ASSESSING THE EARTHQUAKE RISK TO AUSTRALIAN CITIES: NEW DEVELOPMENTS

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ABSTRACT:

Reliable information on the earthquake risk to major Australian urban communities is required to optimise risk mitigation and response actions. AGSO's *Cities Project* continues to develop earthquake risk assessment methods as part of multi-hazard risk assessments for Australian cities. We use case studies to illustrate new developments.

A four-stage generic method to prepare urban earthquake hazard maps has been adapted for use in Australia. Microtremor data provide additional information on natural period of vibration of the ground. The vulnerability of the community is estimated using comprehensive geocoded building, infrastructure and demographic inventories. Fragility and recovery curves describe the vulnerability of physical urban assts. Risk is assessed through a convolution of the hazard and the vulnerability of the elements at risk.

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by

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1. INTRODUCTION

Reliable analysis of the earthquake risk to major Australian urban communities allows emergency managers, planners, insurers, reinsurers and others to optimise risk mitigation and response actions. Our premise is that this risk, largely, is not known at present.

AGSO's *Cities Project,* with partners, continues to develop its earthquake *Risk-GIS* assessment methods as part of multi-hazard risk assessments for Australian cities.

In a strong earthquake, urban damage phenomena are expected to be complex and GIS analysis is probably the only environment capable of handling risk analysis at this scale. Essential ingredients for the earthquake risk analysis process include hazard information for a range of annual exceedence probabilities, comprehensive building, infrastructure and demographic inventories, and vulnerability information for the various elements. Risk is assessed by convolving the hazard, the number of elements at risk and their vulnerability. Stewart (these Proceedings) defines these terms.

Although a computerised risk analysis system is an excellent tool to estimate earthquake losses in near real time in response to a major event, the likelihood of the occurrence of such a major event in Australia is relatively rare. Difficulties are likely to occur in maintaining both the availability of essential datasets and the capability to operate the analysis tools when, and if, required for response. Rather, the primary value of such decision support tools in Australia is to apply them ***before the event*** - to risk analysis, to assessing remediation measures, and to planning for response.

2. CASE STUDIES

The risk to Cairns from various geohazards has been compared [(1)] . This risk is greatest from tropical cyclones, but the Cairns community has a high level of residual risk exposure to less frequent and more severe events, including strong earthquakes. Geohazard events with an annual exceedence probability of 0.2% or less will inevitably cause significant economic harm and some (and potentially significant) loss of life.

Inventory data for Cairns were compiled for individual parcels or at Census Collector District (CD) level, and comparisons of community vulnerability were generalised to the suburb level. We assessed the vulnerability of the Cairns community through an analysis of 26 parameters under the five headings *Setting* (the physical environment, external access and administrative arrangements); *Shelter* (the buildings and mobility of the community to access them); *Sustenance* (lifelines, food, clothing, and medicine); *Security* (the health and wealth of the community); and S*ociety* (language, ethnicity, religion, nationality, community groups, education, awareness). We ranked Cairns suburbs for their contribution to overall community vulnerability and separately for exposure to earthquake. Overall earthquake risk ranking was then calculated through an intersection of these two rankings.

The ten suburbs most at risk to earthquake have diverse compositions. A range of usages are present in Manunda, Parramatta Park and Westcourt; Cairns North contains much tourist accommodation; and Bayview Heights, Earlville, Edge Hill, Mooroobool, Whitfield and Woree are predominantly residential. Newly developed suburbs fare better than old or established suburbs in the ranking, largely through the use of more appropriate building construction types. Interestingly, City does not rank in the top ten positions, simply because of its low total number of buildings, although if the importance and cost of buildings and risk of casualties were considered, its ranking would be higher.

In extreme events, the loss of critical facilities, especially in Cairns North, City, Parramatta Park and Portsmith, will add to the magnitude of the risk posed directly by the hazard event itself. These secondary risks are likely to have an effect for a considerable period of time after the initial impact.

We have not included estimates of dollar losses or casualties in our earthquake risk analysis for Cairns. Available methods for calculating direct earthquake losses mostly refer to ground shaking in terms of the Modified Mercalli Intensity scale, but Modified Mercalli Intensity does not describe ground shaking adequately. We prefer instead to continue to develop earthquake risk assessment methods based on spectral parameters.

Case studies nearing completion include ACT and Mackay, and results of these will be presented at the Symposium.

3. DEVELOPMENTS

A four-stage generic method to prepare code-compliant urban earthquake hazard maps has been applied and is proposed for use in Australia. Microtremor data provide additional information on natural period of vibration of the ground. AGSO has also begun to develop high resolution seismic imaging, *in situ* shear wave velocity measurement and waveform modelling techniques to improve urban hazard estimates.

The Cities Project is commissioning a sensitivity analysis of the methodology used to assess community vulnerability in Cairns. This analysis will determine the significance of individual parameters on the vulnerability assessment and will also test the impact of assessing vulnerability at CD level rather than by suburb.

AGSO, partly funded by Emergency Management Australia, is assessing the suitability of the HAZUS earthquake loss assessment computer modelling programs of the US Federal Emergency Management Agency for Australian conditions. The building inventories we are developing for case studies are compatible with HAZUS categories.

4. REFERENCES

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CHANGED PERCEPTIONS OF EARTHQUAKE HAZARD IN AUSTRALIA - POST NEWCASTLE 1989

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ABSTRACT:

The 1989 earthquake near Newcastle has changed the Australian psyche regarding earthquakes in continental Australia. Engineers and the media now accept that earthquakes are a threat to the safety of the community who are now prepared to use the current loading code for design and construction and to pay for improved monitoring. The risk to major urban areas remains however the stock of old, poorly maintained URM pre-code buildings.

INTRODUCTION :

To appreciate the changed perception of earthquake hazard in Australia since the Newcastle earthquake we have to recall the situation that existed at the time of the earthquake:

- Newcastle was rated zone zero in the Seismic Zone Map that was part of AS2121-1979 (Figure 3.1, p13). However even for buildings in the non-zero rated areas of the map, no earthquake resistant design was mandatory because the State of NSW had not called up the code. The code commentary notes that zone zero did not imply that the risk was zero – just that the mandatory requirements were zero because the implied threat was low.
- The nearest seismograph and accelerograph to Newcastle were in Sydney at Lane Cove and south of Sydney at Lucas Heights respectively, more than 100 km away.
- Neither seismology nor earthquake engineering were taught at the University of Newcastle so there was no earthquake culture amongst the engineering profession.
- There was no earthquake engineering society in Australia to promote knowledge of the principles of earthquake engineering nor to provide post-disaster response advice.
- The previous earthquake history of Newcastle was not recognized by Newcastle City Council and population as a whole.
- There was no record of the ground shaking caused by a magnitude 5 or greater earthquake within 50 km of an epicentre in Australia, no data on the intensity, duration or frequency content of the shaking, nor on how the ground shaking changes with foundation type, rock or soil.

THE LESSON LEARNED

It is my contention that the lessons of Newcastle have not only not been forgotten in the last decade but have substantially contributed to our safety. It is more important that they not be forgotten in the future. As a result of the 1989 Newcastle earthquake much has changed for the better:

- The new Loading Code AS1170.4 has been called up into the Building Code of Australia and an estimate of the 10% in 50 year *pga* ground motion is mapped throughout the continent.
- The Hunter region is now monitored both with seismographs and accelerographs.
- The AEES is a thriving society with a register of professionals able and willing to participate in post disaster response functions.
- An excellent book on the earthquake history of the Newcastle region was published[1] so that no one can now be excused for not knowing the history and potential hazard.

The promise made by the then mayor of Newcastle to facilitate establishment of a chair of Earthquake Engineering at Newcastle University has not eventuated but it was probably always outside the Council's scope to influence the university curriculum.

On the negative side, the old and most vulnerable buildings in 1989 are now older and more vulnerable and the code does not address the issue of their safety unless they are substantially modified. These old buildings contribute most to the risk of failure in earthquakes, another lesson of Newcastle 1989 and of Adelaide 1954 before it.

THE NEWCASTLE EARTHQUAKE ALERT

Video footage of an interview in Newcastle at the time of the earthquake demonstrates that the ground shook strongly for just a second or two, more like an explosion, and that it was not immediately recognised by the interviewee and camera crew as an earthquake. At the ASC in Canberra 300 km away there were only two officers on duty, it being Christmas holiday time, but we felt the slight vibration and ran to the analogue drum recorders in the foyer of the building to investigate. The pen on the Canberra recorder was banging from side to side and as we watched the first P seismic waves arrived at Toolangi near Melbourne, then Moorlands in Tasmania and finally Woomera in South Australia. Digital data was telemetered into the ASC at the time from Alice Springs and Warramunga in the Northern Territory and Mawson in Antarctica.

