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A tale of eight cities: earthquake scenario risk assessment for major Australian cities

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ABSTRACT: Christchurch and Washington DC provide recent examples of a hazard and risk to earthquakes much higher than any envisaged earthquake previously. It was not necessarily a lack of preparedness or research in these locations, but the short earthquake catalogue history in these locations that provided little clues as to the impending threat. There was also lack of planning for "tail-end risk" in an unknown distribution and the fact that such developed nations failed to take a higher factor of safety into account by simply accepting the "475-year earthquake hazard map" for residential construction and not daring to push the boundaries higher.

In this paper, a stochastic earthquake risk assessment is undertaken for Australia looking at lessons from scenarios near our capital cities. The hazard analysis (Schäfer, Daniell and Wenzel, this conference) is combined with an exposure and vulnerability analysis and socioeconomic impact functions in order to present losses and impacts for a first order view of Australian Risk.

It is hoped this analysis will fuel discussions for combined solutions for future earthquake design in Australia to look at combining existing short-term probabilistic seismic hazard assessments with scenario analysis and even "black swan scenarios".

1 INTRODUCTION

Christchurch and Washington DC provide recent examples of hazard and risk of earthquakes much higher than any envisaged earthquake previously. It was not necessarily a lack of preparedness or research in these locations, but the short earthquake catalogue history that provided little clues as to the impending doom. There was also lack of planning for "tail-end risk" in an unknown distribution and the fact that such developed nations failed to take a higher factor of safety into account by simply accepting the "475-year earthquake hazard map" for residential construction and not daring to push the boundaries higher.

Many attempts have been undertaken to identify the seismic risk in Australia over certain locations, with key efforts coming through EQRM and the work of Geoscience Australia (Edwards et al., 2004) as well as through Risk Frontiers and their QuakeAUS model in the production of hazard, exposure and vulnerability models.

Given the short earthquake catalogue, damage data exists from a limited number of earthquakes, with many lessons and extrapolations needed from either analytical modelling or observations from overseas in order to fill in the earthquake damage record for potential analyses. It was decided that to supplement the earthquake hazard work of Schäfer and Daniell (2014), risk calculations would be made for the stochastic earthquake catalogues. Fulford et al. (2002) provide an early view of risk outputs from the Geoscience Australia EQRM model (Robinson et al., 2005), incorporating user workshop data on vulnerability functions, to change a version of HAZUS for Australian conditions.

Numerous lessons have been learnt through Christchurch as to the potential impacts of very large damaging earthquakes on URM (Unreinforced Masonry buildings) (Moon et al., 2014; Ingham and Griffith, 2011) and low code RC buildings such as are built in Australia. The sister city of Christchurch is Adelaide, which has an extremely high URM and light timber Brick Veneer building typology percentage as defined by NEXIS (National Exposure Information System). This model is an attempt to build a rapid, robust metric model exploring the depth of risk data that can be collected from an external perspective; and to provide a tool for discussions into usable risk metrics and assumptions for Australian earthquake modelling.

2 HAZARD MODELLING

A short summary of the parameters used in the hazard modelling will now be made. For further details, the adjoining paper in this conference (Schäfer et al., 2015) contains the hazard modelling assumptions in the robust model.

Hazard Components used in the model

Historical Data Used	Geoscience Australia, McCue (2013 & 2014)
Completeness Periods	automated per seismic source and pixel
No. of events (declustered & not)	24034 (total), 11838 (declustered)
Seismic Source zonation method	Fuzzy Domains
Site effects	USGS Vs30, 1/3 weighting within GMPE (ground motion prediction equation) selection
GMPEs used	(Atkinson & Boore, 2006), (Lin & Lee, 2008), (Allen, 2012), (Somerville et al., 2009)
Uncertainty accounted for	spatial uncertainty / seismic migration (large smoothing kernel), incomplete data record (deterministic scenarios), seismic source mechanism / b-value (fuzzy logic)
PGA-MMI relationships	Atkinson and Kaka (2007) with checks of Bilal et al. (2013), Tselentis and Danciu (2008)via Greenhalgh et al. (1989) as per Daniell (2014)

