COMPUTATION OF RECURRENCE RELATION FOR AUSTRALIAN EARTHQUAKES

CVETAN SINADINOVSKI
AGSO SEISMOLOGICAL CENTRE, CANBERRA, ACT

AUTHOR:

Cvetan Sinadinovski, BSc(Hons) in Physics and MSc in geophysics – "A.Mohorovicic" Zagreb University, PhD in geophysical tomography - Flinders University of South Australia, has worked as a visiting fellow in USA and Europe, and as a software specialist in Sydney and Adelaide. Currently employed as a professional officer in Seismological Centre of the Australian Geological Survey Organisation in Canberra. Member of ASEG, Association of Physicists of Macedonia, Australian Institute of Geoscientists, and AEES.

ABSTRACT:

In order to analyse earthquake hazard, a good knowledge of the relative frequency of earthquakes is required. Selection of the area of interest for computing the recurrence relation is important; if the area chosen is too small for the period of monitoring then the apparent frequency of large events can only be obtained by extrapolation of the frequency of observed small events. In such case the uncertainty in the extrapolated frequency is very high.

A larger area can be taken to compensate the short time interval provided the tectonics and gross geology are similar. In continental Australia, the tectonics everywhere are similar but the gross geology of Western, Central and eastern Australia are sufficiently different from each other that these areas can be considered to be separate zones. In the study area of Southeastern Australia there is no apparent distinction between the seismicity of the Sydney Basin and the adjacent and underlying Lachlan Foldbelt, not for the period of monitoring and historical investigation. Consequently it was taken to be a single zone for assessing earthquake hazard.

Statistical tests of recurrence relations show that a bi-linear curve is a better fit than a linear one over the recorded magnitude range for both the larger (continental) and smaller (zone) scale.

COMPUTATION OF RECURRENCE RELATION FOR AUSTRALIAN EARTHQUAKES

1. INTRODUCTION

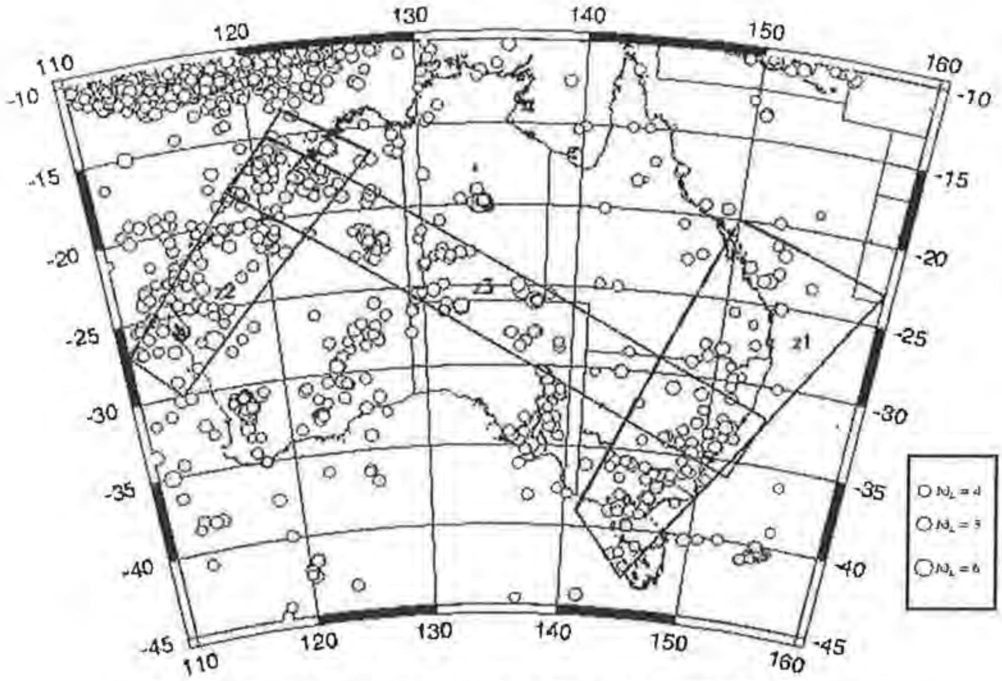
The frequency distribution of earthquakes as a function of their magnitude is of primary importance for seismic investigations. The validity of the results depends on the ability to delineate natural seismogenic areas or zones within the crust where earthquakes are generated by similar processes. Selection of the area of interest for computing the recurrence relation could be done according to different criteria which describe the seismicity. If the area chosen is too small for the period of monitoring then the apparent frequency of large events can only be obtained by extrapolation of the frequency of observed small events. Then the uncertainty in the extrapolated frequency is very high. A larger area can be taken to compensate for the short time interval provided the tectonics and gross geology are similar.

The seismicity of the Australian continent is typical of that experienced for intra-plate environments. Australian earthquakes are shallow and occur within the crust in the top 40km, and most of the focal mechanisms are consistent with horizontal compression. The earthquakes in continental interiors are associated with high local stress concentration and relatively short fault rupture lengths. In situations where faults and other tectonic structures are not obvious at the surface the shape of the seismic zones can not be clearly defined.

In the last hundred years, 26 earthquakes with magnitude of 6.0 or greater were registered in Australia, and on average there were two to three earthquakes per year with a magnitude of 5.0 or more (AGSO Earthquake Database). The distribution of seismic stations can introduce a bias in the spatial distribution of smaller observed earthquakes. To avoid such a bias the spatial distribution of the data sets was analysed only for those times in which the seismic network has been able to identify all earthquakes of the specified magnitude in the Australian continental region. The periods of consistent recordings were 1901-1999 for $M \geq 6.0$, 1959-1999 for $M \geq 5.0$, 1965-1999 for $M \geq 4.0$, and 1980-1999 for $M \geq 3.2$. It should be noted that in these data sets no distinction or identification is made of the temporal and spatial clustering of quakes as foreshocks or aftershocks from a single main shock.

Zones were chosen according to the criteria of earthquake clustering in the continental crust. Statistics have shown that the earthquake hazard across Australia is not uniform (M^{c}Fadden *at al.*, 2000). Then the pattern of the distribution of earthquakes with magnitude above a certain value has to be used. An epicentral map of earthquakes with $M \geq 4.0$ is suitable for zoning in Australian conditions. Figure 1 shows the epicentres of all earthquakes with $M \geq 4.0$ used in this study and the three zones selected from the shear model (M^{c}Cue *at al.*, 1998). It is known that the gross geology of Western, Central and Eastern Australia are sufficiently different and these areas can be considered to be separate zones.

In Southeastern Australia there is no apparent distinction between the seismicity of the Sydney Basin and the adjacent and underlying Lachlan Foldbelt, not for the period of monitoring and historical investigation. Consequently it was taken to be a unique zone *Z1* for assessing the earthquake recurrence (M^{c}Cue, 2000, *personal communications*). The other two zones covered Western Australia – *Z2*, and an area across Central Australia – *Z3*. It should be emphasised that some parts have been excluded because they may have a different tectonic origin; for example hotspots as opposed to intraplate tectonic. The zones are distorted by the projection used, the eastern and western boundaries are actually parallel.



Earthquake epicentres with magnitude $M_L \geq 4.0$ (AGSO Database)

Fig.1. Epicentral map of all earthquakes M≥4.0 and selected seismic zones

2. THEORY

The relation between the number of earthquakes and their magnitude is routinely approximated by a simple formula, i.e. by a single straight line in log-linear coordinates (Gutenberg and Richter, 1949)

$$\log N = a - bM \qquad \ldots(1)$$

where *N* is the cumulative number of earthquakes per year, *M* is the local or Richter magnitude and *a, b* are constants related to the level and the slope. Data are treated by grouping of *N* according to the magnitude classes.

Numbers of earthquakes were counted for the declustered dataset of magnitude 3 and more in magnitude intervals of 0.2 which is about the uncertainty in magnitude. The dataset referred to as a declustered data set, has the same magnitude ranges but the identifiable foreshocks or aftershocks were removed. A quake was considered to be a foreshock or an aftershock and was removed if it was within a certain distance of *d* km of the main shock (M^cCue, 1990) where

$$d = 10^{(M-4.11)/1.65} \qquad \ldots(2)$$

M is the magnitude of the main shock, and if the quake occurred within 10 years for magnitude 7, within 1 year for magnitude 6, within 3 months for magnitude 5, and within 10 days for magnitude 4.

Kárník (1971) mentioned that in some cases for the weakest and the strongest earthquakes, the (log *N, M*) distribution deviated from linearity and some other approximation could be applied. A standard statistical χ^2-test was performed to assess which recurrence relation best matched the observed distribution of events.

3. ANALYSIS

Data were extracted from the AGSO earthquake database and declustered within the described parameters. The magnitude ranged from $M_L3.2$ to $M_L7.2$. Figure 2 is a plot of the cumulative number of counted earthquakes per year in Australia against magnitude.

