australia is one of the most difficult on the globe to characterise, due to intraplate tectonics with faults capable of producing Mw7.0 earthquakes in the vicinity of several major Australian cities like Adelaide or Perth, yet a recorded history of less than 250 years. The lack of long-term historical earthquake data makes it extremely difficult to sufficiently quantify return periods of large events in most locations. Although the majority of sources in Australia represent low to moderate seismicity characteristics, they are still capable of causing major damage in many Australian communities. Recent studies of the tectonic faulting mechanisms of Australia and new developments in handling uncertainties of low seismicity regions are used to develop detailed probabilistic hazard maps for Australia's major capital cities. In addition, characteristic earthquake scenarios are developed for various return periods for these locations. The assessment of uncertainties within the intraplate setup of Australia and the short earthquake record is taken into account when calculating the strong seismicity return periods. This study provides a detailed insight into the probabilistic and deterministic seismic hazard of Australia and its major cities for various time periods, especially for the consideration of risk modelling.

1 INTRODUCTION

The quantification of seismic hazard in a stable continental region is very challenging. Not only is general earthquake return period characterization linked to a significant amount of uncertainties, but also the problem of limited data and insufficient knowledge about the underlying processes of earthquake generation and migration within such a tectonic setting is problematic.

Several attempts have been undertaken to identify the seismic hazard in Australia. Classically, developing seismic hazard maps has been based on identifying seismic source zones, simplified polygons which contain a certain level of uniform activity, linking it for the generation of probabilistic hazard maps to a time-independent Poisson process (Kagan & Jackson, 2007). This standard way of handling seismicity works sufficiently well in regions with a long record of seismicity, a uniform distribution of magnitude completeness and frequent earthquake activity. None of these components however can be taken for granted when analysing the characteristics of the Australian continent. The earthquake record of Australia is highly limited, covering at most 220 years in some places, but for the majority a period of around 100 years. When considering the return periods of earthquakes with huge damage potential, (generally magnitudes larger than 6), the data record is in many places insufficient to give decent estimates for such events. Recent studies focused on these issues, like the latest Australian seismic hazard map (Burbidge, 2012) which contains detailed reviews and use of local seismicity patterns, general earthquake catalogues and using paleoseismic data (Clark & Leonard, 2014) to determine return periods of fault ruptures around major Australian cities. Ninis & Gibson (2006) combined fault models with slip rates assigned with historic seismicity in NSW to bridge the gap between both methods. The results indicated an increased hazard along faults and a decreased hazard further away. The crucial element is the definition of the respective slip rates for each fault within a source zone. The limited data on fault geometry and slip rates creates problems and does not allow for a country-wide application of this methodology.

The focus of this study is to build a robust and simple method which shall provide a stable look into Australia’s seismic hazard with a specific focus on accuracy around the major cities. The robustness is achieved by building a time-independent probability without using standard source zonation. Hereby a fuzzy logic for the spatial discretization of Gutenberg-Richter parameters is introduced. Only Australian seismicity is taken into account in this paper with offshore zones e.g. from Papua New-Guinea which contribute to North Australian hazard currently being neglected.

2 METHOD

2.1 Data

The main source of earthquake data is the database of Geoscience Australia (GeoscienceAustralia, 2015). It includes earthquakes from about 1840 until July 1st, 2015, providing 23448 events. All earthquakes of magnitudes larger than 2.0 have been considered. Smaller magnitudes may bias the total hazard with regard to regions with a denser seismic network, where microseismicity can be recorded, in comparison to remote locations without dense networks. As mentioned previously, the general disadvantage is its limited temporal record, covering about 120 years in average. This gap is bridged by implementing the published historic databases of Kevin McCue, which date back to about 1800, providing an additional 800 earthquakes for the catalogue (e.g. (McCue, 2013a), (McCue, 2013b), (McCue, 2013c), (McCue, 2014)). This data provides vital information about the historical seismicity of Australia and thus should not be neglected in regard to the determination of Australia's seismic hazard model. An expert judgement of completeness has been taken into account in combination with generalised completeness methods. The combined earthquake catalogue of instrumental and historic events has been declustered using the declustering method of Schaefer et al. (2014). This has been shown to work in low and high seismicity locations within countries such as Turkey (Schaefer et al., 2015). Hereby, earthquake clusters are identified based on a magnitude-dependent search algorithm in space and time, each cluster is then replaced by an energy-equivalent earthquake representing the sum of all energy magnitudes of foreshocks, aftershocks and the respective mainshock. In total, the declustered catalogue contains about 11838 earthquakes, which are shown in Figure 1.