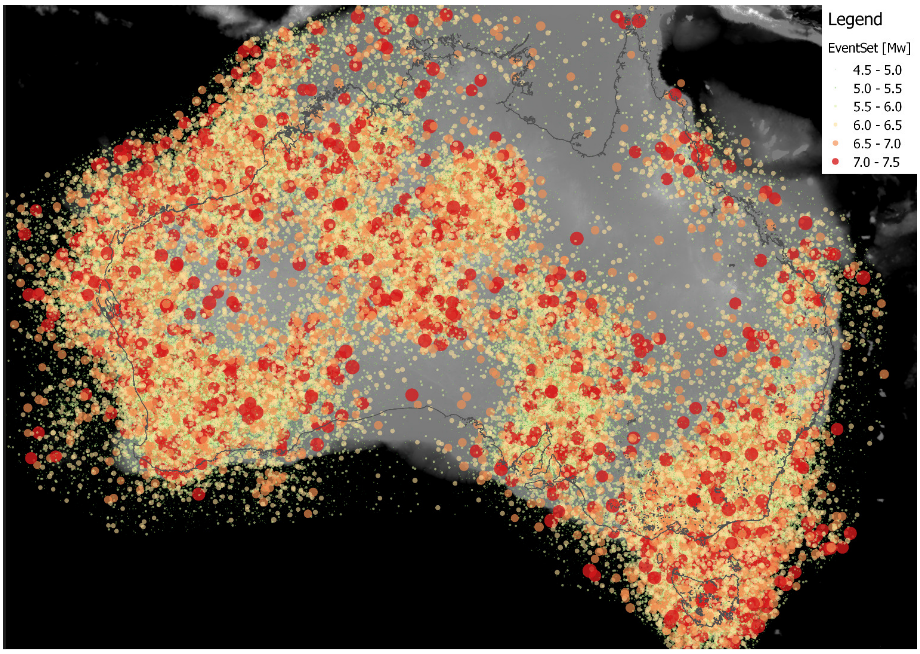

Figure 1: Stochastic earthquake catalogue for 100,000 years from the 500,000 years.

3 EXPOSURE MODELLING

The exposure modelling was a 2 step process. The NEXIS database (Nadimpalli et al., 2007) provides a great census of data on wall materials, roof materials, storey heights and cost data. This was used from SA1 level data. In addition, mesh block data for population and number of dwellings are able to be found on a mesh block level (ca. 300,000 units in Australia) and thus downscaling techniques used in order to evaluate the losses at each point. Unfortunately, as yet, footprint data through OSM is unavailable for all cities.

Population adjustments were made using growth trends to calculate the June 2015 population in each location in order to adapt the 2011 population data to today's terms. A dwelling-weighted analysis was made in addition.

The costing of dwellings vs. non-dwelling construction was examined in terms of the same methodology as used in the LAC (Latin-American and Caribbean) risk profiles of the World Bank where gross capital stock (replacement costs) are calculated in conjunction with bottom up replacement costs (per m2) as examined through the work of NEXIS. In this case a difference of more than 70% exists. The net capital stock (actual value of all dwellings, including contents) is calculated at ca.$1.7 trillion AUD (Australian dollars). When taking the Perpetual Inventory Method into account, a value of ca. $2.9 trillion AUD, including fixed contents, is calculated. Taking into account demand surge and non-fixed contents and service lives, this can be as high as $3.6 trillion AUD.

