

# MITIGATION OF EARTHQUAKE RISK TO BUILDINGS AND INFRASTRUCTURE

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## ABSTRACT:

The GEOSCIENCE AUSTRALIA Project examining earthquake risk to the cities of Newcastle and Lake Macquarie has demonstrated that building practise does not follow required specification even when the 1989 experience has clearly shown the weakness inherent in certain traditional forms, and that buildings housing public safety facilities such as fire, ambulance and police stations are vulnerable to a degree which can put the community at greater risk than would be tolerable. This paper describes the background to the conclusions of the AGSO Report and raises into question the unsafe margin in accepted risk by communities.

## 1. INTRODUCTION

In September 2001, AGSO – Geoscience Australia issued an Interim report of work it is carrying out on earthquake risk to communities in the Cities of Newcastle and Lake Macquarie (Stewart, et al. 2001). The technical work is presented in several papers to this conference. The GEOSCIENCE AUSTRALIA Interim Report concluded that though doing nothing or insuring were feasible strategies for domestic buildings in Australia, two alternative mitigation strategies are available and could be adopted by individuals and organisations, are suggested:

- ensure the code compliance of all new structures; and,
- protect essential facilities such as hospitals, schools and emergency units by housing them in structures with low vulnerability.

These simple conclusions are very similar in essence to the conclusions of the IEAust 1990 Report (Melchers 1990). They would, if adopted nationally, have implications for technical training, trade practise and construction supervision of infrastructure and buildings in Australian cities, and for the management of many public buildings. This paper elaborates on these conclusions, giving some background to support their inclusion in the GEOSCIENCE AUSTRALIA Interim Report.

## 2. HISTORICAL RECORD OF THE 1989 EARTHQUAKE

Following the 1989 Newcastle Earthquake a considerable body of descriptive and interpretative material was prepared by a wide group of writers, investigators and professionals. Some of the primary documents which record response at the time are:

- 1) "The Unexpected Catastrophe (1989) This excellent compilation holds written, visual and audio material collected by the Newcastle City Library with assistance from an INDNDR grant, and collated and edited by Ajita Lewis of the library.
- 2) "Newcastle Earthquake Study", (Melchers 1990) The Institution of Engineers, Australia, recognising that valuable evidence of how buildings in Australia react under earthquake stress would soon be lost as restoration work commenced, took the lead in commissioning this remarkable document which was produced only months after the event and which contains powerful and pertinent recommendations. The Institution approached the NSW Government who engaged the CSIRO and the University of Newcastle to undertake this study.
- 3) "A Report on Earthquake Zonation Mapping of the City of Newcastle for Newcastle City Council", (CERA 1995). This study was fully funded by the Council of the City of Newcastle, and was compiled by Dr Jack Rynn, then of the University of Queensland. The report has been considered by Council and its staff but has not been made available publicly.
- 4) "The earth was raised up in waves like the sea... (Hunter 1991). This book has researched written records of the time and presents an historical survey by Cynthia Hunter of the experience of earthquakes in the Hunter region over the last two hundred years. It records events back to 1801 in the Hunter Region.
- 5) "Factors Influencing the Structural behaviour of Residential Buildings in Newcastle Following the December 1989 Earthquake", (Irwin Johnston and Partners NSW Pty Ltd 1991). The Insurance Council of Australia and GIO

commissioned this report to examine the factors affecting damage to small buildings, both at the time and in the period following the earthquake.

- 6) "Damage and Repair of Public Buildings" (NSW PWD 1992). This valuable report records inspections of over 1000 public buildings and the repair of over 600 State Government buildings.
- 7) Proceedings of the annual seminars of the Australian Earthquake Engineering Society (AEES) (Samali and Butler 1999; Gregson, et al. 1998; Cuthbertson, et al. 1997; Griffith and Butler 1996; McCue 1994; Wilson, et al. 1993; McCue and Hince 1992), etc.

### 3. RISK AND ACCEPTABILITY

The quasi-mathematical risk function adopted in the GEOSCIENCE AUSTRALIA Interim Report states that risk is a function of the hazard, the elements at risk, and their vulnerability to that hazard. In a paper to the 1999 AEES Conference Stewart (Stewart 1999) postulated that this Risk Function should be expanded to include "Acceptability" as a variable. This was argued against from the floor and the proposition has not been substantiated, and yet, two years on, the concept of another dimension to risk hovers still. The analysis of risk from earthquake in Newcastle, which suffered so disastrously in 1989, leaves open the issue of some other factor in risk assessment.

The recommendations of the I.E.Aust. Report (Melchers 1990), which included reference to the fragility of unreinforced masonry as a structural material, the consequences of damage to High Voltage ceramic insulators and the need to protect public safety facilities, are well known in Newcastle building and technical circles but are flagrantly disregarded or are ignored. How well known and how much are they ignored in the wider Australian practice? The following points which are substantiated by documentation or the authors' observations illustrate the dichotomy between experience and the various professions' learned responses.

#### *Some illustrative incidents from the 1989 Newcastle Earthquake:*

- The Junction Primary School suffered extensive collapse of the outer skin of a cavity brick wall onto an area which would be occupied by children for much of any school day. The public response to death or serious injury of school children would be significant.
- The collapsed section of the Newcastle Workers Club would have held many times the number of people several hours later in the day.
- The exit driveway from the Hamilton Ambulance Station which provided emergency service to casualties at the Worker's Club was partially blocked by collapsed brickwork which chance could have rendered impassable, affecting rescue.
- The Hamilton Telephone Exchange suffered severe shaking and structural damage, with much equipment dislodged from alignment. Inspection left those responsible in wonder that no failure in telecommunications occurred.
- Failure of HV insulators at the Killingworth Sub-station resulted in loss of power for two and a half hours. Several more hours of outage would have resulted in setting in the potlines at Tomago Aluminium with a direct financial cost of several hundred million dollars and indirect costs far greater.



*Some observations of current attitudes and practise:*

- Face-fixing of wall ties in brick veneer construction is relatively common; Australian practise allows nailed face-fixing which has negligible resistance to earthquake load cycles. The New Zealand requirement for screw face-fixing is resisted by agencies and the trades.
- Mortar for brick work is usually site mixed using imprecise measuring equipment. The practise of incorporating workability additives which reduce durability is again widespread after a period of strict observance to codes following the 1989 earthquake. These result in mortar not conforming to specification and clearly weaker than required.
- Where alterations are made to an existing structure the present Code AS 1170.4 - 1993 (AS1170.4 1993) only requires that resistance to earthquake forces is not less than that before alterations are made (with certain other qualifications). Much of the existing commercial building stock remains in use and its structure is changed over time to accommodate new or refitted uses. Under this policy incompetent structures will remain in use for many years even though extensive modifications are made over time. The requirements for good design practise are not supported by a policy which tolerates incompetent work on existing structures.
- The refurbishment and upgrading of existing buildings is sometimes extensive and occurs without competent and independent supervision or inspection. The present practise allows considerable shedding of responsibility to the building owner, whether or not that person understands the responsibility accepted, and in spite of exposure of the public to consequent risk.

These anecdotes are not presented as statistical arguments but as illustration that the thread termed "Factor of Safety" was very thin for much of the infrastructure subject to the 1989 earthquake and is not necessarily any stronger under present building practise.

#### **4. SELECTED RECOMMENDATIONS OF THE 1990 I.E.AUST. REPORT**

At this point it is worth examining selected conclusions from the I.E.Aust Report (Melchers 1990). The following extracts are stated in their near full form as they appropriately state the first response of experts following the 1989 earthquake.

##### *Minimum Earthquake Design Requirements For Australia - Existing Buildings*

"R4.2 It is considered that in general upgrading of existing buildings, structures and facilities in Newcastle for earthquake resistance is not justified. However, upgrading should be evaluated for; buildings which have suspended awnings or parapets or other projections likely to be dangerous to the public under earthquake conditions; buildings, structures and facilities having a possible post-disaster or lifeline function (eg. Hospitals, fire-stations etc.); buildings and places of public assembly and where significant loss of life may be incurred in an earthquake event; and buildings and structures containing or supporting hazardous materials or processes.

R7.1 The powers of Local Councils to enforce compliance with structural safety requirements ... should be improved. This applies in particular to situations where public safety is considered by Council to be at risk. ....

R7.2 Structural safety approvals, inspection, supervision, and certification should be carried out by engineers appropriately qualified and experienced as defined by the relevant professional body (ie. The Institution of Engineers. Australia).

R7.3 Consideration should be given to establishment of a national register of structural engineers complying with requirements under R7.2. The register should be recognised at all levels of government.”

#### *Quality In Design And Construction*

“C8 There is inadequate understanding at most levels in the building industry of the need to achieve high quality of construction. There is also inadequate appreciation at the unskilled and skilled trade level of the rationale for specific practices prescribed in building specifications. The problem appears to be particularly acute in relation to masonry construction, but is also of importance in concrete construction.

R8.1 The requirements of current Masonry Codes should be observed at all levels in the building industry for all forms of masonry.

R8.2 Trade courses in masonry construction should be mandatory for bricklayers. Such courses should consider basic structural engineering aspects associated with masonry construction.

R8.4 Undergraduate programs in civil and in structural engineering should be encouraged to consider earthquake engineering, masonry construction, and quality management in their syllabi.

C9 Risk management for buildings may be uneven across building jurisdictions due to different policies, procedures and practices. This applies state-wide and nationally to building approvals, structural design, inspection and supervision and control of risk after construction. It is recommended that the Building Regulation Review Task Force take note of this matter.

R10 All architects and engineers (of all disciplines) should be made aware that the need to design for earthquakes also applies to mechanical, electrical and other equipment.”

Most of these recommendations are as applicable today as they were in 1990 and have been reinforced by the AGSO Newcastle project. How are the professions to respond to this?

## **5. THE BUILDING STOCK OLD AND NEW**

#### *Variation of Vulnerability*

Building stock vulnerability is not a stationary process, but is highly time-dependent. It is influenced, for new stock, by improved construction and code enforcement, and for existing stock by deterioration, upgrading and refurbishment. There is one theory (body of opinion) that in the inner zone of Newcastle where much damage occurred in 1989 the building stock is weaker than before the earthquake. This view assumes that structures were subject to repetitive loaded cycles, close to failure state for many, and that cracking and loss of load-path coherence will have occurred to some which were not notably damaged. There is another opinion that the building stock is stronger than before, because the weakest structures have either collapsed or have been strengthened.

The first theory (opinion) is conservative, the second accepts an unspecified risk. What is the situation in the several very large and old cities in Australia?

#### *Strengthening Existing Buildings*

A code for the strengthening of buildings was issued in 1998, AS 3826 – 1998 (AS3826 1998) but has no status in regulation nor in the Building Code of Australia. This provides comprehensive detail on means of strengthening typical small to medium buildings found in temperate Australia to resist earthquake forces. The code was developed from the

extensive work done in Newcastle following 1989 to repair small buildings and bring them back to use.

#### *Newcastle Council's Hazard Mitigation Program*

Following 1989 Newcastle City Council held a database of buildings which had been inspected for possible damage from the earthquake. Some of these were deemed to be structurally unsound and a process of liaison with owners, inspections and consultation was set up to resolve the potential hazard. The responsibility for action was uncertain and the climate of recovery from disaster and economic hardship required sensitivity by the authorities. Newcastle City Council has done this admirably and a large number of these buildings have been restored to use, with application of the strengthening code, or are in the process of repair. Only a small number of buildings remain classified as "high risk". Newcastle has made an attempt to upgrade building resilience to earthquake loads. What is the risk in other Australian cities?

#### *Buildings of High Public Sensitivity and Potentially High Exposure*

The GEOSCIENCE AUSTRALIA Interim Report (Stewart 1999) included surveys of buildings across the two municipalities. Almost all public safety buildings (fire, ambulance and police facilities) were identified and details of their vulnerability recorded. Many of these were identified as a vulnerable form of construction, or were located in areas of high ground-shaking susceptibility. Their proportionally high rate of vulnerability is explained by their age (many are very old, cavity brick structures) or by the use of features such as gables or long span roofs which may be inadequately anchored to brick walls. This finding reinforces the need to survey and where necessary strengthen this category of building.

#### *Building Compliance*

Though local government in NSW (and possibly in other jurisdictions) does now have power to enforce compliance, there can be an unwillingness to use this power for reasons of politic and community attitude. Responsibility is too easily shed by a deeming attitude which leaves the ultimate owner and the third party public accepting liability.

#### *Building Details*

Several building details in common practise have been identified as out of enforceable specifications and leading to incompetent structural resistance to earthquake loads, as follows:

Timber framing – nail sequences for timber connections and bracing are often deficient in number of nails and incompetently applied shear panels.

Masonry – face fixed ties are often used because timber shear panels are designed; these are nailed, but a screw fixing would give adequate resistance to earthquake loads.

Masonry – clay and plasticisers are added to make mortar more workable, leading to weak masonry and lack of resistance in the long term.

#### *Mechanical & Electrical Equipment*

Electrical Insulators – these are rigid, brittle and vulnerable. They are critical elements in the response stage of many natural disasters including earthquake.

Machinery isolation – even following the 1989 earthquake, standby generators at a major Newcastle Hospital had not been restrained onto foundations leading to potential failure under earthquake loads.

## 6. CONCLUSIONS

Following the 1989 Newcastle earthquake engineering expertise and judgement produced a set of recommendations to reduce public exposure to damage and casualty from earthquake. Some recommendations have been adopted and are effective, others are stipulated but are ignored in practise, whilst several have not been addressed. The GEOSCIENCE AUSTRALIA Newcastle Interim Report has reinforced the validity of most of these recommendations. Building practise should be improved for existing as well as for new structures, and public safety facilities should be examined and where needed reinforced.