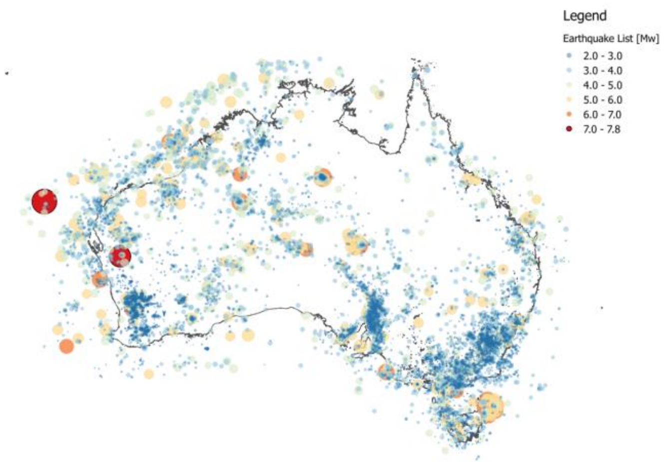

Figure 1: A visualisation of the declustered earthquake catalogue for Australia used in this study

2.2 Seismic Sources

In general, seismic sources are used for spatial discretization of seismic hazard, e.g. to determine Gutenberg-Richter parameters (Gutenberg & Richter, 1944). The usual approach involves the use of distinct seismic sources with sharp boundaries, which often leads to sudden jumps in the spatial mapping of a stochastic catalogue. In this study, a fuzzy logic is used. Seismic sources or domains are identified by non-overlapping vector elements. The determination of Gutenberg-Richter parameters is based on earthquake events in the vicinity of each seismic source. The fuzzy element is then based on the probability contribution of each earthquake. For example, if one event is located in between two sources, it has an equal probability of being part of one or the other, and in addition a 1 % chance to be part of a general background activity. The actual geometry of seismic domains resemble patterns in seismic activity and tectonic constraints, e.g. the separation between Craton and non-Craton, regions with dominant fault structures like the Flinders Ranges or the South-Western Yilgarn Craton. Each source represents its own seismic process with distinct Gutenberg-Richter characteristics. The seismic activity is computed on a grid using pixels with a cell size of 10x10 km. For each cell, a pair of Gutenberg-Richter parameters is computed which are used to build the probability density function for the stochastic earthquake modelling. Hereby, the computation of b-values has been undertaken using the probability contributions of seismic domains around the each pixel. Finally, the values have been projected in between each domain using a weighted nearest neighbour algorithm. The general base rate of seismic activity, the “a-value” of the Gutenberg-Richter computation is based on a smooth seismicity with a smoothing kernel of 100 km. Finally, the most active pixels have been capped to 75% of their maximum value to reduce the impact of local peaks.

2.3 **Hazard Modelling**

The seismic hazard modelling is based on a stochastic process. To account for the large spatial uncertainties of seismic activity, a sufficiently long time interval has to be simulated to determine the expected average ground shaking within a certain time period. In this study, a return period of 500 years is investigated for which 1000 simulations have been undertaken leading to 500,000 years of earthquake history. The location-dependent mean of all these simulations is considered a sufficient estimation of seismic hazard. In addition, the respective standard deviation provides insight into more conservative estimates for each location. The selection of ground motion prediction equations is separated in both Craton and non-Cratonic areas, roughly split into Western and Eastern Australia. For both areas, the GMPEs of Atkinson & Boore (2006), Lin & Lee (2008), Allen (2012) have been used, Somerville et al. (2009) provides functions for Craton and non-Craton and have been assigned respectively. While the first two are considered globally applicable, the latter two are based on Australian data. The weighting is as follows:- 1/6 for each of the two global functions and 1/3 each for the Australian functions. Only the global GMPEs use Vs30 soil conditions, for which the values of USGS (Allen & Wald, 2009) on a spatial resolution of 1x1 km have been used. In regard to continent-wide assessment of seismic hazard, the grid has been scaled to a resolution of 5x5 km nationwide, and for a city-based assessment, the original resolution of 1x1 km was applied.