The paper records had to be changed and the arrival times read and typed into the computer program. With such a sparse network it was difficult to determine an accurate epicentre quickly and, because most of the analogue stations were clipped no reliable magnitude could be determined for some hours. An aftershock monitoring team could not leave Canberra until 6 hours after the earthquake because of the lack of a readily available aftershock kit.

Compare that with the situation today; data from more than 30 stations of the National Seismographic Network throughout Australia are telemetered into AGSO in near real time. Many of the stations have triaxial broad-band seismometers as opposed to the vertical short period stations of 1989. An earthquake alert system interrogates this telemetered data and pages seismologists 24 hours per day when an earthquake is detected so that a rapid earthquake alert and tsunami warning can be provided to the Emergency Management Agency, governments and media. This system is backed up by an independent pager system operating on a separate seismograph network in SE Australia and alternative communications carrier by the Seismology Research Centre. Earthquakes can normally be located and advice provided in a 30 to 40 minute time frame.

Earthquakes of magnitude 3.0 or more can be detected in the Hunter region on the National network and smaller earthquakes are recorded on the four local area network stations, one component of the North Lambton station is telemetered into the Newcastle Regional Museum and onto a drum recorder. In addition there are now several digital triaxial accelerographs in Newcastle.

As a result of the Newcastle earthquake AGSO now has a modern accessible six station aftershock kit which has been successfully deployed in Australia and Papua New Guinea.

THE GROUND SHAKING IN NEWCASTLE

In December 1989 there were no instruments in Newcastle capable of recording the ground shaking. Coalmine blast recorders were saturated. Any analysis of the failure of the Workers Club or Junction Motel is dependent on a knowledge of the earthquake input.

Temporary instruments were installed the day after the earthquake in a small network around the city in time to record the single small aftershock which had proven most useful.

Following the Newcastle earthquake, AGSO and State Government representatives met in early 1990 and agreed that all cities of 50,000 people should be instrumented with seismographs and at least two accelerographs, one on rock, the other on soil (the joint urban monitoring program - JUMP). There were not sufficient funds for the seismographs but AGSO purchased the accelerographs and the States installed and maintain them. This strategy has been very successful since most of the stations have recorded earthquakes. In 1994 a magnitude 5.2 earthquake struck Cessnock[2,3], its epicentre only 30 km west of the 1989 earthquake and this time good recordings were obtained of the ground motion, not just in Newcastle but also in Sydney and on dams south of Sydney in the distance range 43 to 300 km.

The aftershock data has been used to estimate the *pga* in Newcastle during the 1989 earthquake. Wesson[4] and Sinadinovski[5] used independent synthetic methods, phase spectrum and empirical Greens function respectively, to estimate the *pga* of the 1989 Newcastle earthquake resulting in substantially identical results of about 0.2g.

NEWCASTLE'S CONTRIBUTION TO THE NEW LOADING CODE

A number of earthquakes in the magnitude ranges 5.0 to 5.3 and 4.0 to 4.3 have now been recorded in NSW, Victoria, South Australia and Western Australia in recent years on JUMP and other instruments. Suitably scaled, these recorded *pga*'s are being used in a new attenuation equation in the current revision of the Loading Code.

In a separate study[6] a rock spectrum has been developed for the Loading Code from a carefully selected suite of accelerograms recorded worldwide and scaled to a peak ground velocity of 50mm/s which is typical of the 1 in 500 year peak ground velocity for most southeast Australian cities. Comparison of the synthetic accelerograms of the Newcastle earthquake against this spectrum are very encouraging.

REMAINING PUZZLES

The Newcastle area has been hit by earthquakes of magnitude about 5 in 1837, 1841, 1842, 1868, 1925, 1989 and 1994. The Hunter region network that has been operating since 1990 was expected to record numerous smaller earthquakes but few have been observed, the latest a micro-earthquake on 12 August 1999. Why?

Sydney and Newcastle are only 100 km apart and both are in the Sydney Basin yet their earthquake histories of the last 150 years are dramatically different. Why?

DISCUSSION

The reference list and code progress show the benefits of having a vibrant earthquake engineering society with close interaction between engineers and seismologists in Australia and strong links to the IAEE and NZNSEE.

AEES members have made a strong contribution to the development of the new loading code through membership of the Standards committees and participation in AEES, NZNSEE and PCEE conferences.

Monitoring must be for the long term! Each earthquake teaches seismologists and earthquake engineers vital lessons for improving community safety in a cost effective manner. For the first time we have hazard maps and spectra in the new Loading Code which are relevant to Australian earthquakes. More data will allow us to further optimise the hazard and risk analyses. Some Australian buildings should be instrumented.

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ACCELERATING SEISMIC ENERGY RELEASE BEFORE MODERATE TO LARGE EARTHQUAKES: THREE AUSTRALIAN EXAMPLES

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ABSTRACT:

There is increasing evidence that a portion of moderate to great earthquakes worldwide are preceded by a period of accelerating seismic energy release before their occurrence. Here we describe examples of this phenomena associated with recent Australian earthquakes; namely the 1997 M=6.2 Collier Bay, Western Australia, the 1997 M=5.1 Burra, South Australia and 1999 M=4.7 Appin, New South Wales earthquakes. The time and size scales associated with this phenomena, years to decades in time and tens to hundreds of kilometers in space, have likely impeded their prior recognition. These sequences can be modeled with a power-law time-to-failure relationship that gives reasonable predictions of the time and magnitude of the mainshock. In general, the predicted occurrence times of the Australian examples, are one to several years before the actual mainshock. We place these examples into context by comparing them to cases from other settings.

1 Introduction

It is observed that some fraction of moderate to great earthquakes are preceded by an increase in smaller magnitude events in a broad region surrounding the oncoming mainshock during the years to decades before the event. When the earthquake strain release in these regions is viewed as either cumulative seismic moment or Benioff strain (the square root of seismic energy), the rate of seismic energy release is seen to accelerate as the time of the mainshock is approached. In some cases this accelerating energy release can be modeled with a time-to-failure relationship[8] that gives reasonable predictions of the time and magnitude of the mainshock event. In addition, the size of the region over which this acceleration takes place scales with the size of the oncoming mainshock (hereafter called the critical region). This behavior has now been recognized in both plate boundary and intraplate regions. Here we describe examples of this behavior before three recent moderate Australian earthquakes, using them to illustrate the main features of accelerating seismic energy release prior to moderate-to-large events.

2 Background

The three largest earthquakes (M $\geq$ 7) in the San Francisco Bay region of northern California (1868, 1906, and 1989) were preceded by a period of accelerating seismic moment release in the decades before those events[7]. Bufe and Varnes[3] modeled these accelerating sequences (quantifying energy release as Benioff strain) using a power-law time-to-failure relationship of the form:

$$\Sigma\Omega(t) = A + B(t_f - t)^m \qquad (1)$$

where Ω is Benioff strain, t_f is the time of the mainshock, t is the time at which $\Sigma\Omega$ is sampled, m is the power-law exponent, and A and B are constants to be determined. They found, using only pre-mainshock earthquakes, reasonable predictions of the time (within a few years) and magnitude ($\pm$ 0.5 magnitude units) of the mainshock could be made[3]. Recent work in other regions suggests similar levels of accuracy in intermediate-term predictions[2].

Besides an acceleration in the rate of seismic energy release, three other features characterize this phenomena[5]: a) the earthquakes that comprise the accelerating sequence occur outside the rupture zone of the mainshock, b) the size of the region over which the acceleration occurs scales with the magnitude of the mainshock, and c) the increased seismicity rate is limited to events within about 2.0-3.0 units of the mainshock magnitude.

3 Three Australian Examples

In early 1999 we began researching the catalog of Australian earthquakes to see if there were examples of this behavior within Australia. We wished to examine main-shock events for which there was an earthquake catalog complete for events within 2.0 magnitude units of the mainshock for a considerable time period (preferably decades) prior to the mainshock. We focused our search on M $\geq$ 5 earthquakes that occurred during the mid-to-late 1990's. Initially four earthquakes met our criteria, the 1994 M=5.4 Ellalong, NSW earthquake, the 1996 M=5.0 Thompson Dam, Victoria earthquake, 1997 M=5.1 Burra, SA earthquake, and 1997 M=6.2 Collier Bay, WA earthquake. During the course of our study an M=4.7 earthquake occurred near Appin, NSW; after a brief review it was decided to also include that event.

Upon reviewing the four events initially selected, we realized that the timing of two of these events (1994 Ellalong and 1996 Thompson Dam) may have been influenced by human activities. The 1994 Ellalong earthquake was very shallow (depth = 1.4 ± 2.3 km) and located near or possibly beneath the active Ellalong Colliery(6). The 1996 Thompson Dam earthquake has been identified as an example of reservoir-induced activity(4). In addition, the 1994 Ellalong earthquake is located very close in both space and time (30 km and 5 years) to the 1989 M=5.6 Newcastle, NSW earthquake. For the above reasons these two events were excluded from further study.