The spread of response to the 1990 recommendations demonstrates a concept of risk which does not conform to the straightforward expression given in Section 3. Is there another variable reflecting acceptance of risk before an event which is not tolerable after the event, or is it too great an ignorance? Are the professions implicated in this ignorance?

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# EARTHQUAKE VULNERABILITY IN THE NEWCASTLE REGION

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## ABSTRACT:

As part of the AGSO – Geoscience Australia Risk Modelling Project for the cities of Newcastle and Lake Macquarie, a comprehensive investigation of the earthquake vulnerability of buildings has been undertaken. This has included an innovative field survey and the development of appropriate building vulnerability damage-loss curves. The field survey undertaken has resulted in a statistical representation of the study area's building inventory, with details that define vulnerability, including construction age, size and type. The survey results presented here have been used to classify structures into building categories that have similar earthquake performance characteristics. Building vulnerability loss curves have been generated for these building classes using the "Capacity Spectrum Method" based on building parameters that describe earthquake performance as determined by a panel of experts. Some of these curves are presented, with the implications of performance differences discussed.



## 1. INTRODUCTION

AGSO – Geoscience Australia is committed to investigating and evaluating the risks posed by natural hazards to Australian urban communities. As part of this process, the Risk Modelling Project is involved in developing the methodology required to do this. This paper addresses the vulnerability of buildings to earthquakes.

A number of methods are available for predicting the performance of buildings when subject to earthquake shaking. The most basic method employs the use of the Modified Mercalli scale of Intensity (MMI) (Dowrick 1996). In this method, MMI is typically related to an average insurance percentage loss as shown in Figure 1, based on the experience of real events and expert opinion. Variations of this method, while useful, vary significantly, estimate ground shaking by structural performance (not vice versa), and do not relate structural performance characteristics such as the natural period of vibration and structural ductility to the building vulnerability. The methods generally do not consider structural, non-structural and contents losses separately. Also, there is a lot of uncertainty due to the lack of well-defined ground motion attenuation relationships and soil amplification factors in terms of MMI. Hence, we have chosen to adopt a method which addresses these issues more effectively. The method we have adopted is based on the 'Capacity Spectrum Method' (CSM) as employed in the 'HAZUS' earthquake loss estimation software (National Institute of Building Sciences 1999).

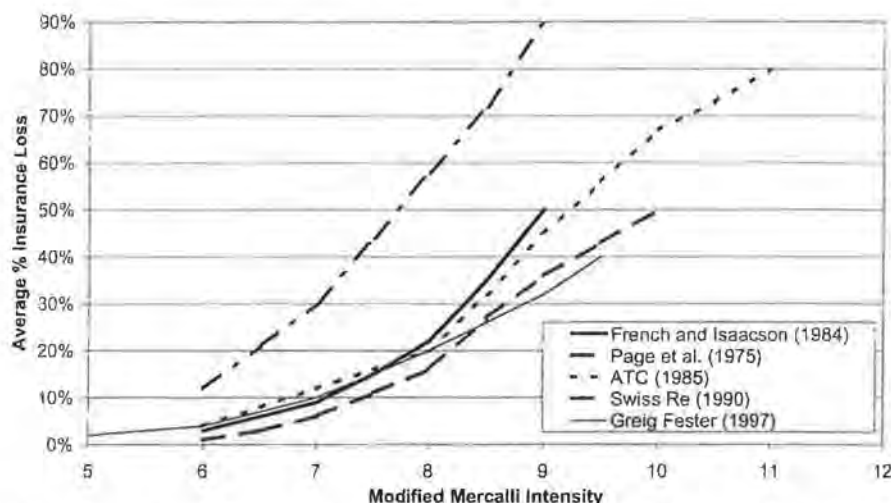


Figure 1: Insurance loss curves for brick construction (adapted from Greig Fester 1993 and 1997). The Greig Fester (1997) curve is based on data from the 1989 Newcastle earthquake. The other curves come from overseas sources (ATC-13, 1985; French and Isaacson, 1984; Page et al., 1975; Swiss Re, 1990).

## 2. THE CAPACITY SPECTRUM METHOD

The CSM considers the structural characteristics of a building through a nonlinear capacity curve, and the ground motion characteristics by way of an elastic response spectrum as shown in Figure 2. To account for the inelastic damping that occurs as a building becomes damaged (yields) and absorbs energy, the elastic spectrum is reduced

to the inelastic spectrum. Where the inelastic spectrum coincides with the capacity curve, the response displacement ( $S_d$ ) of the structure is thus found.

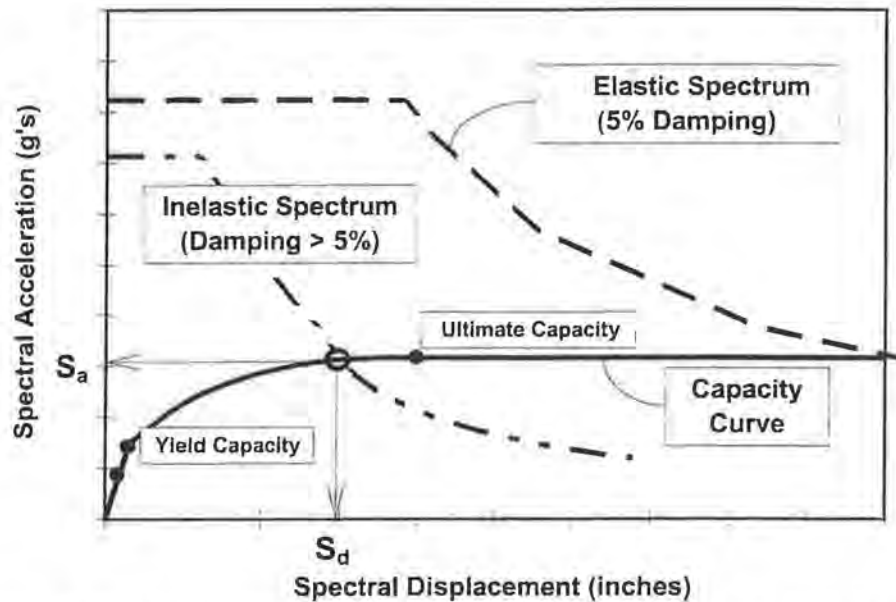


Figure 2: The Capacity Spectrum Method (adapted from HAZUS, 1999)

The value of  $S_d$  is then used to determine the probabilistic structural damage state (ie. complete, extensive, moderate or slight damage), which then in turn implies the economic loss and casualty probability. Contents damage is determined via consideration of the peak ground acceleration (PGA), and non-structural damage is determined via consideration of both  $S_d$  and PGA.

Further details of the method are given elsewhere (HAZUS, 1999). However, it should be noted that the elastic response spectrum varies depending on the expected ground motion. Also, the capacity curve and demand spectrum are constructed based on the following parameters:

- $C_s$  - design strength coefficient (fraction of building's weight),
- $T_e$  - true "elastic" fundamental-mode period of building (seconds),
- $\alpha_1$  - fraction of building weight effective in push-over mode,
- $\alpha_2$  - fraction of building height at location of push-over mode displacement,
- $\gamma$  - "overstrength" factor relating "true" yield strength to design strength,
- $\lambda$  - "overstrength" factor relating ultimate strength to yield strength,
- $\mu$  - "ductility" factor relating ultimate displacement to  $\lambda$  times the yield displacement (ie., assumed point of significant yielding of the structure),
- $B_e$  - elastic damping ratio,
- $\kappa$  - equivalent viscous damping modifier.

Although the Capacity Spectrum Method is believed to be better than most MMI approaches, some work (ATC-40, 1996; Chopra and Goel, 1999; Stehle et al., 2001) has suggested that the method has some deficiencies in predicting the structural inelastic dynamic response when compared to more accurate time-history analysis techniques.

However, the results obtained using the method appear to be adequate (see Section 6) for the time being until further work is performed.

### 3. AUSTRALIAN RESPONSE SPECTRA AND BUILDING VULNERABILITY PARAMETERS

For use of the CSM in Australian case studies, suitable response spectra and building vulnerability parameters have been developed. Response spectra have been developed for a range of site classes in the Newcastle region using ground acceleration records representative of Australian conditions (see companion paper by Dhu et al.).

Building vulnerability parameters have been determined via a panel of experts for unreinforced masonry, timber frame and reinforced concrete frame buildings (Stehle et al., 2001). These building types make up a significant proportion of Australian building stock. Parameters for other building types have been based upon default HAZUS values (HAZUS, 1999).

### 4. DAMAGE LOSS CURVES

A suite of damage loss curves has been generated for a wide range of building structural and usage types, for different site classes (C to G) within the Newcastle region (Stewart et al., 2001). Example curves for a residential unreinforced masonry building are shown in Figure 3.

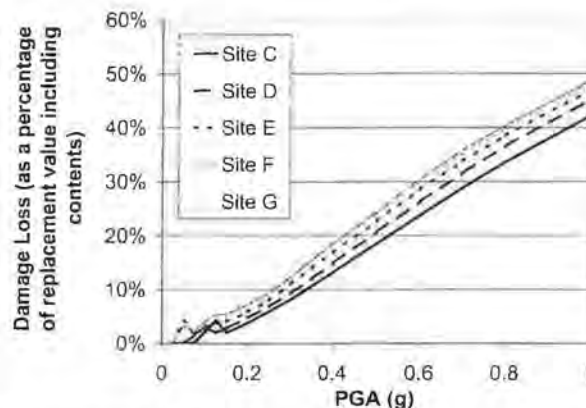


Figure 3: Damage loss curves for a residential unreinforced masonry building

### 5. BUILDING INVENTORY

A footpath survey of the study region was conducted to determine the building inventory. A sample rate of approximately 1 in 10 was adopted for most of Newcastle and coarser rates were used for the rest of the study region. The survey was conducted using GPS receivers to record building locations. Building details such as wall, roof and foundation materials, dimensions, age and usage were recorded on palmtop computers. For example, the distribution of buildings, according to external wall type, is shown in Figure 4. A digital image of the building was taken for each site and linked to the data for verification purposes. The surveyed building details were used to categorise the structural types of the buildings. Further details are given by Stewart et al. (2001).



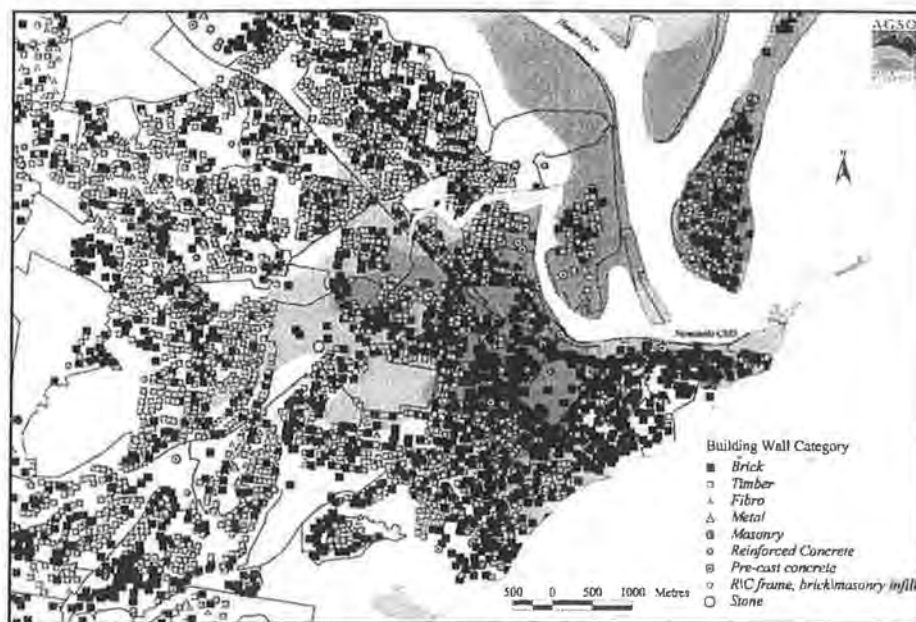


Figure 4: Distribution of buildings in the Newcastle area according to wall type

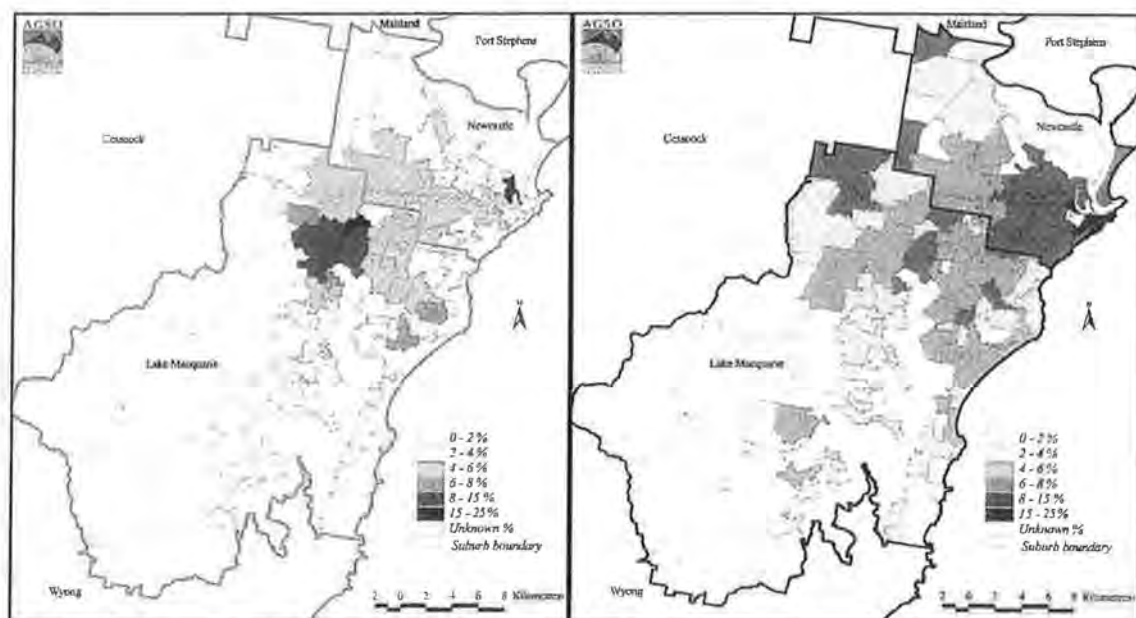


Figure 5: 1989 Damage loss by suburb – modelled (left) versus NRMA figures (right)

## 6. COMPARISON WITH THE 1989 NEWCASTLE EARTHQUAKE IMPACT

The impact of the 1989 Newcastle earthquake has been simulated using the vulnerability modelling methodology presented here. The earthquake source parameters and attenuation characteristics are discussed in the companion paper by Sinadinovski et al. (2001). The damage loss ratios by suburb are shown in Figure 5 and there is a reasonable correlation between synthesised and insurance figures. Aggregate results match well - \$775 million (synthesised) compared to \$862 million (actual). A detailed comparison of the modelled and recorded impacts is presented by Stewart et al. (2001).