To establish a more complete insight into Australia’s seismic hazard with respect to its capital cities, deterministic scenarios have been computed to create a set of 3 representative events for certain return periods. Hereby, we provide brief subjective estimates of the likelihood of such events, not exactly as they are presented here, with similarity between their characteristics.

3 **THE AUSTRALIAN HAZARD MODEL**

3.1 **Australia**

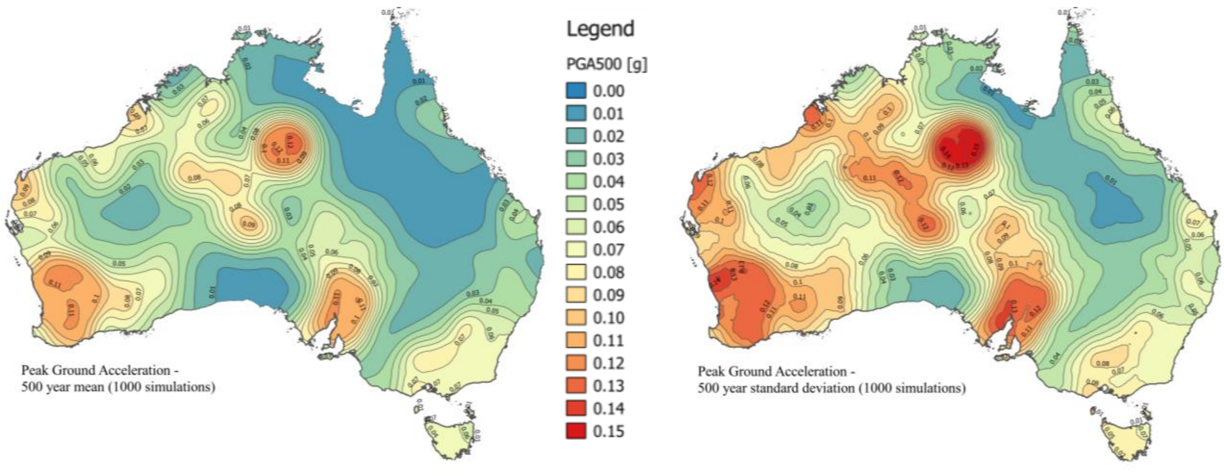

Figure 2: Plot of the mean 500-year exceedance Peak Ground Acceleration (left) and the respective standard deviation (right) based on 1000 simulations on a 5x5 km grid in g=9.81 m/s².

Based on the descriptions described above in Section 2, a hazard model has been assembled to capture the mean 500-year exceedance ground shaking PGA based on 500,000 years of seismic modelling with a minimum magnitude of 4.7. With regard to a country-wide assessment, deterministic modelling has been neglected but is taken into account for the assessment of the seismic hazard of the capital cities. To avoid local peaks and to give a broader view, the calculated ground shaking map for all of Australia, using a 5x5 km grid has been smoothed, using a Gaussian kernel with a smoothing density of 100 km. The high resolution ground shaking maps for the city assessments with a 1x1 km grid were smoothed using a 10 km kernel. The impact of smoothing is the reduction of local peaks, and the blurring of modelling uncertainty, leading to a decrease in peak ground shaking with respect to the original unsmoothed computation of about 20%.

