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VULNERABILITY OF RESIDENTIAL STRUCTURES IN AUSTRALIA

Edwards, M. R.[1]; Robinson, D.[2]; McAneney, K. J.[3] & Schneider, J.[4]

SUMMARY

This study compares two different approaches for estimating the probability of earthquake damage to typical residential structures. The first is an empirical approach using intensity-based hazard and insurance claims data from the 1989 M_L 5.6 Newcastle earthquake, the most costly in Australian history. The second is an engineering-based approach that defines hazard in terms of spectral acceleration and utilizes the Capacity Spectrum methodology to estimate building response. The sensitivity of the latter to the choice of building parameters is explored using both HAZUS values and others specifically derived for Australian construction. Comparison of the two approaches is particularly important in countries like Australia where a paucity of ground motion recordings and damage data make model calibration and validation problematic.

INTRODUCTION

Assessment of the earthquake risk posed to a built environment requires vulnerability relationships that relate hazard exposure to physical damage. Empirical relationships relating the intensity of ground shaking to repair cost or claims data have been developed and used by the insurance industry. Vulnerability relationships of this type typically relate subjective Modified Mercalli intensity (MMI) observations to the expected damage (as a fraction of the insured value) for a representative range of building types [1]. While this empirical approach is well founded in the actual loss experience, it is necessarily restricted to building types for which adequate loss data is available and the potential for extrapolation to other building types or new structural systems it limited. Moreover, the relationships provide little insight into factors that affect building performance in an earthquake and the expected effectiveness of seismic retrofit strategies.

An alternative approach that has found expression in the HAZUS [2] methodology is based on engineering knowledge and judgement of building behaviour during ground shaking. It predicts the level of structural response and from this predicts the probable damage states for a population of structures. While this more recent approach potentially gives greater insights into factors influencing earthquake damage the simplifications required in the analysis potentially limit the accuracy and verification of model

[1] Structural Engineer, Geoscience Australia, Canberra, Australia. Email Mark.Edwards@ga.gov.au
[2] Geophysicist, Geoscience Australia, Canberra, Australia. Email David.Robinson@ga.gov.au
[3] Director, Risk Frontiers, Macquarie University, Sydney, Australia. Email jmcanene@els.mq.edu.au
[4] Group Leader, Geoscience Australia, Canberra, Australia. Email John.Schneider@ga.gov.au

predictions can be difficult. The effectiveness of each of the two approaches is explored in the context of a damaging Australian earthquake.

The New South Wales Newcastle earthquake of the 27th December 1989 provided valuable insights into the behaviour of Australian residential buildings during intraplate type earthquakes. Risk Frontiers (RF) has used intensity based hazard zone delineations and insurance claim data from this event to develop vulnerability curves for residential construction and incorporated them into a stochastic seismic risk assessment methodology. Subsequent to the earthquake event Geoscience Australia (GA) conducted a systematic study of the earthquake affected region of Newcastle/Lake Macquarie [3] in which the seismicity, regolith distribution and building stock at risk were defined. Using a HAZUS type framework and a full probabilistic model the risk posed by earthquakes to the combined study region was quantified. The work entailed some modifications to the residential vulnerability and direct cost models contained in HAZUS to better reflect Australian construction. Both approaches have been deployed using a single earthquake scenario event with direct comparisons made between the RF and GA methods.

In this paper the Newcastle earthquake is described and the two risk assessment methodologies presented. Using the scenario of the Newcastle earthquake and the associated insurance losses the RF and GA methodologies are compared using the results of a series of simulations considering the residential component of the region's building stock. The results permit several observations to be made on aspects of the two approaches including the effects of MMI regolith adjustments to intensity based predictions, the sensitivity of the engineering approach to parameter selection and the significance of incorporating variability in ground motion attenuation and building vulnerability. The utilisation of both approaches in a combined methodology is explored using the observations made.

THE NEWCASTLE AND LAKE MACQUARIE REGIONS

Newcastle and the adjacent Lake Macquarie regions are located in the Australian State of New South Wales (Figure 1). Newcastle, which sits astride the Hunter River, was settled in the early 19th Century and was a centre for coal extraction, agricultural support, maritime activity and administration. The original settlement was able to draw on the resources of these activities with significant building undertaken during the late 1880's in brick and masonry. Lake Macquarie was also settled in the late 19th Century though the rate of settlement was much slower. No major commercial centre was established before 1900, so the type and scale of structures in Lake Macquarie is 20th Century with a predominant use of timber framing. The composition of the current residential component of the building stock in the study region identified in Figure 3 is summarized in Table 1.

The seismicity in Australia is low compared to the more seismically active intraplate regions of the world. The combined Newcastle/Lake Macquarie region experiences seismic activity above the Australian national average with the region assigned a 475 year return period peak ground acceleration (pga) for a stiff site of 0.11g in the Australian earthquake loadings standard [4]. The corresponding stiff site spectral value at a period of 0.3s is 0.265g. The earthquake risk study for the region [3] found regolith to have a profound effect on the site hazard with the 5% damped spectral acceleration values at a 0.3s period exceeding 0.5g in many areas of the region. Furthermore, when the moderate hazard is combined with the vulnerability of older Australian masonry structures, a moderate earthquake event can represent a significant loss to the region. This was the case for the 1989 Newcastle event described below.

THE NEWCASTLE EARTHQUAKE EVENT

The Richter magnitude 5.6 earthquake which occurred in Newcastle/Lake Macquarie on the 27th December 1989 is termed the Newcastle earthquake. The epicenter and other details of the event can be seen in Figure 1. A peak ground acceleration of 0.24g was estimated for a weathered rock site west of the Newcastle CBD in a later analysis of the event. The event claimed 13 lives and caused extensive damage to buildings and other structures. The insured loss in 2002 dollars was approximately AUD $1.2 billion making it the most damaging earthquake in Australian settled history. The high level of damage for this moderate-magnitude earthquake has been attributed to the presence of deeper regolith beneath many older and more vulnerable masonry structures. Following the event damage assessments were conducted by Newcastle City Council assessors and others and systematically collated into a data set of approximately 3,500 buildings. The distribution of building damage observed in the Newcastle region can be observed in Figure 2 with the corresponding damage rating scale used by the assessors shown in the legend. Unfortunately the damage observations, while useful, could not be used in any verification exercise as the damage states did not correspond with those used in the engineering approach and often the building construction type was not recorded.

