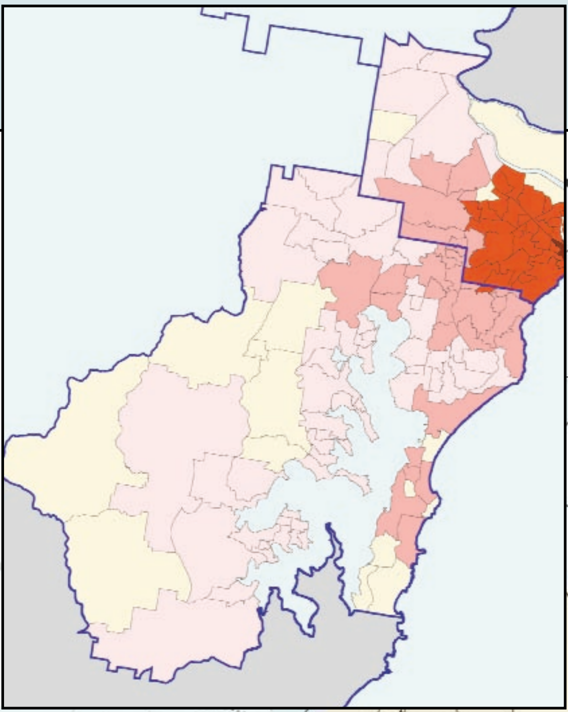
Earthquake Risk in *Newcastle* & LAKE MACQUARIE



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Edited by Trevor Dhu and Trevor Jones

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DEPARTMENT OF INDUSTRY, TOURISM & RESOURCES

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EARTHQUAKE RISK IN NEWCASTLE AND LAKE MACQUARIE

Edited by Trevor Dhu and Trevor Jones

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and in cooperation with

The City of Newcastle

Hunter Water Corporation
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City of Lake Macquarie

1 SUMMARY (T. JONES AND T. DHU)

This Chapter summarises the important results of the earthquake risk assessment of Newcastle and Lake Macquarie. The summary presents the essential aspects of the risk assessment techniques used, the important results and conclusions, and suggests options to mitigate the earthquake risk in Newcastle and Lake Macquarie.

1.1 Background

At 10.27 am on the 28 December 1989 an earthquake measuring 5.6 on the Richter scale shook Newcastle, Australia's sixth most populous city. This moderate-magnitude earthquake claimed 13 lives and caused extensive damage to buildings and other structures. This event clearly demonstrated that moderate-magnitude earthquakes, which frequently occur in Australia, have the potential to dramatically impact Australian communities.

Natural hazards devastate Australian communities almost every year. In response to the danger posed by these natural hazards, Geoscience Australia developed the Cities Project. This initiative began in 1996 and is focused on research to measure and mitigate risks faced by Australian urban communities from a range of natural hazards including earthquakes. The ultimate objective is to improve the safety of communities, and consequently make them more sustainable and prosperous.

1.2 Introduction

In addition to the devastating 1989 Newcastle earthquake, at least four other earthquakes of magnitude 5 or greater have occurred in the surrounding Hunter region since European settlement in 1804. Some of these earthquakes caused damage in areas that, at the time, were sparsely populated. Similar events, were they to occur today in populated areas, would certainly cause significant damage. The frequency with which these events have occurred in the Hunter region suggests that earthquakes pose a genuine threat to the communities there.

This study presents the most comprehensive and advanced earthquake risk assessment undertaken for any Australian city to date. It has focused on the economic losses caused by damage to buildings from earthquake ground shaking, and not on the impacts from other, secondary hazards such as soil liquefaction and surface faulting. The study has adopted a probabilistic approach that makes allowances for the variability that is inherent in natural processes as well as the uncertainty in our knowledge.

The results from this project will assist decision-makers involved in local and state government, policy development, the insurance industry, engineers, architects, and the building and finance industries to manage potential damage and loss of life from earthquakes in Newcastle and Lake Macquarie. The results also have implications for the earthquake risk facing larger Australian cities such as Sydney, Melbourne and Adelaide. This is due to a number of factors, including similarities between the earthquake hazard in Newcastle and Lake Macquarie and other parts of Australia, and similarities between the urban environments, particularly the composition of the building stock.

We emphasise that this report should be regarded as the best and most recent assessment of earthquake risk in Newcastle and Lake Macquarie. However, we acknowledge that there are limitations in the models and data we have used, and that we have an incomplete understanding of the natural variability inherent in ground shaking and building response.

The results, interpretations and conclusions could change with the incorporation of new data and with different model assumptions.

Therefore, the reader should not take action based on information in this report alone.

1.3 Methodology

The general risk assessment philosophy adopted by the Cities Project has been developed from the joint Australia/New Zealand Risk Management Standard, (AS/NZS4360, 1999). It can be expressed conceptually as follows:

Risk = Hazard * Elements at Risk * Vulnerability of the Elements at Risk

For the specific case of earthquake risk assessments, this process can be described by the flowchart in Figure 1.

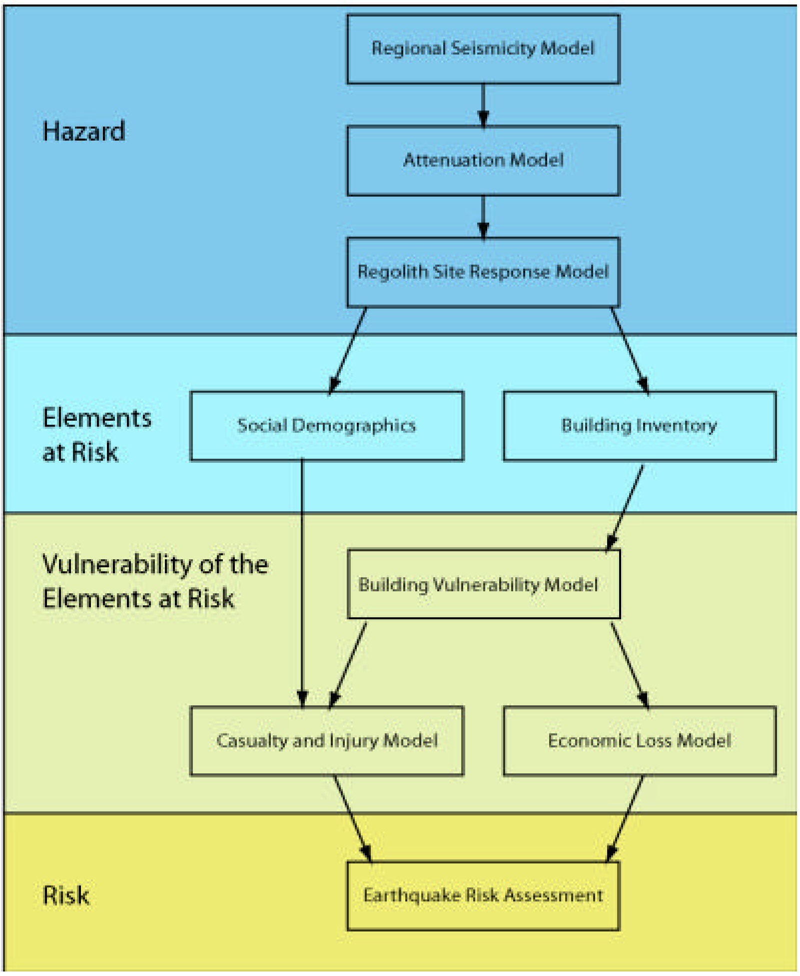

Figure 1.1: Flowchart describing the earthquake risk assessment process as applied to Newcastle and Lake Macquarie

A brief overview of the key assumptions and models used in the Newcastle and Lake Macquarie earthquake risk assessment is provided below. For a detailed description of the adopted methodology, the reader is directed to Chapters 3 to 6.

