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EVENT-BASED EARTHQUAKE RISK MODELLING

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ABSTRACT :

Geoscience Australia's Earthquake Risk Model (EQRM) is an event-based tool for modelling the ground motion and loss associated with individual earthquake scenarios as well as probabilistic seismic hazard (PSHA) and risk (PSRA) analysis. It has been used to conduct PSHA and PSRA for many of Australia's largest cities and it has become an important tool for the emergency management community which uses it for scenario response planning. This tool is being refined for use in Australian earthquake monitoring programs to provide automatic loss estimates within minutes of an earthquake occurring.

An open-source beta-release version of the software is freely available on SourceForge (https://sourceforge.net/projects/eqrm). It can be used for hazard or risk analyses in any region of the world by supplying appropriately formatted input files. Source code is also supplied so advanced users can modify individual components to suit their needs.

KEYWORDS: earthquake risk, earthquake hazard, open-source, Australia

1. INTRODUCTION

Earthquake risk analysis has become increasingly important to ensure mitigation strategies are studied and potential emergencies planned for. The need for open source tools for modeling earthquake risk is rapidly gaining recognition in the broader earthquake engineering community (eg. the recent Global Earthquake Model initiative led by the Global Science Forum of the Organization for Economic Cooperation and Development). The nature of a risk assessment depends on its purpose, however in the broadest sense earthquake risk studies can be categorized into scenario and probabilistic analyses. A fundamental of both styles of assessment is the ability to simulate individual earthquake events and realistically incorporate and communicate uncertainties.

Modeling earthquake scenarios involves an analysis of expected ground motion and/or the estimation of loss for events of interest. Events can be identified in advance via geological studies and scenario simulations undertaken to assist with emergency response exercises, mitigation planning and providing advice to the community. Alternatively, software can be linked with seismic networks to provide real time estimates of losses for events as they are observed. This is the idea behind PAGER (http://earthquake.usgs.gov/eqcenter/pager/), project JRA3 of NERIES (https://neries.knmi.nl/) and REDAS implemented by the Philippine Institute of Volcanology and Seismology.

Probabilistic Seismic Hazard Analysis (PSHA) and Probabilistic Seismic Risk Analysis (PSRA) provide a framework for which uncertainty in the size, location and likelihood of 'plausible' earthquakes can be incorporated to model the potential impact of future events. Earthquake hazard is typically measured in terms of the level of ground shaking that has a certain chance of being exceeded in a given time period (Standards Australia, 1993; Frankel et al., 2000; Stirling et al., 2002). Similarly, earthquake risk, defined as the likelihood that social or economic consequence will be suffered (McGuire and Arabasz, 1990), can be quantified by the level of loss (in financial terms) that has a certain chance of being exceeded in a given time period (Robinson et al., 2006). Typically, PSRA focus on the direct financial loss associated with earthquakes, as is the case in this paper, however indirect losses and economic flow on effects can also be considered.

Geoscience Australia's Earthquake Risk Model (EQRM) is a multi-purpose software package for earthquake hazard and risk analysis. It can be used in 'scenario mode' to model ground motion or financial loss to a building inventory for an event of interest. Alternatively, with a few small changes to the input parameters, the EQRM can be used in 'probabilistic mode' to generate a catalogue of synthetic events which are representative of all 'plausible' events in a region. The EQRM utilises this catalogue to undertake a probabilistic seismic hazard analysis (PSHA) and/or a probabilistic seismic risk analysis (PSRA) for a building inventory of interest. A beta-release version of the EQRM is freely available with an open-source license from SourceForge (https://sourceforge.net/projects/eqrm/).

In this paper we demonstrate the use of the EQRM with two case studies. The first case study models losses for a single catastrophic scenario on the Morwell Monocline in Victoria, Australia. The maximum credible earthquake of magnitude Mw 6.9 is simulated and used to demonstrate the style of products that the EQRM can provide emergency planners for both contingency planning prior to an event and rapid response information. In the second case study we demonstrate the ability of the EQRM to perform PSHA and PSRA. This case illustrates the sensitivity of PSHA and PSRA to the choice of ground motion model and the technique used to combine multiple ground motion models.