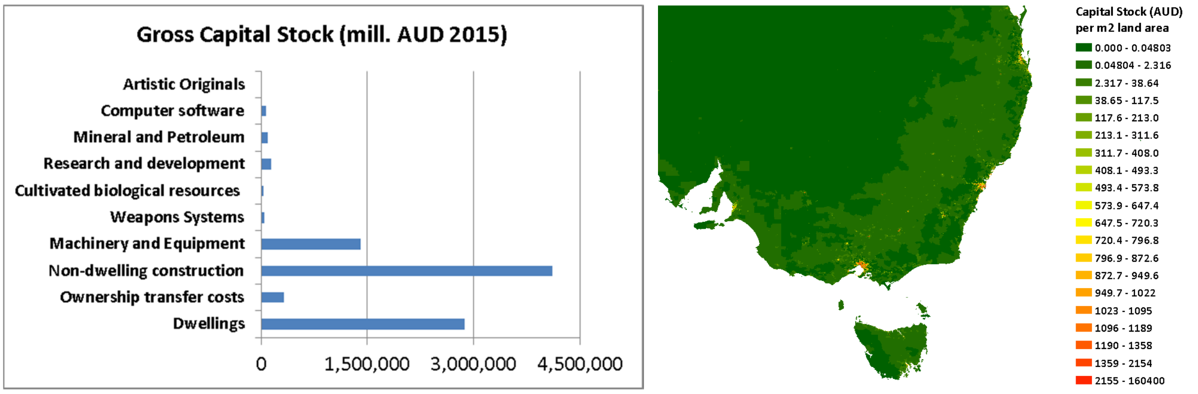

Figure 2: Left: Gross capital stock estimates as calculated using ABS (Australian Bureau of Statistics) (2014) and Daniell (2014); Right: Gross Capital stock per m2 land area in SE Australia.

By comparison, a value of over $4.5 trillion is shown in NEXIS for a combination of dwellings and contents. There is the possibility that the classification of certain buildings as dwellings vs. commercial buildings accounts for some of this difference. In this case, however, the resolution between the values is a reduction by 18% of the values in NEXIS. For Non-dwelling construction, a reduction of 3% is made for commercial and no change for industrial when making the same adjustments. The total values of gross capital stock in non-dwelling construction include road value, port infrastructure, agriculture and many other components that are not accounted for in other studies. The resolution of the top-down and bottom-up solutions is often a good tool for resolving costs of assets (Gunasekara et al., 2015). $6.2 billion in all other assets are calculated in Australia in terms of gross capital stock. Of these, $5.1 billion are deemed to be at similar risk to the existing infrastructure in case of earthquake (removing weapons, research stocks etc.). A split as in HAZUS and EQRM as to structural and non-structural (acceleration sensitive and drift sensitive) is undertaken.

4 VULNERABILITY MODELLING

In terms of vulnerability modelling for Australian building stock there is much effort that has been undertaken in the past into examining loss metrics (Edwards, 2004). A review of papers from the AEES over the last 25 years, in addition to other external papers, was undertaken. Over 45 functions were found for various typologies from different events. The results for some of the URM functions are shown below.

The non-structural acceleration sensitive portion in Australian building typologies provides much damage, as seen in recent earthquakes such as the Moe and Kalgoorlie events; and this requires that the damage ratios around and before yielding of the structure are taken into account. Calibration was undertaken in this study in order to take this into account. The original EQRM functions were originally very high, and provided an overestimation of loss at high intensities when compared to historical events such as 1989 Newcastle.

The problem with a lack of damage data inside Australia above intensity VII or of ground motions above PGA (peak ground acceleration) of 0.1g means that information from other countries is required in order to examine the potential loss effects. In this respect, upper bounds through Christchurch and other such events reaching above intensity VIII provide invaluable evidence and data for potential future events.

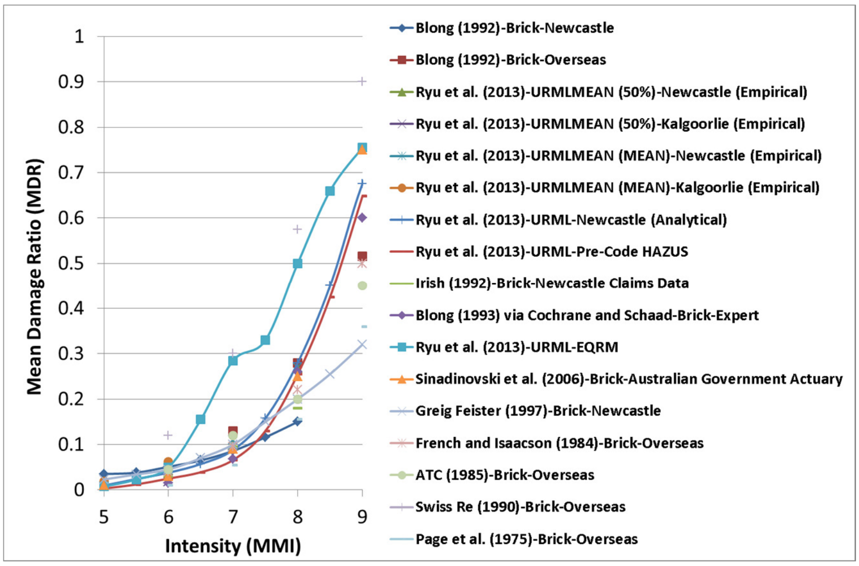

Figure 3: Brick/URM buildings showing the damage ratio vs. intensity from mainly Australian functions