1.3.1 Earthquake Hazard

The earthquake hazard in a region can be described in terms of *the level of ground shaking that has a certain chance of being exceeded in a given amount of time*. For example, it is common to describe earthquake hazard in terms of the level of ground shaking that has a 10% chance of being exceeded in 50 years. In order to calculate the earthquake hazard, three key models are needed, specifically:

- a *regional seismicity model*, which describes the chance of an earthquake of a given magnitude occurring in a year;
- an *attenuation model*, which describes generally how earthquake ground shaking or intensity decreases with distance away from the earthquake source, and;

- a *site response model*, which describes how local regolith (soils, geological sediments and weathered rock) will affect the ground shaking experienced during an earthquake.

The *regional seismicity model* was created from historical seismicity and an interpretation of the earthquake occurrence on local geological structures. The model describes the chance of occurrence of earthquakes with moment magnitudes ranging from 4.5 through to 6.5, as these were thought to be the events likely to inflict damage on the study region.

The *attenuation model* of Toro et al. (1997) was used in this study. This attenuation model was developed for central and eastern North America, a region of the world that is thought to have similar attenuation characteristics to Australia. However, it must be emphasised that no explicit study has been conducted on the suitability of this model for Australian conditions.

The *site response model* was developed from detailed geotechnical data which were acquired primarily in the Newcastle municipality, and to a lesser degree the Lake Macquarie municipality. These data were used to classify the study region into six different site classes. State-of-the-art modelling techniques were then used to determine how ground shaking on regolith (soils, geological sediments and weathered rock) would differ from ground shaking on an unweathered rock outcrop.

1.3.2 Elements at Risk

Geoscience Australia undertook a comprehensive field survey in order to document the characteristics of buildings in the study region that contribute to the building's vulnerability during an earthquake. This survey obtained vital information such as wall construction type and building usage for approximately 6,000 buildings in the study region. In addition to surveying a sample of the general building stock, an effort was made to survey all essential service facilities such as hospitals, and ambulance and fire stations.

1.3.3 Vulnerability of the Elements at Risk

Earthquake vulnerability models are used to estimate the level of damage caused by a given level of ground shaking for a wide variety of building types. For the purposes of this study, building damage due to earthquake ground shaking was calculated using the method described in Kircher et al. (1997). The vulnerability models were developed specifically for Australian building types. This approach allows the calculation of damage on the basis of building type. For example, given a certain level of ground shaking, the damage to an unreinforced masonry structure would be different from the damage to a timber-framed structure.

Models based on work from the Federal Emergency Management Agency (FEMA) in the United States were used to convert estimates of building damage into estimates of economic loss. In this study, economic loss is defined in terms of the restoration cost of local buildings and their contents. The models from FEMA were calibrated using the cost of restoration for local buildings. FEMA models were used to calculate casualty losses in terms of injuries and lives lost.

1.3.4 Earthquake Risk

As mentioned previously, the earthquake risk to the study region is a combination of the earthquake hazard, the elements at risk and the vulnerability of those elements to earthquake ground shaking. In this study, these three components have been combined by:

- conducting computer simulations of approximately 1,200 earthquakes across the study region, each with its own magnitude and probability of occurrence based upon the regional seismicity model;
- using the attenuation and site response models to determine the level of ground shaking from every simulated earthquake at each of the surveyed buildings;
- using the vulnerability models to calculate the damage and economic loss to every building from each earthquake, as well as the related casualties, and;
- aggregating the losses across all the buildings in the study region to produce an estimate of loss for each of the 1,200 simulated earthquakes.

1.3.5 Incorporation of Variability

Any attempt to model natural processes or phenomena should incorporate some of the variability that is inherent in nature. For example, in this work we have classified the entire study region into six different regolith site classes. However, it is unrealistic to believe that every point within a single regolith site class will respond to an earthquake in precisely the same manner. Similarly, it is unrealistic to believe that every timber-framed building in the study area will suffer the same amount of damage given a certain level of ground shaking.

A detailed description of how natural variability has been incorporated into this study can be found in Chapters 3 to 6. However, in essence, the natural variability was incorporated by allowing the model parameters to vary in the simulations. One result of incorporating this variability is that two buildings of the same type, which experience the same level of ground shaking, may suffer different levels of damage. Similarly, the site response and attenuation models were allowed to vary in each earthquake simulation.

1.3.6 Verification of the Risk Assessment Methodology – The 1989 Newcastle Earthquake

A computer simulation of the 1989 Newcastle earthquake was used to test the risk assessment methodology used in this work. The results of the simulated earthquake were compared against records of the actual damage experienced during the 1989 event. For a detailed comparison of the simulated results with those recorded after the event, the reader is directed to the attached main report. When considered on a broad scale, the results of this comparison are very encouraging. For example, the simulated economic loss for the study region in 1989 dollars was of the order of $1.1 billion. This simulated economic loss is for both insured and uninsured properties. In comparison, in the aftermath of the 1989 earthquake, the insured losses in 1989 dollars were estimated to be $862 million[1].

1.4 Earthquake Risk Assessment Results

1.4.1 Earthquake Hazard in the Newcastle and Lake Macquarie Region

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. The Australian earthquake loading standard, AS1170.4-1993, presents earthquake hazard in terms of an ‘acceleration coefficient’ that has a 10% chance of being exceeded in 50 years. This acceleration coefficient is considered to be equivalent to peak ground acceleration. A comparison of the earthquake hazard from AS1170.4-1993 with the equivalent hazard calculated in this study is presented in Figure 1.2 and Figure 1.3. Both maps have the same trend of increasing hazard towards the north-east of the study region. The hazard calculated within this study is typically greater than the hazard suggested by the Australian earthquake loading standard.

The hazard maps presented in Figure 1.2 and Figure 1.3 were calculated using a measure of ground shaking (i.e. peak ground acceleration) that would be experienced on a rock outcrop. However, the buildings in Newcastle and Lake Macquarie are not built on rock, but rather on varying thicknesses of regolith. Note also that the damage experienced by buildings is often influenced not only by the peak ground acceleration, but also by the level of ground shaking at a specific period of vibration. For example, low- to medium-rise structures are typically more vulnerable to ground shaking that has a period of vibration of approximately 0.3 s than they are to peak ground acceleration. Figure 1.4 presents an estimate earthquake hazard on regolith based on the response of idealised low- to medium-rise structures. This figure clearly demonstrates that the soils and geological sediments from rivers, streams, wetlands and barrier sands have a greater level of hazard than the weathered rock material which covers the rest of the study region.