The spatial distribution is similar to the results of Burbidge et al. 2012, since both models use actual seismic density values. The significant difference is that of using a longer earthquake record and a different method in discretizing seismic sources. There was no differentiation with respect to seismic hotspots, such as that of Tennant Creek. Considering the distribution of seismic activity all over Australia, the current version provides a larger spatial extent leading to a less restrictive localization of seismicity, especially in regard to fault activity in many parts of Australia which is unknown. For all major cities except for Brisbane, the modelled mean ground shaking for a 500-year return period (ca. 9% chance of exceedance in 50 years) exceeds 0.06g. Especially for Perth, where local soil effects become important and the distant shaking impact of earthquakes located in the Yilgarn Craton have a strong impact, a ground shaking of 0.12 g in average is found.

The hazard model has been built primarily for the quantification of hazard for the capital cities, thus each capital city is described in more detail in the following section. A probabilistic ground shaking map is introduced for each city and its surroundings, and also various deterministic scenarios have been computed with respect to local seismic history and tectonic features. Scenarios are presented given their magnitude, location, likelihood and return period and their seismic source. In general these are aligned on distinct faults or by indicating tectonic offspring, is considered part of the general background activity in the region. The given return period is based on the whole city region and not necessarily indicative of the seismic source itself. The results for each scenario event are shown based on a proximity analysis of ground shaking in a 50 km diameter around the CBD area, providing mean, maximum and standard deviation of ground shaking.

3.2 Adelaide

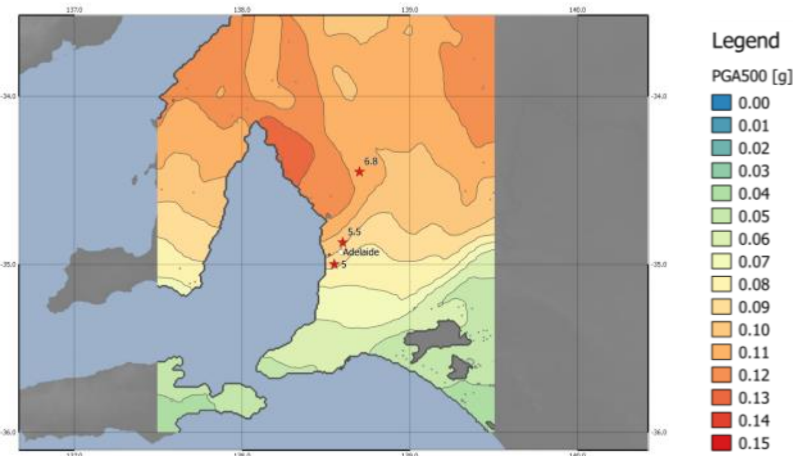

Figure 3: Plot of the mean 500-year exceedance PGA around Adelaide on a 1x1 km grid in g=9.81 m/s².

The seismic hazard around Adelaide is dominated by the active orogeny of the Flinders Ranges and Mount Lofty Ranges. The distribution of seismic activity increases northwards, with higher ground motions for the northern suburbs of PGA around 0.1-0.12 g and lower PGAs for the south of Adelaide of about 0.08 g. With respect to earthquake density, the activity is significantly smaller in the south. Adelaide itself has several faults crossing the city indicating possible maximum magnitudes of more than 6.8 (Clark & Leonard, 2014) in a NE-SW trend. The region around Adelaide has been frequently hit by strong earthquakes over the last 180 years. The strongest earthquake on record occurred in 1902 in the bay of St. Vincent with major damage recorded in Warooka. The most recent strong earthquake within the city fault scarps was in 1954 with a magnitude of 5.4 causing $171 million AUD damage (2015 adjusted) (Daniell and Love, 2010). The return period of events with magnitudes of 3-4 is about 10-20 years which may cause local slight to moderate damage. In 1897, the region was hit by a magnitude 6.5 earthquake near Beachport, about 350km SE of Adelaide. This local activity hotspot however does not show up in the given hazard maps. The seismic background activity along the South-Australian-Victorian volcanic arc is very low and statistical analysis does not give useful insight into the return period of such events in the region. This effect will be studied in depth in the future given the 1897 and 1948 events affecting the region.