For the remaining events plus the 1999 Appin earthquake, several initial search radii were selected based upon the relationship between area and magnitude seen for other cases(5). Cumulative Benioff strain was computed starting at the earliest date from which the earthquake catalog appeared to be complete at a magnitude level 2.0 units below the mainshock magnitude. All three cases showed evidence for accelerating energy release with time prior to the mainshock. A preliminary fit of equation (1) to the cumulative Benioff strain prior the 1997 Burra and Collier Bay earthquakes yielded estimated mainshock times and magnitudes within 3.3 years and 0.5 magnitude units of the actual mainshocks.

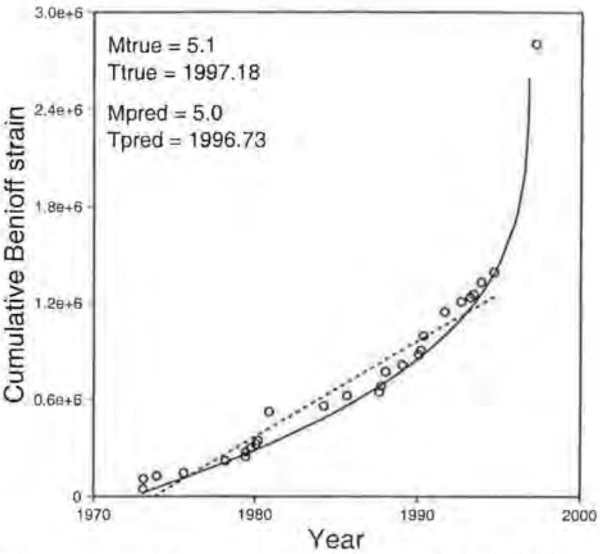
Based upon the results above, we decided to search for optimal radii using the methodology of Bowman *et al.*(1). In this method the mainshock time and magnitude are fixed and the search radius varied. The fit to equation (1) is calculated together with a least-squares linear fit to the same data. The ratio of the power-law rms error to the linear rms error is used as a measure of goodness of fit. The radius at which this function is minimized is taken as the optimal radius.

Figure 1 shows the cumulative Benioff strain release within 70 km (optimal radius) of the epicentre of the 1997 Burra, South Australia earthquake, together with the corresponding fit to equation (1) and a linear seismic release model. Of the three cases, the seismicity prior to the Burra event generally yields the most accurate predictions of the time and magnitude of the oncoming event. For all three cases (Appin, Burra, and Collier Bay), the error in the predicted times and magnitudes varied according to size of the search region and magnitude range of preceding events used; in general predictions were within 4 years and 0.5 magnitude units. In all cases the predicted times were earlier than the actual event times.

4 Discussion and Conclusions

An important issue when attempting to model the time of history of seismic release in any region is the quality and consistency of the earthquake catalog. The most important factors are the magnitude level at which the earthquake catalog is complete and the consistency of magnitude determination through time. We have found that the earthquake catalog in the vicinity of the 1997 Burra event appears

Figure 1: Cumulative Benioff strain (square root of seismic energy) release for M $\geq$ 2.5 earthquakes (circles) within 70 km of the epicentre of the 1997 M=5.1 Burra earthquake, together with the corresponding time-to-failure (solid line) and linear (dashed line) model fits. The predicted and true earthquake times and magnitudes are also shown. A power-law exponent (m) of 0.3 was used in equation (1).



to be the most consistent and complete. The earthquake catalog in the vicinity of the 1997 Collier Bay earthquake suffers from completeness problems. Ideally we need a catalog complete at a magnitude 4.0 level for that case; our work suggests the completeness level since the mid-1960's is closer to 4.5. The case for the 1999 Appin earthquake is more complicated. There are systematic differences in magnitude determination in that region after 1994 between earthquake catalogs kept by the Australian Geological Survey Organization and the Seismology Research Centre, with the SRC catalog having smaller magnitudes for larger events. At present, we are assuming that the AGSO catalog is the more consistent over time, since the SRC installed new instrumentation near Sydney in 1992 (A. Pascale, pers. comm.). We note, however, that our conclusions about the Appin sequence are very dependent upon the earthquake catalog used.

Although the three sequences examined here all show positive results, not all large earthquakes in Australia show this behavior. For example, the 1988 Tennant Creek earthquake sequence was preceded by very local foreshock activity over the course of one year but no regional earthquakes during the thirty years prior to the mainshocks; this behavior is not consistent with the pattern reported here[5]. We are pursuing ongoing theoretical and computer simulation studies to define under what physical conditions the behavior reported here can be expected to occur.

Figure 2 shows the relationship between the size of the region in which the accelerating energy release sequences occur and the magnitude of the mainshock. The three Australian cases described here fit together well with observations from the USA, suggesting that the scaling between mainshock size and area is similar in both places.

We have found three examples of accelerating seismic energy release before recent moderate Australian earthquakes. The fit of a power-law time-to-failure relationship to this data yields reasonable predictions of the time and magnitude of the mainshocks, with the predicted times generally being several years before the actual mainshock occurrence. The size of the region over which the accelerating seismicity occurs scales with the mainshock magnitude and is consistent with observations from other parts of the world. These results suggest it may be possible to make useful intermediate-term predictions of moderate earthquakes in some parts of Australia.

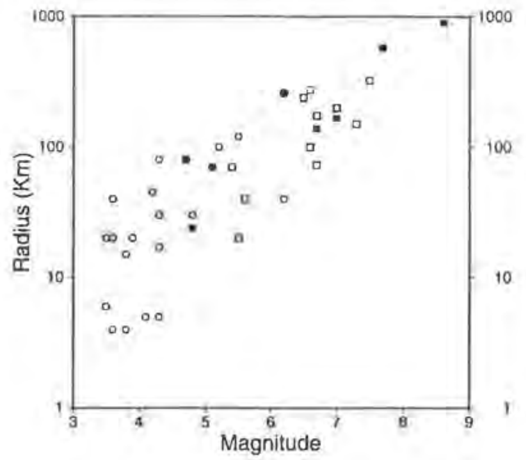


Figure 2: Critical region radius versus mainshock magnitude for cases of accelerating seismic energy release in Australia (closed circles), central USA (open circles), California (open squares), and other plate boundary regions (closed squares). Modified from Jaumé and Sykes[5].

Acknowledgements

We thank the AGSO, PIRSA, and SRC for sharing earthquake catalog data with us. We thank D. Varnes for reviewing the manuscript. This work was supported by the Australian Research Council and the sponsors of QUAKES.

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PLEISTOCENE FAULTING OFFSHORE NEWCASTLE, NEW SOUTH WALES

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ABSTRACT:

Sparker reflection profiles show a Pleistocene-age Newcastle fault offshore of Newcastle, Australia. The fault is expressed as a monocline that strikes N30^{0}W, similar to the strike of the focal mechanism solution of the 1989 Newcastle earthquake. The southwest block is uplifted which is consistent with the shallowly southwest-dipping nodal plane of an aftershock of the earthquake. Although the Newcastle fault does not extend far enough north to have caused the earthquake, it is oriented so that it is capable of an earthquake under the present stress regime. Further study is needed: (1) to map the southeastern extent of the fault so that possible rupture area and magnitude can be calculated, (2) to dig wells to correlate the Quaternary stratigraphy across the monocline to determine the uplift rate, and (3) a continued effort to find subsurface evidence for the fault strand that did cause the earthquake.

1. INTRODUCTION

Sparker reflection profiles were acquired over the Newcastle fault, off shore of Newcastle, to test the hypothesis that this fault could be responsible for the 1989 Newcastle earthquake. The profiles identify a monocline in near surface sediments, which trends northwest and has the southwest side up (Figure 1). This monocline is consistent with a southwest-dipping thrust fault and thus, with one of the nodal planes of the focal mechanism solution of the earthquake[1].