Medium- to high-rise structures are typically more vulnerable to ground shaking that has a period of vibration of approximately 1 s. Figure 1.5 presents the earthquake hazard on regolith based on the response of idealised medium- to high-rise structures. In this figure, the highest hazard can be seen to be associated with the coastal and riverine deposits in the eastern and north-eastern parts of the study region.

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[1] *Insurance Disaster Response Organisation, 2002, www.idro.com.au.*

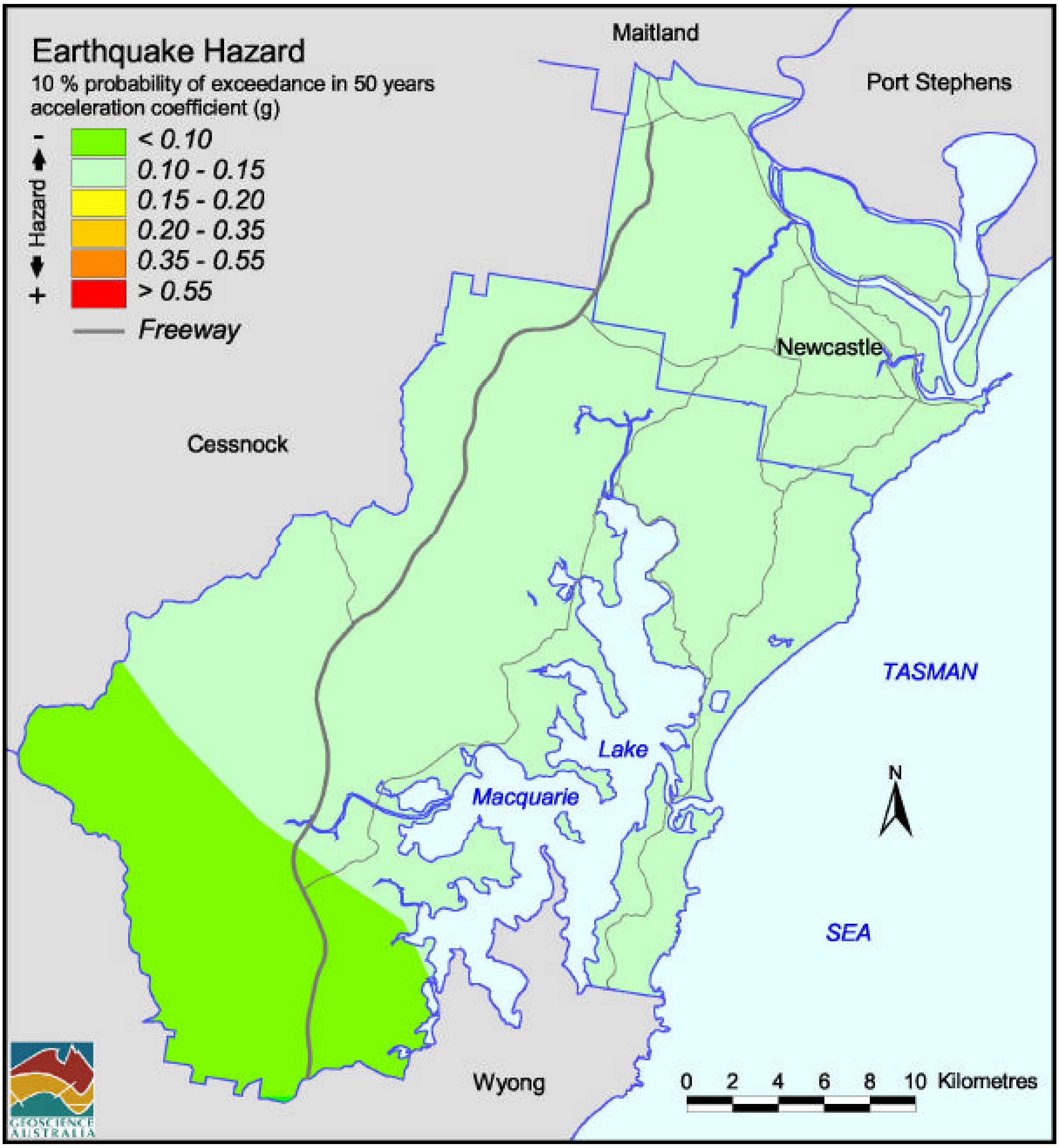

Figure 1.2: Earthquake hazard on rock in Newcastle as suggested by the Australian earthquake loading standard, AS1170.4-1993. Earthquake hazard is defined as the acceleration coefficient (considered equivalent to peak ground acceleration) that has a 10% chance of being exceeded in 50 years