Table 1: Deterministic Scenarios for the Adelaide region

Mw	Latitude [°]	Longitude [°]	Depth [km]	Likelihood	Return period [years]	Seismic Source	PGA [g] MEAN / STD / MAX
5	138.56	-35.00	5	likely	~75	Tectonic	0.026 / 0.053 / 0.468
5.5	138.60	-34.87	10	usual	~100	Fault	0.057 / 0.078 / 0.430
6.8	138.70	-34.45	10	possible	250-750	Fault	0.298 / 0.219 / 1.067

3.3 **Brisbane**

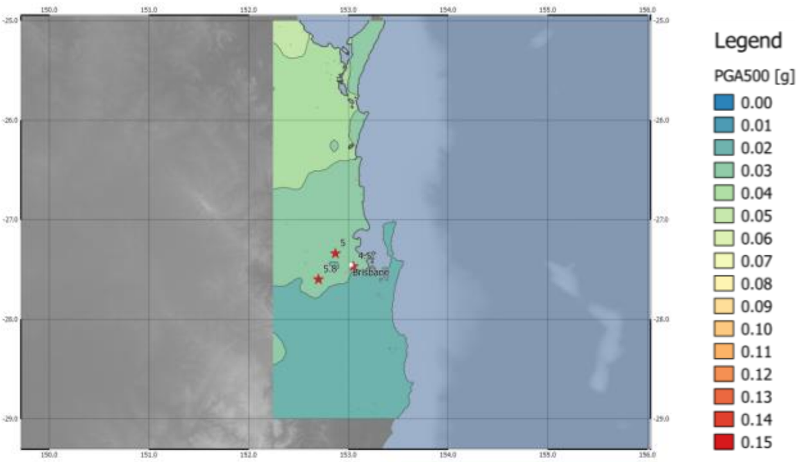

Figure 4: Plot of the mean 500-year exceedance PGA around Brisbane on a 1x1 km grid in g=9.81 m/s².

Brisbane displays the lowest calculated seismic hazard for all major cities in Australia. The probabilistic modelling indicated around 0.03g on average for a 500-year exceedance. In addition, the historic record of the region is rather limited with the strongest earthquake around Brisbane having a magnitude of 4.8 in 1913 near Coalstoun Lakes, with its offspring questionable. Two more events of magnitudes 4.4 and 4.3 have been observed in the past and micro seismicity of magnitudes 1-2 all over the region may indicate the possibility of future moderate earthquakes occurring around Brisbane itself. Nevertheless, there are no faults identified so far which could contribute to a significant amount of seismic activity or even strong magnitude events.

Table 2: Deterministic Scenarios for the Brisbane region

Mw	Latitude [°]	Longitude [°]	Depth [km]	Likelihood	Return period [years]	Seismic Source	PGA [g] MEAN / STD / MAX
4.5	153.05	-27.47	3	Likely	~70	Tectonic	0.032 / 0.048 / 0.563
5.0	152.87	-27.34	10	Usual	~120	Tectonic	0.040 / 0.040 / 0.278
5.8	152.60	-27.41	10	possible	~500	Tectonic	0.060 / 0.076 / 0.546

3.4 Canberra and Sydney

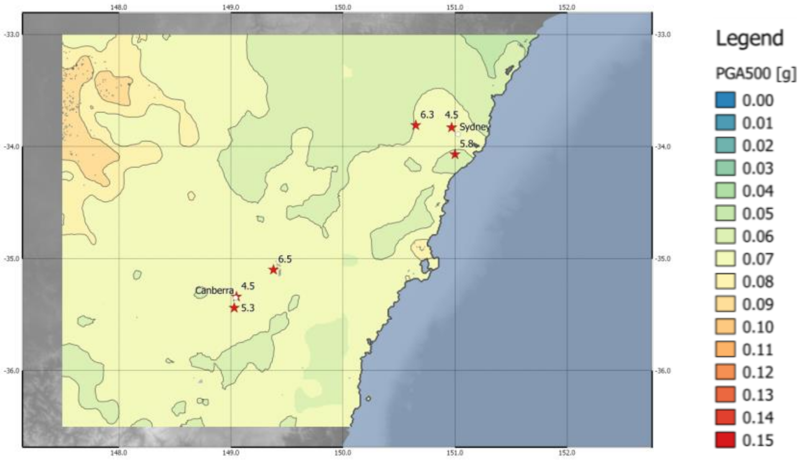

Figure 5: Plot of the mean 500-year exceedance PGA around Canberra on a 1x1 km grid in g=9.81 m/s^2.