The capacity spectrum method was used to reproduce functions in terms of pre-code and low-code. A conversion from PGA to MMI (Modified Mercalli Intensity) was then used for calibration. An adjustment based on Atkinson and Kaka (2007), and a set of calibrated functions using the European Macroseismic method (Giovinazzi, 2005), via equating the mechanical outputs to intensity adjustments in terms of the loss functions, was used. This allowed for comparable metrics to be analysed compared to empirical data. As with any vulnerability quantification, uncertainties include the spectral response used, uncertainty in the damage data around a certain value (beta distribution used) as well as extrapolation of empirical losses above certain values. In addition, the seismic quality of the building stock was only given a basic change based on the NEXIS age factor (pre-1980 vs. post-1980 stock). For the mechanical method, calibration was undertaken in order to check the assumptions of "Pre-code" and "Low code".

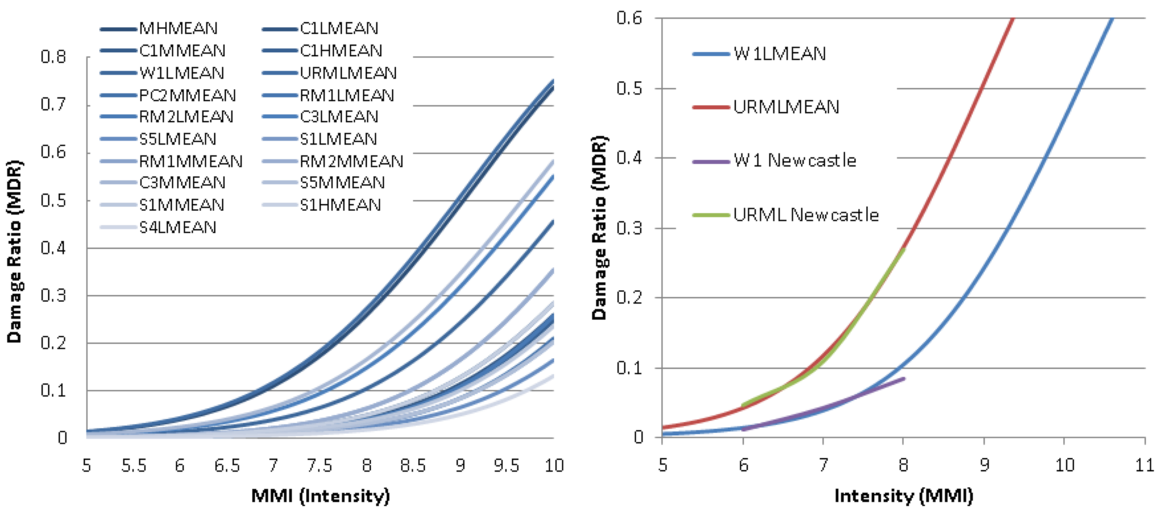

Figure 4: Left: MDR of the vulnerability functions used in the study for the 37 typologies. Right: A comparison of URM and timber building loss vulnerability functions used in the study, with the empirical loss data from Newcastle.

Along the same lines as Ryu et al. (2013), it was found that the existing EQRM functions had much higher estimates, and thus European and US (HAZUS) typologies were adapted to fit the model data. For unknown vulnerability functions (with no data), the same estimated parameters of code influence, ductility and additional system response were kept constant from the fitted system in order to create a reasonable set of functions for Australian conditions. For casualty functions, three methods were considered for vulnerability functions: HAZUS-oriented casualty functions which were based on quasihistorical/expert functions; semi-empirical/analytical casualty functions based on the work of Jaiswal et al. (2014) for different typologies; and the socioeconomic fragility functions of Daniell (2014). For the analysis below, the empirical methodology was described in Daniell and Wenzel (2014) last year: the coefficients of 11.5 and 0.14 were used in addition to HDI (Human Development Index) and time-of-day calibration for the analysis, however any of other options would also be reasonable.

5 RISK MODELLING

Australia has a very distributed earthquake loss in comparison to other countries, given the area of the country and the distributed nature of major cities. In a recent study of Central American nations, PML250 (Probable Maximum Loss event at a 250 year return period) values of around 12% of capital stock are quite common (Gunasekara et al., 2015). In Australia, lower seismicity (yet high vulnerability) and the distributed nature give a PML250 around 0.25% (structures only). However, given the value of Australian capital stock (total) that can be affected by earthquake is around $9 trillion AUD, this economic cost at a 250 year return period is in the order of $20 billion AUD.