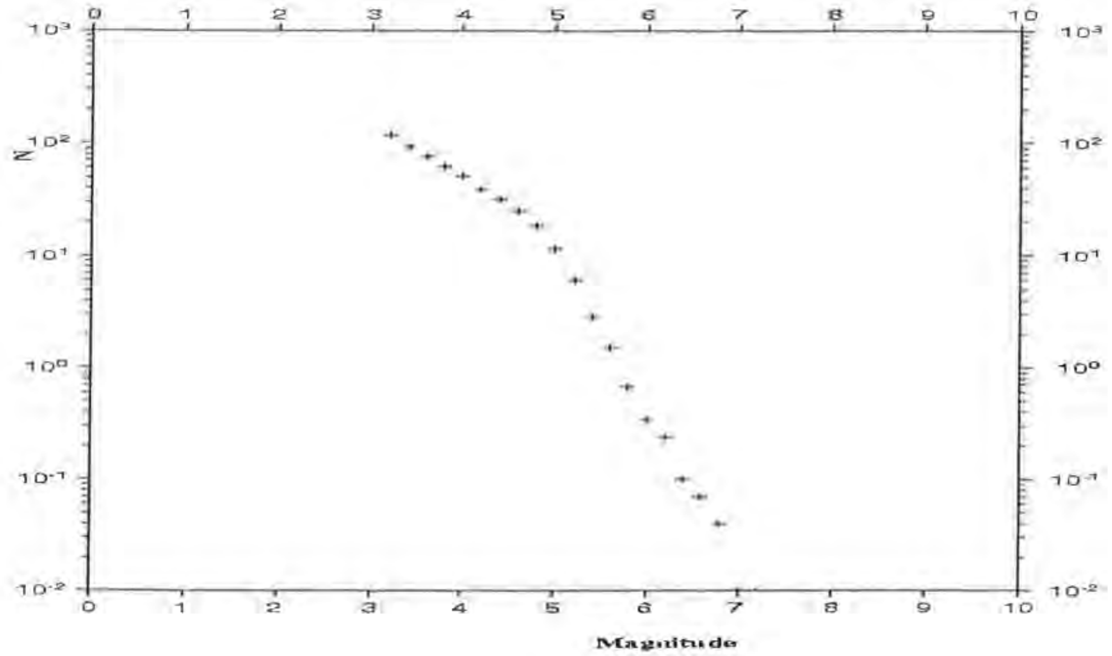


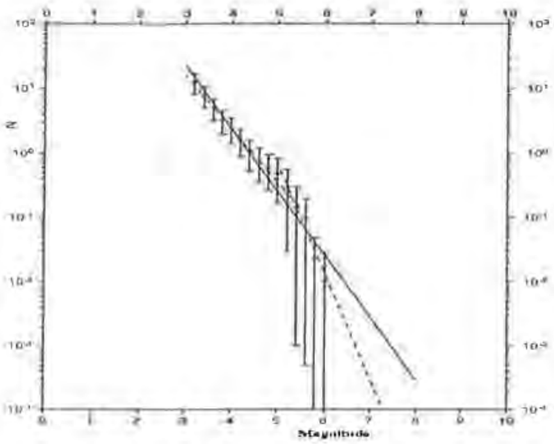
Fig. 2. Plot of the cumulative number of earthquakes per year in Australia against the magnitude (declustered)

From the diagram it is obvious that a straight line will not fit well, particularly for the larger earthquakes, and approximation with two linear segments will fit much better. Also there is a significant change of slope around the magnitude 5.2±0.1 and that position should be further investigated.

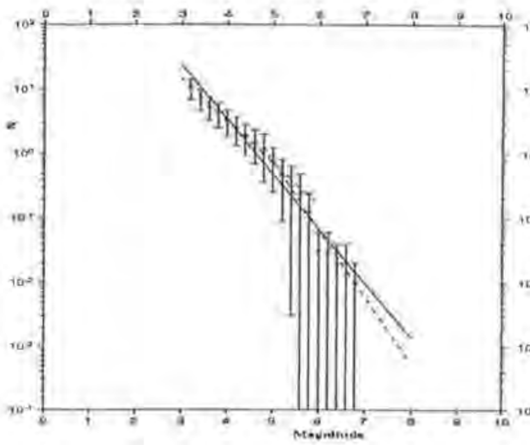
In the next stage, data were extracted for the three defined zones from the AGSO earthquake database and declustered as described earlier. In zone *Z1* the magnitude ranged from $M_L3.2$ to $M_L6.0$ with only one recorded earthquake with M=6.0. In zone *Z2* the magnitude ranged from $M_L3.2$ to $M_L6.8$ with three recorded earthquakes with M≥6.0. In zone *Z3* the magnitude ranged from $M_L3.2$ to $M_L6.6$ with five recorded earthquakes with M≥6.0.

Figure 3 is a plot of the cumulative number of earthquakes per year in each zone against the magnitude when foreshocks and aftershocks are removed. The coefficients for the straight line least-squares-fit in the Southeastern zone *Z1* were a = 4.3 and b = -0.98. The coefficients for the straight line least-squares-fit in the Western zone *Z2* were a = 3.9 and b = -0.85, and the coefficients for the straight line least-squares-fit in the Central zone *Z3* were a = 4.3 and b = -0.91.

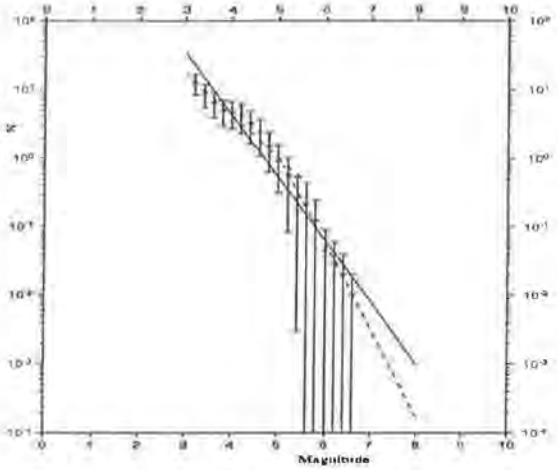
From the graph it is evident that a straight line does not fit well, particularly for larger earthquakes, and an approximation with two linear segments is much better. Again there is a significant change of slope around the magnitude 5.2±0.1, which is consistent with the previous position.



a)



b)



c)

Fig. 3. Plot of the cumulative number of earthquakes per year for the Australian zones against the magnitude (a – Zone1, b – Zone2, c – Zone3). The error bars represent $\pm 1\sigma$, standard deviation. The two-segment solution is shown by dashed lines and the single segment by the solid line.

Worldwide data are often better fitted by a bi-linear curve than by a linear one over the recorded magnitude range. Kárník (1971) discussed the nature of the observed phenomenon and related the discontinuity point to the fracturing of the material subjected to stress. Later Aki (1999) explained the discontinuity through physical terms of source size saturation effects. It is normally accepted that earthquakes in stable continental regions only occur in the brittle upper crust and that above a certain magnitude at which the whole width of the brittle crust is ruptured the magnitude can only increase by rupturing a longer fault zone at constant width. That situation could potentially occur at magnitudes around 6 where one could expect another cusp.

Further comparison between the three selected zones was done when the number of earthquakes was normalised to a unit area of 10,000km^2. Then the calculated coefficients for the level and the slope in the bi-linear least-squares-fit in the zones were respectively:

Z1	a = 2.44	b = -0.83	M≤5.2	a = 7.0	b = –1.7	M≥5.2
Z2	a = 2.11	b = -0.65	M≤5.2	a = 4.11	b = –1.06	M≥5.2
Z3	a = 1.77	b = -0.61	M≤5.2	a = 4.9	b = –1.25	M≥5.2

On figure 4 the normalised bi-linear segments for all three zones in Australia are superimposed. A χ^2-test was performed to assess which of the linear and bi-linear recurrence relations best matched the observed distribution of events with magnitudes greater than 5. The test results show that the probability of the observed distribution being produced by the bilinear fit is much higher than with the straight line. Namely, for zone *Z1* - 98% as opposed to only 18%, for zone *Z2* - 98% as opposed to 30%, and for zone *Z3* - 98% as opposed to 20%,.

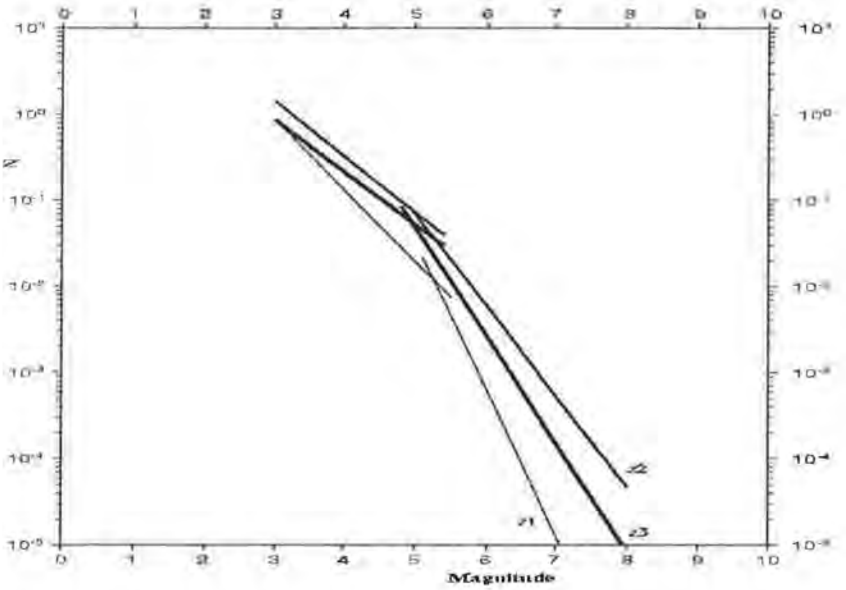


Fig. 4. Normalised bi-linear earthquake recurrence relation for Australian zones

4. DISCUSSION

On the basis of these results it is concluded that the straight-line fit overestimates the recurrence rate of large events and the bi-linear model describes much better the recurrence of earthquakes in Australia. This is especially critical when estimates of maximum magnitude are required for periods much longer than the observation time in zones where only few large earthquakes have occurred. For example, the values of a maximum magnitude defined in zone *Z1* as the 10,000-year magnitude are 7.1 and 8.4 respectively. The effect on the 500-year *pga* such as used in AS1170.4 is minimal.