## 7. CONCLUSIONS

The vulnerability of buildings in the cities of Newcastle and Lake Macquarie has been modelled using the Capacity Spectrum Method and inventory data obtained by a footpath sample survey. Verification of the method using observations of damage from the 1989 Newcastle earthquake gives confidence to adopting the approach in a comprehensive risk assessment, as is presented in the companion paper by Schneider et al. (2001). However, further model development is required and the uncertainties need to be addressed in a comprehensive fashion.

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# EARTHQUAKE HAZARD IN THE NEWCASTLE REGION – SITE AMPLIFICATION

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**John Schneider** is the Research Group Leader for Geohazards and Risk at AGSO - Geoscience Australia. John's primary research interests are in the development of natural hazards risk assessment methods for application to urban centres, with a particular emphasis on earthquake hazards.

## ABSTRACT:

Variations in the amount and type of alluvium present in a region can cause earthquake ground shaking to be significantly amplified, hence causing dramatic variations in the localised earthquake hazard. The Newcastle and Lake Macquarie region has been divided into five site classes in order to capture this variability. Geotechnical data from cone penetrometer logs, microtremor data and published material were combined to create detailed geotechnical models for each of the site classes. Period dependent amplification factors, calculated using one-dimensional equivalent linear modelling, demonstrated that all of the classes containing alluvium had maximum amplification factors between 2.5 and 4.0. A comparison of the calculated amplification factors with those in the current and draft earthquake loading standards demonstrated significant differences between the factors. Amplification peaks at resonant periods are not reflected in either the current or the draft standards, and the draft standard tends to be conservative at periods greater than approximately 0.75 s.



## 1. INTRODUCTION

AGSO – Geoscience Australia has a key role is to analyse the risk posed by natural hazards to urban communities. As part of this work, a comprehensive analysis has been undertaken to evaluate the earthquake risk in Newcastle and Lake Macquarie. As part of this analysis, a detailed study of local geological and geotechnical conditions has been used to create site class models for the region. These models have then been used to calculate period dependent amplification factors for the region. Due to the level of detail in this modelling, the site factors proposed here are thought to be more suitable for the Newcastle and Lake Macquarie regions than the factors proposed in either the current or the draft earthquake loading standards.

## 2. SITE CLASSES

The geology of the Newcastle and Lake Macquarie municipalities comprises minor basins of Quaternary sediments, deposited during the last 20 thousand years, overlying bedrock that was deposited over 200 million years ago. The bedrock consists of sedimentary rocks of the Sydney Basin, including the coal horizons of the Newcastle Coal Measures. The Quaternary sediments were laid down in a marine influenced environment, with estuarine muds and tidal delta sands comprising the most dominant depositional systems (Roy et al., 1995).

The study area was divided into five site classes in order to capture the spatial variability of the region's geology, specifically:

Class C (Weathered Bedrock), defined as 20 m of weathered bedrock overlying strong rock. This class has been defined as typical of regions lacking Quaternary sediments;

Class D (Thin Clay/Silt), defined as 12 m of clays and silts overlying the weathered bedrock model of class C;

Class E (Thin Sand/Clay/Silt), comprising 4 m of sand overlying 8 m of clays and silts. As with class D, these sediments are overlying the weathered bedrock model;

Class F (Intermediate Sand/Clay/Silt), a thicker version of class E, consisting of 10 m of sand overlying 12 m of silts and clays, and;

Class G (Intermediate Sand), defined as 30 m of barrier sands overlying the weathered bedrock model.

Figure 1 presents cross sections of the geotechnical models used for each of the site classes. The geotechnical models for site classes D, E and F were determined primarily from cone penetrometer test (CPT) data collected by the University of Newcastle. These data were only available from within the Newcastle region (Figure 2). Consequently, these site classes were defined in the Newcastle region and then extrapolated to the remainder of the study area (Figure 2). Site class G was defined on the basis of engineering borehole data published by Douglas (1995) as well as microtremor data collected by Geoscience Australia in an extensive field survey. Site class C was defined primarily from expert opinion of staff from the NSW Department of Public Works and Services, who referred to weathering profiles of a similar thickness in nearby parts of the state (NSW Department of Public Works and Services, 1998).

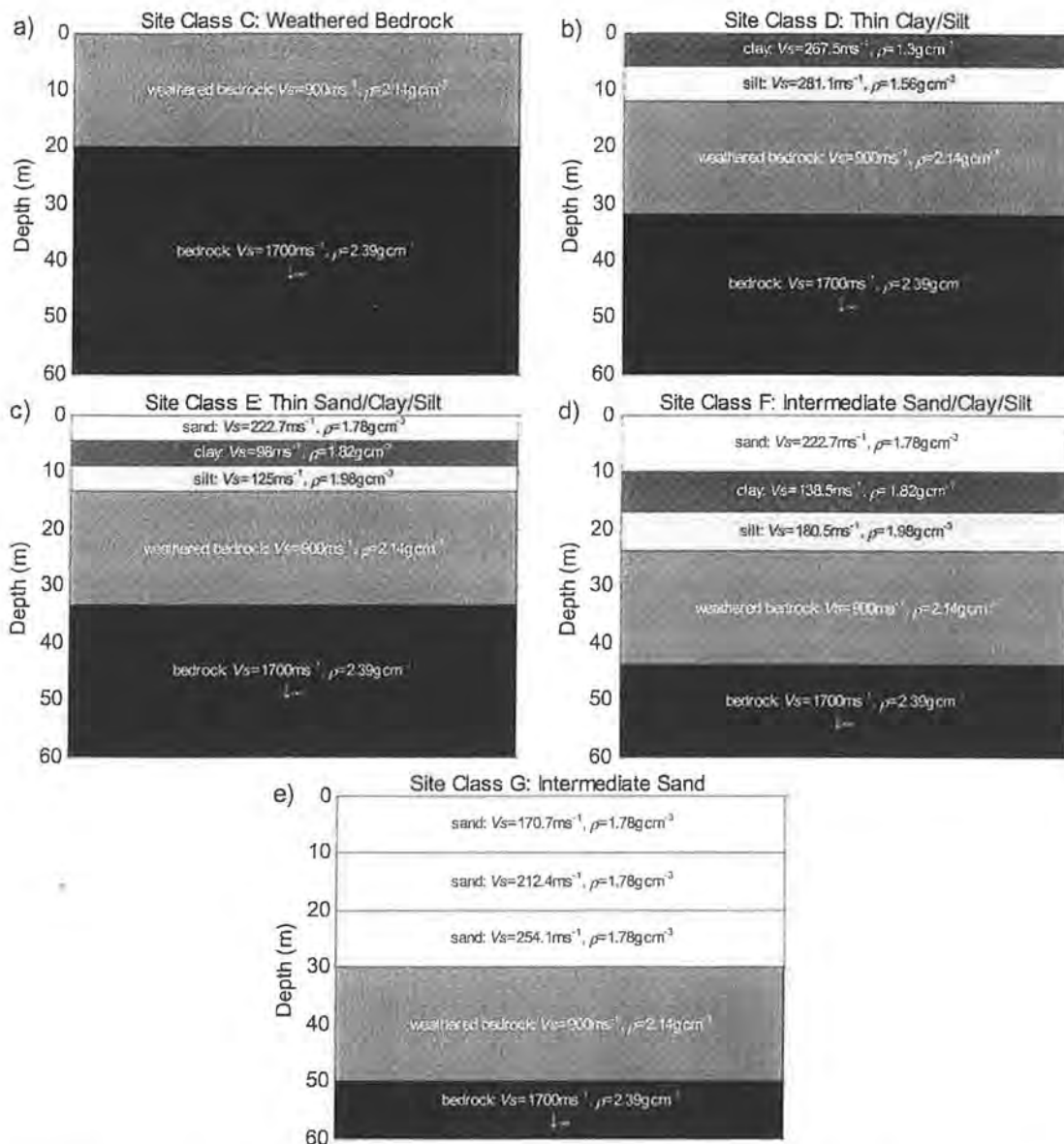


Figure 1: Geotechnical models used for Newcastle and Lake Macquarie site classes.

### 3. AMPLIFICATION FACTORS

ProShake (EduPro Civil Systems, 1999), a one-dimensional, equivalent linear modelling package was used to calculate amplification factors for the five site classes in the Newcastle region. Fourteen strong motion records were used in the calculation of amplification factors for each of the site classes (Table 1). Table 1 highlights the variability in the peak ground velocity (PGV) of these records. The PGV of an earthquake will influence the amount of amplification experienced. Hence, the records used in this study have all been scaled to a PGV of  $100 \text{ mm s}^{-1}$  in order to provide a consistent intensity of ground shaking from one record to the next.

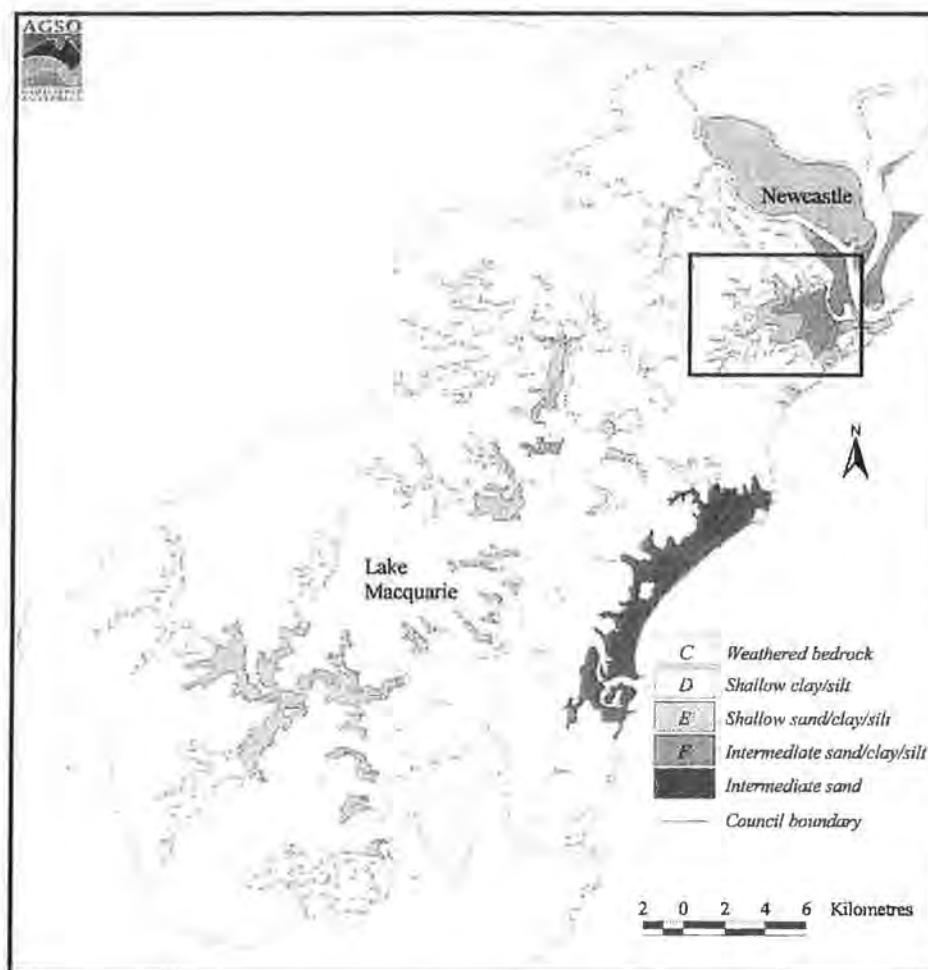


Figure 2: Distribution of site classes within the Newcastle and Lake Macquarie regions. The black box highlights the region where CPT data were available.

A comparison of the amplification factors with those suggested by the current Australian Standard for earthquake loading (AS1170.4, 1993), as well as the draft Australia/New Zealand Standard for earthquake loading (DR00902, 2000) is presented in Figure 3. Before interpreting these results, it should be emphasised that the rock spectrum in the current standard is more conservative than the rock spectrum in the draft standard. Figure 3 suggests that the current standard's amplification factors are distinctly smaller than the factors in the draft standard. However, this difference is to some degree accounted for by the difference in the associated rock spectra.