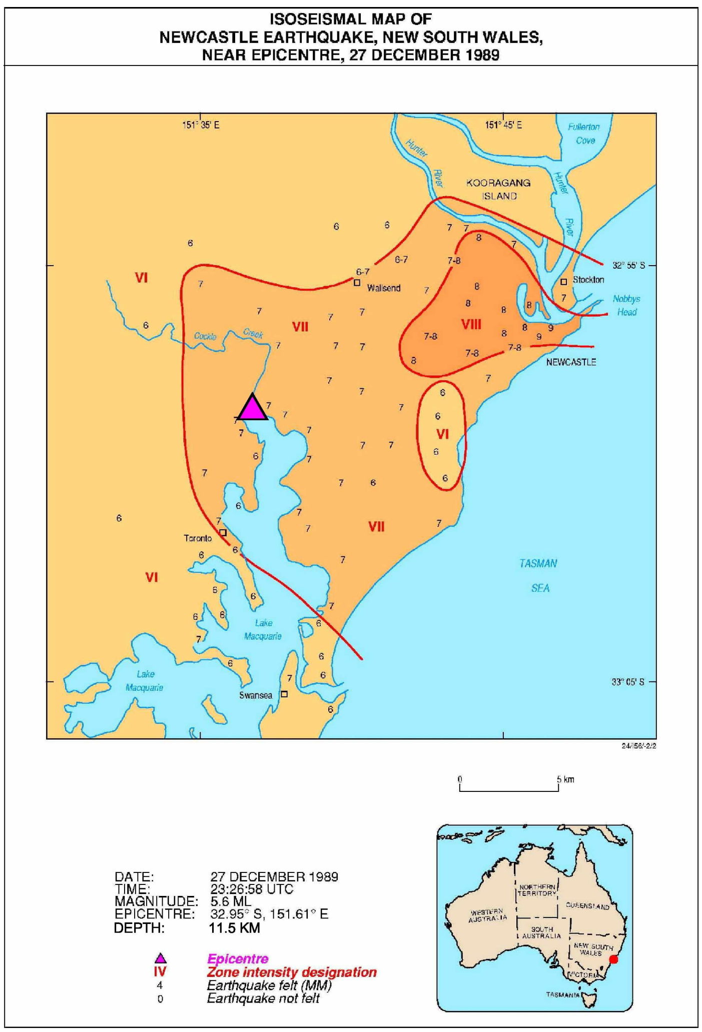

Figure 1: Isoseismal data from the Newcastle 1989 Earthquake. The triangle indicates the epicentre of the earthquake event.

Table 1: Newcastle/Lake Macquarie residential building stock composition and associated vulnerability and cost models

<table>
<tr><th>Description</th><th>Number of Buildings Surveyed</th><th>Number of Buildings Represented</th><th>Geoscience Australia Structural Model</th><th>Risk Frontiers Vulnerability Model</th><th>Direct Cost Model</th></tr>
<tr><td>Brick Veneer Walls With Tiled Roof</td><td>882</td><td>28,053</td><td>W1BVTILE</td><td rowspan="4">OTHER</td><td rowspan="2">Brick Veneer</td></tr>
<tr><td>Brick Veneer Walls With Sheet Metal Roof</td><td>69</td><td>1,446</td><td>W1BVMETAL</td></tr>
<tr><td>Timber Clad Walls With Tiled Roof</td><td>1,267</td><td>23,196</td><td>W1TIMBERTILE</td><td rowspan="2">Timber Clad</td></tr>
<tr><td>Timber Clad Walls With Sheet Metal Roof</td><td>1,085</td><td>15,873</td><td>W1TIMBERMETAL</td></tr>
<tr><td>Double Brick Walls With Tiled Roof</td><td>560</td><td>7,065</td><td>URMTILE</td><td rowspan="2">BRICK</td><td rowspan="2">Double Brick</td></tr>
<tr><td>Double Brick Walls With Sheet Metal Roof</td><td>206</td><td>2,109</td><td>URMMETAL</td></tr>
<tr><td>Totals</td><td>4,069</td><td>77,742</td><td colspan="3"></td></tr>
</table>