This study shows that the same pattern emerges on both large (whole country) and small (zone) scale. Nevertheless, the three selected zones manifest different internal characteristic evident through the variation of the *a* and *b* coefficients. In general, the statistics show that the Southeastern Australian zone is less seismically active than Western and Central Australian zones, and WA zone has the highest potential of producing large earthquakes. However, the statistics are only a quantitative indication as it is not possible to estimate in advance the capacity of a region to store energy, nor to determine its exact physical condition.

5. REFERENCES

Aki, K. (1999) Scale dependence in earthquake processes and seismogenic structures, ACES Workshop, Brisbane, pp 437-441.

Gutenberg, B. and Richter, C.F. (1949) Seismicity of the Earth and associated phenomena, Princeton Univ. press.

Kárník, V. (1971) Seismicity of European Area – Part 2, D. Reidel Publishing Company, Dordrecht, Holland.

McCue, K.F. (1990) Australia's large earthquakes and recent fault scarps, J. Structural Geology, Vol 12, No 5/6, pp 761-766.

McCue, K.F., Somerville, M., and Sinadinovski, C. (1998) GSHAP and the proposed Australian earthquake hazard map, AEES conference, Perth, pp 18/1-5.

McFadden, P., Sinadinovski, C., McCue, K.F., and Collins, C. (2000) Is earthquake hazard uniform across Australia?, AGSO report, Canberra.

INFREQUENT DISASTERS - HOW TO MAINTAIN COMMUNITY AWARENESS AND PREPAREDNESS. LESSONS FROM THE AITAPE PNG 1998 TSUNAMI

H.L. DAVIES[(1)], J.E. REID[(2)] AND R.M. DAVIES[(3)]
(1) GEOLOGY DEPARTMENT, UNIVERSITY OF PAPUA NEW GUINEA
(2) SCHOOL OF EARTH SCIENCES, UNIVERSITY OF TASMANIA
(3) GEMOC NATIONAL KEY CENTRE, DEPARTMENT OF EARTH AND PLANETARY SCIENCES, MACQUARIE UN IVERSITY, NSW

AUTHORS:

Hugh Davies is Professor of Geology at the University of Papua New Guinea. In association with the PNG National Disaster Management Office, he has been closely involvrd with studies of the 1998 Aitape Tsunami.

James Reid is an Associate Lecturer in Geophysics at the University of Tasmania. He holds B.Sc. (Hons) and M.Sc. degrees in geophysics from the University of Sydney, and a PhD in geophysics from Macquarie University, Sydney.

Rondi Davies is currently a postdoctoral research fellow at Macquarie University, Sydney. She holds a B.Sc. (Hons.) degree in geology from the University of Sydney, and a Ph.D. in geology from Macquarie University.

ABSTRACT:

One of the reasons that the 1998 Aitape tsunami resulted in such an enormous loss of human life is that the population was unaware of the risk posed by tsunamis, and was unable to recognise the warning signs. This paper discusses the reasons why community awareness of tsunami risk was so low, the steps now being taken to promote such awareness in Papua New Guinea and the potential implications of the Aitape tsunami for Australia.

Paper No. 23

ABSTRACT

On the evening of July 17th 1998, a tsunami near Aitape, PNG claimed 2000 lives, injured more than 1000 people, and displaced 10,000 survivors to re-settlement villages inland. The warning signs of the impending tsunami were a sharp disturbance from a shallow local earthquake; the withdrawal of the sea to beyond the normal low tide mark; and a roaring sound that some likened to the roar of a large jet plane. People were drawn to the water's edge by their natural curiosity at these unusual events. Had they recognised the warning signs for what they were and fled inland, fewer lives would have been lost and fewer people injured.

There are two reasons why people did not recognise the warning signs. A major factor was that there had been no catastrophic tsunami in PNG since 1930 (although there had been one in West Papua as recently as 1996). The quiescence of 68 years seems to have been long enough for communal memories to fade, and hence for community awareness to weaken. By way of contrast, in the 50 years leading up to 1930 there had been a number of catastrophic tsunamis, including the major event generated by the collapse of Ritter volcano in 1888, with the probable result that tsunami awareness was high. The small loss of life at the time of the 1930 tsunami was said to have been because people had recognised the warning signs and knew to run inland.

The second reason for low awareness in 1998 was that Government initiatives to promote tsunami awareness in the 1970s (when the risk posed to PNG by tsunamis was promoted by the late Ian Everingham of Port Moresby Geophysical Observatory) had virtually lapsed in succeeding decades. Beginning in July 1998, the PNG Government has embarked upon a program to increase tsunami awareness and preparedness. This has involved the use of radio and television, and preparation and distribution of booklets, posters, pamphlets and video tapes. The main thrust of the program has been directed at school children in years 6-8, nationwide.

INTRODUCTION

In July 1998 a major tsunami struck part of the north coast of the island of New Guinea, destroying all structures in its path and killing 2000 people. By enquiring after the event we found that people in the disaster area generally had been unaware of tsunami hazard, and did not recognise the warning signs. Had they done so, fewer would have been killed and the ensuing trauma would have been reduced.

The reason that there was little awareness and that warning signs were not recognised is that damaging tsunamis are infrequent. Tsunamis are rare events, and communities affected by them eventually forget the destruction caused. Life resumes on sectors of coast that were once devastated, and the recollections of the warning signs fade from the communal memory.

Australia too has a history of infrequent disasters. Examples that come to mind are the Newcastle earthquake of 1989 and the Thredbo landslide of 1997. In both cases there was very little or no community awareness of the potential hazard and an inadequate level of preparedness.

The infrequent disaster is, by its nature, difficult to identify or characterise in advance, difficult to plan for, and has a traumatic effect on the human population. There is no store of accumulated wisdom that helps people to cope. People do not recall when such an event last occurred.

It is useful to contrast the infrequent disaster with the situation in Rabaul, PNG at the time of the major volcanic eruption in 1994. The Rabaul community knew about eruptions – they had experienced one 57 years before – and thanks to a concerted public awareness program, knew what to expect and what action to take. The result was that the population evacuated the danger area voluntarily, there was very little loss of life, and trauma, although certainly present, was less than would otherwise have been the case.

The lesson we can draw from Rabaul is that there is a need to prepare the public for the infrequent disaster, just as there was for the more frequent volcanic disaster. The Aitape tsunami becomes a case in point.

TSUNAMIS

Tsunamis are common events around the rim of the Pacific. The Aitape disaster was not unique but, rather was one in a series of catastrophic tsunamis that occurred in the western Pacific in the 1990s. These included Flores Island in Indonesia in 1992 (1700 killed), Okushiro, Japan, in 1992 (239 killed), East Java in 1994 (230 killed) and Biak, West Papua, in 1996 (107 killed).

A tsunami is a rhythmic movement of the water column and can be generated by any major disturbance of the sea floor. The disturbance may be movement of the sea floor on a fault; a submarine slump or landslide; or a submarine volcanic eruption. A tsunami that develops locally (a near-source tsunami such as are most in Papua New Guinea) will arrive at the nearest coastline within 10-20 minutes. Because this time interval is so short, it is difficult for even well prepared authorities to provide any warning of a near-source tsunami. The only measures which can be taken are to ensure that people are aware of and recognise the warning signs, and know what to do. The appropriate action in the event of tsunami warning signs is simply to move away from the coast or climb to higher ground. The usual warning signs of a tsunami are:

- a prolonged sharp shaking of the ground caused by a nearby shallow earthquake, followed by;
- a lowering of sea level to below the normal low-tide mark; or
- a roaring noise.

THE AITAPE TSUNAMI

On 17 July 1998, about 20 minutes after a damaging local earthquake, a succession of at least three waves struck the Aitape coast of Papua New Guinea. The waves were highest (10-15 m) and the damage most severe on a 14-km sector of coast (D-F in Fig. 1). In this sector all structures were destroyed, leaving only some concrete foundations. Waves swept inland as far as 500 m across the swampy coastal plain, felling 30m-high trees and stacking them like matchwood. Along the adjacent coast for a total length of 40 km waves up to 4 m high destroyed structures that were near the water's edge, including the grand old church at Sissano (A-H in Figure 1). The tsunami caused 2000 deaths, injured more than 1000, and displaced 10,000 people from their homes.