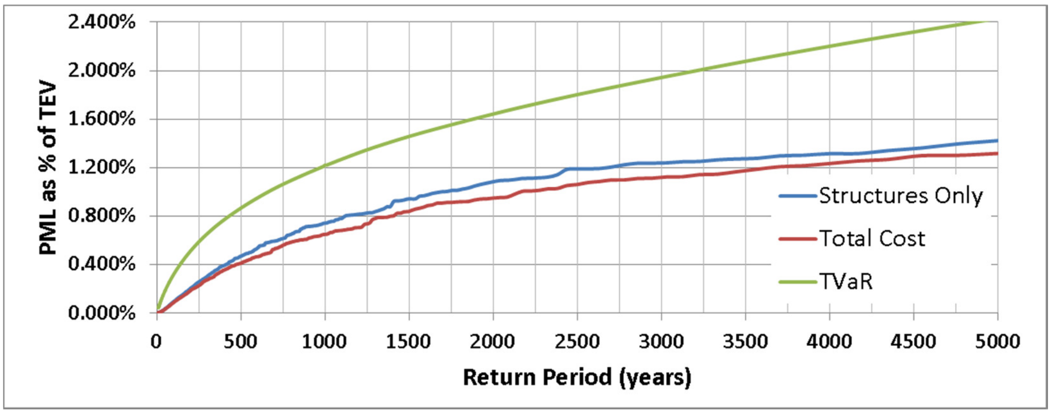

Figure 5: The PML curve for Australia (structures only considered; all stock and tail value at risk (TVaR))

Around 75% of the AAL (Annual Average Loss) comes from events below PML1000 across Australia. In the report of Fulford et al. (2002) in Newcastle they found that 82% of AAL came from below PML1000. Significant non-structural damage occurs as a percentage of non-structural and structural for smaller events with acceleration sensitive components particularly at risk.

The TVaR (Tail Value at Risk) represents the average economic loss given that an event occurs at over a certain return period. This a useful value for making decisions as to tail risk. The $TVaR_{250}$ was calculated to be 0.587%, as compared to 0.226% as the PML_{250}.

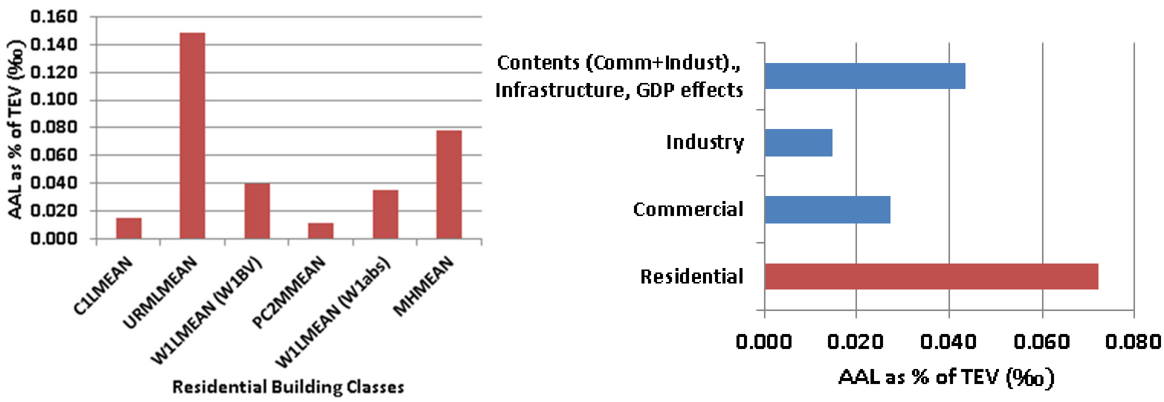

Figure 6: Left: Residential Building Class AALs (‰); Right: AAL (‰) in each use class/economic class

The AAL for the various typologies is a good way to start examining the most vulnerable features. Unreinforced masonry buildings (as seen in the 2011 Christchurch earthquake) are the most vulnerable building typology, with a total AAL around 0.14‰. This is around 3 times higher than that of the brick veneer/timber based buildings. These results are very consistent with the results of Ryu et al. (2013)

where URM was shown from a Mw5.35 event to be 2.5 times and from a Mw6.5 event 3 times. Age factors showed slight differences in loss across suburbs in major cities, with older buildings having slightly higher loss ratios. Storey height also played a minor role, with mid-rise buildings often having slightly higher loss ratios than high or low rise depending on spectral period adjustments.