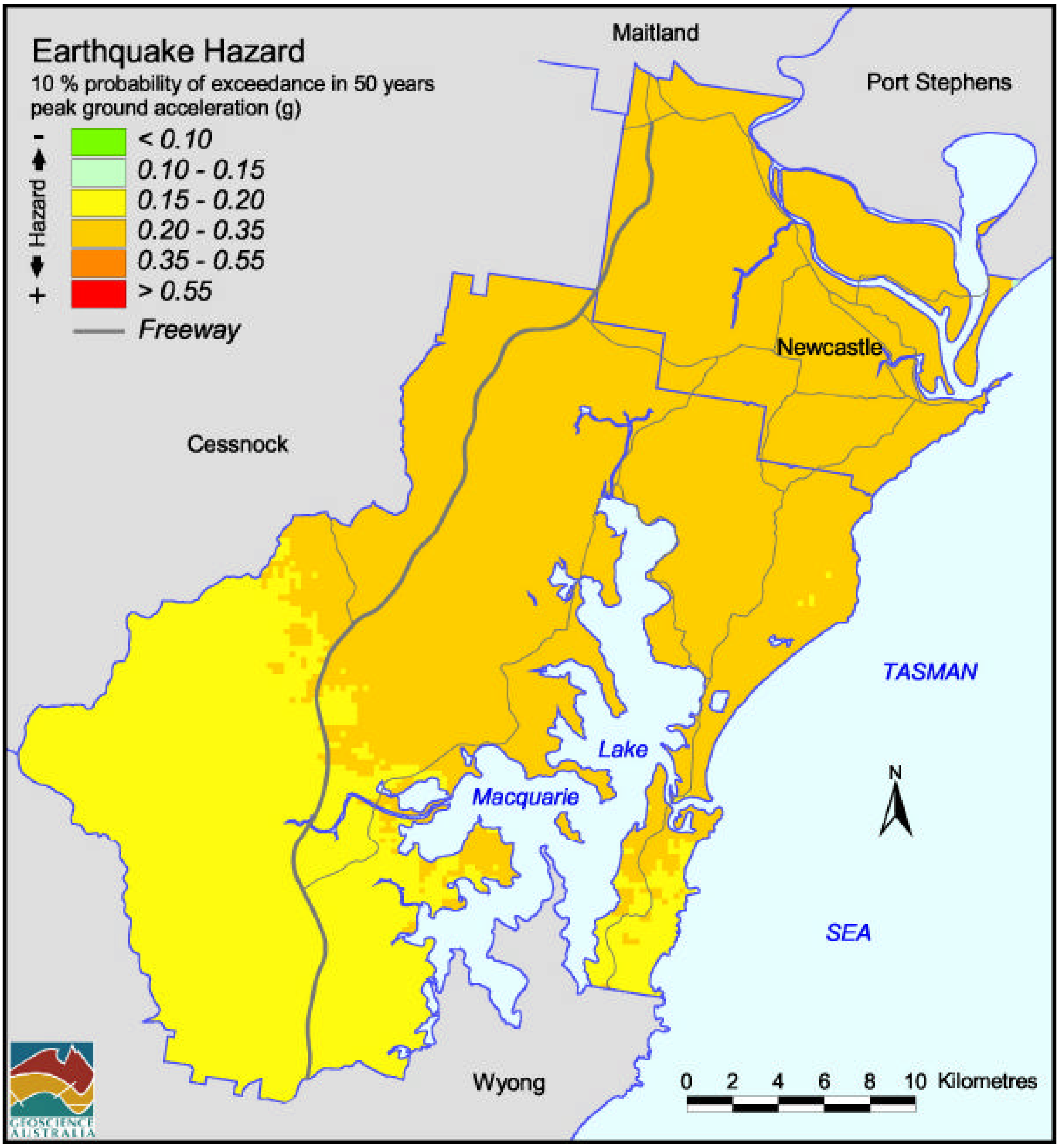

Figure 1.3: Earthquake hazard on rock in Newcastle as suggested by the hazard assessment conducted for this study. Earthquake hazard is defined as the peak ground acceleration that has a 10% chance of being exceeded in 50 years

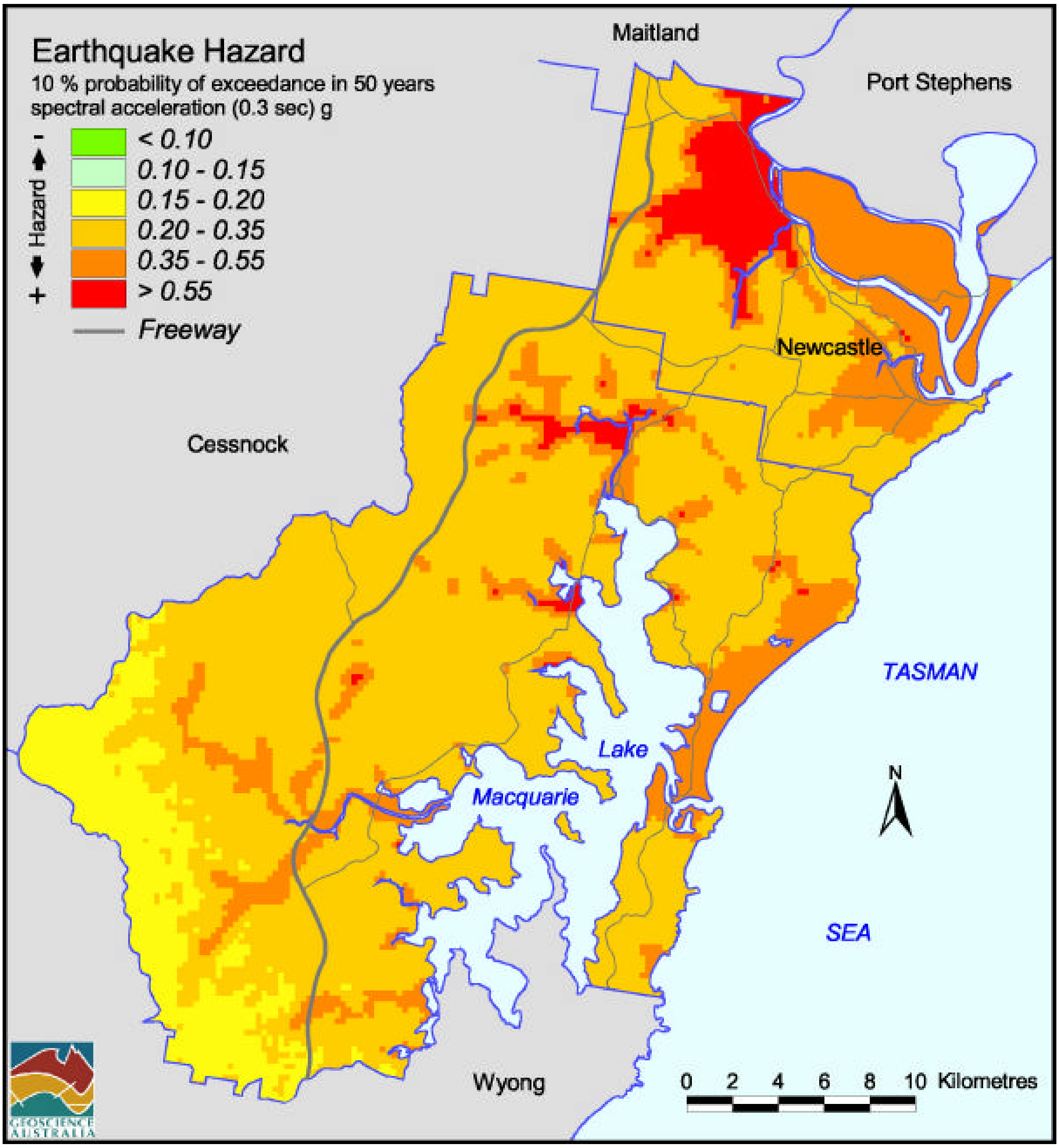

Figure 1.4: Earthquake hazard map on regolith with a 10% chance of being exceeded in 50 years. Hazard is defined by the response of idealised low- to medium-rise buildings with a natural period of 0.3 s. Note that the soils and geological sediments from rivers, streams, wetlands and barrier sands have a greater level of hazard than the weathered rock material which covers the rest of the study region