Canberra has so far been spared in terms of strong earthquakes affecting it, however the seismic history and tectonic features around indicate a significant seismic hazard. Within 500 years, the average of experienced ground shaking is calculated to be around 0.07 g. There have been several historic events with magnitudes larger than 5 around Canberra; the 1871 Adelong earthquake, the 1886, 1934 and 1949 Gunning earthquakes or a magnitude 4.7 in 1940 close to Canberra itself. There are several fault scarps around Canberra, but recent earthquake history does not correlate well with neotectonic fault geometries. The potential for damaging earthquakes in and around Canberra is significant.

The seismic hazard for Sydney is similar to Canberra. There are faults all over the region, often still related to active orogeny and other tectonic intraplate processes. The 1989 Newcastle earthquake was significant proof of the general hazard in the region, even, when taking a look at the probabilistic map, being just on the corner of the seismically dominant regions. Sydney itself may face a similar event as like Newcastle in the future. Thus the average ground shaking for 500 year exceedance is estimated to be about 0.07 g. The Newcastle region was hit several times in history by strong earthquakes with magnitudes larger than 5, but the recorded microseismic activity is low and thus the probabilistic map does not pick up the Newcastle seismicity very well (again indicated future studies being required).

Table 3: Deterministic Scenarios for the Canberra (top 3) and Sydney (bottom 3) region

Mw	Latitude [°]	Longitude [°]	Depth [km]	Likelihood	Return period [years]	Seismic Source	PGA [g] MEAN / STD / MAX
4.5	149.05	-35.34	5	Likely	~50	Tectonic	0.016 / 0.020 / 0.237
5.3	149.03	-35.44	10	unusual	~150	Fault	0.032 / 0.028 / 0.251
6.5	149.38	-35.10	10	possible	~250	Fault	0.080 / 0.100 / 0.702
4.5	150.97	-33.83	5	Usual	~100	Tectonic	0.024 / 0.027 / 0.231
5.8	151.00	-34.07	10	unusual	~250	Fault	0.062 / 0.055 / 0.398
6.3	150.65	-33.81	10	possible	>500	Fault	0.097 / 0.092 / 0.574

3.5 Hobart

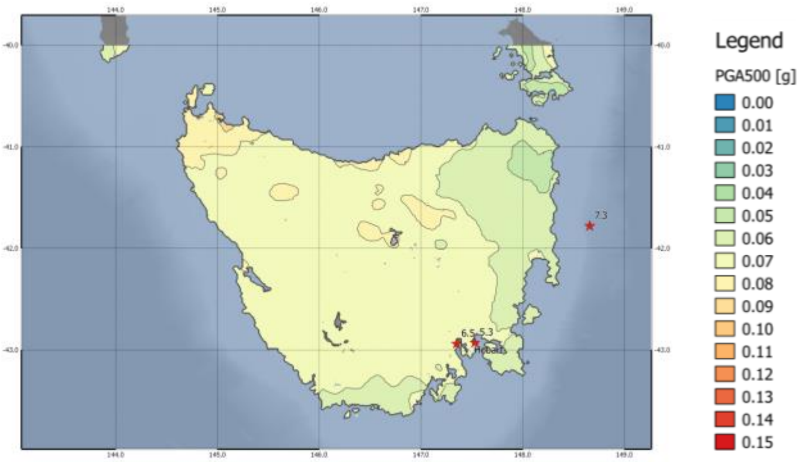

Figure 6: Plot of the mean 500-year exceedance PGA around Hobart on a 1x1 km grid in g=9.81 m/s².