The AAL of only structures totals around 429 million AUD, with this total being around 0.047‰. The calculated life value AAL is 378 million AUD, leading to interesting implications for casualty insurance due to earthquake. For $2.5 trillion, Walker (2003) gives an AAL of around $210 million; thus the AAL is lower than this estimate (perhaps due to the percentage of new stock, and the additional commercial and industrial values today). The risk results are significantly higher than that of GAR (2015).

5.1 *Where are the hotspots?*

Using aggregated PML curves over the greater city regions and the rest of each state, a view as to city risk can be gained. In this view, only the urban zones are included. It should be noted that depending on stochastic catalogue, Perth and Adelaide interchange as the highest risk. Canberra has the 3rd highest earthquake risk at long periods as well as in AAL (measured in ‰).

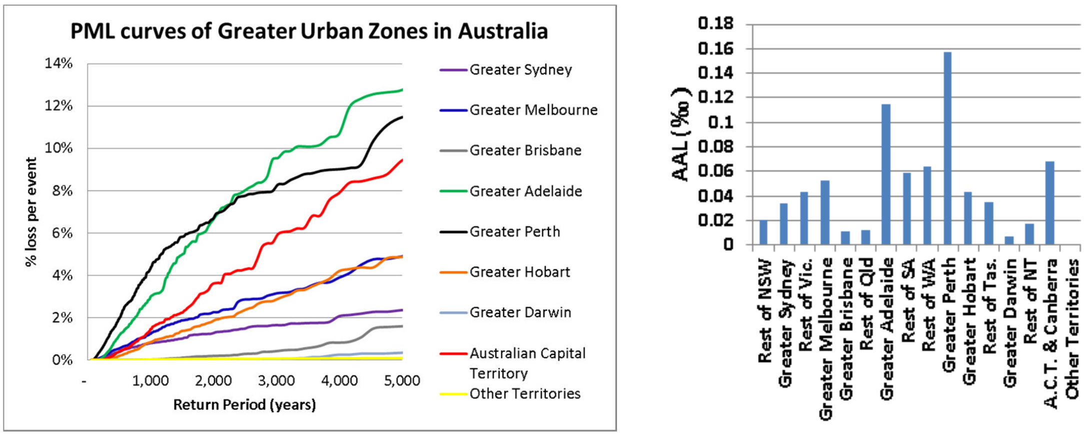

Figure 7: Left: PML curves for capital cities; Right: AAL (‰) for each larger zone

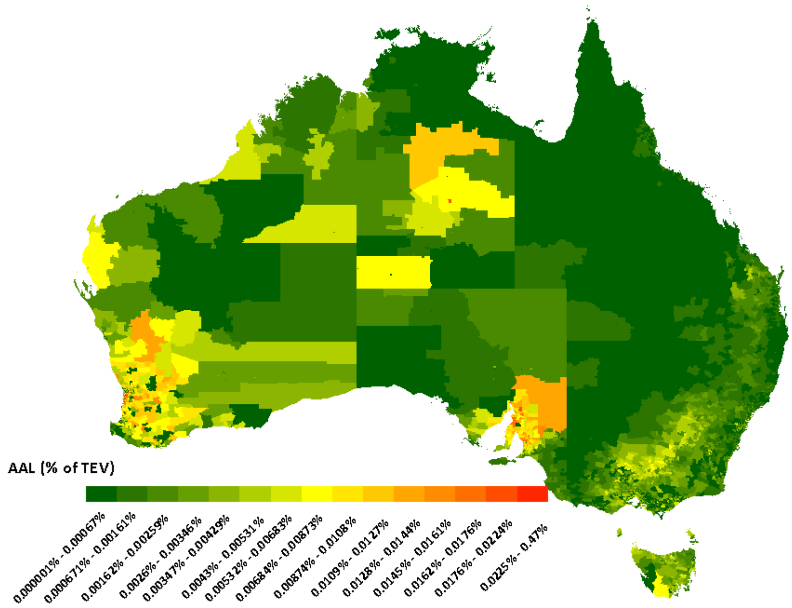

Figure 8: AAL aggregated to SA1 statistical units. It shows higher AALs across SW Australia, Adelaide, Tennant Creek and parts of SE Australia