The scale and human tragedy of the disaster attracted worldwide media attention and a generous and gratifying response from donors and volunteers both within country and overseas. (The volunteers included a team of nurses from Hobart Hospital who relieved the over-worked staff at Wewak Hospital through the succeeding months).

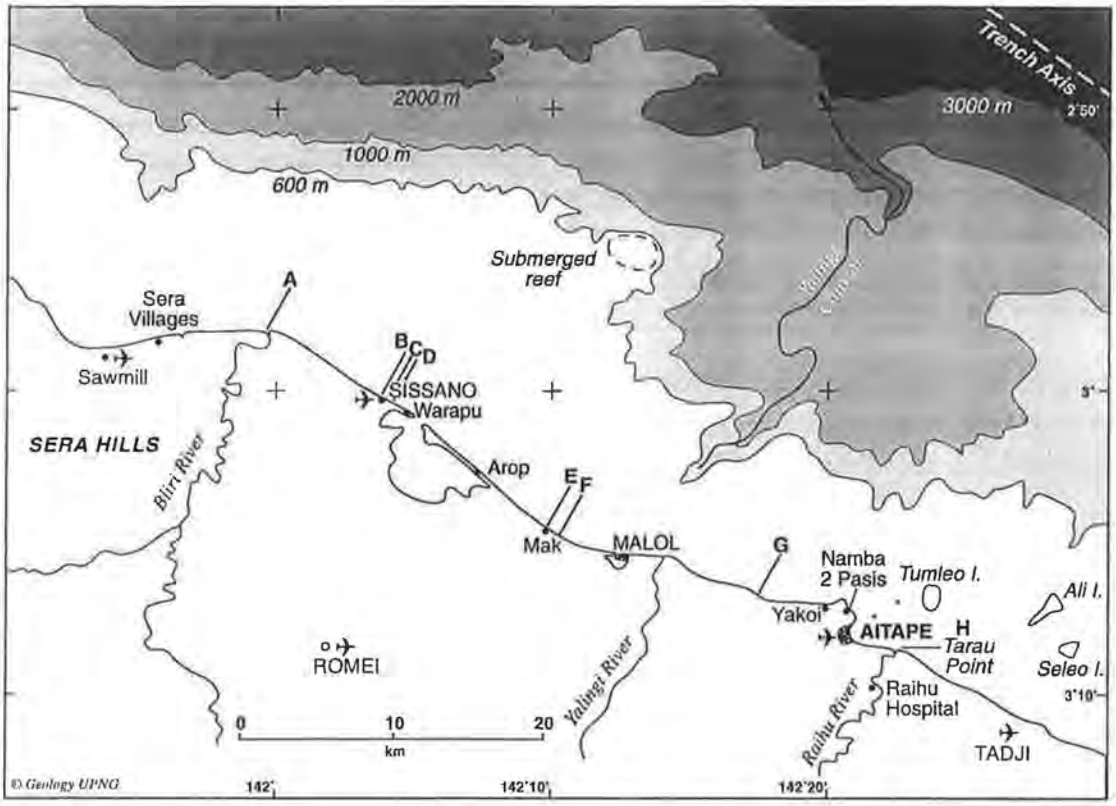


Figure 1. Damage map of the Aitape coast. Between D and F all structures were destroyed and casualty rates were high (20-40 percent of population killed). Between A-D and F-H, only structures close to the water's edge were destroyed and the casualty rate was lower. The submarine canyon is thought to have focussed the energy of the wave on D-F. The submerged reef indicates a history of subsidence along this coast. The bathymetry is reproduced by permission of the Japan Agency for Science and Technology (JAMSTEC), Yokosuka.

AWARENESS AND PREPAREDNESS

Our enquiries in the weeks and months following the Aitape disaster revealed that very little awareness of tsunamis had existed amongst the Aitape communities. Older males recalled that there were tsunami stories in their oral history. Younger people were however generally unaware, and most were taken completely by surprise. None had any prior knowledge of the warning signs.

The lack of awareness had two significant effects. One was that people did not recognise the warning signs and so did not take evasive action. The other was that people were uncertain what had happened, why it happened, and whether it might happen again. This uncertainty was, and still is, a factor in how individuals coped with the experience. For example, there remains a widely-held belief that the tsunami was man-made and was launched by a foreign power, or by rival village communities. This in turn contributes to continuing instability in the survivor communities.

The lack of awareness is a function of the infrequency of tsunamis. There had been no major tsunami on the Aitape coast in the preceding 100 years, and the interval could have been even longer. Over such a period of time communal memories will fade and any community awareness generated at the time of the previous major tsunami is lost. In contrast, when two tsunamis struck the Madang-Bogia coast only 42 years apart (1888 and 1930) the people recalled the earlier event, recognised the warning signs, and ran inland. The result was only a small number of deaths (Everingham, 1977). Similarly, on the west coast of the island of San Cristobal, in the Solomon Islands, tsunamis are sufficiently frequent that people move inland at the time of any strongly felt earthquake (Everingham, 1977).

AWARENESS INITIATIVES

The lessons of Aitape have been learned and tsunami awareness is now a priority of the Papua New Guinea government. Activities have included the convening of a conference of scientists, disaster managers and survivors to review, analyse and learn from the Aitape disaster (Davies, 1999); the distribution of tsunami booklets to 4000 schools nationwide; the inclusion of tsunami studies in the primary and high school curricula, the preparation and distribution of tsunami posters, and releases on radio and television. Currently 200,000 tsunami pamphlets are being printed in both English and Tok Pisin (Pidgin English) for distribution nationwide through schools and as inserts in the national newspapers. In addition, teams from the PNG Red Cross are visiting coastal villages throughout PNG to promote awareness and preparedness.

However, much remains to be done, particularly as regards preparedness. This includes the development of an effective disaster response capability; inspection of all coastal facilities and towns, especially in the high risk areas, to identify facilities that are at risk from tsunamis; and to take remedial action, where possible.

The Aitape tsunami has been studied more than any previous tsunami in terms of its effects, its origins, and its aftermath (e.g., Davies 1998; McCue, 1998; Kawata et al. 1999; Okal, 2001; Tappin et al. 1999; Ripper et al., 2000; Synolakis et al., 2001). From the outset the tsunami intrigued the investigators because it was anomalous that such a relatively moderate earthquake (M7.1) could trigger such a severe tsunami. As a result of the investigations, most of the experts now agree that the tsunami was caused by a submarine slump or landslide, and that the earthquake served only as a trigger. This conclusion has implications for coastal cities worldwide, including the cities of the Australian seaboard. For the Australian case add to this the evidence that there have been catastrophic tsunamis on the eastern Australian coast in the past (e.g., Bryant, 1992).

The United States currently is directing a concerted effort towards tsunami research, preparedness and awareness for their Pacific coast. Perhaps it is time that Australia gave thought to doing the same.

REFERENCES

Bryant, E.A., Young, R.W., and Price, D.M. (1992) Evidence of tsunami sedimentation on the southeastern coast of Australia, Journal of Geology, Vol 100, pp 753-765.

Davies, H.L. (1998) Tsunami PNG 1998 - Extracts from Earth Talk, University of Papua New Guinea, Waigani.

Davies, H.L. (1999) Report on the PNG and Region Tsunami Conference - PARTIC - Madang, September 1999, PNG National Disaster Management Office, Waigani.

Everingham, I.B. (1977) Preliminary catalogue of tsunamis for the New Guinea/Solomons region, 1768-1972, Bureau of Mineral Resources, Australia, Report 180.

Kawata, Y., Benson, B.C., Borrero, J.C., Borrero, J.L., Davies, H.L., deLange, W.P., Imamura, F., Letz, H., Nott, J., and Synolakis, C.E. (1999) Tsunami in Papua New Guinea was as intense as first thought, EOS Transactions of the American Geophysical Union, Vol 80, pp. 101, 104-105.

McCue, K. (1998) An AGSO perspective of PNG's tsunamigenic earthquake of 17 July, 1998. Aus-Geo International, Vol 9, 1-2, December 1998.

Ripper, I. D., Anton, L., Letz, H., and Moihoi, M., Preliminary account of the scientific investigations of the 17 July 1998 Sissano Lagoon (Aitape) tsunami, Papua New Guinea Department of Mining Geological Survey Report 2000/1.

Okal, E. A., (2001) T waves from the PNG sequence: Timing the slump, Journal of Pure and Applied Geophysics Special Issue on the Aitape Tsunami (accepted).

Synolakis, C., Okal, E., Watts, P., Borrero, J., Davies, H., Tappin, D., Silver, E., Sweet, S., Bardet, J-P., and Grilli, S. (2001). The Slump Origin of the 1998 Papua New Guinea Tsunami, Journal of Pure and Applied Geophysics Special Issue on the Aitape Tsunami (accepted).

Tappin, D.R., Matsumoto, T., Watts, P., Satake, K., McMurtry, G.M., Matsuyama, M., Lafoy, Y., Tsuji, Y., Kanamatsu, T., Lus, W., Iwabachi, Y., Yeh, H., Matsumoto, Y., Nakamura, M., Moihoi, M., Hill, P., Crook, K., Anton, L., and Walsh, J.P. (1999) Sediment slump likely caused the 1998 Papua New Guinea tsunami, EOS Transactions of the American Geophysical Union, Vol 80, pp. 329, 334, 340.