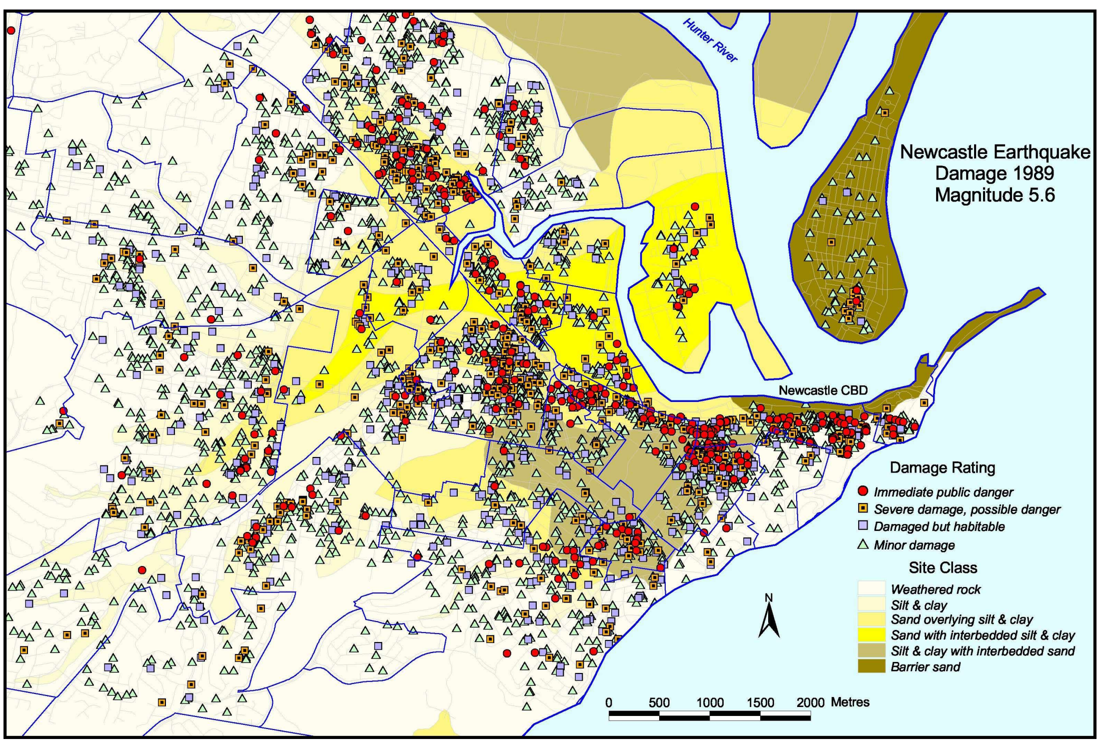

Figure 2: Surveyed Newcastle earthquake damage

The overall insurance loss for residential structures in Insurance Council of Australia (ICA) Zone 46 was around 3.5% of the insured value [5]. This insurance zone is much larger in area than the Newcastle/Lake Macquarie study region as can be seen in Figure 3 so an indicative loss was derived for the study region of principal damage using census data and by making four assumptions:-

1. Census totals of residential occupancies (including multiple occupancy dwellings such as blocks of apartments) have the same proportionality to the number of discrete residential structures both outside and inside the study region.
2. Losses outside the study region were negligible.
3. The mean replacement cost of individual residential structures outside the region was identical that within the study region.
4. The proportion of insured structures outside the region was the same as that within thereby avoiding any regional weighting.

The percentage loss of 5.3% was obtained by factoring the original 3.5% estimate with the ratio of the respective residential occupancy populations (1.51) summarised in Figure 3. Given that Newcastle is a large city by Australian standards, it follows that higher density apartment and flat type dwellings will be more predominant in the study region than in the balance of ICA Zone 46. This would effectively inflate the house population of the study region and lead to an under-estimation of the true population ratio based adjustment factor. This may be largely compensated for by the inherent over-estimation of actual damage by insurance figures associated with under-insurance, post disaster reconstruction cost inflation and the repair of pre-existing damage as earthquake damage. On balance the loss figure of 5.3% is considered a useful figure for comparative purposes.

RISK ASSESSMENT METHODOLOGIES

Natural hazard risk assessment is typically comprised of the key steps illustrated in Figure 4. Each step provides input into the succeeding commencing with the probabilistic hazard model through to direct damage losses that are aggregated across the study region. Where a single earthquake scenario is used instead of a full probabilistic study, the end product of the sequence is total consequential loss rather than risk. For this comparative exercise the single Newcastle event scenario was simulated and direct damage percentage losses to the residential building subset determined. Vulnerability models were available for contents losses but this was a small component of the Newcastle earthquake damage and for this reason was excluded. The original field survey [3] of 6,300 buildings shown in Figure 5 represented the total of 102,000 Newcastle/Lake Macquarie structures believed to be present at the time of the 1989 earthquake. This field surveyed data set was sampled to obtain a representative residential sub-set of 4,069 residential structures that represent a corresponding sub-population of 78,000 homes. The damage losses derived from the 4,069 buildings were factored up in the modeling process by appropriate factors to obtain the losses for the full population. The sub-set data included indicative building floor areas so individual replacement values could be determined using cost models covering a range of residential building types in the loss assessment process. Specific aspects of the two assessment methods are described separately below within the framework presented in Figure 4.

Intensity Based Approach

In the RF intensity based approach the MMI intensity of ground shaking at representative building sites across the study region is predicted and converted to a damage loss using simple vulnerability expressions. The percentage loss of the sub-set is adjusted to a loss across the region by the process described earlier. The elements that comprise the intensity based assessment approach are presented as a flow chart in Figure 6. For the purposes of this comparative study the GA software EQRM [6] was modified to permit the RF intensity based approach and associated parameters to be run in parallel with the engineering approach keeping several inputs into the two processes common to both. Aspects which are unique to the intensity based approach are discussed below.