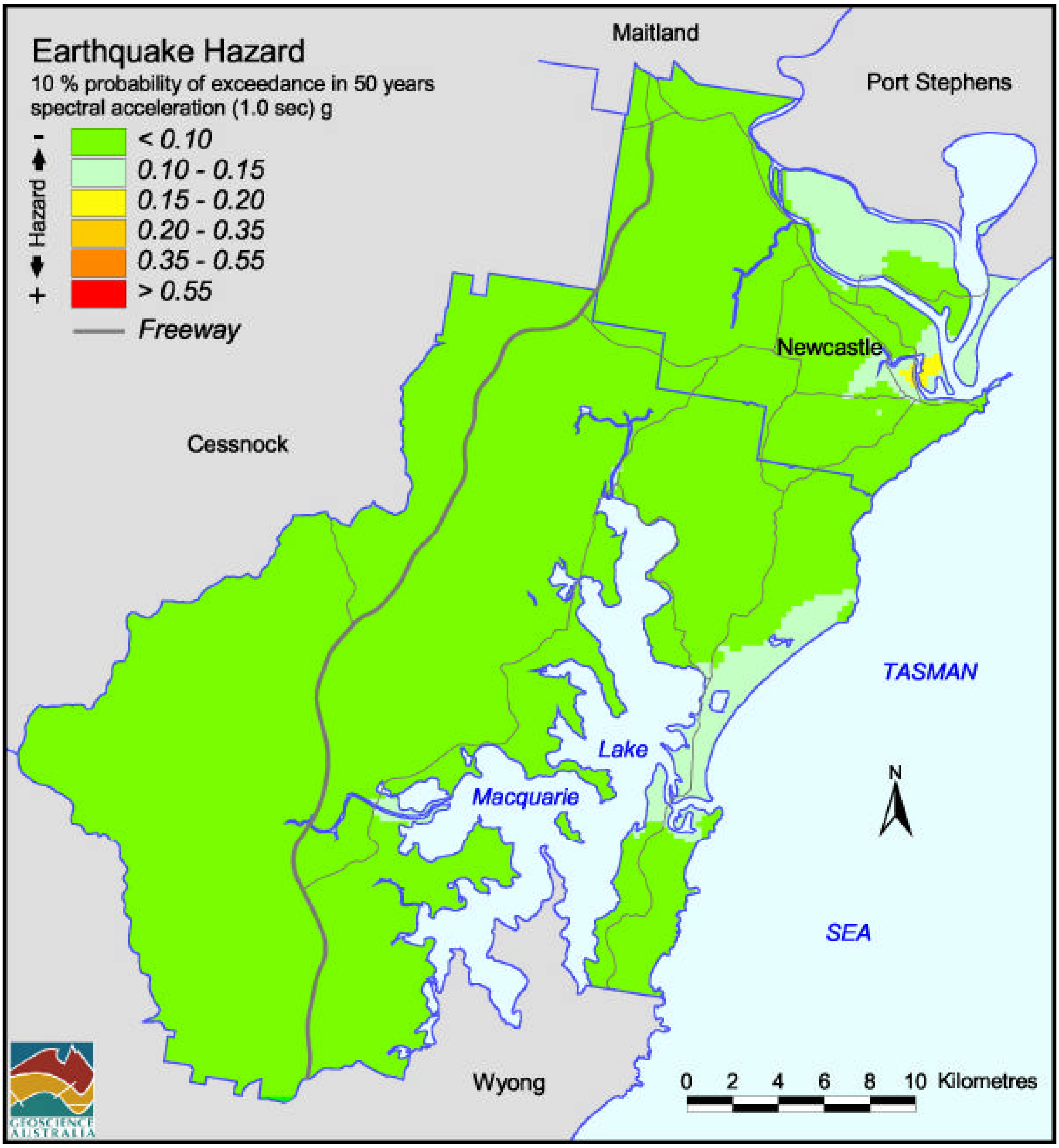

Figure 1.5: Earthquake hazard map on regolith with a 10% chance of being exceeded in 50 years. Hazard is defined by the response of idealised medium- to high-rise buildings with a natural period of 1 s. Note that the highest hazard is associated with the coastal and riverine deposits in the eastern and north-eastern parts of the study region

1.4.2 Earthquake Risk in the Newcastle and Lake Macquarie Region

The earthquake risk to a region can be described in many ways. However, a common expression is in terms of a risk curve (also called a probable maximum loss or PML curve). A risk curve for the study region is presented in Figure 1.6. This curve describes the probability of the study region incurring various minimum levels of economic loss within a single year. Economic loss is expressed as a percentage of the total value of all buildings and their contents in the study region. For example, the Newcastle 1989 event had a simulated loss on the order of 7.2% of the total value of the building stock and associated contents. Locating this point on the risk curve suggests that this level of loss has a probability of about 0.0006 of being exceeded in any single year. This annual probability corresponds to a return period of around 1,500 years for the 1989 Newcastle earthquake, and for other events that would have a similar impact on Newcastle and Lake Macquarie.

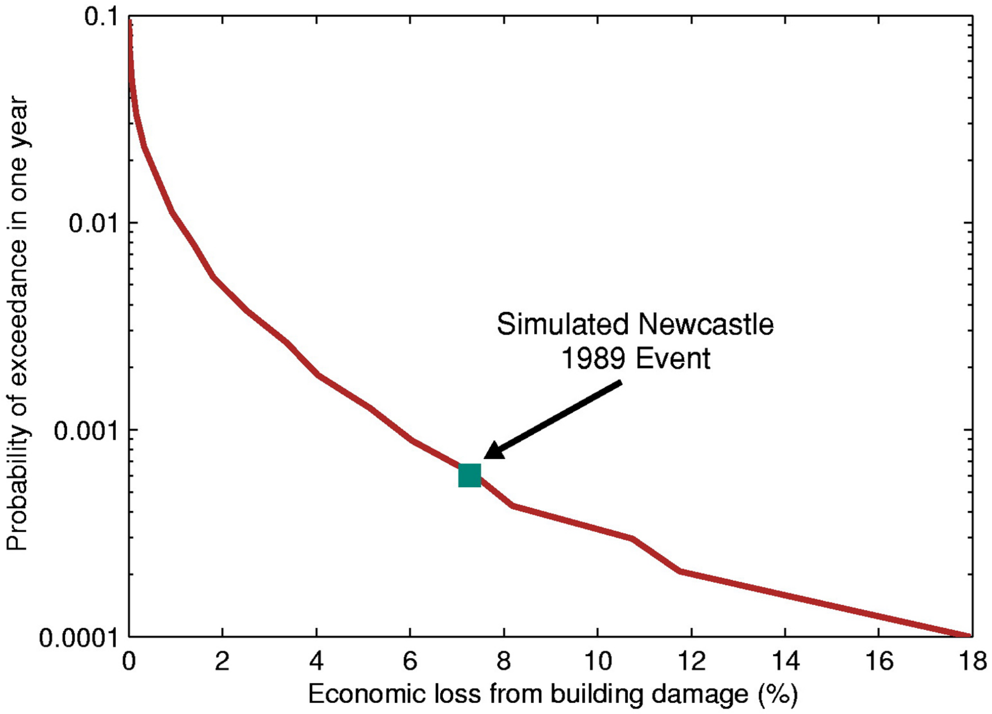

Figure 1.6: Risk curve (probable maximum loss curve) for the Newcastle and Lake Macquarie region. Economic loss is expressed as a percentage of the total value of all buildings and their contents in the study region

The majority of the earthquake risk in the study region is from events that have probabilities of occurrence in the range of 0.02 to 0.001 (return periods of 50 - 1,000 years). This suggests that the risk to the region is primarily from relatively infrequent events with low or moderate impacts. In contrast, very frequent events will have low impacts, and consequently they pose little risk to Newcastle and Lake Macquarie.