2.CASE STUDIES

In this section we demonstrate the use of the EQRM by discussing modeling results from two different regions and modes of operation. It is important to recognize that the following results are more demonstrative of the EQRM's capability as opposed to complete risk assessments of either region. As with all modeling packages, the ability of the EQRM to provide accurate estimates of hazard/risk depends on the quality of input parameters for the region of interest. Creating detailed models of a region's seismicity, identifying an appropriate combination of ground motion models, modeling amplification and classifying exposure requires considerable effort. The case studies presented herein use input data with a range of different approximations. Not all of the results represent complete risk assessments; rather they are a reflection of our current understanding of the factors that drive earthquake risk in the regions of interest. We anticipate that results will change as further detailed analysis of the regions are undertaken and inputs improved.

2.1. Scenario Earthquake Impacts in the Latrobe Valley, Victoria, Australia

The Latrobe Valley is located in central Victoria approximately 135 km to the ESE of Melbourne. The region has a population of approximately 71,000 people living in the City of Latrobe and is home to Victoria's major power generators. The region also contains the Morwell Monocline which has been interpreted as a ~50 km long structure capable of generating earthquakes with moment magnitudes up to approximately Mw 6.9. The recurrence of earthquakes on this structure is uncertain and the focus of ongoing work. However, the fault appears to have had at least 80 m of vertical displacement in the last two million years. Based on the very simplistic assumptions that:

- all of this displacement was caused by the largest earthquake that this structure could accommodate (*i.e.* Mw 6.9); and
- a Mw 6.9 event would cause 1.5 m of vertical displacement,

at least 53 Mw 6.9 events would have to have occurred to generate this displacement. Assuming that these events have been evenly spread across the last two million years implies that Mw 6.9 events have a return period of approximately forty thousand years on this specific structure.

In this paper we use the EQRM to generate and investigate the potential impacts of a Mw 6.9 event on the Morwell Monocline. This study has focused on impacts to residential structures and is intended to provide a demonstration of the style of information that can be provided by the EQRM. This event was modeled with a centroid depth of 15 km and a dip of 60^{o} to the west. Figure 1 presents a map of the peak ground acceleration (PGA) on soil for this study. This ground motion was calculated using a ground motion model designed for eastern North America (Toro et al., 1997) due to the absence of an appropriate Australian specific ground motion model for rock motions. Median motions were used and no variability was included in this study. Local soil conditions were then incorporated using national scale site-response models developed collaboratively with Risk Management Solutions (McPherson and Hall, 2007).

Residential building exposure in the region was provided by Geoscience Australia's national exposure information system (NEXIS). This inventory was derived from a variety of State and National scale statistical datasets and provides a representative inventory for residential structures for any region in Australia. The structures are described as a function of both the structure type (e.g. un-reinforced masonry with tile roof, timber frame with fibro walls and metal roof, etc.) and the usage (e.g. separate house, semi-detached, etc.). It also provides an approximate value for each structure. The EQRM uses the capacity spectrum method (Kircher et al., 1997a; Kircher et al., 1997b; FEMA, 1999), an engineering based approach, to estimate damage for each scenario. Australian specific building categories are introduced to incorporate Australian building design and the capacity and fragility curves updated (Fulford et al., 2002a; Robinson et al., 2005).

The spatial variation of modelled residential losses for this scenario is illustrated in Figure 2. Losses are illustrated as a percentage of the total building value. This figure provides invaluable information on the level of damage sustained as well as identifying areas which should be the priority for any search and rescue operation. For example, the majority of severely damaged structures (*i.e.* more than 50% damage) are located near the actual earthquake. However, some structures as far as 50 km from the earthquake rupture have still suffered in excess of 5% damage. In addition to providing a spatial distribution of damage, the EQRM can produce broad estimates of casualties associated with this event (Table 2.1). These figures have been generated using the casualty models from HAZUS and should be treated as only broadly indicative.

Table 2.1 Casualty and fatality estimates for the Mw 6.9 earthquake on the Morwell Monocline

Severity	Totals
Total regional population exposed	312,983
Level 1: Injuries will require medical attention but hospitalisation is not needed	7,000
Level 2: Injuries will require hospitalisation but are not considered life threatening	2,000
Level 3: Injuries will require hospitalisation and can become life threatening if not promptly treated	200
Level 4: Victims are killed by the earthquake	370