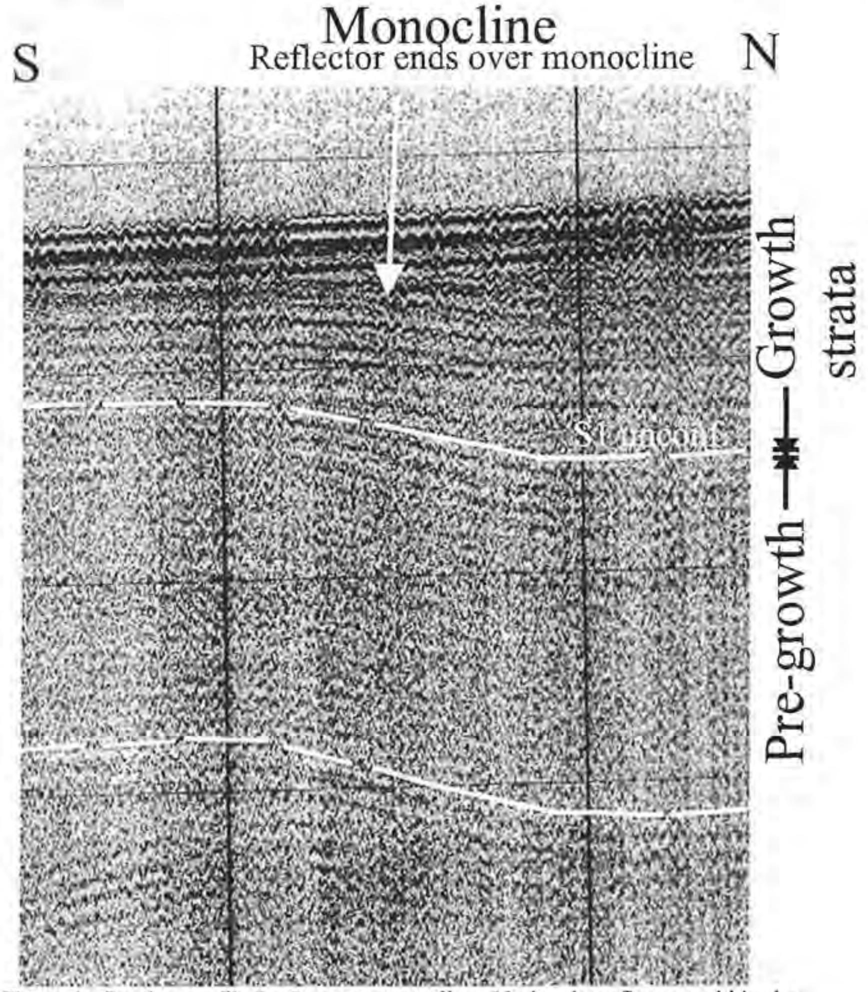

Figure 1: Sparker profile Lm7 across monocline. Notice the reflectors within the growth strata which pinch out over the monocline. The strata between the marked horizons does not change thickness across the monocline suggesting that it is older than the structure. The strata above the S1 unconformity has increased thickness northeast of the monocline suggesting that it is concurrent with growth on an underlying south-west dipping fault.

Newcastle has had 5 earthquakes in its short recorded history, 1841, 1842, 1868, 1925 and 1989[2]. The 1989 earthquake was a M5.6 event that killed 12 people and did over $1 billion damage. Following the 1989 Newcastle M5.6 earthquake, the search for surface expression of the earthquake was concentrated onshore where the moderately north-east-dipping nodal plane would reach the surface[1,3]. Partly due to budgetary restrictions, little effort was made to determine whether the shallowly southwest-dipping nodal plane could represent the fault responsible for the earthquake because it projects offshore. The similarity of the projected fault dip associated with the monocline and the west-dipping nodal plane of the 1989 Newcastle earthquake, and the Pleistocene and younger movement on the associated Newcastle fault suggest that the fault could represent further seismic risk to the Newcastle region.

2. NEWCASTLE FAULT

Far offshore, the structure is a simple monocline. The uplift is about 30m. Near shore, uplift decreases as several strands of the fault die out to the northwest. Growth sediments are restricted to those above the S1 unconformity[4]. Onshore, this unconformity separates Miocene and Pleistocene strata, implying that movement on the monocline and its associated fault is entirely Pleistocene and younger.

The fault has been mapped to the southeast over most of the continental shelf. It is not clear how far the fault continues on the continental slope. There is a bathymetric ridge on the slope based on US Defense Mapping Agency data (Figure 2). Successful mapping of the structure down the slope will help predict the extent of the seismic hazard it represents.

To the northwest, the fault separates into several strands, including a small backthrust as it dies out. The fault does not extend far enough north to have been responsible for the 1989 Newcastle earthquake. Reverse fault systems often have steps in them in which displacement is transferred from one fault to another. If this were the case, the fault would necessarily need to have stepped to the left because seismic reflection coverage offshore, west-northwest of Newcastle precludes a young fault there.

The geometry of the fault can be modelled based on the shape and amplitude of the monocline. The absence of a backlimb on the monocline suggests a relatively planar fault. The dip of the associated fault could have a range of values. The observation of the monocline is consistent with a southwest-dipping reverse fault that would uplift the southwestern block. The geometry of the monocline is not consistent with a northeast-dipping normal fault, and such a young fault would be precluded by the stress regime observed in the 1989 earthquake. It cannot be determined, at this time, whether there is any lateral movement on the fault. To date, 8 seismic reflection lines have traversed it from 2 cruises. This coverage is sparse enough to have missed any en echelon structures that would be associated with strike-slip movement on the fault. Nevertheless, the uplifted southwest block suggests a significant reverse component of slip. Analysis of stresses in coal mines shows values of a horizontal $\sigma 1$ of up to 30 MPa[5,6], suggesting either reverse or strike slip should be the dominant fault type.

3. IMPLICATIONS AND DISCUSSION

This fault may indeed be young and active. However, it does not extend far enough to the northwest to have been the fault responsible for the 1989 Newcastle earthquake (Figure 2). There are similarities between the earthquake and this fault. The strike and the uplift of the block southwest of the fault are consistent with the

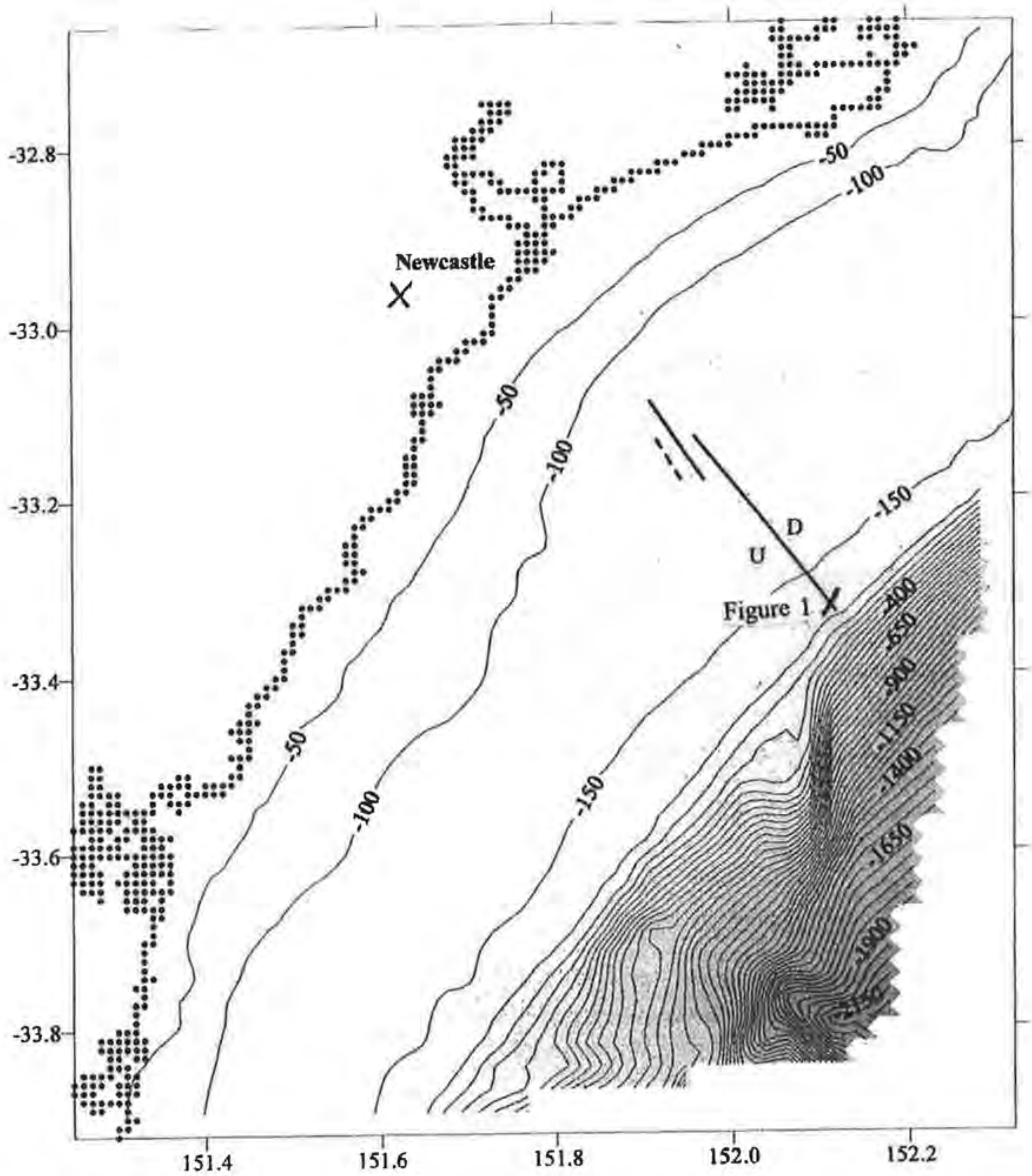

Figure 2: Bathymetric contours of the continental shelf and slope. The contour interval is 50 m. The lines in the centre right of the map are the monoclines associated with the Newcastle fault. The southwest side is up. The short line at the southwest end of the monoclines is the location of Figure 1. X marks the epicentre of the 1989 Newcastle earthquake. Notice that on the continental slope, there is a ridge that may be associated with the fault.

west-dipping nodal plane of the focal mechanism solution for the earthquake[1]. Although this structure may not be directly responsible for the earthquake, it may be related to the fault that is responsible.