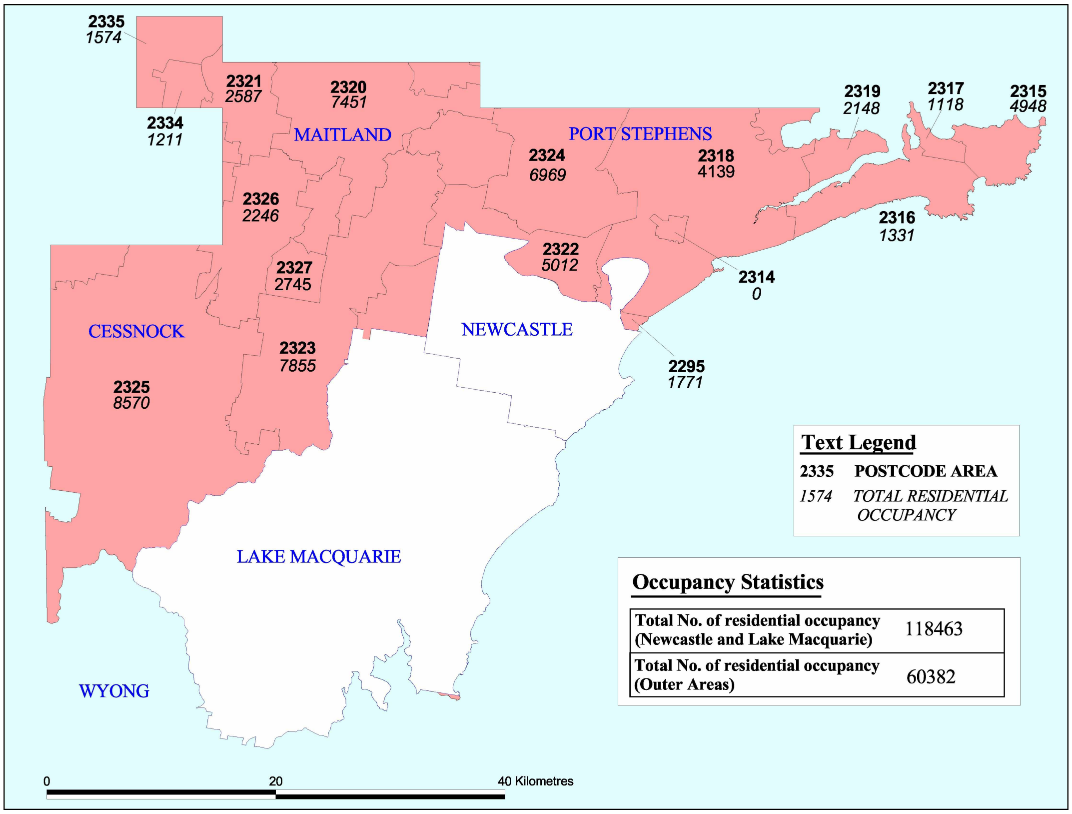

Figure 3: Residential occupancies in Insurance Council of Australia Zone 46. The Newcastle/Lake Macquarie study region is shown in white.