Figure 3a demonstrates that both the current and the draft standards have very similar factors to those calculated for weathered rock (class C). The amplification factors calculated for site classes containing sediments (classes D, E, F & G) are generally similar to those in the current standard (Figures 3b – 3c). However, the amplification factors calculated here have a peak value at some resonant period. At this resonant period, the factors from the current standard are significantly smaller than the calculated factors (Figures 3b – 3c). Consequently, the current standard is not conservative enough to accommodate these resonant amplifications.



| Earthquake        | Date            | Mag             | Station Name             | Dist (km) | PGV (mms <sup>-1</sup> ) | Comp       |
|-------------------|-----------------|-----------------|--------------------------|-----------|--------------------------|------------|
| Coalinga          | 09/05/83        | Ms = 4.7        | SGT (Temp)               | 14        | 54.9                     | 80         |
| Coalinga          | 09/05/83        | Ms = 4.7        | SGT (Temp)               | 14        | 70.1                     | 350        |
| <b>Nahanni</b>    | <b>23/12/85</b> | <b>Mb = 5.4</b> | <b>Iverson</b>           | <b>7</b>  | <b>490.7</b>             | <b>10</b>  |
| <b>Nahanni</b>    | <b>23/12/85</b> | <b>Mb = 5.4</b> | <b>Iverson</b>           | <b>7</b>  | <b>560.8</b>             | <b>280</b> |
| <b>Northridge</b> | <b>17/01/94</b> | <b>Ms = 6.6</b> | <b>CIT Seis. Station</b> | <b>41</b> | <b>530.4</b>             | <b>90</b>  |
| <b>Northridge</b> | <b>17/01/94</b> | <b>Ms = 6.6</b> | <b>CIT Seis. Station</b> | <b>41</b> | <b>515.1</b>             | <b>360</b> |
| <b>Northridge</b> | <b>17/01/94</b> | <b>Ms = 6.6</b> | <b>Mt. Wilson</b>        | <b>45</b> | <b>54.9</b>              | <b>90</b>  |
| <b>Northridge</b> | <b>17/01/94</b> | <b>Ms = 6.6</b> | <b>Mt. Wilson</b>        | <b>45</b> | <b>76.2</b>              | <b>360</b> |
| <b>Northridge</b> | <b>17/01/94</b> | <b>Ms = 6.6</b> | <b>Pacoima Dam</b>       | <b>19</b> | <b>310.9</b>             | <b>265</b> |
| <b>Northridge</b> | <b>17/01/94</b> | <b>Ms = 6.6</b> | <b>Pacoima Dam</b>       | <b>19</b> | <b>506</b>               | <b>175</b> |
| San Fernando      | 09/02/71        | Ms = 6.6        | Santa Anita Dam          | 27        | 30.5                     | 3          |
| San Fernando      | 09/02/71        | Ms = 6.6        | Santa Anita Dam          | 27        | 36.6                     | 273        |
| Whittier          | 01/10/87        | M = 6.0         | CIT Seis. Station        | 18        | 42.7                     | 90         |
| Whittier          | 01/10/87        | M = 6.0         | CIT Seis. Station        | 18        | 33.5                     | 360        |

Table 1: Description of earthquake acceleration records used for determining Newcastle amplification factors. The records in bold were used in the creation of the draft Australian standard response spectra (Somerville et al., 1998)

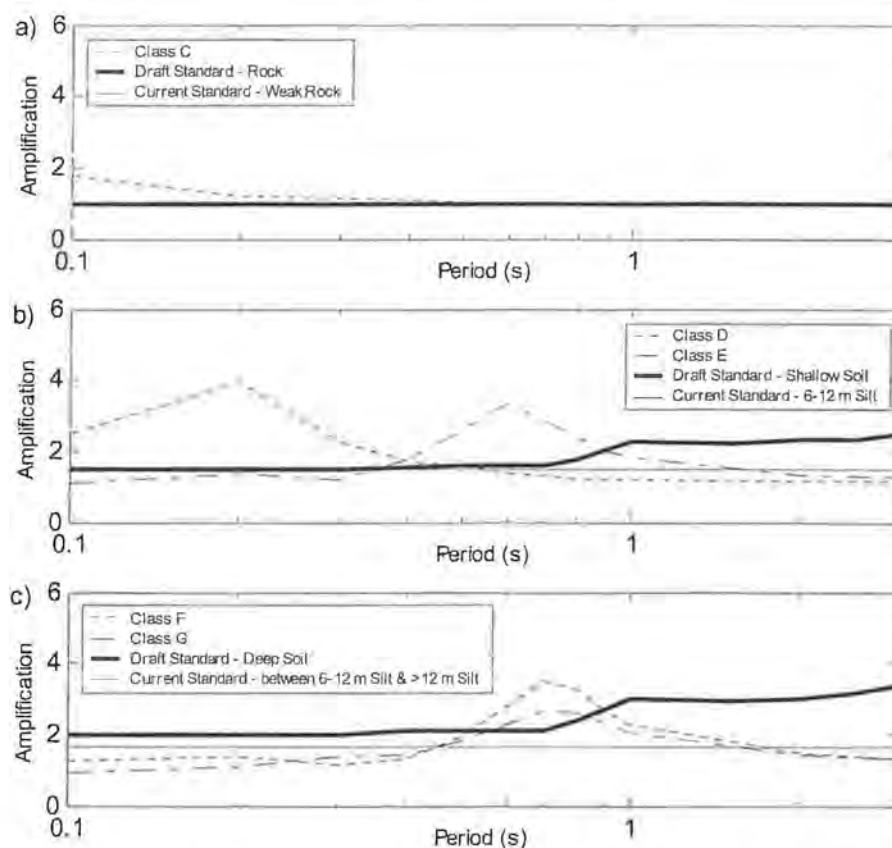


Figure 3: Comparison of calculated amplification factors with the most appropriate factors from both the current and the draft earthquake loading standards. The draft standard provides response spectra rather than amplification factors, so the factors here have been calculated by dividing each spectrum by the spectrum for Rock. The factors for the current standard in part (c) have been interpolated to a value of 1.65.

The amplification factors from the draft standard are similar to the factors calculated in this study for periods less than approximately 0.75 s. However, the values in the draft standard do not reflect the peaks in the calculated factors (Figures 3b – 3c). At periods greater than 0.75 s, the factors from the draft standard tend to be significantly larger than the calculated factors, and consequently are conservative for the study region.

#### 4. CONCLUSIONS

The amplification factors calculated for the Newcastle and Lake Macquarie region have been presented here with no inclusion of uncertainties due to variabilities in the geotechnical models used or the applicability of one-dimensional equivalent linear modelling. Whilst both the geotechnical models and the style of modelling used are believed to be suitable for this region, this is a topic of ongoing research at Geoscience Australia.

Despite the uncertainties within the work, the amplification factors presented here do vary distinctly from those presented in either the current or the draft standards. Whilst this does not imply that the amplification factors within the standards are not generally suitable for Australia, it does suggest that where more detailed information is available, it should be used by local governments in preference to either of the standards.

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# EARTHQUAKE SHAKING SUSCEPTABILITY IN THE BOTANY AREA, NSW

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**Trevor Jones** is a specialist in natural hazard risk assessment in the Urban Geoscience Division of AGSO - Geoscience Australia. He has an extensive background in assessing earthquake hazard and risk in Australia and the Southwest Pacific. He is currently active in developing simulation models for earthquake risk assessment and in assessing natural hazard risk in Australian cities including Perth and Newcastle.

## ABSTRACT:

Botany and its neighbouring suburbs are located on a thick sequence of unconsolidated Quaternary sediments and fill that have the potential to amplify seismic shaking. The region has a high population density and a concentration of major lifeline elements, as well as being the site for major chemical and petrochemical industries. Consequently, the area has been recognized as having the highest risk of earthquake damage in Sydney.

An earthquake susceptibility map for the Botany study area has been generated. Four site classes have been delineated on the basis of surface and sub-surface geology, and available geotechnical data. Approximately 400 microtremor measurements were taken to determine the natural period of the sediments using Nakamura's method. Ground shaking was modelled using the one-dimensional equivalent linear modelling package, Proshake.

The results demonstrate that there is significant potential for amplification of ground shaking in the study area. Compared with shaking on rock, amplification factors of 3 or greater were calculated for all soil classes. The period at which maximum amplification occurs increases with sediment thickness. The intensity of ground shaking has a small but significant effect on the amplification factors. Further work is required to refine the regional earthquake hazard, the geological and geotechnical models, and the vulnerability of the region's infrastructure to earthquakes. However, the study has shown that earthquakes could pose a major risk to this region.



## **1. INTRODUCTION**

The Newcastle earthquake of 28 December, 1989 under the northern end of the Sydney Basin, demonstrated that a catastrophic event could occur in Australia, and that such a catastrophe could be caused by a moderate-sized earthquake. There has been significant seismicity in the Sydney Basin. Historically, most of this seismic activity has occurred around the margins of the Sydney Basin. However, the recording of earthquakes in Australia has been carried out for a very short period of time, and there is no reason why an earthquake could not occur close to, or beneath, the Sydney metropolitan area in the centre of the basin.

The Botany study area lies within the northern portion of the Botany Basin, a sequence of unconsolidated Quaternary sediments. The area is shown in Figure 1. The study area specifically excludes Sydney Airport, which may be covered in a later study.

A significant concern regarding earthquake hazard in urban areas is the potential for the enhancement of seismic shaking in unconsolidated sediments. The Botany area has one of the largest concentrations of major lifeline elements in Sydney, a high population density, and major chemical and petrochemical industries. Lifelines include electricity cables, water and sewer mains, telecommunications and transport routes, Sydney's major port facility, and gas and fuel pipelines. Given the density of lifelines, population and the geological setting, the Botany study area is interpreted to be a high risk area for earthquakes.

## **2. GEOLOGY**

The Botany Basin is a structural depression within a large structural basin known as the Sydney Basin. The basement rocks that underlie the sediments were eroded during a period of much lower sea level. During and since the Pleistocene Period a rising sea level has resulted in the infilling of the former valleys. These unconsolidated deposits are often in the order of 30-35 m thick and may be up to 70-80 m thick.

The Quaternary sediments of the basin are Pleistocene and Holocene in age. They form a continuous depositional sequence that ranges up from terrestrial through estuarine to terrestrial swamp and aeolian deposits. The Holocene sediments are re-worked Pleistocene sediments. Overlying the sediments there are areas of man-made fill. Filling has been undertaken for more than a century to reclaim land for building. The majority of the fill comprises dune sand and dredged sand, but boiler ash, building materials and domestic garbage have also been used. The most extensive area of fill within the study area is around Port Botany. The adjacent Sydney Airport is also an extensive area of fill.

## **3. ENGINEERING GEOLOGY**

The sediment deposits of the Botany Basin generally thicken towards the South and Southeast. Generally, the sediments are approximately 30-35 m thick; however they may be up to 70-80 m thick in incised valleys. The longest and deepest of the incised channels, the Lakes Valley, extends from Centennial Park southwards to enter Botany Bay at Banksmeadow. There are several other deep channels in the study area. A narrow valley extends northwards for approximately 4 km from just to the east of the

intersection of the airport's third runway and the bay shoreline; and a shorter deeper valley is located approximately 2 km further to the east.

The Botany Basin sediments have been divided into four units. Descriptions of these units are given below.

**UNIT 1:** This lower-most unit is only found in deep valleys in the bedrock topography. It is generally found below RL-40 m. These Pleistocene sediments comprise fluvial sand with minor gravel in the bedrock channels and grade up to interbedded sand and mud with estuarine shells. The unit may be up to 30 m thick. The sands are generally of medium grainsize and are dense.

**UNIT 2:** These Pleistocene sediments are similar to those in Unit 1, but with more mud and peat (organic mud). This unit is 5-15 m thick. The clays are stiff to very stiff, and are often fissured in the upper 3-4 m of each bed. In the western portion of the basin the alluvial clays overlie residual clay soils of the Ashfield Shale that are interpreted to be very stiff to hard. Sands are interpreted to be dense.

**UNIT 3:** These Pleistocene sediments predominantly comprise medium-grained sand with discontinuous peat and mud lenses, especially in the upper part. The sands may be in the order of 30 m thick and are distributed over the entire basin. Sand is generally dense to very dense and this consistency distinguishes them from overlying Holocene sands.

**UNIT 4:** This upper-most unit is Holocene in age and comprises loose sand, soft mud, peat and organic clay. The peat generally occurs in sinusoidal channels. The Sheas Creek estuary contains 4-5 m of tidal flat mud and swamp deposits formed later. The sediments of this unit are generally re-worked sediments of Unit 3. They are irregularly distributed and may vary from only several metres to 10 m in thickness.

Fill materials predominantly comprise sand that was excavated from dunes to fill interdune swamps or was dredged from Botany Bay. Generally, the fill has not been compacted and sand fill layers would typically be loose.