Regardless of whether or not the fault responsible for the 1989 Newcastle earthquake dips northeast or southwest, the stresses that caused the earthquake appear to be at the proper orientation to cause an earthquake on the Newcastle fault. Until mapping of the structure extends to the continental slope, the magnitude of a potential earthquake[7] cannot be determined.

Further study is needed: (1) to map the southeastern extent of the fault so that possible rupture area and magnitude can be calculated[7], (2) to dig wells to correlate the Quaternary stratigraphy across the monocline to determine the uplift rate, and (3) a continued effort to find subsurface evidence for the fault strand that did cause the earthquake.

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EARTHQUAKE CLUSTERS, SMALL EARTHQUAKES AND THEIR TREATMENT FOR HAZARD ESTIMATION

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Gary wrote his first earthquake location computer program in 1971, and has been trying to learn more about earthquakes since then. He is particularly interested in earthquake hazard analysis, seismic instrumentation and the relationship between earthquakes and dams.

Amy Brown studied Geological engineering at RMIT, and has been working in earthquake hazard analysis at the Seismology Research Centre for several years. She is working on a revised earthquake hazard map of Australia that is more heavily based on regional geology than previous seismicity based maps.

ABSTRACT:

In earthquake hazard studies, several arbitrary decisions relating to small, non-damaging earthquakes may significantly affect results. These relate to:

- declustering of the earthquake catalogue
- the choice of return period which effects the character of design ground motion and the shape of the response spectrum, particularly in areas of low seismicity
- the choice of the minimum magnitude earthquake used in the ground motion recurrence computation

Australia has a large proportion of its earthquakes in shallow space-time clusters. Declustering an earthquake catalogue where events are highly clustered, infrequent and shallow leads to lower estimates of short-term hazard, but significantly higher estimates of long-term hazard.

Because small earthquakes do little damage to structures, ground motion recurrence estimates for structural purposes should either take their spectral content into account, or exclude them from peak motion calculations.

Clusters of small earthquakes provide useful geological constraints for hazard estimates by delineating active faults.

Paper No. 18

EARTHQUAKE CLUSTERS, SMALL EARTHQUAKES AND THEIR TREATMENT FOR HAZARD ESTIMATION

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INTRODUCTION

In earthquake hazard studies, there are several arbitrary decisions relating to small, non-damaging earthquakes that may significantly affect the results. These include:

- the definition of dependent events (foreshocks and aftershocks) as used to decluster the earthquake catalogue.
- the arbitrary choice of the return period (or annual probability of exceedance) can have a dramatic effect on the character of design ground motion, and the shape of the response spectrum. This is particularly so in areas of low seismicity where a short return period will emphasise motion from small earthquakes.
- the choice of the minimum magnitude earthquake used in the ground motion recurrence computation. When attenuation functions are extrapolated outside of the magnitude and distance range of the data used in their derivation, there can be significant effects on hazard estimates that depend on the form of the functions.

CLUSTERS

Australia has an unusually high proportion of earthquakes within clusters. In some areas more than 90% of catalogue events may be included in foreshock-mainshock-aftershock sequences or swarms. Swarms may involve hundreds of events, and often occur at very shallow depths within one or two kilometres of the surface. Although foreshocks and aftershocks can cause some damage, most earthquake damage is caused by the largest event in each sequence. Seismicity studies should consider the recurrence of sequences rather than individual events, and total moment rather than individual magnitudes.

Small shallow earthquakes can give very high peak ground accelerations (PGA). Although these may have the potential to cause non-structural damage to nearby buildings, earthquakes smaller than about magnitude 4 to 5, whether they are foreshocks, mainshocks or aftershocks, rarely cause damage to engineered structures.

Declustering an earthquake catalogue means removing dependent events, including foreshocks, aftershocks, and swarm events (except for the largest event in each swarm). The number of events removed is affected by the definition of dependent event.

Typically, events that are within a given time interval and a given distance of a larger event are regarded as dependent. This time interval and distance may vary with magnitude. The chosen values are arbitrary. For example, a dependent event may be defined as being within three weeks and 20 kilometres of a larger event.

In Australia, aftershocks may last for a very long period. For example, aftershocks of the Tennant Creek earthquakes of 22 January 1988 are continuing almost 12 years later. The Burragorang earthquake of 9 March 1973 was followed by aftershocks that lasted for more than a year.

The decluster interval chosen should perhaps be some small proportion of the return period of a larger earthquake *at the particular location.* A value of about one thousandth of the return period of the largest magnitude in the sequence may be appropriate. The cluster distance could be related to the rupture length for this event.

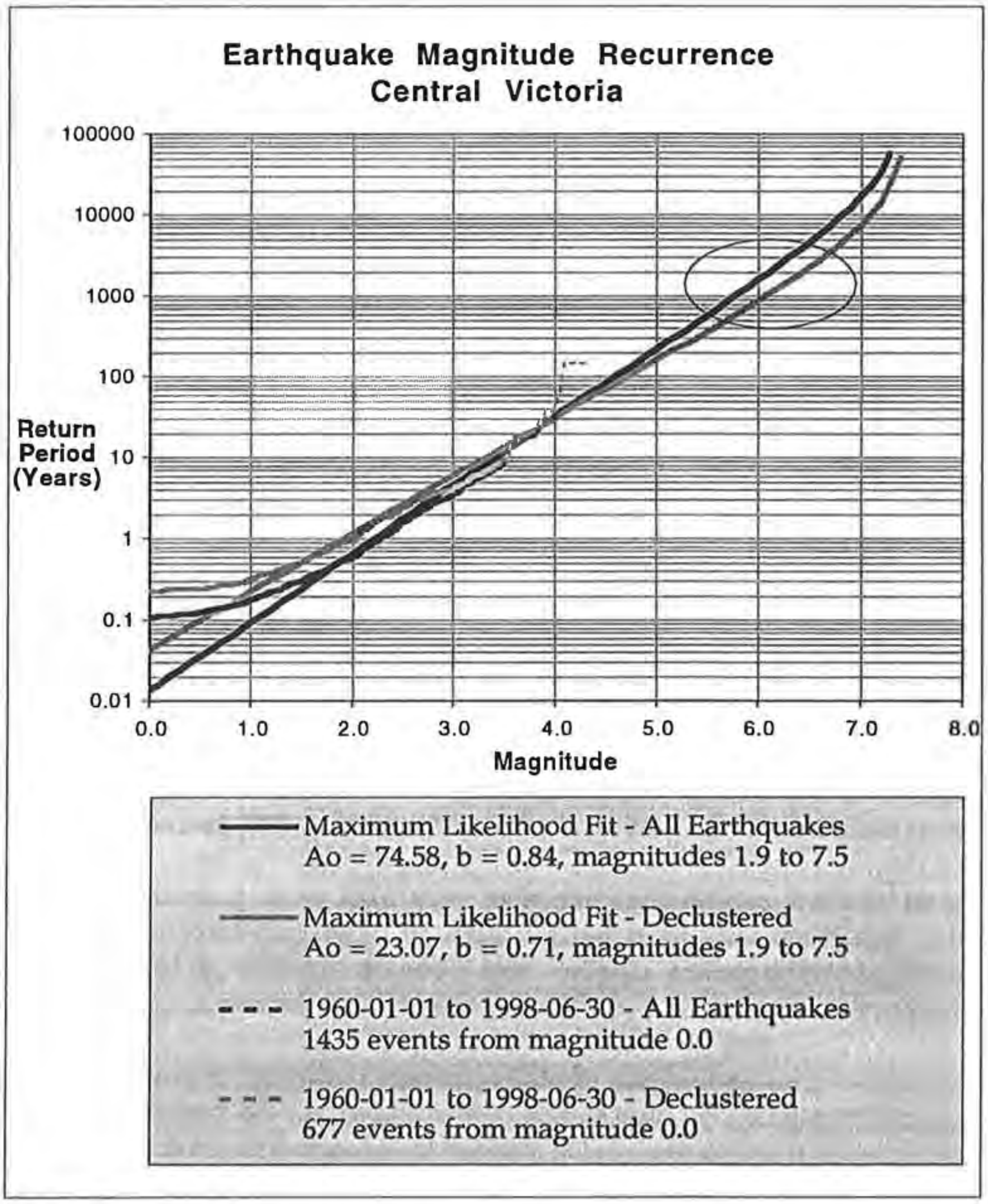

Figure 1: The effect of declustering on an earthquake hazard study in Central Victoria. A dependent event was defined as being within three weeks and 20 km of a larger event. The 1000 year earthquake magnitude for the declustered data is 6.1 compared with 5.7 for a fit using all events.