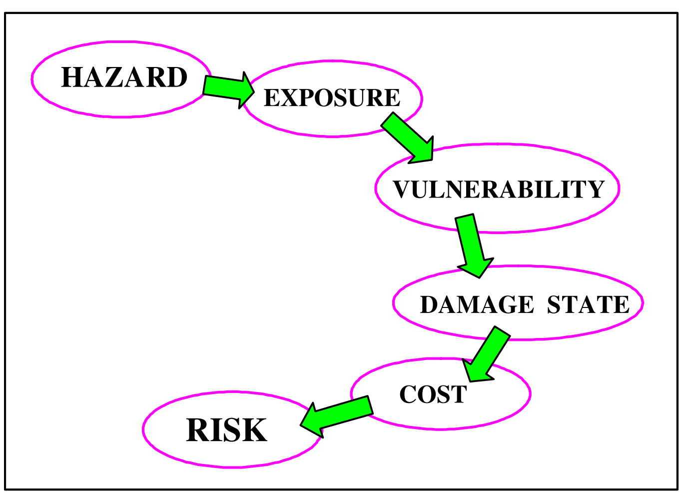

Figure 4: Earthquake risk methodology

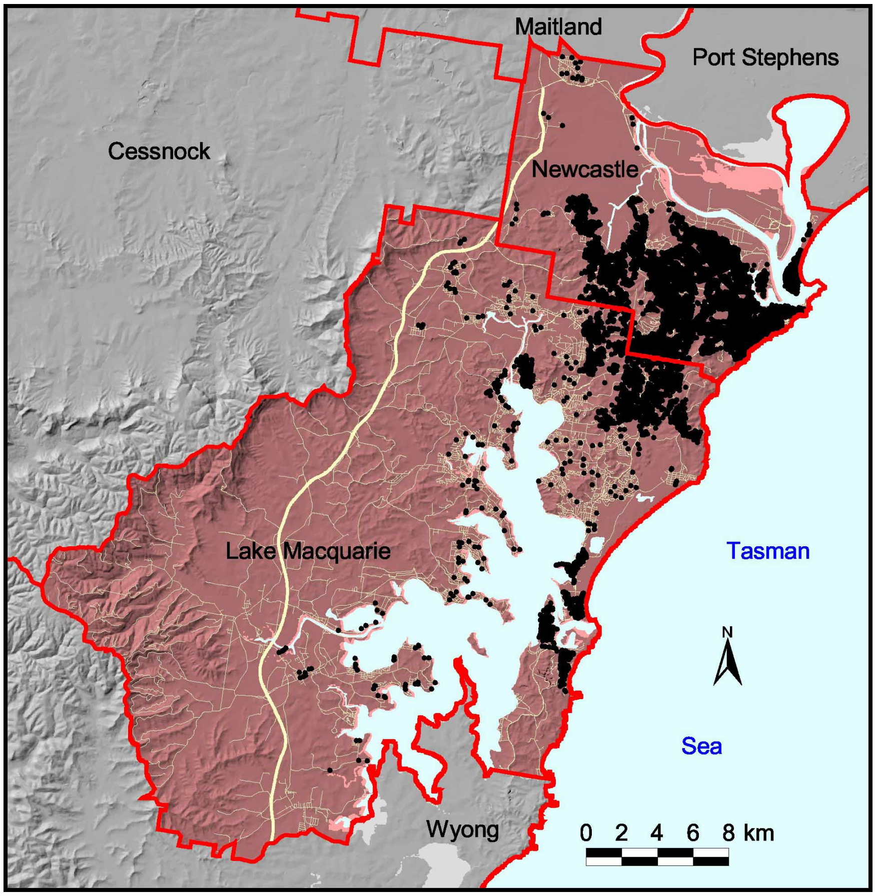

Figure 5: Newcastle/Lake Macquarie regional study building survey locations

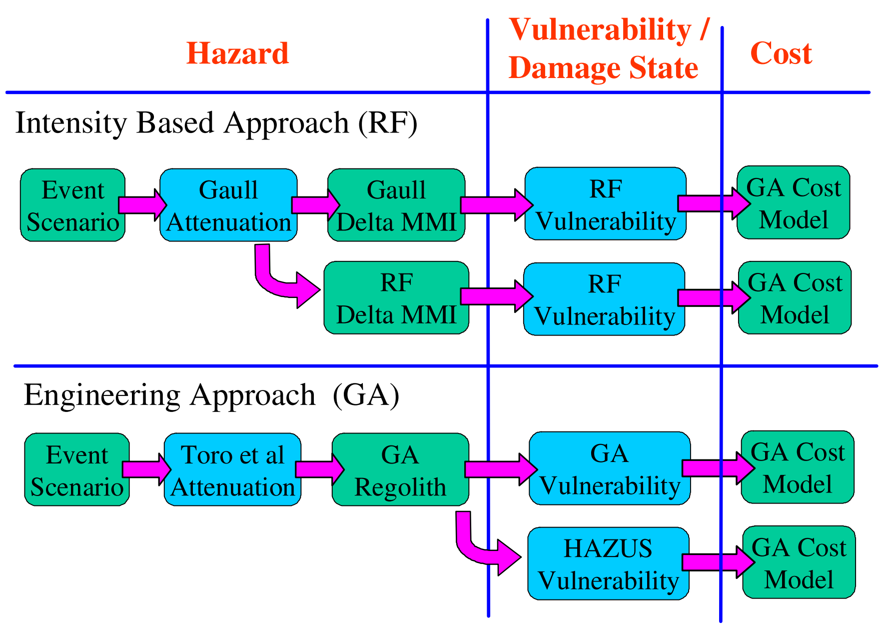

Figure 6: Risk assessment approach flowcharts. Components in which variability has been included are indicated in light blue.

Earthquake Attenuation

The current Australian hazard map [4] was developed using the attenuation relationships developed by Gaull [6]. He derived separate expressions for several regions of the country using a collection of isoseismal maps for a number of Australian earthquakes. The intensity attenuation expression for South-Eastern Australia, which is based on local earthquake magnitude M_L, was adopted for the Newcastle/Lake Macquarie region.

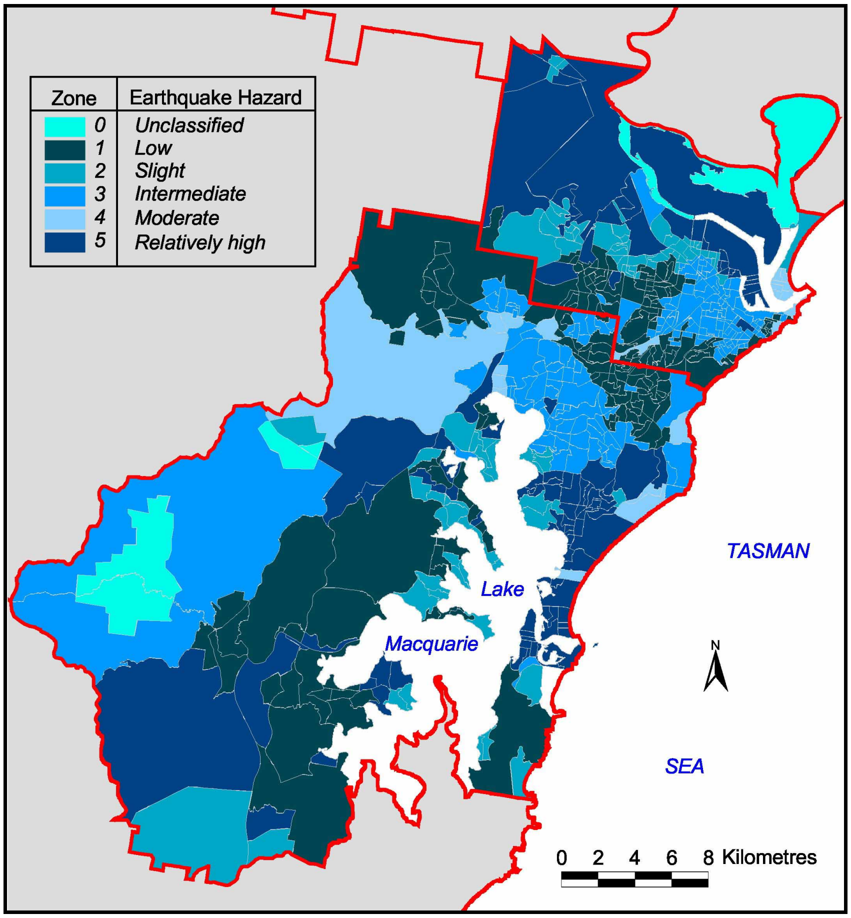

Figure 7: Risk Frontiers' Newcastle/Lake Macquarie region regolith zonation

Regolith Amplification

The attenuation expressions developed by Gaull predict MMI intensities as felt on a firm site. Local regolith can accentuate the intensities, or alternatively its total absence (outcropping bedrock) requires a downward adjustment. RF have classified the regolith across the Newcastle/Lake Macquarie region at the centroids of Census Collection Districts using a 5 zone scale. While the zones described in Table 2 incorporate aspects of building vulnerability related to pre-existing expansive clay activity damage, the site flexibility increases with class number requiring sequentially greater adjustment to the predicted site MMI. Gaull has proposed MMI adjustments in terms of the five RF zones to account for regolith effects which are summarized in Table 3. Also presented in the table are the adjustments independently derived by RF for use in their overall methodology. While the scales have similar steps in MMI the two scales clearly differ on which zone requires zero adjustment. Both MMI adjustment regimes were used in the simulations in conjunction with the RF soil classes to permit comparisons (see Figure 6).

Table 2: Risk Frontiers' regolith zonation descriptions

Zone	Characteristics
1	Shallow soils on competent bedrock. Gentle slopes. Limited to moderate relief.
2	May be slightly affected by earthquake ground shaking, particularly where slopes are steeper. Competent rocks but soils may be plastic or have moderate to high shrink swell potential leading to structural damage over time and predisposing buildings to earthquake damage.
3	Intermediate hazards from ground shaking, differential compaction, and/or slope failure. Thicker soils and sediments of older river terraces and valley fills; well-drained coastal and inland sand dunes; steeper slopes with thicker soils and deposits, including those with minor evidence of slope failure.
4	Moderate ground-shaking hazard. Variable recent alluvial, estuarine and wind-blown deposits, including sands, silts, gravels, organic materials and under-consolidated clays. Water tables may be high. Includes extensive areas of highly reactive soils, collapsing soils and compressible soils leading to foundation damage and cracking of buildings.
5	Relatively high hazard from ground shaking of unconsolidated deposits including poorly-drained recent alluvium, made ground, lake deposits, and deltaic sediments. Sediments range from soft organic muds and silts to sands and gravels. Contact with competent rock is often below sea level.