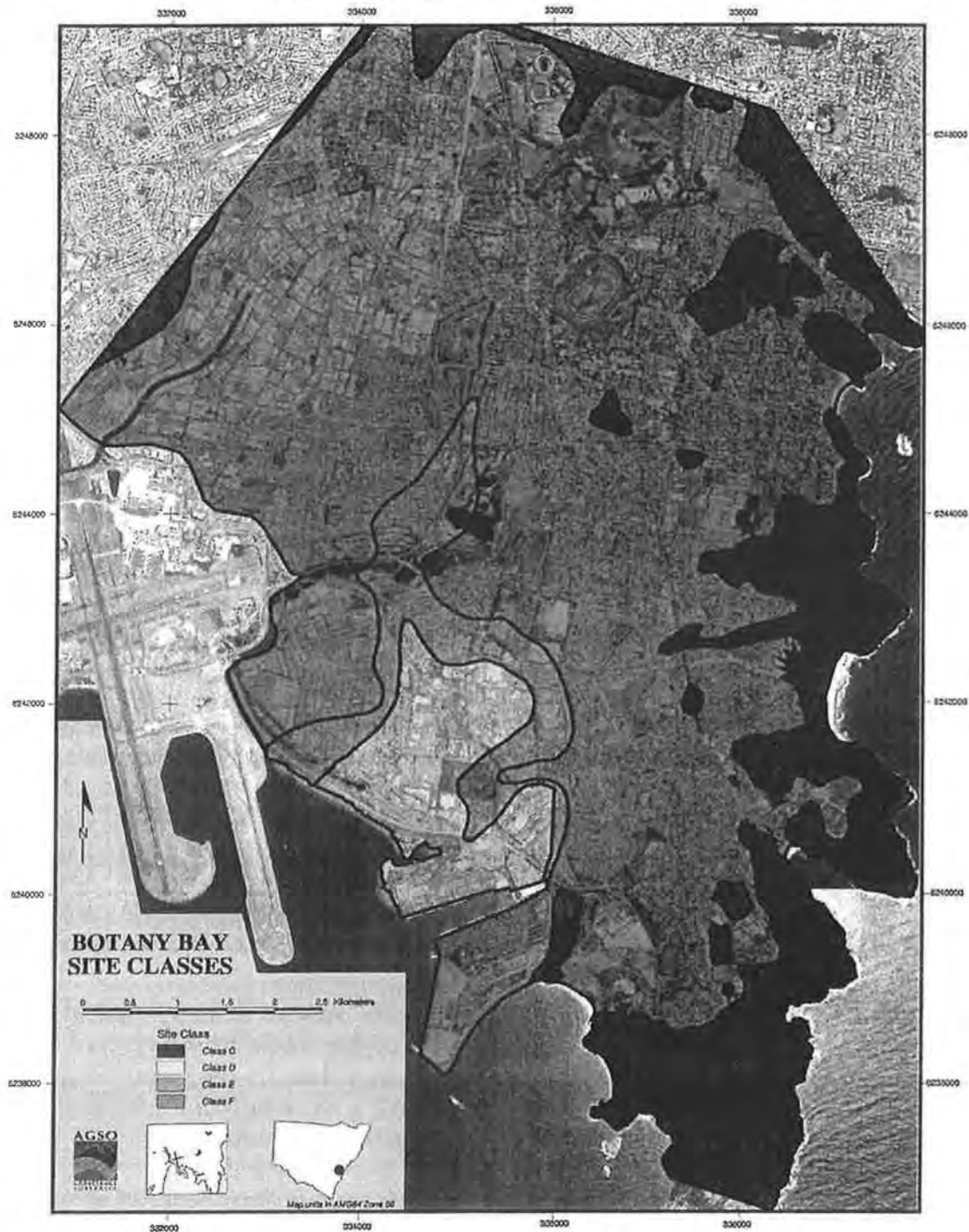
#### **4. DATA SOURCES**

DPWS has summarised data from 340 boreholes in an Excel spreadsheet. This data was derived from a variety of sources including publications and theses. Griffin (1963) interpreted the basin shape and the stratigraphic sequence within the basin from borehole data. Burg (1996) assembled borehole data for the area and made a first attempt at earthquake hazard microzonation. As part of the project, AGSO - Geoscience Australia took 400 microtremor measurements on a 500m grid across the study area.

#### **5. SITE CLASSES**

The region was divided into four different site classes, in order to describe the spatial variability of the sediments. Descriptions of the classes are presented in Table 1 and their distribution is shown on Figure 1.

**Figure 1 Distribution of Site Classes**



**Table 1 Descriptions of Site Classes**

| Site Class | Description  |
|------------|--|
| Class C    | Approximately 20m of weathered bedrock overlying unweathered bedrock   |
| Class D    | Approximately 25 m of Unit 3 sands overlying 40 m of Units 1 and 2. This sediment package is in turn overlying Site Class C.         |
| Class E    | This class is a thinner version of Class D with 25 m of Unit 3 sands overlying 10 m of Unit 1 and 2.                                 |
| Class F    | This class contains 5 m of Unit 4 sediments overlying 20 m of Unit 3 sands. This sediment package is in turn overlying Site Class C. |



A variety of geotechnical parameters were estimated to calculate the amplification factors for each site class, specifically, shear wave velocity, density and strain dependant shear modulus and damping properties of the materials. The strain dependant parameters used were taken from typical curves provided in ProShake, the software that was used for modelling. The parameters used for each model are shown in Figure 2.

## 6. GROUND SHAKING AMPLIFICATION

The ProShake program takes the developed geotechnical models and simulates vertically propagating shear waves passing upwards through them. The response spectra for both the output and input motions are calculated, and the ratio of these two spectra determines the amount of period dependant amplification caused by the model. Amplification of ground shaking is a function of both the local geology and the intensity of the ground shaking that is applied. The modelling has used fourteen different records of reverse faulting earthquakes of magnitudes  $M$  4.7–6.6 and epicentral distances less than 50 km. These records were scaled to a peak ground velocity (PGV) of  $100 \text{ mms}^{-1}$  to represent low levels of ground shaking and  $200 \text{ mms}^{-1}$  to represent higher levels of ground shaking. The resultant amplification factors are summarised in Table 2.

**Table 2 Summary of Amplification Factors for Botany Site Classes**

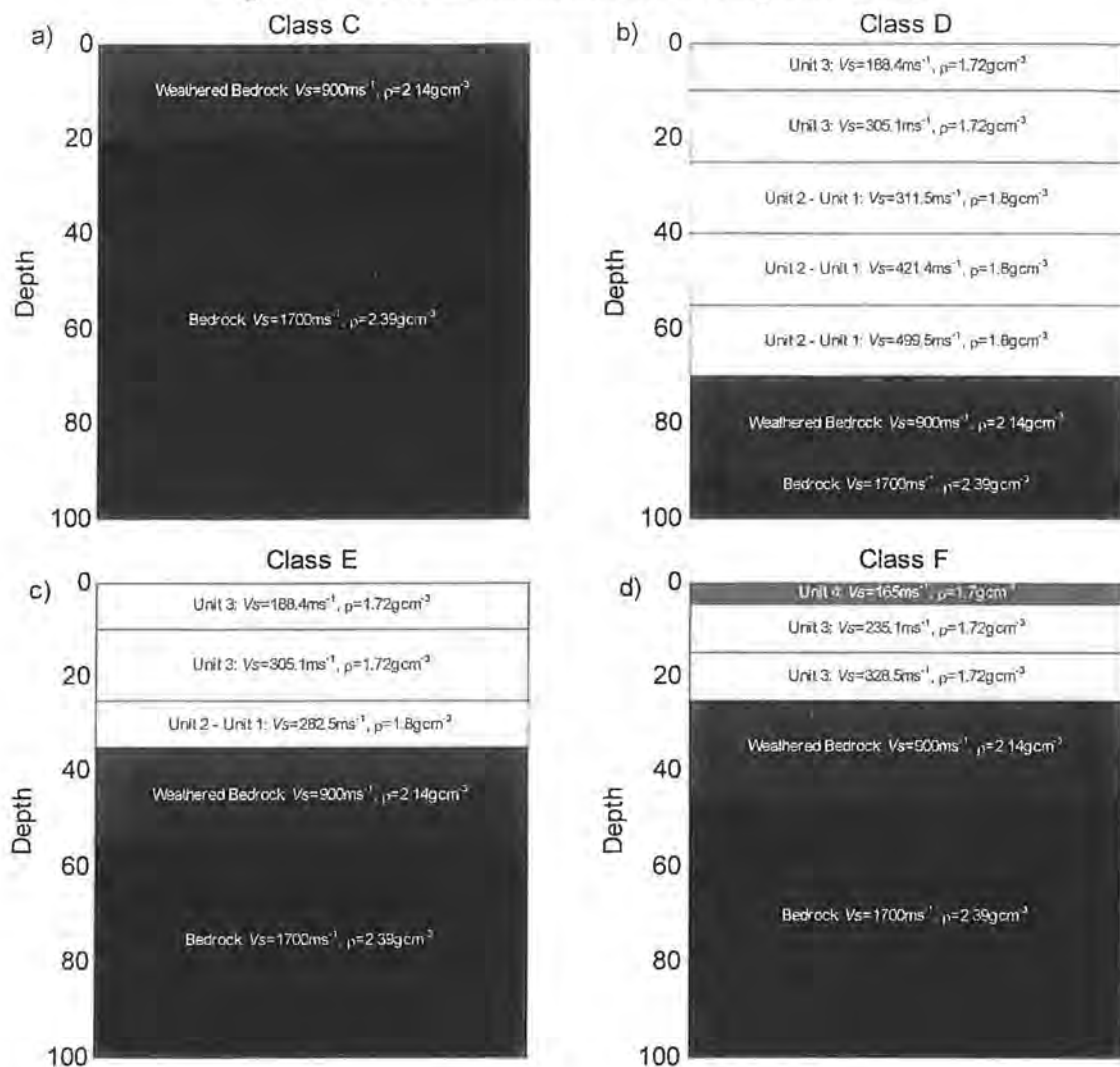
| Site Class /<br>PGV (mms <sup>-1</sup> ) |     | Period (s) |      |      |      |      |      |      |      |      |      |      |      |      |
|--|-----|------------|------|------|------|------|------|------|------|------|------|------|------|------|
|  |     | 0.1        | 0.2  | 0.3  | 0.4  | 0.5  | 0.6  | 0.7  | 0.8  | 0.9  | 1    | 2    | 3    | Ave  |
| C  | 100 | 1.73       | 1.23 | 1.13 | 1.07 | 1.06 | 1.04 | 1.03 | 1.02 | 1.02 | 1.02 | 1.01 | 1.02 | 1.11 |
|  | 200 | 1.75       | 1.24 | 1.14 | 1.07 | 1.06 | 1.04 | 1.03 | 1.03 | 1.02 | 1.02 | 1.01 | 1.02 | 1.12 |
| D  | 100 | 1.38       | 1.79 | 2.37 | 2.17 | 1.97 | 2.29 | 2.79 | 3.55 | 3.75 | 3.57 | 1.80 | 1.57 | 2.42 |
|  | 200 | 0.93       | 1.32 | 1.90 | 1.96 | 1.63 | 1.71 | 1.98 | 2.44 | 2.92 | 3.27 | 1.95 | 1.61 | 1.97 |
| E  | 100 | 1.48       | 1.57 | 1.58 | 1.82 | 2.45 | 3.18 | 3.16 | 2.75 | 2.27 | 2.05 | 1.40 | 1.31 | 2.09 |
|  | 200 | 0.99       | 1.10 | 1.25 | 1.27 | 1.52 | 2.09 | 2.70 | 3.01 | 2.75 | 2.48 | 1.54 | 1.38 | 1.84 |
| F  | 100 | 1.82       | 2.42 | 2.60 | 3.41 | 3.11 | 2.36 | 1.96 | 1.78 | 1.57 | 1.57 | 1.23 | 1.22 | 2.09 |
|  | 200 | 1.45       | 1.97 | 2.41 | 2.97 | 3.21 | 2.68 | 2.24 | 2.01 | 1.72 | 1.68 | 1.27 | 1.25 | 2.07 |

The results demonstrate that there will be a significant increase in the strength of ground shaking felt within the Botany area, as compared to what would be experienced on rock in adjacent areas. Whilst the weathered rock class (Class C) only shows significant amplification for periods less than approximately 0.2 s, all of the other site classes show significant amplification for almost the entire range of periods considered.

The three classes containing alluvium tend to have amplification peaks at periods that are closely related to the overall thickness of sediment. As the sediment thickness increases, so does the period of peak amplification. This suggests that Site Class D will tend to amplify ground shaking at periods corresponding to the natural period of vibration of mid- to high-rise buildings. In contrast, site class F will tend to amplify ground shaking at periods corresponding to the natural period of vibration for low-rise to mid-rise buildings.

More intense applied ground shaking has a small but significant effect on the amplification factors. The amplification factors are reduced for most of the periods considered and the peaks typically occur at slightly higher periods (see Table 2).

**Figure 2 Geotechnical models for Botany Site Classes**



## 7. CONCLUSIONS

The modeling presented within this study is preliminary in the sense that there has been little analysis on the uncertainties within either the modeling process or the geotechnical parameters used. Nevertheless, all of the site classes containing alluvium had amplification factors greater than three, indicating that significant amplification of ground shaking would be expected for the majority of the Botany study area. The results here suggest that earthquake hazard is significantly increased in this part of Sydney compared to many other parts on rock. However, a more comprehensive study needs to be undertaken to fully understand the risk posed by earthquakes.

## 8. REFERENCES

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# PROBABILISTIC EARTHQUAKE RISK ASSESSMENT OF THE SOUTH-EAST QUEENSLAND REGION

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**Rob Lacey** holds a Diploma in Geoscience and a BSc (Hons) in Geology and Geophysics using GIS techniques from ANU. He joined the mapping services group at AGSO - Geoscience Australia and, later, its Urban Geoscience Division, where he is responsible for image processing and geospatial analysis.

**John Schneider** is the Research Group Leader for Geohazards and Risk at AGSO - Geoscience Australia. John's primary research interests are in the development of natural hazards risk assessment methods for application to urban centres, with a particular emphasis on earthquake hazards.