Excluding cluster events from a Cornell-McGuire probabilistic earthquake hazard study may suggest that declustering would reduce the apparent hazard in the area. However, as shown in figure 1, declustering lowers the relative number of small to large earthquakes (the b value). After extrapolation to the long return periods for larger earthquakes, this leads to a *higher* apparent hazard than when clustered events were included. Declustering also increases the apparent uncertainty in the estimates of the activity rate and b value because of the reduced number of events.

EFFECTS OF SMALL EARTHQUAKES

Earthquake hazard depends on the amplitude, frequency content and duration of the ground motion. Earthquake magnitude affects all three factors significantly. The distance from the earthquake affects amplitude, but has relatively little affect on frequency content and duration.

Earthquakes smaller than about magnitude 4 rarely do any damage to structures. Ground motion recurrence estimates for structural purposes should either take their spectral content fully into account, or exclude small events from ground motion calculations. In stable continental regions, where events are infrequent and very shallow, inclusion of small events can give estimates of PGA that are high and misleadingly conservative.

Clusters provide useful geological constraints for hazard estimates by delineating active faults. Modern portable digital seismograph systems in dense arrays, with high sample rates and precision timing, can locate cluster events to within 100 metres or better in both epicentre and depth. It may then been possible to associate the activity with a particular fault, previously known or unknown. A nearby active fault will significantly increase hazard estimates.

ATTENUATION FUNCTIONS

The shape of the response spectrum of earthquake ground motion varies significantly with magnitude and distance. Figure 2 shows response spectra for the attenuation function given by Sadigh and others, 1997. The magnitude and distance ranges of the data used to derive the function are emphasised.

Small earthquakes produce relatively little low frequency motion, so the gradient of the spectrum up to peak response increases significantly with decreasing magnitude. The frequency at which the peak response acceleration occurs also increases with decreasing magnitude.

The proportion of high frequency motion relative to low decreases with distance, because high frequency motion is attenuated with distance at a greater rate than low frequency motion.

For distances that are small relative to the rupture dimension (up to 10 km for M 6.0), there is relatively little variation of spectral acceleration, and thus little variation in spectral shape. Of course, by definition, the low frequency spectral displacement will increase a little with increasing magnitude for nearby events.

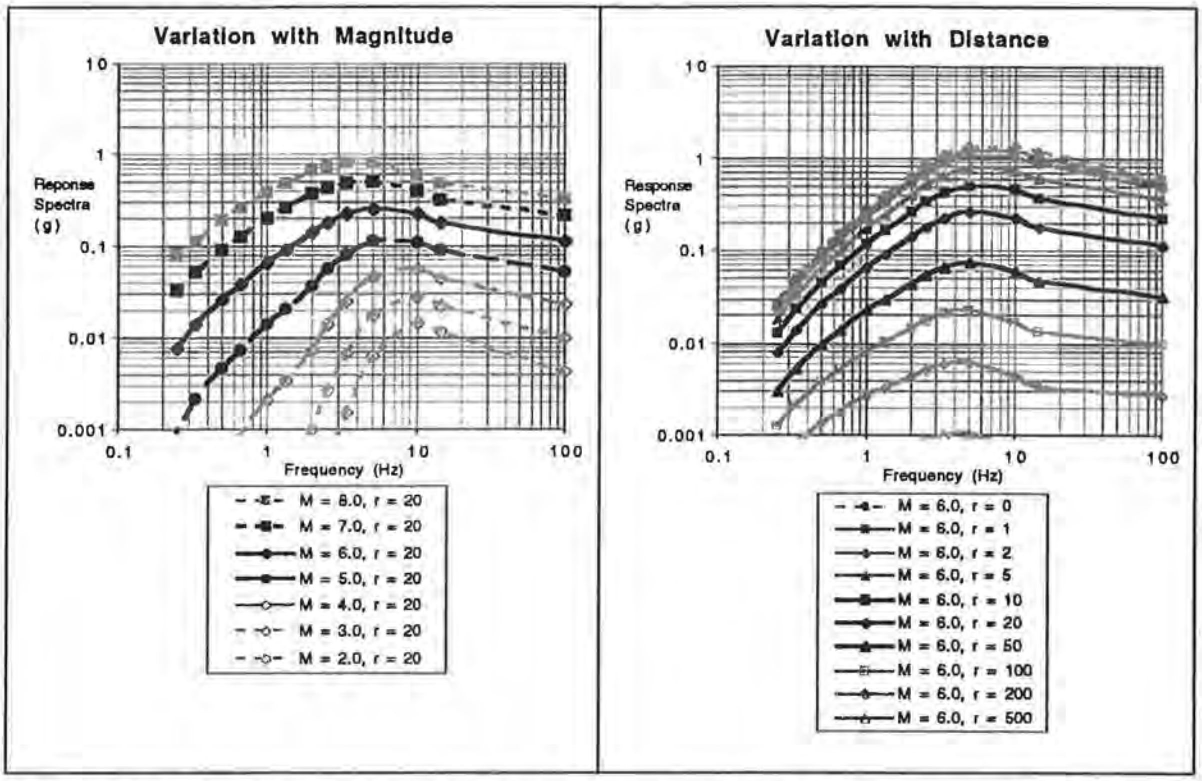

Figure 2: Sadigh 1997 attenuation for horizontal motion, 5% damping, and rock sites. The solid black lines show magnitude and distance ranges best constrained by the data. The response spectral acceleration at 100 Hz is numerically equal to the PGA.

EARTHQUAKE HAZARD ESTIMATES

To illustrate the problems associated with indiscriminate use of small earthquakes in earthquake hazard estimates, a comparison was made of uniform hazard spectra computed using the EZ-FRISK program (Risk Engineering Inc, 1997) for return periods of 1,000 and 10,000 years, and for two modern spectral attenuation functions (figure 3).

One of the attenuation functions was produced by Toro, Abrahamson and Schneider (1997), using data from central and eastern USA. These are areas of low attenuation and high stress drop earthquakes, comparable with central and Western Australia. The other function is by Sadigh and others (1997), as used above. It was derived using data from western USA, which has higher attenuation and lower stress drop earthquakes. This gives lower high-frequency ground motion than the Toro function, and is more suitable for application in eastern Australia.

The same seismicity model was used for all calculations, with values typical of Victoria including a relatively low activity level, b value of 1.0, maximum credible magnitude of 7.5, and earthquake depths to 10 km. Spectra were computed for horizontal motion on bedrock, with probability of exceedance of 0.5 and damping of 5%.

For each of the attenuation functions and return periods, spectra were computed considering earthquakes from magnitude 1.0 to 7.5, from 3.0 to 7.5, and from 5.0 to 7.5.