Very high impact events can also occur in the region. However, because these events are rare they only contribute relatively small amounts to the annualised risk to Newcastle and Lake Macquarie. For example, events with impacts at least as severe as the Newcastle 1989 event only contribute about 18% of the total annualised risk. These events have return periods of greater than 1,500 years, and their impacts will be greater than 7.2% of the total value of all the building stock, including contents. Note that these events, with return periods greater than 1,500 years, have a greater than 6% probability of occurring in any 100 year period.

The risk curve allows us to obtain an estimate of the annualised risk posed by earthquakes to the study region. The results of this study suggest that, on average, the Newcastle and Lake Macquarie region will suffer an estimated economic loss of around 0.04% per year. This corresponds to an annualised loss of the order of $11 million per year. If we assume a value of $250,000 for an 'average' residential building and its contents, then the annualised loss for this 'average' building and contents is around $100 per year. It should be noted that although this is the annualised loss for the entire study region, the annualised loss varies quite significantly from building type to building type. For example, buildings constructed from unreinforced masonry (cavity brick construction) have a higher annualised loss than any other building type in the study region (Figure 1.7).

However, there are many more timber frame buildings in the study area than unreinforced masonry buildings. Consequently, timber frame buildings make a greater contribution to the total risk in the study region than unreinforced masonry buildings.

Figure 1.8 presents the annualised loss by suburb, and clearly demonstrates that the loss varies spatially across the study region. This variation in loss can be partially attributed to differences in the building stock across the study region. However, the underlying regolith also affects the annualised losses, with areas that are built on substantial thicknesses of regolith, such as parts of the Newcastle municipality, having noticeably higher annualised losses than some other areas.

It is also possible to determine the relative contributions to the risk from earthquakes of different magnitudes at varying distances from the buildings within the study region. Over half the earthquake risk in the study region is due to earthquakes with moment magnitudes around 5 at distances of less than 30 km. This result further suggests that that the majority of the risk in the region can be attributed to moderate-impact, relatively infrequent events rather than high-impact, but extremely rare, events.

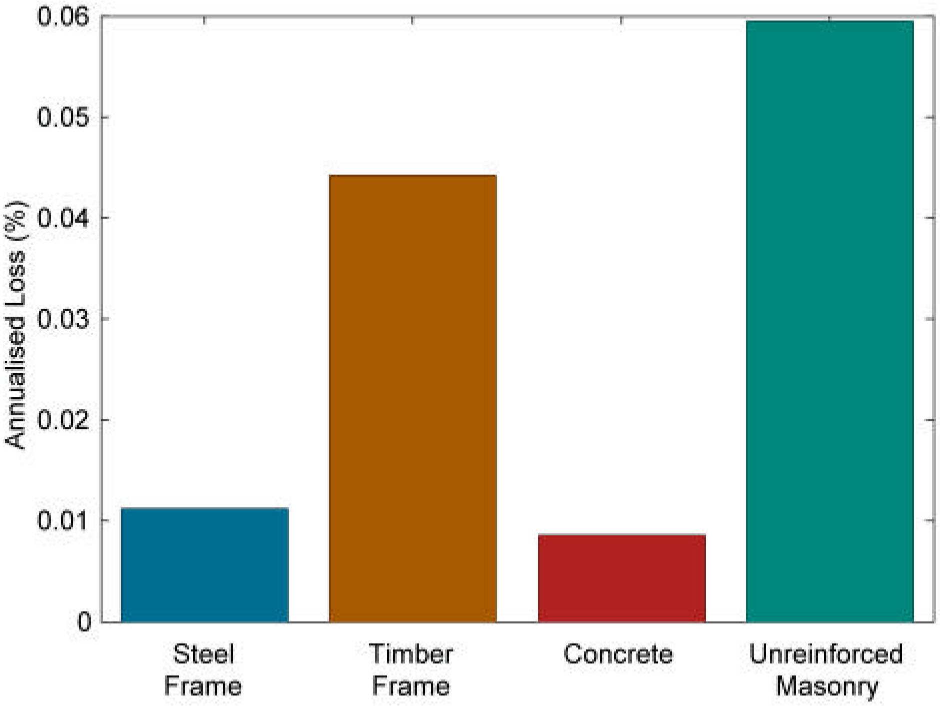

Figure 1.7: Annualised loss for a selection of building types in the study region. The annualised loss for a specific building type is described as a percentage of the total value of that building type and its contents in the study region