**Denis Hackney** holds a BSc (Hons) in Geophysics from ANU. He has worked with AGSO - Geoscience Australia's Cities Project on earthquake site classification, and especially microtremor techniques, in several major eastern Australian projects.

## ABSTRACT:

We have estimated the earthquake risk to residential buildings and their contents as part of AGSO's study 'Natural hazards and the risks they pose in Southeast Queensland'. Southeast Queensland has a population of about two million and is one of Australia's fastest-growing urban areas. Expert geological opinion was canvassed to produce a single, uniform earthquake hazard Tasman Sea Margin Zone and, with an adopted site class model, numerous earthquake scenarios were generated as inputs to the risk calculations. The residential building stock is largely timber frame and has low vulnerability. The parameters for the building capacity models were developed with the assistance of an expert forum of structural engineers. Probabilistic loss estimates were determined for a range of Annual Exceedence Probabilities (AEP), for the entire region and for each Census Collectors District. For the region, damage costs of around 0.3% have an AEP of 0.2%.



## **1. INTRODUCTION**

This paper summarises the earthquake risk assessment results from the study 'Natural hazards and the risks they pose to South-East Queensland' (Jones et al., 2001). The South-East Queensland report is the most recent of three multi-hazard risk assessments for Queensland cities published by AGSO - Geoscience Australia.

## **2. EARTHQUAKE RISK ASSESSMENT METHOD**

Our earthquake risk assessment for the South-East Queensland community is based almost entirely on scenario analysis of damage to residential buildings (houses and flats). These buildings comprise about 94% of all South-East Queensland buildings.

The earthquake risk assessment comprises the following processes.

- An earthquake hazard model was prepared for South-East Queensland. This model calculates the likelihood of earthquake ground shaking occurring in the South-East Queensland region. The model also accounts for local site effects that can amplify earthquake ground shaking.
- A South-East Queensland property database was prepared, containing data on approximately 647,000 residential buildings provided by eight local governments.
- The damage to South-East Queensland residential buildings was estimated using earthquake loss software developed by AGSO. This software estimates building damage using the capacity spectrum method described in HAZUS<sup>®</sup> (FEMA, 1999).
- Probabilistic loss estimates were determined for a range of Annual Exceedence Probabilities (AEP). The results are presented at the level of Census Collectors District (CCD) and also for the entire region.

## **3. EARTHQUAKE HAZARD MODEL**

A single, uniform earthquake hazard source zone was prepared with the guidance of a panel of geological and seismological experts (Stewart and Jones, in preparation). The Tasman Sea Margin Zone (TSMZ) extends from northern Bass Strait into Queensland as far North as latitude 24° S. It is bounded in the West by the 150 m AHD topographic contour of the Great Dividing Range, and in the East by the continental shelf margin.

Three site classes were prepared to determine the relative severity of earthquake shaking (Table 1). Figure 1 plots the response spectra for the site classes. A site class was assigned to each CCD. Site natural periods and thicknesses were determined from an extensive microtremor survey conducted by AGSO - Geoscience Australia and QUAKEs and from geotechnical data.

The spectrum for Site Class B (rock) is taken from ANZS DR 00902 (Standards Australia, 2001). The spectra for Site Class C and Site Class D were developed by multiplying the values of the rock spectrum by amplification factors derived for Eastern United States. The amplification factors for Site Class C were developed for New Madrid Class L28 ('soft' sediments of thickness 3-23 m). The amplification factors for

Site Class D were developed for New Madrid Class M28 ('soft' sediments of thickness 24-54 m).

Table 1: Earthquake site classifications (abbreviated)

| Site Class | Description  | South-East Queensland setting  |
|------------|--|--|
| B          | Rock.  | All rock outcrop in South-East Queensland (all rock units older than Tertiary).  |
| C          | Thin sediments overlying rock. Sediments with natural periods of vibration less than 0.5 s (sediment thicknesses in the range 3-23 m approx.).   | All Quaternary sediments with thicknesses estimated in this range. Landfill may overlie these units.   |
| D          | 1. Thick sediments overlying rock. Sediments with natural periods $\geq 0.5$ s (sediment thicknesses in the range 24-70 m approx.);<br>OR<br>2. Weathered profile in residual soils and colluvium overlying Tertiary geological units. | 1. All Quaternary sediments with thicknesses estimated in this range. Landfill may overlie these units; OR<br>2. All mapped Tertiary rock units. |

Earthquakes with magnitudes of 5, 5.5, 6 and 6.5 were used to generate the hazard scenarios. Individual scenario 'earthquakes' were generated in each cell of a regular 10 km by 10 km square grid with sides of 300 km (i.e., a total of 900 scenario earthquakes for each magnitude). We used the attenuation formula of Toro et al. (1997) to calculate PGA at each CCD centroid. The response spectra, scaled by the input value of PGA, were used as input into the building damage model.

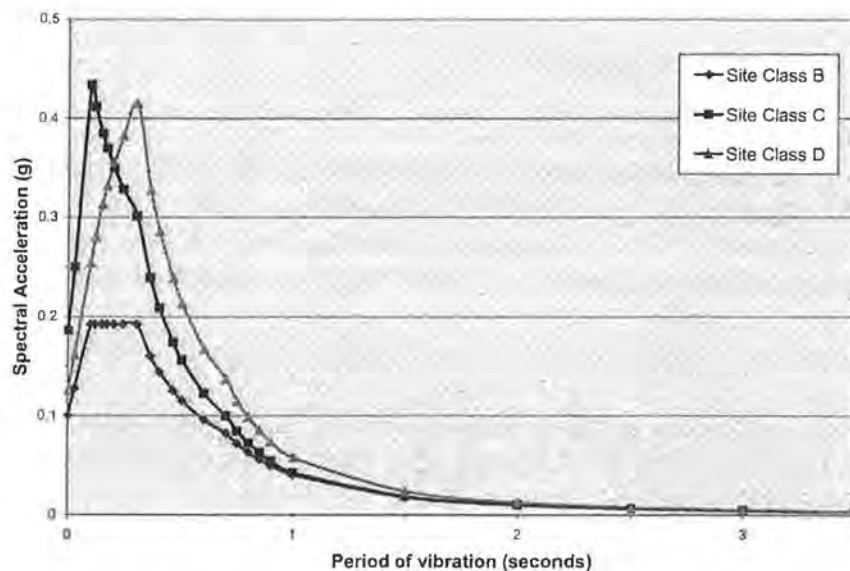


Figure 1: Normalised response spectra for South-East Queensland Site Classes B, C and D. Spectra are elastic and 5% critically damped

#### 4. BUILDING DAMAGE MODEL

We estimated the composition of the residential building stock with regards to the type of load-bearing frame or wall (Table 2). Eight local governments were consulted on the composition of the building stock.

Table 2: Estimated construction types of South-East Queensland houses and flats

| Construction type  | Houses | Flats |
|--|--------|-------|
| Light timber frame low rise  | 97.5%  | 69%   |
| Reinforced concrete frame low rise   | 0      | 8.5%  |
| Reinforced concrete frame medium rise  | 0      | 7%    |
| Concrete shear walls medium rise   | 0      | 4%    |
| Concrete shear walls high rise   | 0      | 2%    |
| Reinforced concrete frame with unreinforced masonry infill panels low rise                                       | 0      | 1%    |
| Reinforced concrete frame with unreinforced masonry infill panels medium rise                                    | 0      | 3%    |
| Unreinforced masonry low rise  | 2%     | 0.5%  |
| Reinforced masonry buildings with reinforced concrete floors (concrete block buildings with concrete slab floor) | 0.5%   | 5%    |

The methodology used defines damage by the interstorey drift ratio or by PGA, depending on the building component considered (structural, non-structural or contents). The capacity spectrum performance parameters of Australian residential buildings have been determined by a group of experts (Stehle et al., in prep.). Damage states and costs of repair were assessed.

Statistical uncertainty/variation in the input ground motion, the building capacity curve and in the damage state thresholds are accounted for in the methodology. The result is that a group of buildings of the same building category and subject to the same ground motion will be in a range of damage states.

#### 5. RISK ASSESSMENT RESULTS

A summary of the earthquake damage losses in the South-East Queensland region is given in Table 3 and plotted in Figure 2.

A probabilistic distribution of earthquake damage risk across the South-East Queensland region is shown in Figure 3. The annual risk to each CCD is shown. The risk is defined in terms of the percentage of the average repair or replacement cost of a "typical" residence including contents (multiplied by an annual probability of one).

#### 6. CONCLUSIONS

South-East Queensland faces a moderately low risk to its residential buildings from earthquakes. The annual risk is about an order of magnitude lower than the risk calculated for Newcastle (Stehle et al., 2001). Local site conditions and construction type will have a significant influence on the distribution of damage. The probability of



death is low from any of the scenarios we considered. The predominance of timber frame construction is a positive earthquake risk factor.

Table 3: Estimated damage for South-East Queensland residential buildings

| ARI (years) | AEP    | Damage (repair or replacement cost of equivalent no. of buildings destroyed) | Damage (repair or replacement cost expressed as % of total replacement cost) |
|-------------|--------|--|--|
| 100         | 1.0%   | 60   | 0.01%  |
| 200         | 0.5%   | 450  | 0.07%  |
| 500         | 0.2%   | 2000   | 0.31%  |
| 1000        | 0.1%   | 3900   | 0.60%  |
| 2000        | 0.050% | 7100   | 1.1%   |
| 5000        | 0.020% | 13 000   | 2.0%   |

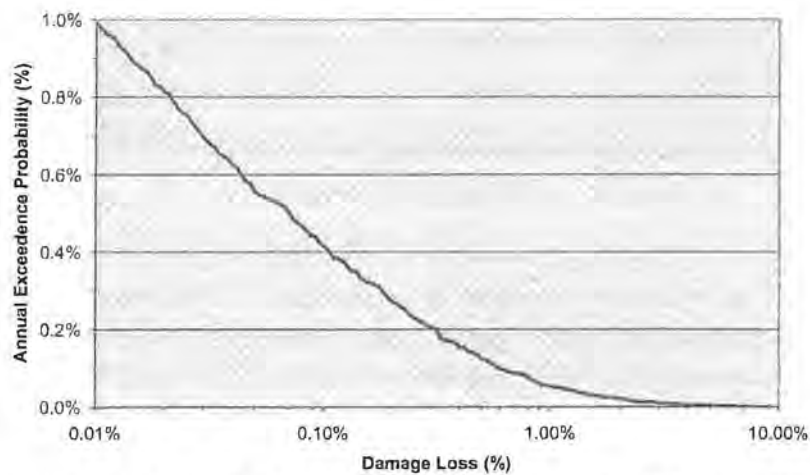


Figure 2: Annual Exceedence Probabilities for residential building damage in South-East Queensland

We have modelled the damage to residential buildings only. Other significant direct losses could be incurred through damage to non-residential buildings, to lifelines, through business interruption, and through social and cultural impacts.

The uncertainties in the earthquake risk assessment are significant. The reader is referred to the original report (Jones et al., 2001) for a discussion of limitations and uncertainty.

The earthquake risk in South-East Queensland is largely from low probability, high consequence events. Effective management of this type of risk may be handled appropriately at state, federal and corporate levels.

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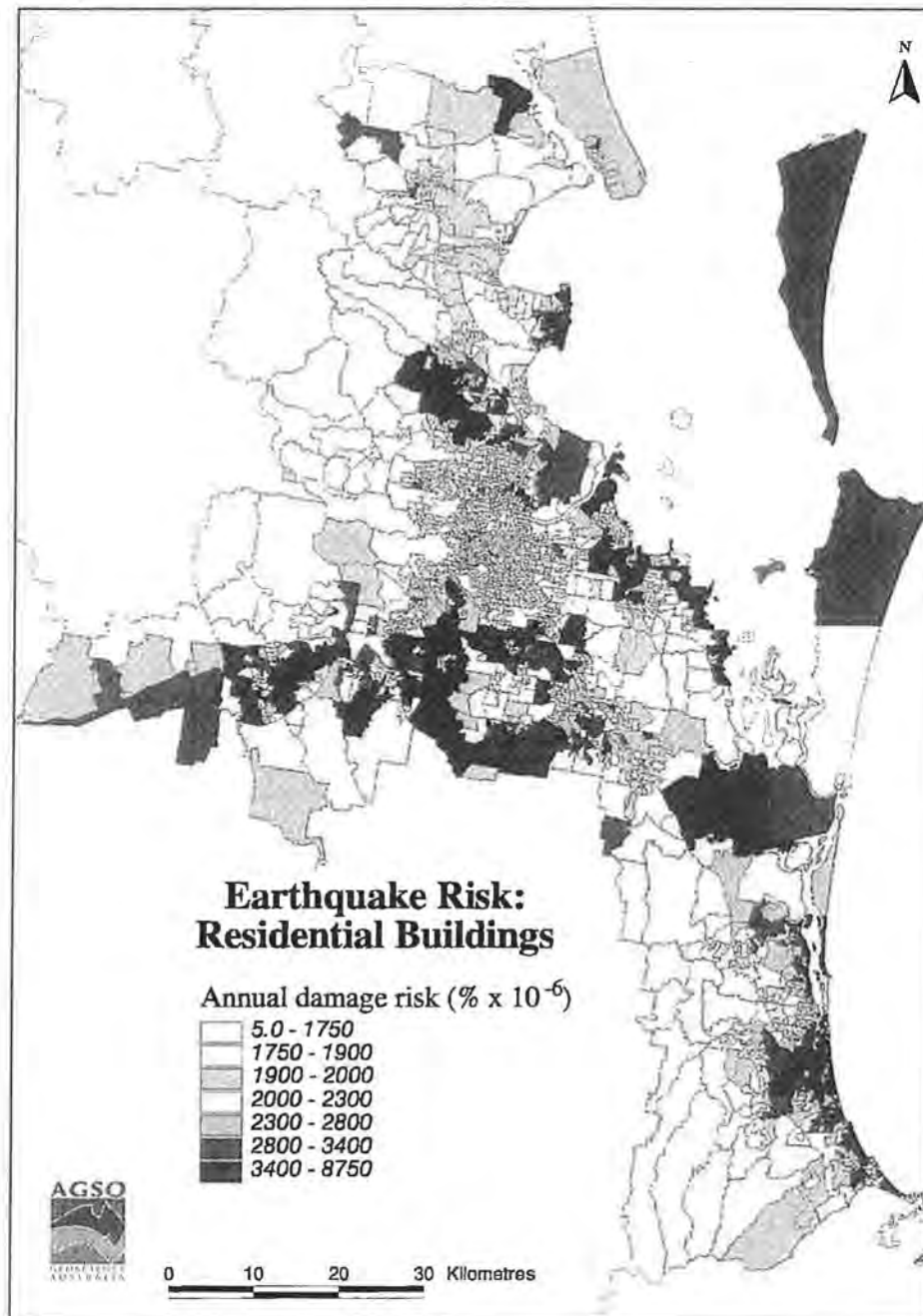


Figure 3: Annual earthquake risk to residential buildings

# SEISMIC HAZARD MICROZONATION, A COMPARISON OF DIFFERENT METHODOLOGIES THAT HAVE BEEN USED IN AUSTRALIA.

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## ABSTRACT:

Over the past decade several seismic risk microzonation studies have been conducted in urban areas throughout Australia. An inspection of the various methodologies used in these studies indicates that, although a certain degree of commonality exists in the data collection methodology, considerable differences exist in the manner in which the raw data has been analysed and interpreted.