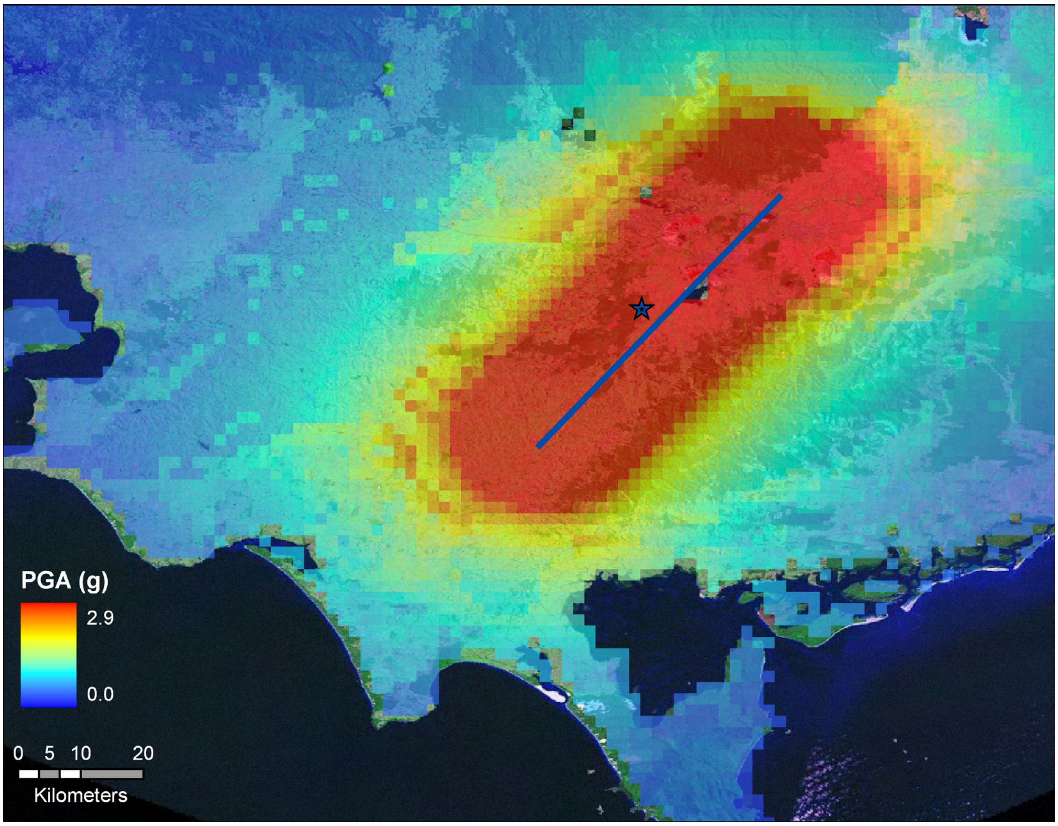

Figure 1 PGA on soil for a Mw 6.9 earthquake on the Morwell Moncline.