DISASTER RESPONSE - INSURANCE

HUGH KHULL
RACT INSURANCE PTY LTD

AUTHOR:

Hugh Khull, FAII, CIP, ARM (USA), is the General Manager of RACT Insurance Pty Ltd in Hobart, Tasmanuia.

ABSTRACT:

December 28, 1989, changed a perception in the insurance industry, if not all of Australia, that, as a country, Australia is free of devastating earthquakes.

Paper No. 24

DISASTER RESPONSE - INSURANCE

True, there have been earthquakes in the past and, true, they had caused damage but they had mostly centred on remote or sparsely populated areas. Because of the vastness of Australia, the sparsity of its population and the lack of density of its urbanisation, as well as its intra plate location, Australia was considered to be largely free of frequent devastating earthquakes that affect countries which are on the edges of the world's tectonic plates.

Newcastle changed that and brought a lot of lessons home to the insurance industry. There were very few people working in it at the time who remembered the '54 Adelaide earthquake and how claims were handled and so, in Newcastle, it was very much a case of learning on the job.

Earthquakes bring particular problems to handling claims because of where the worst damage occurs and the type of damage. The disaster we are most familiar with in Australia is bushfire. Bushfire usually occurs in less densely populated areas, the buildings damaged are usually residential homes and the damage to properties is usually substantial, if not total. But with an earthquake, the damage is not total. Large parts of buildings are left standing, often in a precarious state, there is the danger of after shocks causing further damage to weakened buildings, a lot of the worst damage is in older densely populated and commercial areas.

The first problem to be faced is access to the affected areas, ensuring the safety of assessors and adjusters, demolition of the remainder of the building then removal of debris.

Newcastle demonstrated that Australia is not immune from earthquakes. They can happen anywhere and Tasmania is no exception. In 1854, Hobart was shaken violently by a large earthquake and, on September 14, 1946, an earthquake of 7 on the Richter scale occurred off the East Coast. In January this year, an earthquake with a magnitude of 3.2 shook the South East and was felt as a slight tremor in Hobart prompting warnings of the "inevitable" big one.

There is a history of seafloor earthquakes in the Western Tasman Sea and between Tasmania and Antarctica. In May, 1989, a major earthquake occurred near Macquarie Island which registered somewhere around 8.5 on the Richter scale. The tremor was felt slightly in Hobart - the area affected covered some thousands of square kilometres.
Transpose that area over the Tasmanian landmass should such an earthquake come ashore and be centred on, say, The Lake Edgar fault or near Launceston and we have the potential for major damage.

What lessons then can we learn from the Newcastle experience and, more recently, the Sydney hailstorm? If a serious earthquake should strike Hobart or Launceston, or for that matter any other city in Australia, then there are a number of lessons the insurance industry can take note of from Newcastle.

CLAIM LODGEMENTS

The first is in actually managing the number of claims that come in. Prior to the Newcastle earthquake, there was no experience to draw on relative to claim lodgement patterns. There is no statutory or contractual time limit in which claims must be lodged and our only defence against late notification, under the terms of the Insurance Contracts Act, is where we can successfully argue prejudice and that would probably only reduce the claim by the amount the delay had caused the claim cost to escalate. Usually, following a disaster, there is a first flush of claims and then a lingering but diminishing tail. In Newcastle, claims continued at a steady rate for many months with one company even tracking an increase. Part of this may have been because people waited, because they only had slight damage or believing they would have difficulty in getting builders and other trades people. However, part of the reason for slow lodgement could be as a result of the peculiar nature of earthquake damage. A building could be slightly damaged but the damage be unnoticeable until the building settled, or later heavy rains, such as occurred in Newcastle, bring roof damage to the notice of owners who were not even aware their property had been damaged.

EXISTING DAMAGE & REACTIVE CLAY

Many claims that were lodged after the Newcastle earthquake were for relatively minor damage, such as minor cracking. It is not uncommon for a building to crack slightly in plasterwork and even around brickwork as it settles after building. Because they live with it every day, many people don't notice it until something happens to make them take notice, such as an earthquake.

Newcastle also experienced heavy rain after the earthquake which lasted well into the year (1990) followed by an extended period of drought. Many parts of Australia are, as we know, reactive clay soil and many of the claims that came in late were for cracking, unrelated to the earthquake but caused by movements in the reactive clay soil. As you can imagine, this gave rise to many costly disputes as home owners found it impossible to believe, understandably, that the damage to their house that had subsequently become evident was not earthquake damage.

OLDER HOMES & CONSTRUCTION FAULTS

Hobart and Launceston, like Newcastle, have many older homes and buildings – many of these buildings are double leaf brick built in the late 1800's or early in the 20th century. In Newcastle, many of these properties were found to have a number of problems:-

- Shallow, inadequate or no proper foundations. A lot of older homes are built on sandstone block foundations laid on a bed of sand or have brick or timber piles without proper footings and providing limited support.
- Weak mortar which has lost its strength by the effluxion of time and corroded or inadequate ties between the brick leaves. These walls had no resistance to earthquake loadings and the outer leaf often collapsed.
- Settlement and long term structural deterioration.

The standard household building policy in Australia provides reinstatement and replacement cover, that is, the insurance company will repair or replace the building to a condition equal to but not better than its condition when new. The policies also cover extra cost of reinstatement necessary to meet Council building codes or Government requirements.

Although damaged properties could be repaired, there were cases when the earthquake repairs should only have been carried out once pre-existing problems with foundations and footings were remedied by the owner. In the absence of a statutory or building code requirement, that work should be at the owner's cost. On the other hand, was there any point in carrying out repairs on substandard foundations – this could only lead to further problems in the future. The term 'betterment' and the question of who paid for upgrading of foundations and repairing existing foundations were at the centre of many disputes.

A number of major home insurance companies have an average or Co Insurance Clause in their policy. The effect of the Co Insurance Clause is to require the owner to contribute to the cost of repairs if the home is underinsured. This lead to similar problems to 'betterment' – many people simply did not have the money to contribute. Some companies chose not to apply average, others did not and still others did not have the

clause in their policy. The varying treatment of claims caused some adverse comment and it is an issue that insurance companies will have to be clear on in the future. My view is that average will have to disappear from policies in the future.
There was also an unrealistic expectation that better building and engineering techniques would remove latent defects from the building and, in many cases, this just could not be done. Rebuilding brick walls upon poor foundations or on existing inappropriate footings in reactive soils would inevitably lead to the new walls cracking. The only answer would be to rebuild the footings and this raises the question of betterment previously discussed.
Builders are required to insure their work against poor workmanship and structural defects for 7 years. However, given the nature of earthquake damage and the constraints in effecting repairs, there could be recurring defects, not the fault of the builder but stemming from the foundations the work was built on. This was a concern of builders in Newcastle, which has to be addressed early in the claim process to ensure building owners are fully aware of the problem. Nevertheless, it is one which can only lead to disputes and which needs a good workable resolution process. As it turned out, there were many thousands of claims re-opened to carry out further repairs.

FRAUD

And, of course, there was always the perennial problem with fraud.
There were many claims where owners tried to get work done that was not earthquake related. Sometimes this was not fraud but a genuine belief that the damage was caused by the earthquake. But, in many cases, there was collusion between trades people and owners to get additional work done or quotes for repairs to garages, car ports, verandahs, decks, chimneys and other parts of the building that did not exist, in the expectation of a cash settlement. Then there were unscrupulous trades people who produced quotes which bore no relationship to the damage, seeking to make a fast buck from people's misfortune.
And then there were the trades people who were not trades people – people who saw the opportunity to exploit a situation. From my own experience, I know that the busiest people straight after the disaster were the printers – printing letterheads, business cards, quote forms, invoices, etc., for newly licenced builders!

OTHER PROBLEMS

There were other problems – arising from conveyancing and subsequent recurring damage or damage which later became apparent. Damage to underground sewer and water pipes and electrical services, the hidden assets which was not apparent until much later, the effects on property values not to mention the social disruption. There were many lessons learnt from the Newcastle earthquake.

THE SYDNEY HAILSTORM – A SUCCESS STORY

The Sydney Hailstorm struck on the 14th April, 1999, causing extensive and severe damage to large areas of Southern Sydney. Claims lodged exceeded 50,000 buildings, 61,000 motor vehicles, 60 boats and 8 aircraft – in all, well over 110,000 claims were lodged.
The way in which claims for the damage were handled there is an interesting case study and, because of its success, is a model which will doubtless be used in future disasters.

On the 23rd April, the Minster for Emergency Services established the Southern Sydney Recovery Task Force to co-ordinate the restoration and repair work.
The Task Force was a joint State Government/private sector organisation and it was an integral part of the three stage response to the disaster:-

Stage 1	Emergency Response
Stage 2	Recovery
Stage 3	Final Restoration

The Task Force's role was to co-ordinate Stage 2 and its objectives were:-

- "To recover physical infrastructure and buildings to enable the community to return to normal life
- To establish the basis for full restoration of the community's physical asset base" i.e. to get people dry and safe and living a normal life as soon as possible.