Hobart is located on the southern tip of Tasmania. Probabilistic modelling, which is dominated by recent decades of seismic density indicates an average ground shaking of 0.07 g, but the region is dominated by an almost equally distributed moderate seismicity with frequent earthquakes of magnitude 4-5. Most of these events occurred more than 50 years ago with the last event in 1958 about 100 km NW of Hobart with a magnitude of 5.3. In NE offshore Tasmania, a sequence of several strong earthquakes hit the continental shelf of Australia from 1884 until 1907. There is no applicable method so far to identify the return period of these strong seismicity events along the passive continental margin and it also does not show up when building seismic hazard maps with limited data record and seismic density as an activity indicator. Further investigations on the tectonic offspring of these events is thus advisable.

Table 4: Deterministic Scenarios for the Hobart region

Mw	Latitude [°]	Longitude [°]	Depth [km]	Likelihood	Return period [years]	Seismic Source	PGA [g] MEAN / STD / MAX
5.3	147.53	-42.93	8	usual	~100	Fault	0.034 / 0.035 / 0.325
6.5	147.35	-42.94	10	unusual	Unknown	Fault	0.119 / 0.090 / 0.706
7.3	148.66	-41.78	15	possible	Unknown	Cont. Shelf	0.024 / 0.008 / 0.064

3.6 Melbourne

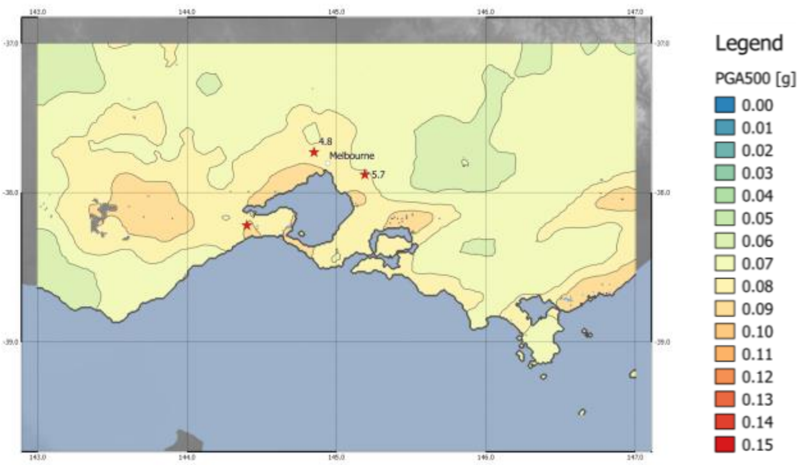

Figure 7: Plot of the mean 500-year exceedance PGA around Melbourne on a 1x1 km grid in g=9.81 m/s².

Similarly to Adelaide, Melbourne is surrounded by various seismic sources. Several fault systems are located around the city both to the West and the East. In addition, a large volcanic zone is located to the East and North-East of Melbourne, as well as to the South-West which might be responsible for a significant part of the seismic activity. In regard to the probabilistic modelling, Melbourne is calculated to experience on average a shaking of about 0.085 g for most parts of the urbanized area while, for some regions along the coastline, increased ground shaking may be observed due to local soil amplification effects. The strongest earthquake around Melbourne occurred in 1885 offshore from the coast to the South-East and possibly had a magnitude of 6.2. It was probably part of an active seismic arc stretching from North-Western Tasmania to Melbourne, which has caused several strong earthquakes. An active onshore region with several faults produced 2 earthquakes with magnitudes stronger 5 in 1969 and 2012.

Table 5: Deterministic Scenarios for the Melbourne region

Mw	Latitude [°]	Longitude [°]	Depth [km]	Likelihood	Return period [years]	Seismic Source	PGA [g] MEAN / STD / MAX
4.8	144.85	-37.73	4	likely	~25	Tectonic	0.030 / 0.038 / 0.442
5.7	145.19	-37.88	10	usual	50-100	Fault	0.053 / 0.054 / 0.327
7	145.06	-38.70	15	unusual	>300	Fault	0.063 / 0.062 / 0.517