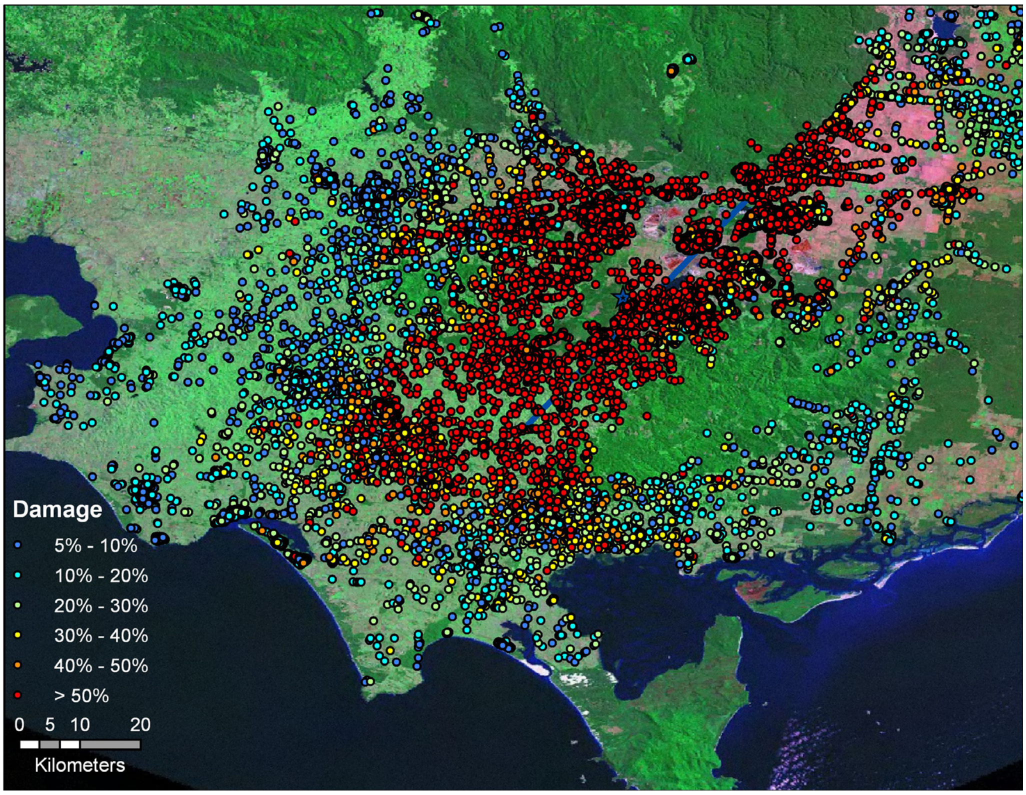

Figure 2 Damage to residential structures from a Mw 6.9 earthquake on the Morwell Moncline.

2.2. PSHA and PSRA in the Newcastle region using different ground-motion models

The Newcastle and Lake Macquarie region is located on the Eastern Coast of Australia, approximately 170 km North of Sydney. The ML 5.6 Newcastle Earthquake occurred on the 27 December 1989. It had an estimate Mw of 5.35 (Dhu et al., 2002) and its epicentre was located approximately 15km to the WSW of the Newcastle CBD and approximately 10km to the NW of the Lake Macquarie CBD (Figure 3). It is the most damaging and costly earthquake to have occurred in Australia since European settlement and is a clear demonstration of the potential for damage from Australian earthquakes. Beyond the insured losses of $862 million (IDRO, 2002), estimates of direct financial loss range from $1 billion (Melchers, 1990) to more than $4 billion (BTE, 2001) in 1989 dollars. Edwards et al. (2004) estimated the loss to be 5.3% of the replacement value of building stock. In addition, there were 13 deaths and over 100 serious injuries reported (Melchers, 1990).

One of the key issues in providing information on earthquake risk is the sensitivity of the results to uncertainties in the underpinning physical models. In this study, we have explored the uncertainties in earthquake hazard and risk associated with the selection of ground motion models for the Newcastle and Lake Macquarie region. While this is only one source of uncertainty in any analysis of earthquake risk, it has been recognized as a significant issue that must be carefully considered (e.g. Frankel et al. 2000, Stepp et al. 2001, Bommer et al. 2005, Sinadinovski et al. 2005). The region's seismicity is categorised into a number of source zones (Dhu et al, 2002), each described by its own pair of Gutenberg-Richter a and b values (Gutenberg and Richter, 1944). These source zones are used with the EQRM to generate a catalogue of synthetic events that capture the diverse range of plausible scenarios (Robinson et al., 2006).

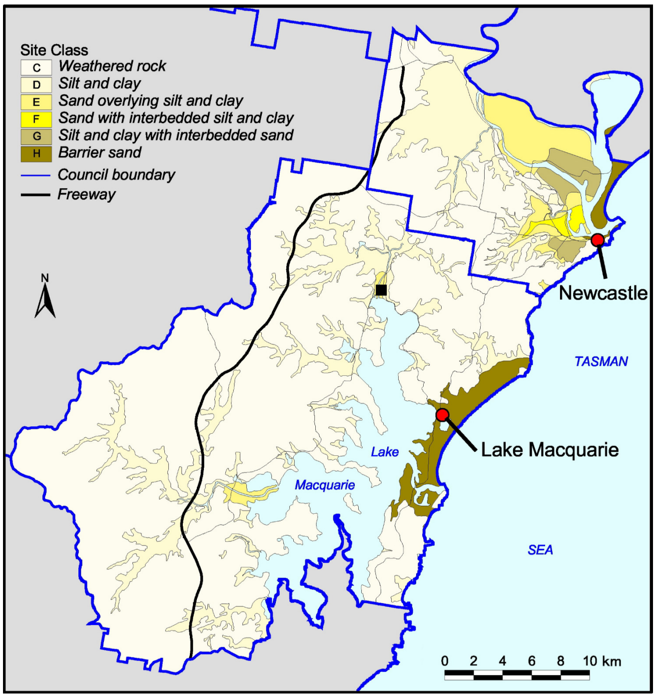

Figure 3 Study region indicating the Newcastle and Lake Macquarie CBDs, the epicentre of the 27 December 1989 M_l5.6 Newcastle earthquake (black square) and the soil classes used to determine amplification factors.