Table 3: Modified Mercalli Intensity modifications for regolith. Zone 1 was considered to equate with bedrock for rock site simulations.

Zone	Gaull MMI Adjustment	Risk Frontiers MMI Adjustment
1	-1.0	-1.5
2	-0.5	-1.0
3	0.0	-0.5
4	+0.35	0.0
5	+0.70	+0.5

Vulnerability Models

Residential insurance loss data from the Newcastle earthquake and the delineations of MMI felt intensity during the event (similar to those shown in Figure 1) were processed by Risk Frontiers to obtain vulnerability models. The loss data plotted against the associated MMI intensity were found to be grouped with unreinforced masonry structures showing a significantly greater vulnerability than those of framed construction. Consequently the two groups of data were separately regressed to give the two vulnerability models "Brick" and "Other" indicated in Table 1.

Cost Models

The percentage losses determined for each of the 4,069 representative buildings were converted into actual dollar losses using a series of building replacement cost models developed for a multi-hazard risk study of the Australian city of Perth [8]. The cost models for each of the building types are a function of the gross floor area of the home as construction costs per square meter diminish with home size. By scaling the individual dollar losses and replacement values to the full population and aggregating across the study region the variation in building value with size and construction form was taken into account. Separate cost models were available for brick veneer, timber clad and double brick walls. Care was taken to apply separate cost models to each of the framed construction wall types for which a single structural vulnerability model was used to obtain the percentage loss. The mapping of cost models is shown alongside the vulnerability models in Table 1.

Engineering Based Approach

In this second approach the demand spectra at representative building sites across the study region are predicted and used to estimate the maximum spectral displacements and accelerations experienced by the representative structures. Fragility relationships for both drift-sensitive and acceleration-sensitive building components are then employed to determine the probability that the building components are in one of several damage states. The direct damage loss is calculated using the replacement value of the structure and adjusted to the actual building population represented by the structure as described earlier. Finally the losses and replacement values are aggregated across the region to obtain an overall percentage loss for the study region. The elements that comprise the engineering based assessment approach are presented as the second flow chart in Figure 6. Aspects of the elements are discussed below.

Earthquake Attenuation

The bedrock earthquake demand spectra for the representative building locations were derived using the attenuation relationships developed by Toro et al [9]. The coefficients selected for the Newcastle event were those developed for the mid-continental US which use moment magnitude to define the event size. The Newcastle M_L 5.6 was converted to M_W 5.35 using an empirical relationship.

Regolith Amplification

The regolith across the Newcastle/Lake Macquarie region was the subject of a detailed study and subsequently categorized into six classes [3]. The classes are described in Table 4 and the spatial distribution of each class can be observed in Figure 8. For each class, period dependent amplification factors have been developed for a range of moment magnitude and pga combinations [3]. The amplification factors appropriate to the Newcastle scenario event were selected and applied to the bedrock spectra to obtain the demand spectra for the structure.

Table 4: Geoscience Australia's regolith classification descriptions

Regolith Class	Description
C	Weathered rock (maximum thickness 15m)
D	Silt and clay (maximum thickness 16.5m)
E	Sand overlying silt and clay (maximum thickness 30m)
F	Sand with interbedded silt and clay (maximum thickness 39m)
G	Silt and clay with interbedded sand (maximum thickness 30m)
H	Barrier sand (maximum thickness 30m)

Vulnerability Models

The engineering approach entails a prediction of maximum building response which is subsequently compared to a family of fragility relationships. Response prediction is achieved using a Capacity Spectrum formulation similar to that proposed by Freeman [10] and incorporated in the HAZUS [2] methodology. The process requires representative push-over behaviour, effective viscous damping, and fragility relationships that represent the vulnerability of the building stock modelled. The HAZUS manual presents parameters that are considered representative of typical US construction that GA has used as a default for some building types. However, for some building structural types GA has undertaken research to revise these parameters to better reflect Australian residential structures. Both the GA and HAZUS parametric value sets were used in this study as shown in the Figure 6 flowchart.

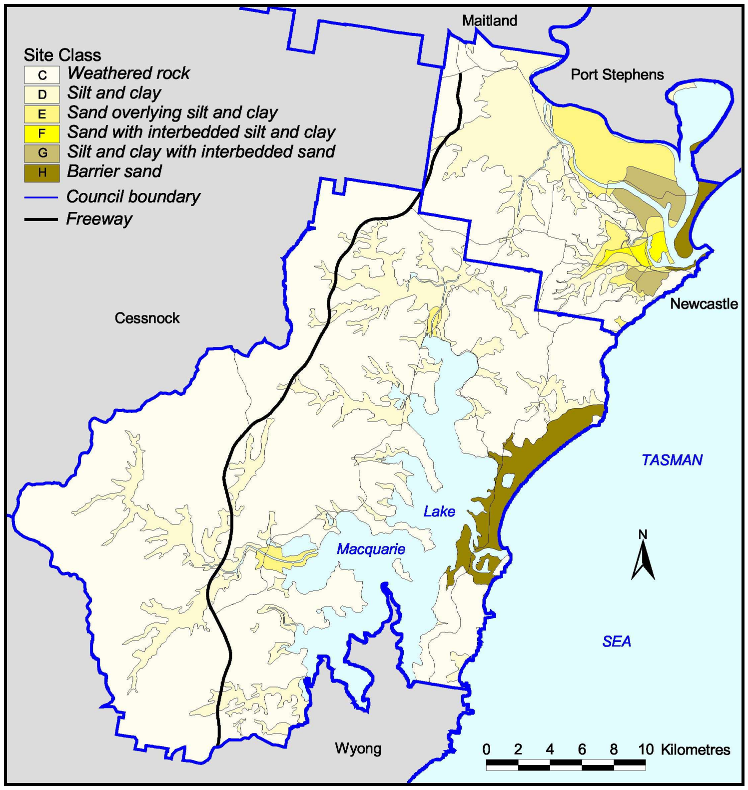

Figure 8: Geoscience Australia's Newcastle/Lake Macquarie region regolith classification

Direct Loss Models
The same Reed Building Data [8] cost models as used for the intensity based approach were used for the engineering approach to ensure the cost model component remained a constant in this comparative study. The mapping of both structural vulnerability and costing models to the residential building population can be seen in Table 1.