This paper compares and contrasts the divers methodologies used in Australia to conduct seismic risk microzonation. It suggests that the diversity in methodologies is not conducive to good engineering practice, usage and codification, and that consolidation and agreement of a common method or methods is desirable. In particular it suggests that an extensible methodology, capable of comparing the relative risk between different urban areas should be used.



## 1 INTRODUCTION

1.1 During the past decade, seismic microzonation has been carried out in a number of Australian urban centres. This includes Perth, Newcastle, Adelaide, Cairns, Mackay, Rockhampton, Gladstone, Bundaberg and Launceston. One of the notable features of these exercises is the variation in data collection techniques, data analysis methods and result presentation used. This paper reviews some recent Australian seismic microzonation methodologies. Standardisation of methodology, for microzonation of seismic ground shaking vulnerability is recommended.

## 2 PERTH MICROZONATION

2.1 In 1989 Gaull and others (Gaull et al, 1991) conducted a seismic microzonation of Perth, Western Australia.

2.1.1 **Data Collection** was carried out using Kelunji Classic digital seismographs fitted with L4C3D transducers collecting 32 samples per second (Gaull et al, 1991). One instrument was located at a bedrock reference site, and other similar instruments were located at target sites. Five target instruments were used to obtain microtremor readings at over 100 sites, with approximate 3 km spacing. To minimise the effects of social noise, the measurements were taken at 'late night' hours. Measurements of about 100 s duration were obtained by simultaneously triggering the target instruments and the reference instrument.

2.1.2 **Data Analysis** began with selective Fourier Transformation of the 'quietest' 32 s bursts of horizontal velocity time series data. Conditioned spectral ratios of chosen target spectra over the reference spectra were then calculated. How the horizontal data was combined, if combined at all, is not stated. Unspecified smoothing was applied to the spectra prior to rationalisation. It is not clear whether power spectra, spectral moduli or some other amplitude spectra were used. Averaging four time-dispersed ratios and applying a specified attenuation function to approximate known strong motion data produced the final spectral ratio for each target site.

2.1.3 **Presentation of Microzonation Results** consisted of producing contoured maps of the target site's adjusted spectral ratio values at 0.2, 0.5, 1.0, 2.0, 3.0 and 5.0 Hz.

## 3 NEWCASTLE SITE RESPONSE ANALYSIS

3.1 Sommerville, Kagami and McCue conducted a seismic analysis of a number of target sites in Newcastle in 1991 (Sommerville et al, 1993). Whilst this analysis does not constitute what may be considered a *microzonation*, it is relevant to the present discussion in that the data collection and analysis methodology used are applicable to seismic microzonation surveys in general.

3.1.1 **Data Collection** was carried out in a manner somewhat similar to that used in Perth, save that in this instance the sampling rate was 125 samples per second, and measurement durations of 33 s were employed. Two separate experiments were

conducted: one using the reference site method, and one using the Nakamura method (Nakamura, 1989). For the Nakamura experiment, simultaneously triggered measurements were not required, and data was collected during daylight hours. As the purpose of the exercise was to compare pre-selected sites, as opposed to conducting an areal microzonation, site spacing was not considered to be relevant.

3.1.2 **Data Analysis** proceeded by deriving modulus spectral ratios of the target to reference site horizontal data (in the case of the reference method), and the horizontal to vertical data (in the case of the Nakamura method). Data sets of 16 s duration were used as input to the Fourier Transformation. Resulting frequency values up to 15 Hz were considered. As with the Perth methodology, it is not clear how the horizontal data were combined. Although the authors make a point of stating that the equipment configuration used in the Newcastle exercise was identical to that used in Perth, it is unclear whether similar analysis methodology was used. Consequently, it is unclear what conditioning was applied during derivation of the spectral ratios, in terms of smoothing or scaling – or any other technique.

3.1.3 **Presentation of Results** consisted of comparison of the spectral ratios obtained from alluvial sites with those obtained from rock sites; and comparison of the spectral ratios obtained from day time recordings, with those obtained at night.

## 4 CAIRNS MICROZONATION

4.1 The seismic data collection for this project was carried out in 1997, by staff from the Queensland University Advanced Centre for Earthquake Studies (QUAKES) and AGSO Cities Project.

4.1.1 **Data collection** was carried out in 1997 using Kelunji D-series seismographs fitted with CMG-40T sensors (Jaume et al, 1997). Site spacing of about 500 m was used in 'densely populated parts', and 'wider spacing' was used in 'agricultural regions'. The background earth motion was recorded for 200 s at each site. Recordings were taken at 409 sites. Interpretation of Jaume et al (1997), based on the length of the data window used for analysis, implies that a sample rate of 100 samples per second was used.

4.1.2 **Data Analysis** consisted of an adaptation of the Nakamura method. Overlapping 40.96 s windows of recorded ground motion data were conditioned by removing any linear time drift (*detrended*) and the data values at each end of the windows had a 5% cosine taper applied to them. Five Nakamura spectral ratios were produced for each of the two horizontal recordings, at each of the sites. These ten spectra (for each site) were then smoothed twice using a five-point boxcar filter (cf. Turnbull, 2001, p 65), and then averaged to produce the final Nakamura spectra for each site. The final spectra were inspected and each given a *quality rating* ranging from A to D according to whether the degree of the *stability* of the spectral ratio estimate was considered to be of high or low quality respectively.

4.1.3 In **Presentation of the Results**, only spectral ratios of qualities A, B or C were used. For each spectral ratio the frequency of the fundamental resonance peak was categorised as being in the ranges: 0 to 2 Hz; 2 to 4 Hz; 4 to 6 Hz; greater than 6 Hz; or,

No Resonance. The recording sites were then plotted on a map using a different symbol for each category.

## 5 MACKAY MICROZONATION

5.1 In her 1995 Honours Project Report, Roberta Zammit presents what she claims to be the first microzonation map of Mackay (ibid. p54). At the 2<sup>nd</sup> Annual AGSO Cities Project Workshop, held in Townsville in 1998, a brief report (Jones et al, 1998) indicated that an earthquake risk assessment of the city, conducted under the auspices of the Cities Project, had been carried out, in conjunction with similar projects undertaken in Cairns and Gladstone. It is presumed that the methodology used in this project was similar to that used in Cairns and Gladstone.

5.2 **Zammit's contribution** to the microzonation comprises the production of a contour map that categorises the Mackay city area according to alluvial depth, and calculation of theoretical shaking frequency for four sites.

5.2.1 **Data Collection and analysis**, as such, consisted of interpretation of the Queensland Department of Primary Industries' bedrock contour map for the Mackay area. The bedrock contours were used to depict areal categorisation of: rock (lowest risk); alluvium between 1 and 10 m deep; alluvium between 10 and 20 m deep; and, alluvium greater than 20 m deep (highest risk). Based on the alluvium depth and shear velocity at four sites, the theoretical fundamental resonant frequency is calculated.

5.2.2 **Presentation of Results** is by means of colouration of the bedrock contour map to indicate the four categorised risk areas, and indication of the most at risk building heights at the four sites where fundamental shaking frequency was theorised.

## 6 GLADSTONE MICROZONATION

6.1 In 1997 staff of the AGSO Cities Project carried out a seismic microzonation of Gladstone, Boyne Island and Tannum Sands at the request of the Gladstone City and the Calliope Shire Councils.

6.1.1 **Data collection and Analysis** was carried using equipment and methodology similar to that used in Cairns; save that the background earth motion was recorded for 400 s at each site (Jones et al, 1997).

6.1.2 **Presentation of Results** was by means of *hazard maps* relating to three categories of building height: High-rise (10+ storeys, 0.25 to 1.5 Hz; Medium-rise (4 to 9 storeys, 1.25 to 3.75 Hz; and, Low-rise (1 to 3 storeys, 3 to 10 Hz). This information, along with parametric descriptions of 5000 individual buildings and basic information for another 7000 buildings, has been incorporated into a Geographical Information System (GIS). Using this GIS various *vulnerability scenarios* can be displayed.



## 7 BUNDABERG MICROZONATION

7.1 As part of his Masters Degree Thesis this author conducted a preliminary earthquake risk microzonation of Bundaberg City (Turnbull, 2001).

7.1.1 **Data collection** was carried out in 1998 and 2000 using Kelunji Classic seismographs fitted with Springnether S6000 sensors. Site spacing of about 1 km was used in the final results. The background earth motion was recorded for about 120 s at each of about 90 sites at a sample rate of 100 samples per second.

7.1.2 **Data Analysis** consisted of an adaptation of the Nakamura method. The two horizontal and one vertical ground motion components were divided up into sets of 10.24 s unconditioned, non-overlapping data. This produced 10 to 12 spectra for each component. These were arithmetically averaged to produce three spectra for each site. The horizontal spectra were then combined by arithmetic average, and the Nakamura ratio hence derived. For each site, the Nakamura spectrum was divided into three mutually exclusive frequency ranges: 0.5 to 1.1 Hz (corresponding to High-rise buildings of 10 to 20 stories); 1.1 to 2.9 Hz (corresponding to Medium-rise buildings of 4 to 9 storeys); and 2.9 to 10 Hz (corresponding to Low-rise buildings of 1 to 3 storeys). Within each of these frequency ranges (i.e. building categories), for each of the sites, the average Nakamura *gain* was calculated, and the maximum gain value for each category was noted. Within each category, for each site, an equally weighted linear interpolation was used to map the average Nakamura gain, to the standard building code site factors (AS1170.4-1993). The interpolation method is shown in Figure 1. This method has the advantage of allowing data sets from divers areas to be combined in such a manner as to provide a relative comparison of the hazard between the areas.

| Relationship of the average gain ( $\bar{G}$ ) within the frequency range of interest at a particular site, to the maximum average gain ( $G_{Max}$ ) within the same frequency range at all sites. | Microzonation Site factor ( $S_M$ ) |
|---|-------------------------------------|
| $\bar{G} < 1.0$   | 0.67                                |
| $1.0 \leq \bar{G} < (\bar{G}_{Max} * 0.25)$   | 1.00                                |
| $(\bar{G}_{Max} * 0.25) \leq \bar{G} < (\bar{G}_{Max} * 0.50)$  | 1.25                                |
| $(\bar{G}_{Max} * 0.50) \leq \bar{G} < (\bar{G}_{Max} * 0.75)$  | 1.50                                |
| $(\bar{G}_{Max} * 0.75) \leq \bar{G} \leq \bar{G}_{Max}$  | 2.00                                |

**Figure 1: Microzonation Site Factor Interpolation**

7.1.3 **Presentation of Results** was by means of contoured *relative risk* maps for each category of building, based on the relative risk implied by the Microzonation Site Factor.

## 8 CONCLUSION AND RECOMMENDATION

8.1 Although most of the recent seismic microzonations carried out in Australia have the common feature that variations of the Nakamura method were used to analyse the field data, subtle variations in that method have been employed. In addition, considerable variation in presentation of results exists. Within the confines of this paper it has been possible only to generally describe the methodologies and presentations. In addition, not all of the urban areas that have been treated have been considered. Notably

the work done at Adelaide (McCue & Love, 1997), Rockhampton (McCue & Boreham, 1996) and Launceston (Michael-Leiber & Jensen, 1997) has been omitted.

8.2 If the results of past and future studies are to be incorporated into the Australian Building Code, then some form of commonality in earthquake risk microzonation methodology has to be decided on. This would necessarily involve standardisation of data collection, data assessment, and results presentation. An extensible methodology, that allows aggregation of diverse data sets, so that the relative vulnerability to ground shaking between dispersed areas can be derived, is recommended.