3.7 **Perth**

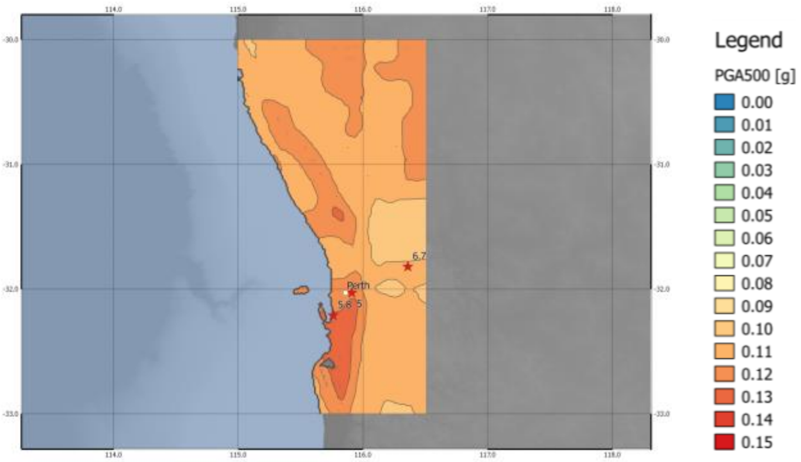

Figure 8: Plot of the mean 500-year exceedance PGA around Perth on a 1x1 km grid in g=9.81 m/s².

Perth faces the highest calculated seismic hazard of all major cities in Australia. On average, a ground shaking of at least 0.12 g is expected, which is mainly related to amplification effects on soft soil due to distant events e.g. offshore or on the Yilgarn which produced the second largest onshore earthquake in the recorded Australian history near Meckering with a magnitude of around 6.7. This source area is a major threat for Perth, especially with regard to long-period distant shaking effects. Taking a radius of 100 km of the region around Perth itself, the seismicity is rather inactive with the largest magnitude of 4.5 in 1877. However, considering seismic migration and the opening of new fault scarps closer to the urbanized area of Perth, strong earthquakes are not unlikely. In addition, earthquake activity along the continental shelf may cause additional hazard. Several faults have been identified by Borissova et al. (2015), possibly explaining the 1946 magnitude 5.7 earthquake.

Table 6: Deterministic Scenarios for the Perth region

Mw	Latitude [°]	Longitude [°]	Depth [km]	Likelihood	Return period [years]	Seismic Source	PGA [g] MEAN / STD / MAX
5.0	115.91	-32.02	5	usual	~100	Tectonic	0.051 / 0.065 / 0.517
5.8	115.76	-32.21	10	unusual	~150	Cont. Shelf	0.067 / 0.086 / 0.587
6.7	116.36	-31.82	10	possible	~350	Fault	0.134 / 0.146 / 0.975

4 **CONCLUSION**

This study provides a new look into the seismic hazard of Australia by estimating probabilistic smooth seismicity as well as deterministic scenarios with respect to various return periods for major cities. In addition, the smooth seismicity is based on an asperity-linked earthquake frequency model which serves as an enhanced localization of seismic activity. Considering that the selection of ground motion prediction equations is similar to previous studies such as Burbidge (2012) or Schaefer & Daniell (2014), the most important change is related to return period characterization and a more complete earthquake catalogue. The results indicate a slightly higher hazard than these previous studies and are closer to what the tectonic-based hazard assessment of Clark & Leonard (2014) proposed. The threat to the major cities of Australia can be considered non-negligible. For all cities except for Brisbane, a peak ground acceleration of on average 0.06-0.1g can be expected to be exceeded at least once within a 500-year period, considering local peaks up to 0.5 g in average. Earthquake events with intensities of VII to VIII have to be expected on these similar time scales with the risk being calculated from this stochastic hazard analysis in the companion paper within this conference (Daniell, Schäfer and Wenzel, 2015, this conference).

Nevertheless, a hazard study of an intra-plate dominated seismic environment is linked to a large amount of uncertainties and when adding a limited data record which is very small compared to the usual return periods of significant magnitudes, any model proposed, independent of its assumptions will be incorrect, but contribute to the best estimate available (a combination of different methodologies and assumptions). Detailed tectonic investigations regarding the seismic offspring of various sources are advised especially for hotspots like Tennant Creek or the activity along the major continental margins offshore Tasmania, Queensland and Western Australia, as well as the quantification of hazard due to secondary sources (Schäfer et al., 2015, this conference).

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