Simulations
The simulations performed reflect the flow charts in Figure 6 and are summarised in Table 5. The run combinations sought to eliminate variables to enable an unbiased comparison between the two approaches being studied. Simulations included a bedrock scenario in which the building population throughout the region was assumed located on rock. This attempted to eliminate the regolith variable but required the adoption of the notional bedrock site zone for the MMI adjustments identified in Table 3. Simulations used the regolith as mapped for each respective approach to permit comparisons with the adjusted insurance losses. Finally simulations included and excluded variability to explore how uncertainties in the modeling elements can impact upon the predicted damage.

Variability was not defined for all elements of the RF risk methodology. While an updated attenuation uncertainty was provided by Gaull [11] (σ=0.93 given for NSW as opposed to the published σ=0.37 in ref.7) and building vulnerability uncertainty was derived by RF, a corresponding uncertainty in the MMI adjustments for regolith was not available. While regolith amplification uncertainty was available for the GA methodology it was not incorporated to maintain consistency in the implementation of the methods. It is noted that some regolith amplification uncertainty is inherently incorporated into Gaull's attenuation relationship uncertainty due its stiff site predictions and associated shallow regolith variability inclusion.

To capture the effect of variability in the ground motion and building vulnerability models, the Newcastle event was simulated 1,000 times with parameters randomly selected from their respective probability distributions. For each simulation the loss at each of the 4069 representative structures was determined and aggregated across the region as described above to obtain a single loss value. Hence from the 4 million building loss predictions 1,000 loss values were determined giving a distribution of predictions about a mean.

RESULTS

The mean percentage losses for each simulation run are presented in Table 5. Where variability was incorporated into the run the coefficients of variance (COV) and the standard deviations are also presented. The distributions of the simulation predictions themselves are presented in Figure 9 for bedrock and regolith. The reduced variability in predictions for the RF intensity based method can be clearly observed.

Table 5: Simulation run results summary

Wall Construction Type	GA Using Updated Building Parameters and Variability	GA Using HAZUS Building Parameters and Variability	RF With Gaull Attenuation and Gaull MMI Adjustments and Variability	RF With Gaull Attenuation and RF MMI Adjust. With No Variability	Number Of Buildings
Unreinforced Double Brick	12.7 (1) (1.08) (2) [8.5] (3)	4.5 (0.67) [14.7]	15.1 (1.06) [7.1]	9.4 (0) [0]	766
Timber Framed	5.5 (0.49) [9.0]	1.8 (0.15) [8.2]	7.5 (0.27) [3.6]	5.2 (0) [0]	3303
All Residential	6.3 (0.46) [7.24]	2.1 (0.15) [7.1]	8.4 (0.27) [3.2]	5.6 (0) [0]	4069

(1) Mean percentage loss μ_L unbracketed.

(2) Standard deviation σ_L of percentage loss in round brackets.

(3) Coefficient of variation $= \left(\frac{100 \times \sigma_L}{\mu_L}\right)$ in square brackets.

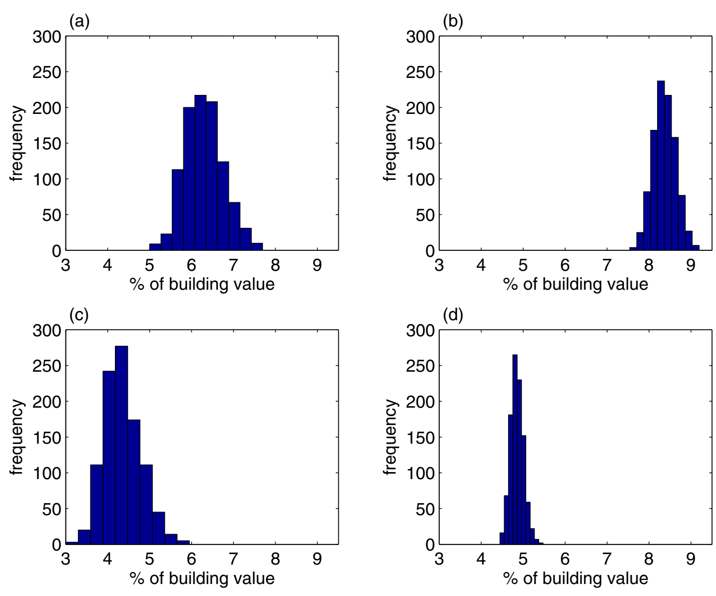

Figure 9: Simulation run dispersion; a) GA on regolith; b) RF on regolith; c) GA on bedrock; d) RF on bedrock

The loss components sustained by unreinforced masonry and framed residential structured were also sub-sampled to provide a measure of the vulnerability of the two types. In Table 6 the results from the GA simulation runs which used both the Australian and HAZUS building parameters are compared with those from the RF simulation with the Gaull regolith adjustments.

For each of the GA and RF approach simulations one particular variability inclusive combination of parameters was anticipated to more accurately predict the Newcastle insurance loss. For the GA engineering approach the favoured combination was a regolith simulation using Australian building parameters. For the RF intensity approach the combined Gaull attenuation and regolith adjustments in conjunction with the RF vulnerability models was expected to give the best prediction. The predicted losses of 6.3% and 8.4% compare reasonably well with the 5.3% insurance value given all the uncertainties of the regional assessment that sought to assess the losses to nearly 80,000 homes. It is noted that if the RF Mercalli adjustment values for regolith are used a much improved prediction of 6.4% loss results which is essentially identical to the GA value and within 20% of the reference insurance value.