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# EARTHQUAKE RISK MODELLING IN AUSTRALIA AND IMPLICATIONS FOR RISK TREATMENT

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## **ABSTRACT.**

Probabilistic earthquake risk models are being used as the basis for the development of the Australia-New Zealand building code and for application to a wide range of risk treatment options. This paper provides an overview of earthquake risk modelling and discusses key issues that limit the accuracy and applicability of models as well as some of the priorities for research to address these issues. The paper also presents a brief introduction to a study of the Newcastle earthquake being undertaken by AGSO-Geoscience Australia, as a benchmark study of earthquake risk in Australia.



## 1. INTRODUCTION

Risk is the combination of hazard x elements at risk x vulnerability. It is essentially the probability that something bad will happen to something or someone from a given hazard over a period of time. Earthquake risk can be formally quantified via the processes outlined in Figure 1:

- The earthquake hazard model combines the probability of occurrence of earthquakes of any given magnitude and location with the distribution of ground shaking amplitude or soil failure at the surface of the earth.
- The elements at risk are the buildings, people, social function, lifelines and other infrastructure that make up our urban or built environment.
- The vulnerability of the elements at risk can be expressed as the potential for physical damage, economic cost or loss, loss of function or loss of life, or other social or environmental impact.
- Hazard, elements at risk and vulnerability are combined in a risk analysis to determine the probability of occurrence of various hazard events and their consequences or impact.

## 2. KEY ISSUES

The major limitation to the development of robust earthquake risk models is the lack of data. Damaging earthquakes are a relatively rare occurrence in Australia. Our ability to forecast the occurrence of future earthquake events and to estimate their consequences is dependent on the availability of information about past events. The most significant damaging earthquake to have occurred in Australia since major urban development began is the magnitude 5.6 Newcastle earthquake in 1989. In the absence of more earthquakes, there are many things that can be done to improve our understanding of the risk and to capture this knowledge into useful risk models.

Earthquake risk models are designed to allow us to combine what we know from past events in order to extrapolate to the future. The best models are a combination of historical data and parametric representations of our physical understanding of the process. Thus we do not rely on having had a major damaging earthquake in Sydney in order to predict its probability of occurrence or impact. Several specific issues are identified below, together with suggested research needs and priorities.

Earthquake occurrence. Present earthquake hazard models of Australia are based on simple statistical regressions of magnitudes and locations of historic events. The models assume earthquakes occur in a uniform random pattern over a given geographic area or a geologic domain and that the underlying rate of occurrence is constant or independent of time. The relationship of earthquakes to active faults is largely unknown. What is needed is a better understanding of the state of stress and strain of the Australian plate, and its relationship to occurrence of earthquakes. This information will only be gained through a long-term commitment to research in paleoseismology, geodynamics and tectonics. Through this research we will be better able to identify potentially active faults and areas where large damaging earthquakes are most likely to occur in our lifetimes.

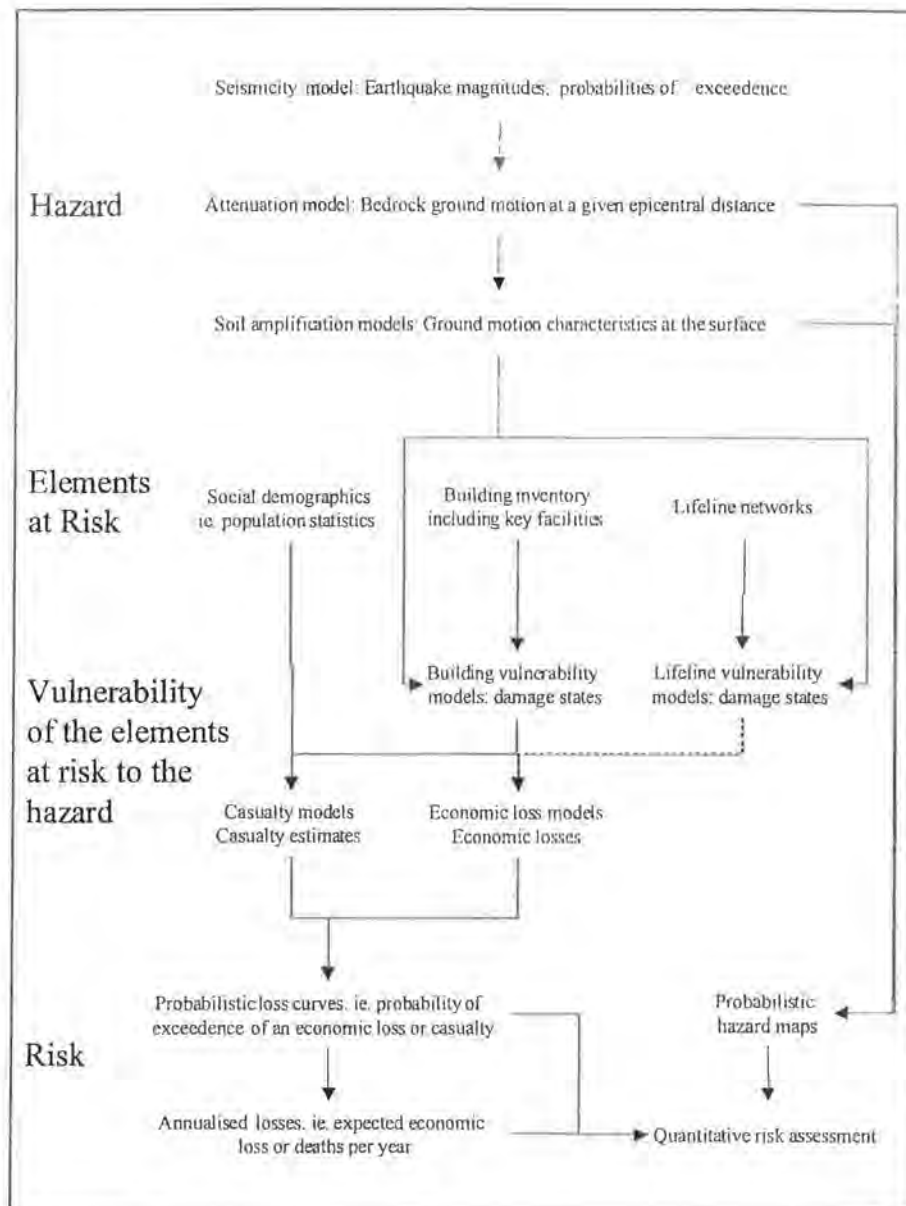


Figure 1. Flowchart of earthquake risk modelling process

Seismic attenuation. Seismic attenuation models predict the level of ground shaking to be expected as a function of magnitude and distance from the location of an earthquake. Present models for Australia rely on limited data from seismic intensity observations and either ignore near-surface soil conditions or consider only a uniform “rock” condition (e.g., Gaull et al. 1990). In the development of probabilistic hazard models, it is common practice, and indeed considered “state of the art”, to apply attenuation models developed from other continents (e.g., Lucas Heights review). It is not known, for instance, whether earthquake ground motion in eastern Australia is more consistent with an active tectonic environment (e.g., western North America or Japan), or whether it is more consistent with a stable continental region (e.g., eastern North America or India). The differences are large and fundamental. One or more Australian-based models can and should be developed utilising existing data from earthquake network observations and seismic crustal studies. These data can be supplemented by specific

wave propagation studies using aftershocks and mine blasts, and simulations of earthquakes using deterministic and stochastic ground motion models.

Site amplification and soil failure. Site amplification and soil failure models predict the details of local effects of earthquakes at the ground surface. Ideally, the acceleration or velocity as a function of frequency (or period) of vibration, or the permanent displacement of the ground are provided. These values provide the basis for estimating building damage or other impacts on the urban environment. Very little information is available about the dynamic properties of soils in Australia to know how they would respond to earthquake shaking. Key data include shear wave velocity, damping and stratigraphy as a function of depth, depth to bedrock and depth to water table, grain size, clay-silt-sand content, and blow counts. Typically, geotechnical studies undertaken for foundation engineering address bearing capacity under static loads, but not dynamic properties of soils under earthquake loads. Significant progress can be made on improving site classifications for earthquake ground response by supplementing existing geotechnical and surface geological data in urban areas with seismic microtremor and seismic cone measurements. Both of these approaches are being used successfully in our present studies in Newcastle. There is evidence that airborne magnetic observations can also be used to constrain soil depths under certain conditions, but this method remains untested for earthquake hazard applications.

The soils data can be used to develop site amplification or failure classes using simple one-dimensional analyses (e.g., Dhu et al. 2001) which assume vertical propagation of seismic waves through the soil column. This approach can be particularly effective in areas (e.g., Newcastle) where there are reasonably shallow and recent (e.g., Quaternary) sediments overlying rock. In deep sedimentary basins or areas with a very gradational seismic velocity, it may be appropriate to evaluate basin response in terms of the effects of two- and three-dimensional wave propagation, provided the high-frequency response (e.g., above 1 Hz) of principle concern to the impact on most structures can be captured or approximated in the analysis.

Elements at risk. Inventories of buildings and classifications of structure types are needed to establish the 'elements at risk' for input to earthquake vulnerability and risk analysis of urban centres. These data are not commonly collected, and certainly not to specifications appropriate for assigning buildings to vulnerability classes. It is important to note that it is not necessary to obtain information about every building or facility. Detailed characterisations can be limited to critical facilities (e.g., hospitals, fire stations, lifelines), together with statistically-based sampling of common commercial and residential buildings types. Emphasis should be placed on sampling information about common structural systems and clearly identifying characteristics of buildings that would mitigate or exacerbate damage in an earthquake (e.g., shape irregularity, soft story, applicable building code, maintenance or condition).

Vulnerability. Earthquake hazard in Australia is dominated by moderate shaking, with relatively high energy in the high-frequency portion of the spectrum. The overall general performance of structures under these conditions is reasonably well understood in terms of yield points and total failure, but the details of vulnerability in terms of intermediate damage states is poorly constrained. While Australian building design and



practice is similar in many respects to other parts of the world, there are differences in detail that make direct comparisons with earthquake experience elsewhere difficult. Moreover, it is extremely difficult to translate estimates of physical building damage into economic costs and time of repair.

Simplified approaches to developing 'damage curves' (e.g., Stehle et al. 2001a) can provide constraints on damage states, but are only approximate and are limited by lack of calibration data. More detailed and potentially accurate dynamic analyses are well-suited to individual structures, but have yet to be proven practical for developing damage curves for broad classes of buildings. Some progress has also been made in evaluating the empirical performance of structures in Australia through shake table tests and from post-disaster data collection, especially from the 1989 Newcastle earthquake (Stehle et al. 2001a). Other costs of community/social impact and indirect economic costs are even more problematic; however, we can not begin to understand these and other downstream ripple effects unless we first have a good understanding of the hazard and impact in terms of 'engineering' damage.

Uncertainty. The best models also take into account the uncertainty of their predictive abilities. Models often attribute uncertainty to the randomness of nature, but seldom recognise that a very significant part of the uncertainty is due to our lack of knowledge. In simple terms, the difference between "random" and "knowledge" uncertainty is between what is knowable given present-day scientific thinking or models, and what is not. Without proper accounting of uncertainty our earthquake risk estimates tend to overestimate the confidence of our predictions, which in the long run can only serve to undermine their ultimate application and benefit. It is therefore essential that we strive to incorporate competing approaches and theories for all components of the earthquake model and, where appropriate, develop scientific and engineering consensus of the likelihood that they are actually correct.

Decision Making. The aim of all risk models is to provide value-added information that is useful for making decisions about the treatment of risk. Risk assessment is a necessary but not sufficient part of the process. Analysis results must be put into the context of other risks as well as within the broader context of a range of social, political and economic issues that drive decision-making (or lack of it). Of these, economic factors are probably the easiest to address objectively. Risk treatment options can best be justified in terms of a cost-benefit analysis. For instance, the benefits of improving building codes can be evaluated in terms of the reduction in cost/damage to buildings (and, in turn, injury or loss of life) that might be impacted by future events. A wide variety of treatment options exist, including insurance, building retrofits and codes, emergency-response and land-use planning. An understanding of the risks and the cost-benefits of mitigation form the basis for more informed decision making, whether for a community, a home-owner, or a commercial investor. Earthquake risk models can and should be improved to the point where objective decisions can be made about the options for risk treatment and, of course, earthquake risks need to be put into the wider context of urban risk from other natural, environmental and man-made sources so that objective decisions can be made to treat risks from all sources.

### 3. NEWCASTLE EARTHQUAKE STUDY

A magnitude 5.6 earthquake struck about 12 km from the centre of Newcastle, NSW, on December 28, 1989, causing more than \$1.2 billion in direct losses (Melchers 1990). This is one of the most costly natural disaster to have struck Australia. A complete reassessment of the 1989 event is being undertaken, and used as the basis for the development of a comprehensive earthquake risk assessment model for application to urban centres throughout Australia. The Newcastle earthquake model comprises:

- A hazard model including an expert assessment of the probability of earthquake occurrence (locations, frequency-magnitude distribution, maximum magnitude), ground motion attenuation, and detailed soil amplification factors (Sinadinovski et al. 2001; Dhu et al. 2001).
- A building and lifelines database based on a 10% sample survey of attributes of approximately 8,000 buildings in the Newcastle - Lake Macquarie area, plus census and lifelines data and damage statistics from the 1989 event.
- A vulnerability model for principal construction types and age classes appropriate for Australian conditions, and, especially, Newcastle (Stehle et al. 2001).

Interim results of a complete risk analysis are presented by Stehle et al. (2001b). Results are computed in terms of annual probability of exceedence for direct damage/cost to buildings and lifelines, and for casualties. In this analysis, the 1989 event is placed in the probabilistic context of all possible events that might occur in the area. Finally, Stewart et al. (2001) discuss the status of earthquake damage mitigation efforts in Newcastle and the impact of the present study by Geoscience Australia on these efforts.

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