The Task Force established very close working relationships with the stakeholders, including the insurance industry, the building industry and the affected communities.
The Task Force co-ordinated all the repair process of all insured properties and had as one of its objectives working with industry to ensure the supply of materials, significantly, roof tiles.
It was extremely effective and largely achieved its "unscientific" deadline of repairing all damage within 6 months compared to 3 years for the Newcastle earthquake, although it can be argued that an earthquake produces a greater variety of damage which is perhaps more difficult to repair.
Following the restoration work, the Task Force produced a report, recommending that the operating model should be adopted in future disasters.
It also made recommendations to the various players in the recovery process, including the insurance industry.
These are:-

Personal Focus
The industry should give priority to people's personal needs over the technical management of the claim. This was also a finding following the Newcastle earthquake – one in which, I believe, we have improved but have a way to go. We need to treat people as people with personal problems needing help, not just a damaged building to be repaired.

Single Claim Mindset
The insurance industry should approach a disaster as one single claim made up of myriad small pieces – using a set of guidelines so that all claims are dealt with uniformly.

Customer Satisfaction
The claims management process should be broadened to deliver claims satisfaction, i.e. the repair is completed and the customer satisfied. Issuing a cheque and closing the claim leaves a customer on their own to deal with repairs – which can be difficult if problems arise during repair.
To be fair, I think we do this for individual claims in many cases but, when the pressure is on with many hundreds of claims to be dealt with, there is perhaps a natural tendency to get it finalised and get on to the next one.
Generally though, the Task Force reported that the industry had performed very well.

I.D.R.O.

To build on the success of the industry's performance in Sydney and address some of the lessons, the industry has introduced The Insurance Disaster Response Organisation. "The I.D.R.O. is designed to co-ordinate the response required in disasters so that the industry can work with Government and emergency services to provide the best possible response and recovery service to people … affected by the disaster."
In the past, the old Insurance Emergency Service was supposed to take over and co-ordinate the assessing of claims for all companies.
With the convergence in the insurance industry (the top 10 companies now write around

80% of the business), companies are now attending to their own claims. The I.D.R.O. has been set up to provide assistance to policy holders after a disaster and assist insurance companies by establishing contact with Government at all levels. It is a partnership of insurers, reinsurers, brokers, loss adjusters and Insurance Enquiries & Complaints Limited, all of whom are represented on the National Committee which reports to the board of the Insurance Council of Australia.

Its objectives, following a disaster, are to:-

- Co-ordinate an efficient industry response
- Provide a single point of contact to assist policy holders
- Provide information on how to lodge a claim
- Provide general assistance and advice
- Help policy holders to identify their insurance company
- Establish contact with Government at all levels and represent the industry on any external committee
- Provide accurate information to insurers, Governments and media
- Assist the insurance industry as appropriate to respond to claims
- Conduct a post disaster review

The I.D.R.O. Operations Manual sets out the procedures to follow in the event of a disaster. Time does not permit looking at these in any detail.

In brief, the I.D.R.O. will set in motion procedures which will enable the objectives to be met. Most importantly, in the event that there are any disputes arising out of claims, and inevitably in any disaster there will be some, customers have access to the Insurance Enquiries and Complaints Ltd. Claims Resolution Process to get an economic (free to the customer) resolution to the problem.

With every disaster, and they seem to be getting more frequent, we learn more about how to better deal with the claims that arise. Through its post disaster review process, the I.D.R.O. will learn new lessons which will be built into its procedures to improve the industry response to and performance in the next one.

So, should a massive earthquake occur on the Lake Edgar Fault, the insurance industry is ready to respond.

Most companies have their own in-house disaster recovery plans to mobilise their assessing teams and claims staff and deal with the claims. The I.D.R.O. will co-ordinate, liaise with all players, issue information through press releases and media briefings and assist policy holders to make their claims and resolve disputes.

We just hope it doesn't happen.

LOCAL GEOLOGY, SEISMIC RISK, PLANNING AND INFRASTRUCTURE - HOBART

DR DAVID LEAMAN
LEAMAN GEOPHYSICS, HOBART, TASMANIA

AUTHOR:

David Leaman has more than 35 years experience of Tasmanian geological conditions and contributed to many crustal, structural and seismic evaluations of materials and their relationships. He has also been involved in foundation studies for major infrastructure projects and is aware of what is, or is not, considered. Until 1981 he worked for the Geological Survey of Tasmania and since then has been an independent consultant. He has taught University courses in engineering and environmental geology since 1972.

ABSTRACT:

Hobart exemplifies many Australian cities; it appears to be seismically stable. It is, however, built across a complex rift margin which is demonstrably active in geological terms. The escarpments adjacent to the rift margins are draped with debris know to collapse if saturated or vibrated and there is much evidence for previous bulk failures near the larger faults within the rift. The rift floor contains thick deposits which have resonated with distant earthquakes (to MM VI), and local events (to MM VII), and damage has been recorded.

Further urban development must be guided by knowledge of distribution of sensitive materials, stressed portions of the fault system and hints from low level seismic activity. The most important single piece of infrastructure, the Tasman Bridge, was neither designed, nor built, with a proper ranking of seismic risk in terms of its design life due to invalid assumptions about event recurrence intervals and foundation materials.

INTRODUCTION

This paper will be presented in Hobart and I have chosen this city to illustrate several risk factors and principles even though few local citizens consider the city to have any seismic risk. Hobart has yet been included in the Cities Program (see Jensen, 2000) but is typical of the geological problems, attitudes and issues affecting many Australian cities.

RISK

Risk factors fall into two main classes:
a) concerning the seismic risk itself,
b) the nature and acceptability of any damage from an earthquake event.

Hobart is located in a complex rift valley first formed in mid Jurassic times and which has been greatly modified by Late Cretaceous-Early Tertiary and Mid Tertiary extension. The west bounding fault system (Cascades Fault Zone, CFZ) is compound, large and active (Figure 1): the latest significant events being in 1854 and 1959 (magnitudes M ~ 5.5 and ~ 4 resp.). The Wellington Range uplift is related to this system. The CFZ overlies an ancient basin margin (at least Cambrian in age) and the structural controls may be much older: the modern rift system is not randomly located with respect to these features and patterns of fault dislocations and offsets must reflect underlying structures (Leaman, 1990, 1992). Jurassic dolerite intrusions and feeders are related to crustal elements. Tertiary volcanism was also focussed within the rift (Sutherland, 1976).

Little information is available about recurrence of seismic events and hence risk along the CFZ but recent recognition of displacement and rotation of Late Pleistocene gravels near Granton implies many major events with perhaps a maximum two century recurrence interval. Longer term estimates, based on likely event displacements, for the period from the Jurassic to the present imply events in excess of M3 at intervals of perhaps no more than 25 to 50 years, using normal ratios between magnitude levels (e.g. Gaull & Kelsey, 1999), *somewhere* along the 100 km long zone. This is only slightly less than modern records would suggest but averages the tectonically hyperactive times with peaceful periods (see also Gaull et al, 1990).

The Hobart area is, therefore, at direct risk from the CFZ at periods of 30-100 years as a long term average whilst acknowledging the swarm tendency of historic Tasmanian events (e.g. N Tasmania 1880-1895; Bream Creek, S Tasmania 1986-1988).
Secondary risks derive from earthquakes elsewhere; namely NE Tasmania or central SW Tasmania (including the Lake Edgar Fault area)(Michael-Leiba, 1989). Events in these locations have led to recorded damage and Modified Mercalli intensities up to MM VI in some suburbs. These events have likely recurrence intervals of about 55 and 35 years respectively and recognition of the second group accounts for modified hydro dam designs in southwest Tasmania and the establishment of a monitoring network in 1957.

The risk is influenced by local geology: in particular Tertiary or Recent sedimentation within the rift system. These materials may be poorly or partially consolidated. Most reports of damage or disturbance (up to MMI VII) from events, up to 1960, in western or north-eastern Tasmania derive from observers living on the Tertiary basin fills,