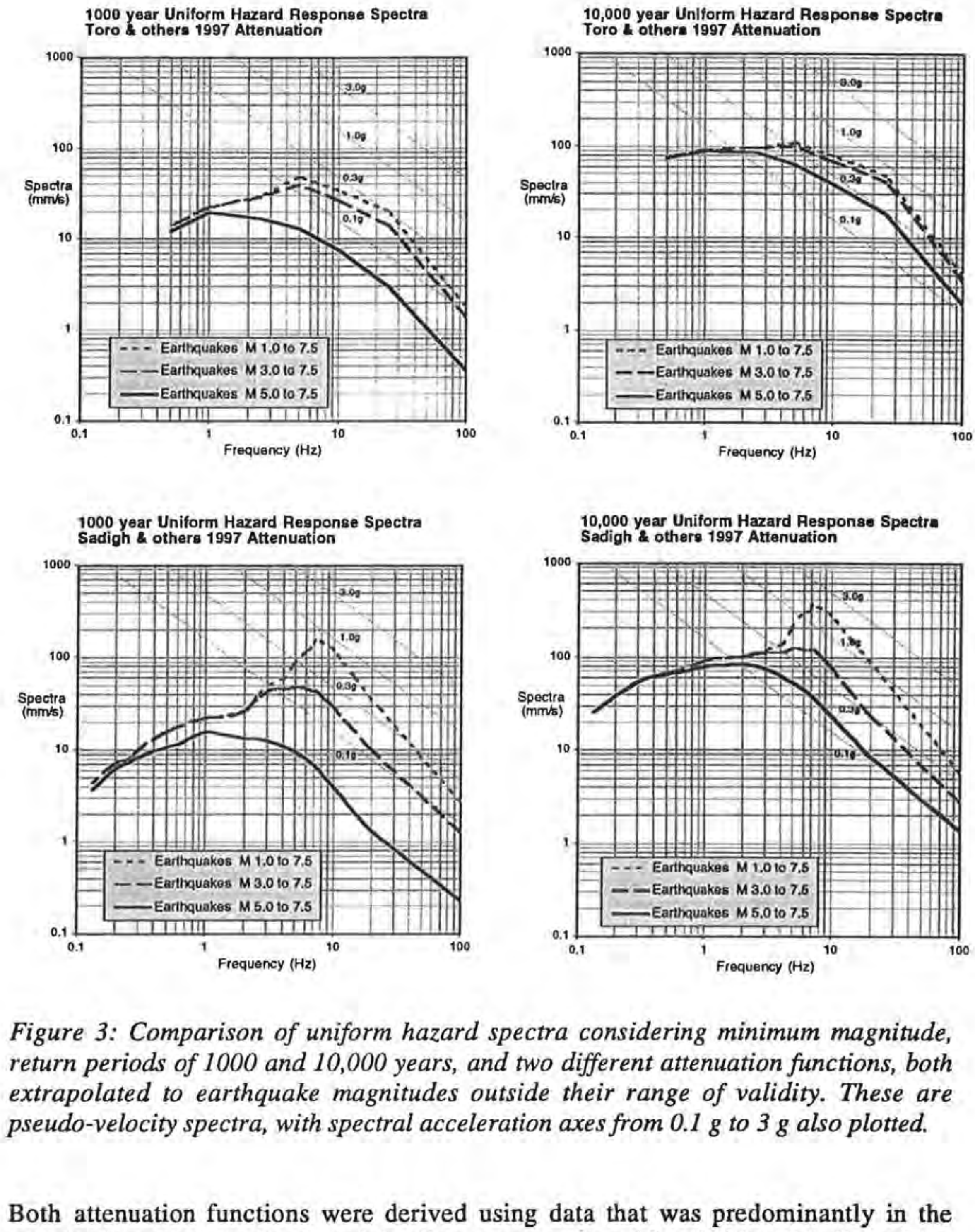

Figure 3: Comparison of uniform hazard spectra considering minimum magnitude, return periods of 1000 and 10,000 years, and two different attenuation functions, both extrapolated to earthquake magnitudes outside their range of validity. These are pseudo-velocity spectra, with spectral acceleration axes from 0.1 g to 3 g also plotted.

Both attenuation functions were derived using data that was predominantly in the magnitude range from 5 to 7, and the distance range from 10 to 100 km. Ideally, neither should be used outside these ranges.

However, earthquake hazard analyses are concerned about large nearby earthquakes, so extrapolation outside the empirically determined ranges is not unusual. This is often knowingly done when extrapolating to larger earthquakes. Extrapolating to smaller earthquakes can have significant and unexpected effects on hazard estimates.

The following observations may be made:

- Microearthquakes smaller than magnitude 3 give almost no contribution at frequencies less than about 4 Hz for either attenuation function. At higher frequencies they give a much higher contribution with the Sadigh function than for the Toro function, with a peak at about 8 Hz.
- The hazard contribution from earthquakes less than magnitude 5 decreases with increasing return period for both attenuation functions. This shows the significance of the arbitrary choice of return period in areas of low seismicity. For return periods of 1000 years or less, a large proportion of the ground motion is from small earthquakes, which have short duration and low hazard.
- The spectra computed using events larger than magnitude 5 are not significantly different for the two attenuation functions at either return period. As expected, the Toro function (for low attenuation, high stress drop) does give greater high frequency content and higher PGA values.

Provided appropriate minimum magnitudes are used, the two functions are both suitable for earthquake hazard studies. We suspect that the Sadigh function gives a more realistic representation of actual ground motion when extrapolated to smaller earthquakes, but would give overly conservative hazard estimates if appropriate minimum magnitudes were not applied.

CONCLUSIONS

Small earthquakes can be useful but misleading in earthquake hazard studies. Declustering an earthquake catalogue is the removal of dependent small earthquakes (foreshocks and aftershocks), and can lead to an *increase* in long term hazard estimates by reducing the relative number of small events to large (the b value).

Particularly in areas of low seismicity, the choice of a short return period can give excessive weight to motion from small non-damaging earthquakes. This can have a significant effect on the shape of computed response spectra.

Elastic response spectra do not adequately reflect the significance of ground motion duration, so earthquake hazard computations must consider minimum magnitudes.

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ESTIMATING SEISMIC HAZARD USING SIMULATED GROUND MOTION

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ABSTRACT:

Determining the potential for earthquake damage at a site requires knowledge of three factors: the properties of the earthquake source, the degree to which seismic waves attenuate as they travel and the degree to which local geological conditions contribute to ground motion. We have constructed a simplified model of wave propagation combining an earthquake source spectrum, an attenuation term and a site-amplification term. This model was inverted using the ground motion spectra of over 150 events recorded on 22 different sites. The result is an estimate of the source spectra of each event, the regional inelastic attenuation coefficient Q, and the site-amplification at the location of each receiver. This information is used as a forward model to predict the ground motion spectra of hypothetical earthquakes at the sites studied. Results suggest that site-amplification is the single most significant effect in determining the potential seismic hazard.

Introduction

In an effort to better quantify seismic hazard and to ascertain the accuracy of the Nakamura estimates (Nakamura, 1989) we have made in previous experiments (Cuthbertson *et al.*, 1998), we have placed seismometers at a series of sites in Brisbane (see Figure 1). Eighteen months into this field experiment we have still not recorded one event with significant signal-to-noise ratio (at least 3) at all frequencies of interest. In this situation it would be impossible to determine an accurate site-response by using either the reference-site method or a traditional inversion based approach, as these methods require a good signal-to-noise ratio across all frequencies of interest. A previous attempt at determining site-response in northeastern Queensland (Winter and Jaumé, 1998) required restricting the observational spectra to below 5 *Hz* because of noise considerations. Nonetheless, in order to obtain an estimate of seismic hazard, an estimate of site-response across a reasonably broad range of frequencies (0-10 *Hz*) is of great importance.

To overcome problems related to low signal quality, we have used a signal-to-noise weighted simple parameterization of the equation of ground motion from an earthquake, based on that used by Andrews (1986). This method allows the extrapolation of earthquakes recorded on at least one seismometer to other stations which did not record the event. Earthquake spectra from any event in the Queensland digital event catalog can be derived with correct removal of instrument response, site-amplification and regional attenuation. These effects can then be selectively reapplied to formulate an estimate of ground motion at any digital site used for a sufficient period of time. In essence, we are able to simulate the ground motion from any earthquake at any site by physical extrapolation. This approach allows the formulation of hazard scenarios for the sites used in the study.

Method

In order to study the effects of local and regional geological conditions on seismic hazard, QUAKES has undertaken a seismic profile of the greater Brisbane area. Ground motion as a function of frequency (f) for arrival k ($G_k(f)$) can be modeled as a convolution of three terms; a source spectra (either an earthquake or blast) ($E(f)$), a path term ($P_k(f)$) and a site-response term ($S(f)$):

$$G_k(f) = E_i(f)P_k(f)S_j(f) \quad , \qquad (1)$$

where i is the earthquake number and j is the site number for event k.

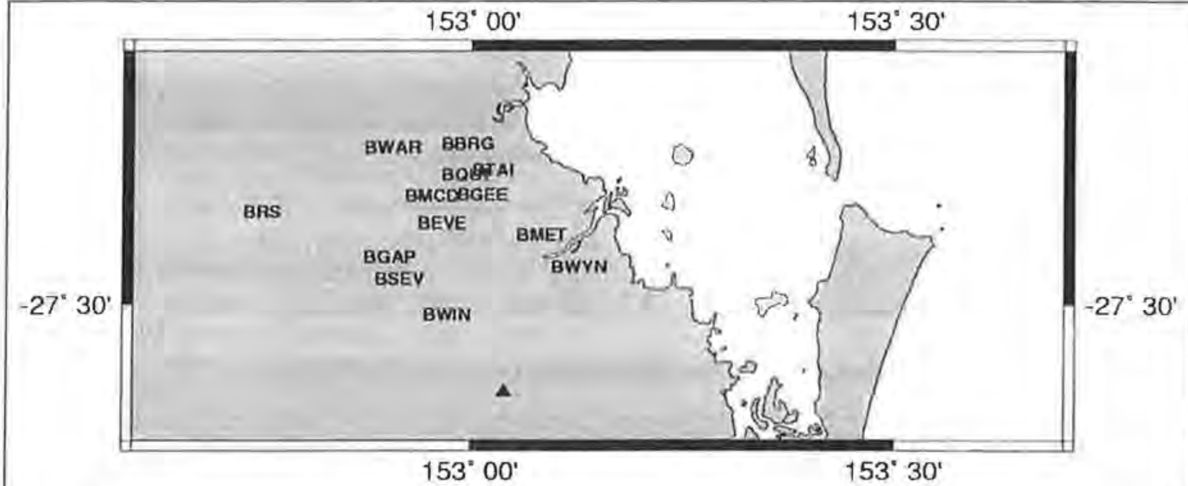

Figure 1: Brisbane area sites used to determine seismic hazard. The triangle indicates the location or the Acacia Ridge earthquake.