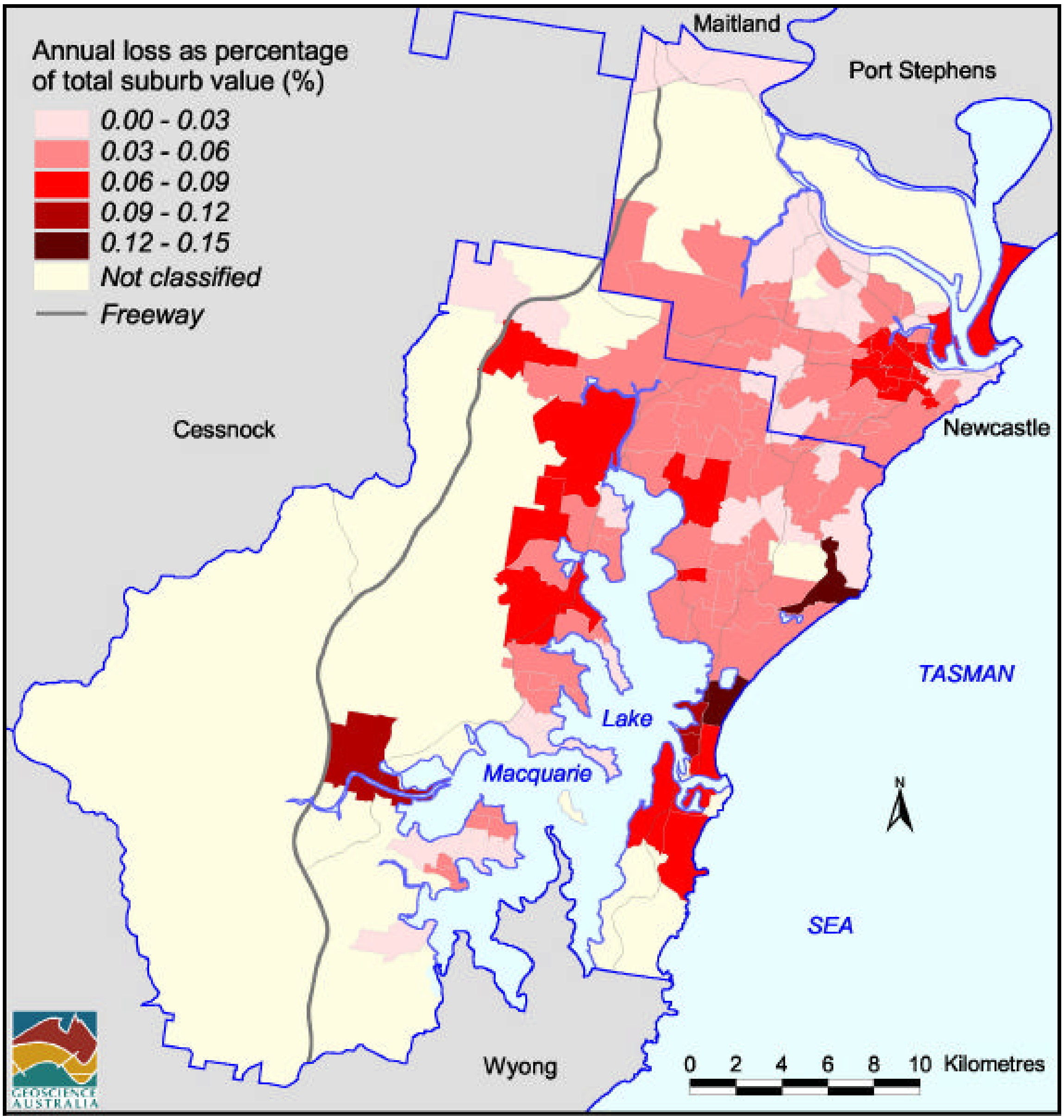

Figure 1.8: Annualised loss by suburb. The annualised loss in each suburb has been calculated as a percentage of the total value of all the buildings and their contents within the suburb. Note that some suburbs have not been classified due to the relatively low number of buildings surveyed

1.5 Summary and Conclusions

The results of our work are dependent upon the accuracy and appropriateness of both the data collected and the models applied in our risk assessment. Further refinement of the models may change some of these results, however, they are a good indicator of the trends and nature of earthquake risk in Newcastle and Lake Macquarie. Our conclusions from this study are:

- The calculated earthquake hazard in the Newcastle and Lake Macquarie region is higher than the hazard suggested by the Australian earthquake loading standard, AS1170.4-1993;
- The regolith in the study region causes a significant increase in the earthquake hazard, and differences in the regolith thickness can cause quite dramatic variations in the hazard and risk across the study region;
- The annualised loss for the study region is of the order of 0.04% or $11 million per year;
- The majority of the annualised earthquake risk in the study region is from events that have annual probabilities of occurrence in the range of 0.02 to 0.001 (return periods of 50 - 1,000 years);

- The risk varies with building construction type, and unreinforced masonry structures have higher average risks per building than other construction types. Brick veneer buildings contribute about half of the total risk. This is partly because they comprise a large proportion of buildings in Newcastle and Lake Macquarie. Timber frame buildings with timber, fibro and other light wall claddings contribute approximately one-quarter of the risk. A further one-sixth of the risk is contributed by unreinforced masonry buildings;
- Damage to residential buildings contributes the vast majority of the risk (approximately 91%). This is largely because residential buildings comprise the vast majority of all buildings in Newcastle and Lake Macquarie;
- The 1989 Newcastle earthquake had an economic impact with a return period of the order of 1,500 years. According to our models, approximately 82% of all annualised risk in Newcastle and Lake Macquarie is due to events with lesser economic impacts than the 1989 earthquake. Thus, events like the 1989 earthquake, or even more catastrophic events, make only a small contribution to the earthquake risk in the region when considered on an annualised basis. However, rare but catastrophic events are very important to emergency managers and the insurance and reinsurance industries;
- Annualised risk varies considerably across Newcastle and Lake Macquarie. It depends on the nature of the underlying regolith, the composition of the building stock and building usage in particular areas. Our results suggest that the suburbs most at risk in Newcastle, determined by a percentage of the total value of buildings and contents in the suburb, are Broadmeadow, Carrington, Hamilton, Hamilton East, Hamilton North, Hamilton South, Islington , Maryville, Stockton, The Junction, Warabrook and Wickham. In Lake Macquarie the suburbs most at risk are Belmont South, Blacksmiths, Caves Beach, Marks Point, Pelican, Swansea and Teralba. Further research into the building parameters for unreinforced masonry construction types may change these conclusions, especially in older suburbs such as Newcastle, Newcastle East, Newcastle West and Cooks Hill. Other Lake Macquarie suburbs such as Cooranbong, Dora Creek, Estelville, Fassifern, Holmesville, Killingworth, Redhead, Toronto and Warners Bay also had high annualised risk in our results, but the results are less reliable because survey rates were low in these suburbs, and the regolith site modelling is inferior to that in Newcastle;
- Over half of the earthquake risk is from moderate-magnitude earthquakes, with moment magnitudes around 5, that occur less than 30 km from the study area. This conclusion has implications for emergency management in the lower Hunter. It may be appropriate to prepare for the possible impacts of such events rather than on catastrophic events that have an extremely small probability of occurring;
- In general, the risk of casualties from earthquakes is low. However, we do not rule out the possibility that casualties in future events could be caused by damage to a single building, or a small number of buildings. It is extremely unlikely that any event capable of causing widespread casualties will occur in the study region;
- The results also have implications for the earthquake risk facing larger Australian cities such as Sydney, Melbourne and Adelaide. This is due to a number of factors, including similarities between the earthquake hazard in Newcastle and Lake Macquarie and other parts of Australia, and similarities between the urban environments, particularly the composition of the building stock;
- The earthquake risk to Newcastle and Lake Macquarie may be reduced gradually over time by improved building construction practices, attrition of vulnerable building stock such as unreinforced masonry, and by reducing vulnerability of existing buildings through renovations constructed to modern code standards;
- Good building practice may be the single, most important, long-term factor in reducing economic losses and casualties from earthquakes in Newcastle and Lake Macquarie.

It should be emphasised that a great deal of variability was included in the models used to generate these results. To some degree this variability was incorporated to account for our lack of knowledge about the various models used in the study. The effect of high levels of variability is to increase the estimates of risk. Future studies on the earthquake risk in the region should focus on improving the models that have been used. This will allow for the variability in the models to be decreased, which will most probably result in a decrease in the estimated risk.