To explore the sensitivity of both hazard and risk estimates to ground motion we model the bedrock ground motion for each synthetic event using three different ground motion models: T97: Toro et al. (1997), AB97: Atkinson and Boore (1997), and S97: Sadigh et al. (1997). We have used each of these models individually as well using two combinations of the three ground motion models. Note that in all cases we use random sampling (see Robinson et al., 2005) to incorporate the aleatory uncertainty associated with each ground motion model.

In the first combination of ground motion models (T97+AB97+S97) the earthquake losses for a single event are calculated for each ground motion model independently and then combined to a single value using a weighted average of the three individual estimates. This technique is referred to as a collapse of the logic tree (Robinson et al., 2005). Similarly, for a hazard estimate ground motion on soil for a single event is calculated for each ground motion model independently and then combined to a single value using a weighted average of the three individual estimates.

In the second technique for combining ground motion models (T97+AB97+S97 (nc)), all three losses (or soil ground motion for hazard) are kept individually and included when determining the risk (or hazard). In this case the ground motion weights are used to scale the likelihood of the observed ground motion, or loss, i.e.:

$$\begin{pmatrix}\text{probability of synthetic}\\ \text{ground motion}\end{pmatrix} = \begin{pmatrix}\text{probability of}\\ \text{synthetic event}\end{pmatrix} \times \begin{pmatrix}\text{weight for}\\ \text{attenuation model}\end{pmatrix}$$

Note that in the second technique the nomenclature (nc) refers to 'no collapse' in recognition that all estimates are kept without creating a weighted average. A detailed description of the two different techniques for combining ground motions is provided by (Robinson et al., 2005).

Local site conditions are incorporated using the site-class model and associated amplification factors of Dhu et al. (2002) to convert the bedrock ground motion to soil motions that are more indicative of anticipated surface motions. The building inventory is attained from a foot survey of the region and includes both residential and commercial buildings and the capacity spectrum method used to estimate losses for all of the synthetic events (Fulford et al., 2002b).

Figure 4 illustrates the 10% probability of exceedance in 50 year (475 year return period) regolith hazard maps for spectral acceleration at 0.3s (referred to herein as the 0.3 s hazard). A NE trend of increasing hazard is clearly evident. This is super-imposed by a visible correlation with the regolith. The influence of ancient river courses, associated with site-class D (clear fingering towards the west), as well the sandy regions (site classes E, F and H) are all visible in the hazard. Comparing the five different hazard maps demonstrates a clear sensitivity of hazard to the choice of ground motion model(s). In general, we observe the following ranking of the 0.3 s hazard:

S97>T97>T97+AB97+S97(nc)>T97+AB97+S97>AB9.

Of particular interest is the noticeable difference between T97+AB97+S97(nc) and T97+AB97+S97 hazard which suggests that hazard is not only sensitive to the choice of ground motion model(s) but also how they are combined when using more than one model.

Figure 5 illustrates the loss exceedance curve for each of the five ground motion options. It indicates losses that are expected to be exceeded in a one-year time frame with different levels of probability. All five ground motion options lead to similar loss exceedance curves for annual exceedance probabilities greater than 0.03. The events that drive loss at this end of the loss exceedance curve are those with the highest probabilities of occurrence. That is, low magnitude events immediately below, or in the close vicinity of, the building inventory

We begin to observe variation between the five risk exceedance curves for annual exceedance probabilities around 0.01. Here, the ranking of loss is:

AB97< T97+AB97+S97 ≈ T97+AB97+S97(nc) < S97 ≈ T97

This suggests that for events with return periods of 100 years or less there is variation between the estimated losses from individual events but that the two techniques for combining the ground motion models lead to similar losses. As the annual exceedance probability decreases below 0.01 we observe a subtle change in the ranking. For example, for an annual exceedance probability of 0.001 we observe:

AB97< T97+AB97+S97 < T97+AB97+S97(nc) ≈ S97 <T97

which indicates that the two techniques for combining ground motion models lead to different losses for the rarer events.