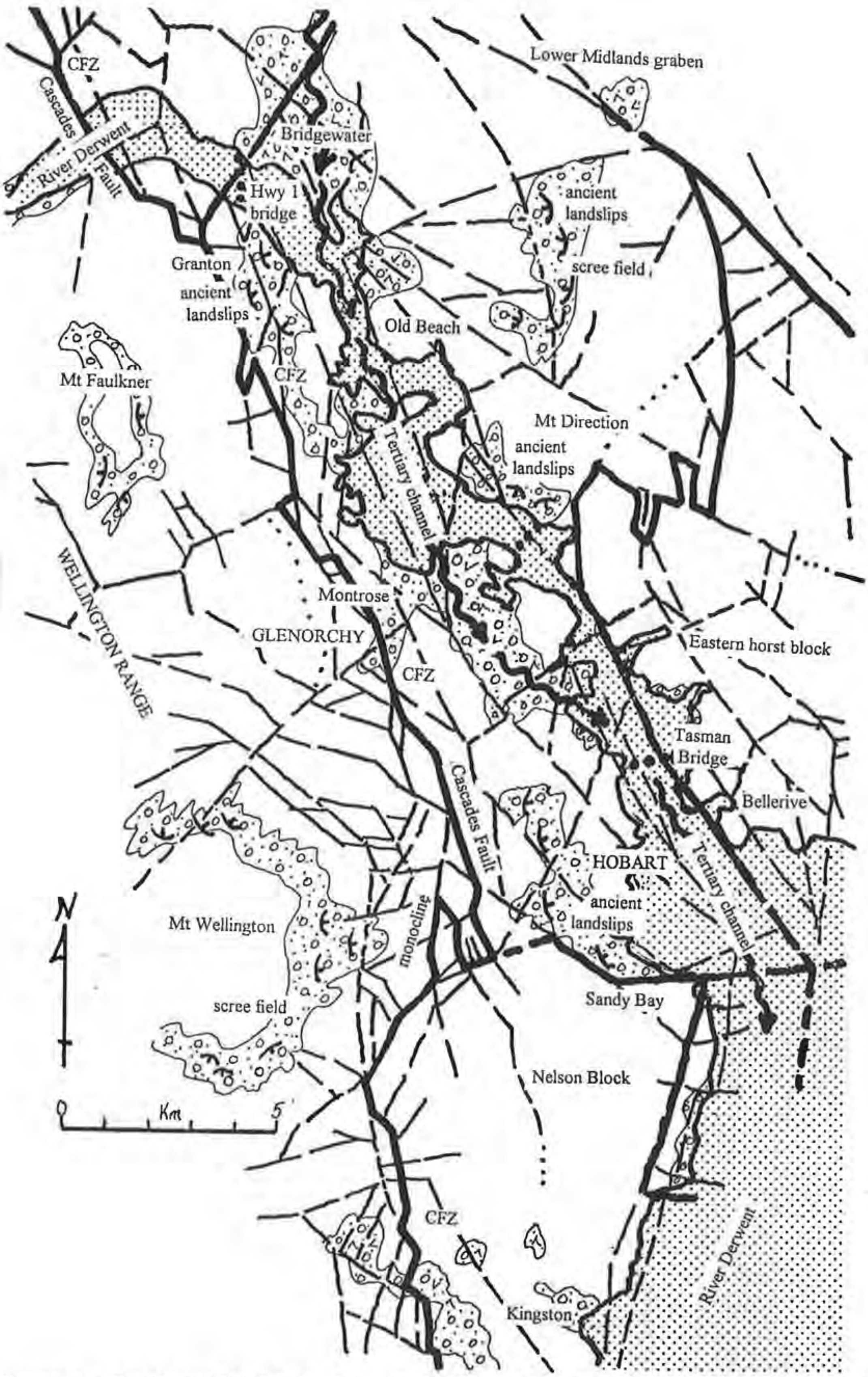


Figure 1: The Cascades Fault Zone in the Hobart Metropolitan Area: the Derwent Rift. Not all small faults shown or identified. Tertiary and Recent deposits shown hatched (volcanics v). Mapping after Leaman (1972) and Forsyth (1999).

especially in Sandy Bay. Many other parts of these basins have now been developed but there has been no sizeable event since about 1959. Modified Mercalli Intensities of no more than III are associated with other rock types for the same events and no general damage has ever been reported where older rocks are involved. All historic damage has been acceptable since no large, recent, local event has occurred along the CFZ within the urban area. The February 1854 event (Alexander, 1986), with epicentre near Montrose (inferred from reports in Hobart Town Courier), affected few since the area was then farmland. Graphic reports were offered by the few residents who had built on the alluvial materials in Glenorchy. No lives have yet been lost and building damage has been limited.

SENSITIVE AREAS

Most responsive materials occur at low elevations within the rift system and many are basin or channel fills (see Figure 1). The River Derwent meanders across its ancient channel and modern, Pleistocene and Tertiary-Cretaceous channels overlap south of Cornelian Bay and north of Glenorchy (Leaman, 1999). Other materials which are either inherently unstable, or which may become unstable, include slope deposits near the horst and margin faults such as along the western side of the CFZ, or Mt Direction. These materials may be destabilised by dense housing and associated garden practices (watering) and many deposits contain evidence of past failures. Most areas with evidence of prior failure can be associated with elements of the fault system and a direct relationship between seismic events and slope stability, with or without climatic or wetting factors, is implied.

The coupling of risk factors and sensitive areas, combined with limited actual experience, indicates that a special building code is required for these areas which provides some guidance concerning the type of foundation, construction style and height of structure. Some provisions of this type are offered in terms of the foundation and reactive soil code (AS 2870). No suitable code presently exists which might give some protection against vibration damage or suggest suitable designs for suspect areas in the Hobart Metropolitan Area. No major piece of infrastructure, whether industrial plant, power station, emergency service, roadway or bridge, should be built on post-Cretaceous material in the Hobart area without due regard for design factors (including height), or material *and* structural response. There is only one such structure in the Hobart area in this situation but it is the critical link in the regional transportation and communication network: the Tasman Bridge.

DESIGN LIFE, SURVIVAL AND RECURRENCE INTERVALS

The Tasman Bridge typifies inadequate planning and design procedures. This bridge replaced a floating bridge: itself flawed by a design which overlooked another class of natural events - southerly storms. The Tasman Bridge design developed from a simple replacement of part of the floating bridge to a higher road capacity elevated concept: all without any satisfactory investigation of the river bed and pile foundation conditions. Water-based, deep drilling technology in the design period (1950-60) was unable to sample the bedrock and the experimental refraction data (velocities less than 1900 m/s) indicating soft sediment conditions were rejected as anomalous since it was assumed there was a rock bottom beneath thick silts (see Leaman, 1977, 1999; Trollope et al,

1966)(Figure 2). The alternative design (suspension bridge) was considered too expensive (double cost - but actual cost of the present bridge!).
Note that the cost judgment was based on estimated costs and did not consider
a) reliability of foundation knowledge: nil (100% for suspension bridge design)
b) risk of collision: now estimated at an event per 30 years (nil for suspension bridge)
c) risk of vibration and settlement by earthquake: uncertain (nil for suspension bridge)

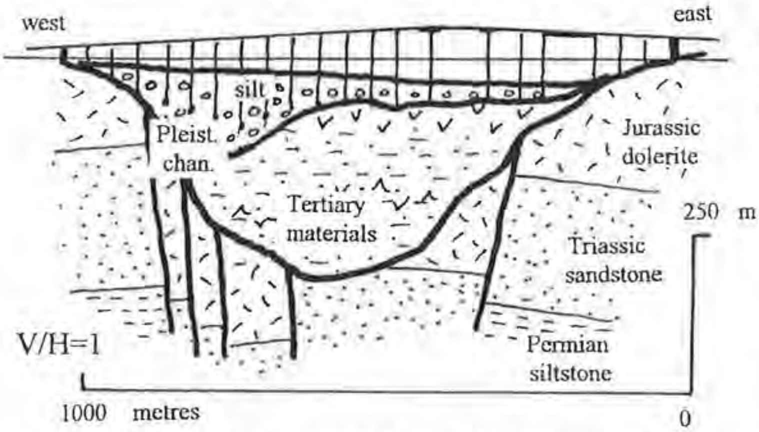


Figure 2.

Tasman Bridge section. Diagram indicates scale of bridge/piers and three channels: modern (silts), Pleistocene (incl. gravels) and Tertiary (sands, clays, volcanics)

The piered design (completed by consultants in Britain) did not seriously consider earthquake risk for three reasons. None was perceived, no data base was available about past events, and the founding materials were thought to be insensitive. The risk effect of strong winds, storms or currents were, however, considered in the design. We do need to wonder whether any consideration would have been given to a data base such as that now in existence given present day attitudes to the risk from rare or natural events - hence this paper. The maximum design height of the bridge in terms of pile and pier length was 80 metres but some piers are up to 110 metres (Trollope et al, 1966). No details of its response to earthquake frequencies have been published and since the last event of significance was in 1946, we cannot know (Michael-Leiba and Jensen, 1993).
If, however, a bridge has a design life of 50 to 100 years, or more, then we must expect two or more threatening events. This is not a good situation.

Had the river bed conditions been appreciated at the time of design comparison and evaluation then, either the design would have been modified and properly costed, or the suspension alternative would have been chosen as the least problematic. An informed design would also have included seismic risk factors. Conclusion: the Tasman Bridge would have looked very different.

This issue and its implication is not dead. The crossing at Bridgewater is scheduled for rebuild or replacement by a modern, higher level design with highway interchanges. The Bridgewater crossing straddles the active branch of the CFZ in the area. A small scarp buried by recent silts intersects the alignment and Tertiary rocks occur at the north end of the present crossing as well as downstream. Should the location be adjusted upstream to better basement conditions? Should a low level design be retained? There is still an opportunity for a better informed decision.

CONCLUSION

We gamble with community resources, lives and emergency services if we fail to consider the interaction between natural risk factors and economic or social costs. The same principles apply to all types of natural risk (flood, slope or coastal failure, volcanic, storm or seismic) and each class must be related to aspects of local geology and the nature of the development undertaken. It must be recognised that the rare, rather extreme event, is the true source of hazard. Humans rarely think in terms of the geological recurrence periods; lives are too short. But these things have occurred, can occur, and will occur again. Only the when and extent of actual damage are uncertain. Assessment of these uncertainties is the crucial element of insurance coverage including financial ability to pay when the event inevitably occurs (Bernstein, 1998).