1.6 Suggested Mitigation Options

- Newcastle City Council and Lake Macquarie City Council should consider adopting the site class maps and the associated, period-dependent median amplification factors in their land planning regulations. The amplification factors could replace the site factor S in AS1170.4-1993 in determining earthquake loadings for structures in Newcastle and Lake Macquarie. The amplification factors that refer to a peak ground acceleration on rock of 0.25 g from a magnitude 5.5 earthquake (Table 4-4) are appropriate, for normal structures, for earthquake loadings with a 10% probability of occurrence in 50 years.
- Enforce the compliance of all new structures with current earthquake loading standards. Two important areas where improvements could be made are in ensuring that mortar quality and wall tie placement and specifications comply with code specifications.
- Provide adequate insurance against earthquakes. Householders, small business operators and corporations should ensure that their earthquake insurance is adequate. The cost of repair or replacement of heritage buildings can be significantly higher than the corresponding costs for modern buildings and so there is potential for heritage buildings to be underinsured to a greater extent than other buildings.
- Protect facilities such as police, fire and ambulance stations and hospitals, which provide essential services following any earthquake event. These facilities could be examined by suitably qualified engineers on a site-by-site basis to assess their performance under earthquake loadings. The survey of essential facilities carried out during this study found that many of these facilities were built on regolith site classes that dramatically increased earthquake hazard and/or were of vulnerable construction types.
- Review earthquake loading standards. In this study, certain levels of building damage were estimated as a result of certain levels of ground shaking. The levels of damage may be more or less than what engineers would have expected from the input ground motions. If the damage predicted by the models is higher than would have been expected by expert engineers, then design standards may need to be made more rigorous. The damage models need to be rigorous for this review of design standards to be meaningful.
- Collect future post disaster damage, economic, social and insured loss data in a systematic, pre-planned way with a high degree of detail and accuracy so that risk assessments will be improved and the amount of variability reduced.
- Collect information on building parameters that contribute to vulnerability to earthquakes on a systematic basis and maintain databases containing this information. This need not be a tedious task if it is combined with similar related information gathering as for example through development approval processes. The information may also be useful for other purposes, for example, as estimating the vulnerability of the community to other hazards such as fire and wind, and would be valuable to the insurance industry. This long term strategy would assist risk assessments and risk management in the future.

1.7 Future Directions for Earthquake Risk Assessment

Many improvements and additions can be made to improve the techniques used in this study. Improvement can be made through new scientific, engineering and socio-economic research, by expanding the scope of the risk assessment to capture other sources of risk outside of what has been assessed so far, and by collecting, compiling and assessing new information to assist these initiatives. Chapters 4 and 6 each contain a discussion of the sources of earthquake hazard and risk variability.

Some important measures to improve earthquake risk assessment in Newcastle and Lake Macquarie are suggested below. The list is not comprehensive.

In this study, we have assessed direct economic losses due to building damage. Our study has not addressed the direct losses from business interruption or the indirect losses to other communities resulting from earthquakes in Newcastle and Lake Macquarie. An assessment of these losses would give a more complete estimate of the total risk due to earthquakes in Newcastle and Lake Macquarie.

The importance of the impacts of earthquakes on ‘lifelines’ such as electric power and water supply needs to be investigated. In Chapter 5, a preliminary analysis was undertaken of the exposure of sewer and water facilities due to their location on the various regolith site classes. Further investigation is required to assess the risk to lifelines in Newcastle and Lake Macquarie. This investigation needs to address the impact that earthquakes could have on lifeline function, as well as the consequent impact on the broader community due to impaired lifeline functioning.

The socio-economic implications of earthquake impacts on Newcastle and Lake Macquarie also need to be assessed. In the first instance, the simplest socio-economic vulnerability models would relate structural damage to the impact on all community activities and the time taken to restore the community to its normal state. Geoscience Australia has assembled some relevant information that could assist such investigations in future, and is working to develop socio-economic loss models for natural hazards.

The methodology used in the modelling approach is a significant improvement over previously published earthquake risk assessment models applied to Australia. However, Geoscience Australia's model will benefit from further validation, which will need to be carried out with the support and cooperation of others.

The engineering vulnerability models need to be checked, modified and produced as necessary to make them appropriate for Australian building stock. This requires a long-term, engineering research effort. Models for some construction types including timber frame buildings were developed by GA and structural engineering experts based on Australian design and construction practice were used in this study. Models for other building types such as some steel frame buildings have been adopted without alteration from US models. The efforts to improve the models should concentrate on the construction types that are the most important contributors to risk, as they have done so far. For Newcastle and Lake Macquarie, these are timber frame structures (especially brick veneer structures) and unreinforced masonry structures. Details such as tile or steel roof, masonry gable ends, parapets and chimneys, number of storeys in low rise buildings, soft storey, are important components of the vulnerability models. Other structural types may be important because, even though they are relatively few in number in the study area, such buildings may be classified as 'important' buildings or house essential services. Concrete frame buildings are one example of such building construction types.

Part of the assessment process for the building vulnerability models is to examine the degrees of structural, non-structural and contents damage, and economic losses, that are predicted by the models for certain levels of input ground shaking. The vulnerability and economic loss models need to be further reviewed by the structural engineering community to improve confidence in the results produced by them. For example, upon further analysis, the results of our modelling may show that significant simulated economic losses are due to acceleration effects rather than lateral displacements. These outcomes should be compared with the expectations of the structural engineering community and the model parameters adjusted if necessary.

The degree of damage and economic loss predicted by the models can be used to assess the appropriateness of earthquake loading standard specifications. For example, is the economic loss predicted by ground shaking with a 10% probability of occurrence in 50 years acceptable to the loading committee, the insurance and construction industries, and to government?

Sensitivity tests should be run by varying parameter values in the models to give alternative estimates of risk. The results may point to areas where efforts should be made to improve the models or collect new data. Reduced variability in the models will lead to more accurate and reliable estimates of risk.

Assessments of future risk based on projections of changes in building stock and demographics would be valuable to the assist decisions on the development of Newcastle and Lake Macquarie. A cost/benefit analysis of the effectiveness of introducing various mitigation measures would also assist the rational development of the cities. Assessments of future risk, and cost/benefit analyses, would be aided by masonry vulnerability models that accounted for building condition.

1.8 Final Remarks

Geoscience Australia is actively developing new techniques and revising its methodologies. Other workers in planning, emergency management, engineering, the insurance industry, the utility corporations, sociology and the finance industry are also putting increasing efforts into risk management for natural hazards including earthquakes. It is our hope that this study will assist these workers, the people of Newcastle and Lake Macquarie, and the broader Australian community, in reducing earthquake risk.

As a final note it should be remembered that, in the aftermath of the 1989 earthquake, there were many studies and recommendations on what should be done to mitigate the effects of future earthquakes. However, thirteen years on, few of the recommendations have been implemented. We urge the relevant authorities to review the recommendations made in this report and previous reports such as that conducted by the Institution of Engineers (Melchers, 1990) and to take appropriate action, so that ultimately we will have safer and more prosperous communities.

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We are grateful to Newcastle City Council for its continued support and encouragement over the course of the project that led to this report. The project was conducted over four years. In this time, two Lord Mayors held office, Cr Greg Heys and Cr John Tate, both of whom personally supported this project. Council officers provided many valuable datasets and other information to the project. These included damage datasets and NRMA Insurance records for the 1989 earthquake, datasets on roads, cadastre, drainage, aerial photographs, and many more. We thank Lynn Gray for his close association with the project. Lynn was influential in providing Council office accommodation for Geoscience Australia staff member David Stewart in Newcastle. Lynn was the Council's point of contact with the project. We are grateful for the advice, guidance, provision of data and keen interest in the project provided by Council officers Col Sandeman and Bob Boyce. We thank Newcastle Regional Museum directors Gavin Fry and, before him, Patrick Filmer-Sankey for their support, especially in relation to the 'Earthquake!' exhibition at the museum.

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