Table 6: Percentage losses predicted for residential building types

Wall Construction Type	GA Using Updated Building Parameters	RF With Gaull Attenuation and Gaull MMI Adjustments	GA Using HAZUS Building Parameters	Number Of buildings
Unreinforced Double Brick	12.7 (1) (1.08) (2) [8.5] (3)	15.1 (1.06) [7.1]	4.5 (0.67) [14.7]	766
Timber Framed	5.5 (0.49) [9.0]	7.5 (0.27) [3.6]	1.8 (0.15) [8.2]	3303
All Residential	6.3 (0.46) [7.24]	8.4 (0.27) [3.2]	2.1 (0.15) [7.1]	4069

(1) Mean percentage loss μ_L unbracketed.

(2) Standard deviation σ_L of percentage loss in round brackets.

(3) Coefficient of variation = $\left(\frac{100\times\sigma_L}{\mu_L}\right)$ in square brackets.

DISCUSSION

The Mercalli regolith adjustment values have a very significant effect on the loss predicted as the vulnerability relationships are highly non-linear. Previous insurance related work by Shepherd et al [12] adopted a zero adjustment for stiff sites with a unit MMI intensity upward adjustment for soft soil sites. This whole unit adjustment may have related to the fundamental point that the MMI measure is not recorded by instrument and is, therefore, subjective. The associated arbitrary rounding was the original inspiration for the use of Roman numerals in the scale to discourage slicing of the scale into decimal fractions. Notwithstanding this, the building vulnerability relationships themselves require decimalization and a refined scale of regolith adjustment is considered justified. The critical point seems to be the zero adjustment zone. The greater downward adjustment of the RF values when compared to Gaull's is due to an assumption that Gaull's attenuation functions are biased by reported damages on softer sites. While it could be reasoned that the vulnerability component should be independent of the event and regolith combination that generated the intensity of shaking, the adjustment does improve the predictions, particularly when variability is excluded from the simulation (5.6% loss). The results suggest that the RF model parameters have been developed together to be used in concert with the Gaull attenuation functions. The hazard work by Gaull, that originally excluded regolith effects, does not incorporate any similar calibration adjustments.

The change from regolith to bedrock in the simulations had a much more profound impact upon the intensity related predictions when compared to the engineering approach. The intensity based MMI adjustments scales were associated with a halving of losses whereas the engineering approach had a third reduction. Reasons for this difference are unclear.

The choice of building parameters for the GA engineering approach was found to have a profound effect on the losses predicted. HAZUS residential models greatly under-predicted the losses (Table 5 - 2% loss compared to the 5.3% insurance value). The modifications incorporated by GA have effected a significant improvement in the estimate (6.3%). The results suggest that the US residential building stock as represented by the published parameters is much less vulnerable than the corresponding Australian construction.

The losses sustained by unreinforced masonry were predicted to be much greater than for framed construction by both methods. This is in line with experience worldwide. The results are summarised in Table 6 and include both GA and HAZUS building parameter results. All three sets of results show a typical factor of two increase in damage in moving from framed construction to full masonry. This numerical result is consistent with observed damage in the Newcastle earthquake [13] with very extensive damage sustained by older double brick structures.

The incorporation of variability into the modelling approach was found to greatly influence loss predictions. The GA approach was found to be the most sensitive with the Newcastle earthquake loss prediction falling from 6.3% with variability to just 2.5% without. The change in loss for both approaches is related to the highly non-linear nature of the vulnerability curves. Any incorporation of the variability associated with the natural processes and the building stock will result in an overall lifting of the mean damage value. Figure 9 shows a greater variability associated with the GA approach than with that of RF. Consequently this adjustment is greater for the GA approach. If the components of the earthquake delivery and building properties have a quantified variability, a probabilistic risk assessment in which a suite of earthquake events are simulated needs to capture this. However for an individual historical earthquake scenario the process will predict the average consequence but cannot account for where in the distribution the ***actual*** earthquake lies. The unique nature of an earthquake event and attendant loss, particularly the wave attenuation between source and site, presents a challenge when comparing predicted losses to insurance data. The issues associated with variability incorporation are the subject of ongoing research at GA.

The verification of engineering models is difficult in the absence of damage and loss data. The lower seismicity of Australia and the dispersion of development across a very large continent mean that a direct earthquake hit on a city such as Newcastle is rare. Hence opportunities to conduct damage surveys tailored to capture the exact verification information needed are rare. Damage surveys conducted after the Newcastle event were of limited verification use due to a different focus. Experimental testing incorporating shaking table specimens and representative ground motions is an alternative route but specimen scale limitations and the need to convert damage states into repair costs remain. In time experimental work will potentially provide much of the Australian data needed for the engineering approach. However, in the interim a combined approach whereby damage can be predicted using both intensity based approaches and the developing engineering models can lead to more robust predictions and improvements in models.

CONCLUSIONS

The following conclusions are drawn from this comparative study:-

- Both the RF intensity based methodology and the GA engineering approach gave predictions of regional residential loss that were of the same magnitude as the insurance data available. Where variability was incorporated the GA approach was within 20% of the reference value. The complete RF approach without the incorporation of variability gave the closest prediction to the insured value with a 6 % departure.
- Load bearing masonry was predicted to experience significantly greater losses than framed construction consistent with observed Newcastle earthquake damage.
- HAZUS building parameters based on US construction greatly under-estimated damage to both masonry and framed residential construction. The GA derived parameters gave much improved damage predictions underlining the importance of developing parameters that represent local construction styles.
- Parametric variability has a profound impact on the engineering approach and a smaller though significant impact upon the intensity based approach. Variability increases mean damage levels due to the non-linear nature of building vulnerability models.
- The combined use of intensity based and engineering model based methodologies is a useful approach in regions of lower seismicity where a paucity of damage data presents challenges to engineering model development.

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