5.2 *What is the real cost?*

Planning for tail-end risk as well as convincing politicians of long-term risk is a very difficult task, given the shelf life of a politician is around 4 years. Often, without major disasters, it is a case of "out of sight, out of mind". Bringing techniques such as life costing into decision-making for cost-benefit ratios for earthquake risk means that retrofitting decisions or building developments become financially viable as opposed to without life costing. This is explained in the adjoining paper of Daniell et al. (2015a) in this conference, with cost-benefit ratios for countries and large-scale building changes. A PML1000 event in Australia has the ability to cause 6500 deaths (mainly due to brittle masonry collapses). The total structural cost of the event will total around $59 billion; yet only these deaths carry with them a life cost of $31 billion (not counting injuries). The structural retrofits for life safety would therefore have a great importance, with the cost being about that of structural cost. Taking into account that this life safety cost is a "deaths only" value, it could be expected that including additional injury costs could be far greater (in Porter (2006) for Northridge, this ratio was about 30 times higher; however, in reality for high death toll events, the ratio would be more likely 1:1). There exists the need in low seismicity countries to take this into account.

Indirect costs in the same order as other such events in other countries have caused close to the same amount as direct costs due to factors such as downtime and business interruption. Using Daniell et al. (2015b), this could be conservatively estimated to be around $40-50 billion in this Australian event.

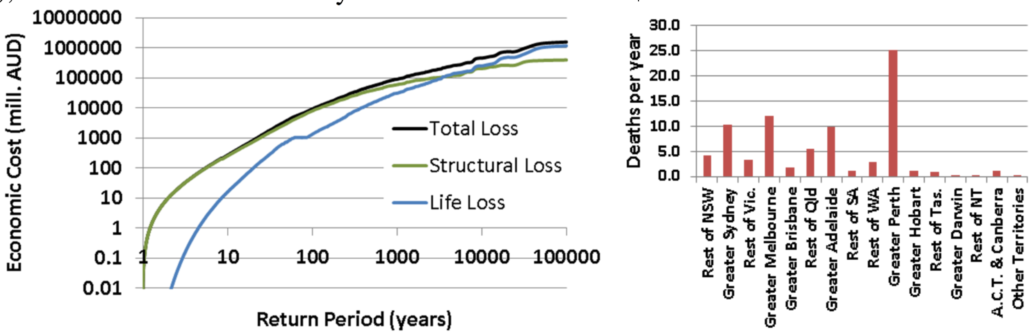

Figure 9: Left: The PML curve for Australia including just structural costs; just the value of life from deadly events; and the combined loss taking into account structural and life values; Right: the annual average deaths NB: most years have no deaths in each location.

Thus, for the 1000 year event, the real cost is likely at least 350-400% of the original structural cost. The effects of demand surge (Olsen, 2008) have only been slightly brought in to the model with a factor of 1.1 made for major events repairs. Historically, this is often much higher, where many repairs occur in a developed nation in short time periods. Interestingly 61% of life risk is above PML1000 yet only 25% of structural risk, showing the significance of major events on life-based economic risk.

6 CONCLUSION

A stochastic risk assessment has been undertaken focussing on Australia and, in particular, the risk to major cities. Among the analysis, scenarios have also been examined around major cities as part of the adjoining hazard assessment by Schäfer et al. (2015), in this conference.

It was found, as expected, that Australia's risk for earthquakes is not necessarily a function of high earthquake hazard, but more so URM building typologies. A key outcome of this analysis was not necessarily the AAL (0.047‰) and PML250 of $20bn value but the fact that life costing should play a role in decision-making within Australian earthquake analyses. There is never one solution to future risk and given the fact that there is very little historical Australian data, assumptions in every component (hazard, exposure and vulnerability) contribute to the different results.

It is hoped this analysis will fuel discussions for combined solutions for future earthquake design in Australia. Combining existing short-term probabilistic seismic hazard assessments with scenario analysis as well as cost-benefit analysis (human and financial) would provide governments with plausible numbers for planning purposes.

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