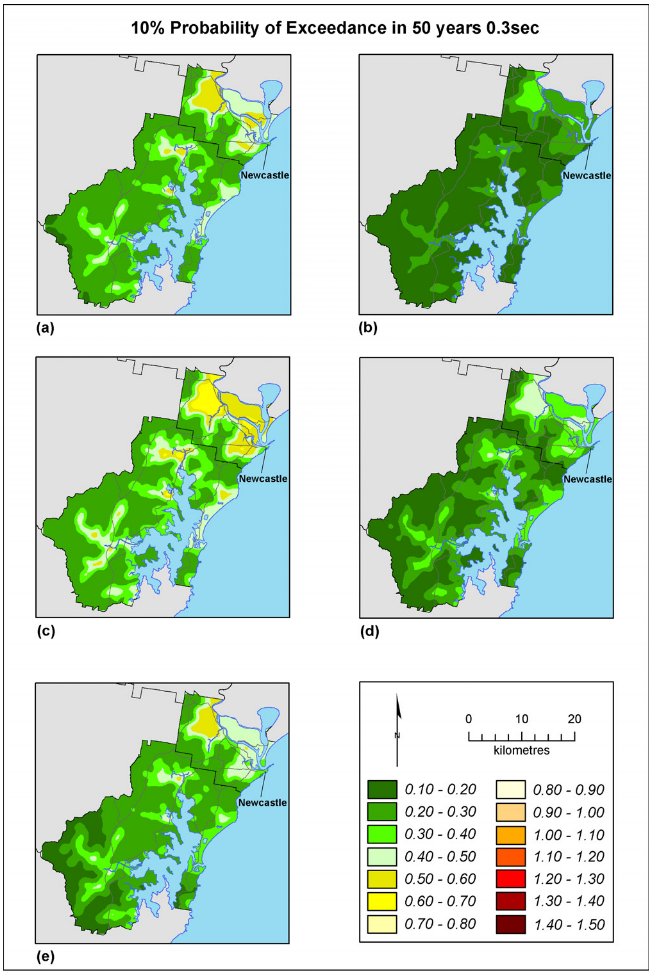

Figure 4 Hazard maps for 10% probability of exceedance in 50 years in the Newcastle and Lake Macquarie region (spectral acceleration at 0.3s). Maps are shown for (a) T97, (b) AB97, (c) S97, (d) T97+AB97+S97 and (e) T97+AB97+S97 (nc).

Annualized loss represents the estimated loss per year when all events from the synthetic catalogue are considered. The annualized losses for each of the five ground motion options are shown in Table 2.2. Robinson (2006) explains how annualized loss is typically sensitive to variations in losses associated with synthetic events having annualized probabilities of exceedance which are greater than or equal to 0.01. Therefore, it is not surprising that the ranking of annualized loss is identical to that of the loss exceedance ranking at annual exceedance probabilities of 0.01 (see above).

Table 2.2 Annualized loss using each of the five ground motion options

Ground Motion Model	Annualized Loss
T97	0.034%
AB97	0.011%
S97	0.034%
T97+AB97+S97	0.026%
T97+AB97+S97(nc)	0.026%

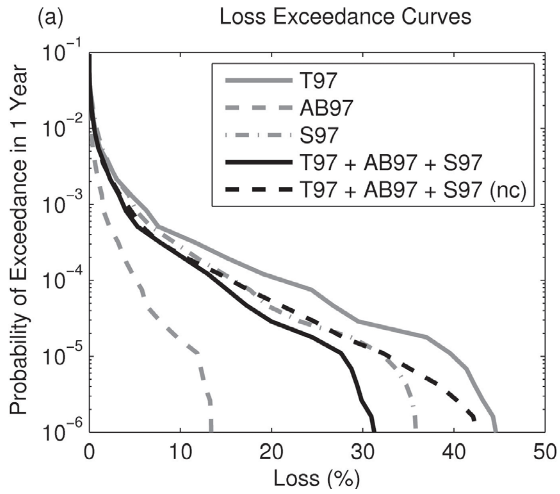

Figure 5 Loss exceedance curves for the Newcastle and Lake Macquarie building inventory using all five of the ground motion options.

3. CONCLUSIONS

Earthquake impact and risk modeling tools provide fundamental information for understanding and better managing earthquake risks. Geoscience Australia's EQRM (https://sourceforge.net/projects/eqrm/), provides an open source software package capable of providing information that can inform mitigation decisions, pre-disaster contingency planning and rapid response. It is important to recognize that tools such as the EQRM are designed to use the best available physics models (such as ground motion, vulnerability etc.) to provide information to disaster managers and decision makers. However the quality and value of this information is controlled by the quality of the input models and it is critical that the uncertainties associated with these models are accurately communicated. For example, this work has provided a simple demonstration of the sensitivity of both PSHA and PSRA to the choice of ground motion models. Such sensitivity analyses should be undertaken for all components of a risk or impact analysis and information gained used to infer uncertainty associated with the final analysis and to prioritize future studies required to refine the results.

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