Path-effects

With the assumption that there is no significant crustal focusing, the path term can be modeled as:

$$P_k = \frac{1}{r_{ij}^n} e^{-\frac{\pi f}{V_s Q(f)}} \quad , \tag{2}$$

with r being the distance from event i to receiver j, n being the coefficient of geometric spreading (1 for body waves), V_s is the regional shear wave velocity (Cuthbertson, personal communication), and Q is regional seismic efficiency (Aki and Richards, 1980).

Ground motion observations

These equations for observed ground motion can be linearized by correcting the ground motion spectra for geometric spreading and taking the logarithm:

$$g_k(f) = e_i(f) + s_j(f) - \frac{\pi f}{V_S Q(f)} \quad , \tag{3}$$

with:

$$g_k(f) = \ln\left(r_{ij}^n G_k(f)\right) \quad , \tag{4}$$

$$e_i(f) = \ln\left(E_i(f)\right) \quad , \tag{5}$$

$$s_j(f) = \ln\left(S_j(f)\right) \quad . \tag{6}$$

Constraints

By itself, this system of equations is singular, and it is therefore necessary to add *a priori* information. We have chosen to use the classic approximation that any sites situated on either granite or metamorphic rock experience no site-amplification. For those sites which were deemed to be "rock" sites an equation was added specifying a flat site-response:

$$\sigma_r s_j(f) = 0 \quad , \tag{7}$$

where σ_r is an estimate of the error in the constraint, i.e. the degree to which the site is expected to deviate from a perfect "flat" site-response. We used an uncertainty of 60 percent. This uncertainty can be reduced through the use of multiple rock sites.

Ground motion simulation

A estimate for the ground motion at a give site due to a given event can be determined simultaneously with the other parameters, by adding an equation similar to Equation (3):

$$g_k(f) - e_i(f) - s_j(f) + \frac{\pi f}{V_S Q(f)} = 0 \quad . \tag{8}$$

This convolves the derived earthquake Green's function, the derived site-amplification term, and the derived attenuation to produce an estimate of ground motion. The advantage of this approach is that a recorded earthquake can be extrapolated to sites upon which it wasn't recorded, allowing hazard scenarios to be created. The derived ground motion estimates also have an automatically computed error analysis.

Solution

These equations can be solved using a traditional weighted inversion (Rawlings, 1988), using the noise-to-signal ratio as a proxy for standard deviation, a similar approximation to that used by Andrews (1986). This process results in an estimate of event source spectra, regional attenuation (Q), local site-amplification, and where specified a ground motion estimate.

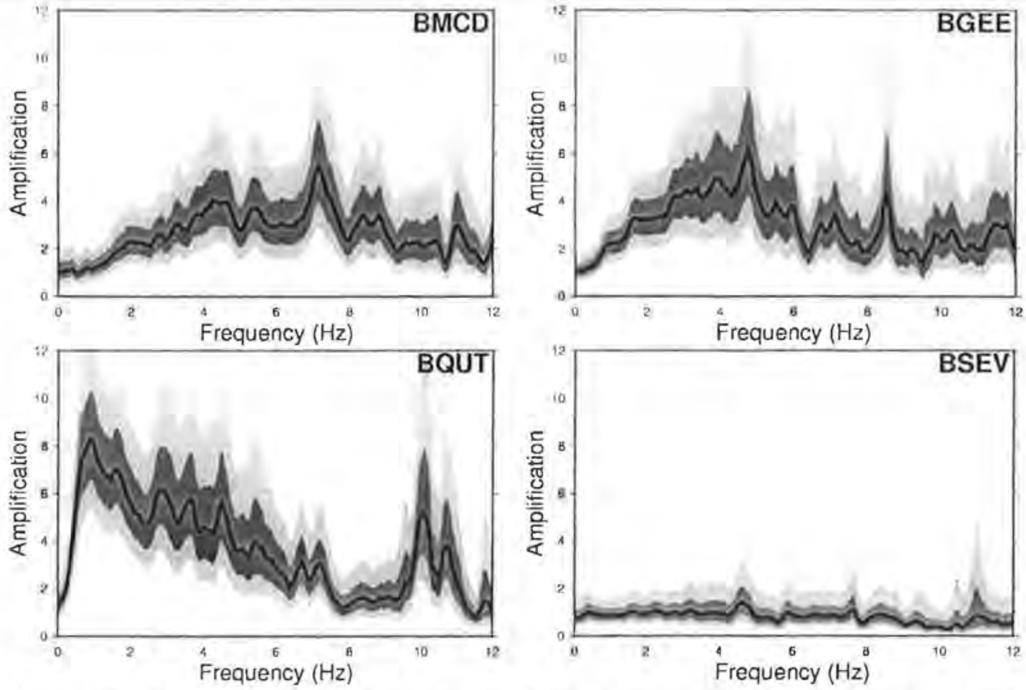

Figure 2: Derived site-amplifications for four of the twenty-two sites. BSEV was constrained to be a rock site. The shaded bars indicate one and two standard deviation limits.

Results

Derived site-amplifications for four sites are shown in Figure 2. BSEV was constrained to be a rock site, BMCD was located on metamorphic rock, and BGEE and BQUT were situated on sediment. All three non-reference sites show significant amplification of seismic waves, up to a factor of eight for BQUT.

Figure 3 shows the simulated ground motion spectra for three sites, BSEV BGEE and BQUT for an event similar to the Acacia Ridge earthquake. Even though BQUT is the furthest site from the event (see Figure 1) it experiences the greatest velocities. This analysis offers significantly more insight that the examination of site-amplification alone. Site BGEE shows an amplification factor of up to six at some frequencies, however at the frequencies where it experiences the greatest amplification the earthquake itself produces little energy. The resulting simulated ground velocity spectrum is nearly identical to the rock site BSEV. BQUT on the other hand has amplification which coincides with the spectra of energy produced by the earthquake, and thus would be expected to experience high velocities.

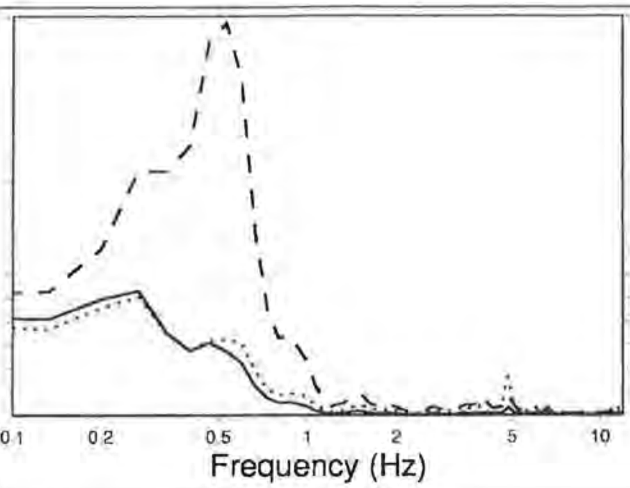

Figure 3: Expected ground motion spectra for an event of the same magnitude and location as the Acacia Ridge earthquake. Black line: BSEV; dotted line: BGEE; dashed line BQUT. BGEE shows significantly greater expected velocity for an event similar to the Acacia Ridge earthquake.

Conclusion

Site-amplification, earthquake spectra, and regional attenuation was derived simultaneously for 22 sites and over 200 earthquakes and blasts. In addition, ground motion from different events was simulated by combining the derived properties. Individual events can be physically extrapolated over the entire network, resulting in hazard scenario for the event. The resulting simulated ground motions offer a significant improvement in the estimate of seismic hazard from site-amplification alone.

Acknowledgements

Funding for this project was provided by the Australian Research Counsel and the sponsors of QUAKES.

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MODELS FOR SEISMIC HAZARD ASSESSMENT IN AUSTRALIA

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POSTER

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ABSTRACT:

The United Nations International Decade for Natural Disaster Reduction has drawn to a close. The next step in the risk mitigation process continues at an ever increasing pace as the population increases and the building stock ages. The problem is acute for areas where earthquakes are frequent but some of the worst disasters have occurred in areas where earthquakes are infrequent and no engineering design or construction precautions have been used.

Intraplate areas like Australia have suffered large earthquakes in the last 100 years, all of them distant from major population centres but the historical record is extremely short.

Various models have been proposed for earthquake occurrence rates in parts or all of the continent and here these are appraised for a new unified map of hazard prepared for different levels of probability. The past-earthquake and uniform hazard models will be compared with the Coulomb model, based on the observed pattern of epicentres and continent-scale lineaments.

An explanation is given on how this map can be used in the new Loading Code in conjunction with a table of dynamic amplification factors and a design response spectrum recently compiled for Australia.

Paper No. 20