Appropriate planning by government authorities at all levels, and actuarial judgments for insurance, requires much information. In seismic terms this depends on description of materials and responses (including finding the materials), requires a history of events and reactions or damage, and some consideration of building options and alternatives. Each category needs low, or trickle, funding regimes and a continuity of observation. Final assessment of the factors will never be possible since the hazard is essentially chaotic but good estimates of probability depend on a rich data base: one of long period. Governments and insurance companies must be prepared to invest in such a data base since they are the ultimate beneficiaries - along with a community which should demand such protection, but is unaware of the need to make such a claim. All risks involved can be minimised.

REFERENCES

Alexander, A., 1986. Glenorchy, 1804-1964. Glenorchy City Council. 381p.
Bernstein, P.L. (1998). Against the odds: the remarkable story of risk. Wiley, New York.
Forsyth, S.F., (1999). Hobart. 1:25000 series digital geological map. Geol. Surv. Tasm.
Gaull, B.A. and Kelsey, P. 1999. Historical felt intensities as a guide to earthquake hazard. Aust. J. Earth Sci., 46, 365-376.
Gaull, B.A., Michael-Leiba, M.O., and Rynn, J.M.W., (1990). Probabilistic earthquake risk maps of Australia. Aust. J. Earth Sci., 37, 169-187.
Jensen, Vagn. H. (2000). Seismic microzonation in Australia. J. Asian Earth Sci, 18, 3-15.
Leaman, D.E., (1972). Hobart. 1:50000 series geological map. Geol. Surv. Tasm.
Leaman, D.E., (1977). The River Derwent. Elwick Bay to Macquarie Point. Geology: facts deductions and problems. Tech. Rep. Dep. Mines Tasm., 20, 85-101.
Leaman, D.E., (1990). Inferences concerning the distribution and composition of Pre-Carboniferous rocks in southeastern Tasmania. Pap. Roy. Soc. Tasm., 124, 1-12.
Leaman, D.E., (1992). Finding Cambrian keys: an essay in controversy, prospectivity and tectonic implications. Bull. Geol. Surv. Tasm., 70, 124-148.
Leaman, D.E., (1999). Walk into History in southern Tasmania. Leaman Geophysics, Hobart. 288p.
Michael-Leiba, M.O., and Jensen, V., (1993). The West Tasman Sea (Flinders Island) Earth-quake of 14 September 1946. BMR J Geol. Geophys. 13, 369-372.
Sutherland, F.L., (1976). Cainozoic volcanic rocks, in Leaman, D.E., (1976). Hobart. Explanatory notes to geological map. Geol. Surv. Tasm.
Trollope, D.H., Freeman, McD., and Peck, G.M., (1966). Tasman Bridge Foundations. J. Inst. Engrs. Aust. 38, 117-130.

A CATEGORISATION OF SEISMIC HAZARD FOR ENGINEERING USE

JOHN S. STEHLE

AUTHOR:

John Stehle is a Ph.D. student at the University of Melbourne and currently working on the Cities Project at the Australian Geological Survey Organisation.

ABSTRACT: *(Full paper not available)*

Performance based approaches to earthquake engineering are widely proposed, however, rarely is this performed with any accuracy or with confident knowledge of the uncertainty. In this paper, the uncertainty associated with earthquake ground motion is illustrated and a categorisation of events is proposed so that conservative engineering assessment of structures can be made.

The categorisation of seismic hazard is performed because the author was concerned about a number of issues. For example, there is and always will be conflicting views on what the seismic hazard is, and in particular what the probability and characterisation of a large event will be, especially in regions with low levels of seismic activity. Also, even in regions of high seismicity with a lot of recorded historical data, identified trends are surrounded by a lot of scatter. In terms of engineering assessments, it seems to be an illusion that a zone rated with an effective peak ground acceleration coefficient of 0.08g could be distinguished from a zone rated at 0.09g or 0.10g which is the case in AS1170.4 (1994). This is clearly evident from the fact that peak ground velocities and displacements are better indicators of damage than PGA.

ACCELERATING SEISMIC MOMENT RELEASE, THE CRITICAL POINT HYPOTHESIS, AND PREDICTING MACROSCOPIC FAILURE

DION WEATHERLEY AND PETER MORA
QUAKES, DEPARTMENT OF EARTH SCIENCES, UNIVERSITY OF QUEENSLAND

AUTHORS:

Dion Weatherley is a PhD student at QUAKES. He is conducting his research on the physics of earthquakes.

Peter Mora is a Professor at The University of Queensland, Director of QUAKES and Executive Director of the APEC Cooperation for Earthquake Simulation. He obtained a BscHons from Adelaide University and a PhD from Stanford. He has worked as a researcher at Thinking Machines Corporation and as a Professor of the IPG in Paris.

ABSTRACT:

Perhaps the most controversial debate in Seismology is whether or not large earthquakes may be predicted. In recent years, this debate has been fueled by the suggestion that the Earth's crust is a Critical Point (CP) system. The Critical Point Hypothesis predicts that cumulative seismic moment release should accelerate in the years to decades prior to a large or great earthquake, in a broad region surrounding the mainshock epicentre. This acceleration may be modelled by a power-law time-to-failure relation, yielding an estimate of the time, and in some cases, the magnitude of the impending large event. The CP Hypothesis maintains that the accelerating sequence of earthquakes is due to the progressive formation of long-range correlations in the tectonic stress field. Such long-range correlations are necessary to permit the occurrence of a large earthquake. Subsequent to the large event, the long-range correlations are destroyed, preventing the occurrence of another large event until the correlations are reformed during a subsequent accelerating sequence. This paper describes the CP Hypothesis and reviews observational evidence which supports this hypothesis. The implications for prediction of large earthquakes, and prediction of macroscopic failure within mines and dams, is discussed.

Accelerating Seismic Moment Release

For some time it has been recognised that the rate of earthquake activity, particularly of moderate earthquakes, changes in the period between large and great earthquakes (Gutenberg and Richter, 1954 [3]). Keylis-Borok and Malinovskaya (1964) [6] proposed that the preparation for a large earthquake involved the occurrence of a number of moderate earthquakes in a broad region surrounding the epicentre of the impending large event. Despite efforts to quantify this preparation process, the lack of a physical basis hampered support for the hypothesis. Voight (1989) [12] introduced an empirical relation describing the behaviour of materials such as metals, rocks, and soil, in the terminal stages of failure. This relation was employed to derive a relation between a measurable quantity (Ω) such as strain or seismic moment, and the time remaining until failure t_f of the form:

$$\sum \Omega(t) = A + B(t_f - t)^{-m} , \tag{1}$$

where A, B, m are empirically determined constants.

Such a power-law time-to-failure relation has been used for several decades, in various forms, to successfully predict failure times of stressed metals and ceramics, landslides, and volcanic eruptions (Varnes, 1989 [11]). In the last decade, a number of researchers have employed Equation 1 to model the seismic moment release within a broad region, prior to the occurrence of a large or great earthquake in a variety of tectonic settings. Jaumé and Sykes (1999) [5] reviewed the reported cases of accelerating seismic moment release. Based upon their review, the authors noted four major characteristics of accelerating seismicity:

1. The rate of seismic moment or Benioff strain release in moderate earthquakes accelerates prior to the occurrence of a large or great earthquake. In many cases, this acceleration can be modelled using Equation 1 to estimate the time and, in some cases, the magnitude of the oncoming event.

2. The moderate earthquakes involved in the accelerating sequence occur primarily outside the rupture zone of the large or great earthquake.

3. The change in rate of earthquake occurrence is limited to earthquakes within about 2.0 units of the mainshock magnitude.

4. The size of the region in which the moderate events occur, scales with the size of the oncoming mainshock.

Large and great earthquakes in California, the Alaska-Aleutian Islands, the New Madrid Seismic Zone, the Virgin Islands, India, Asia, and Japan have been preceded by accelerating sequences of moderate events. The identification of this phenomenon in a variety of tectonic settings and the scaling of region size with mainshock magnitude suggest that a physical mechanism underlies accelerating moment release. However, cases have also been reported in which large earthquakes were not preceded by accelerating moment release. Bufe *et al.* (1994) [2] found no acceleration prior to the 1986 $M = 8.1$ Andreanof Islands earthquake, despite identifying accelerating sequences prior to other large earthquakes in that region. Another case is the three $M > 6.0$ earthquakes which occurred at Tennant Creek, NT in 1988. Prior to 1987, there was no record of $M \geq 5.0$ earthquakes within 500km of Tennant Creek (Bowman, 1992 [1]).

The Critical Point Hypothesis

Although accelerating moment release is not a ubiquitous precursor of large earthquakes, the evidence suggests that accelerating sequences are an expression of a physical process. Power-law event size distributions, such as the Gutenberg-Richter relation, and power-law acceleration in energy release are two features of dynamical systems displaying critical point behaviour. Critical point behaviour was first identified during phase transitions in thermodynamic systems. One of the simplest examples is the phase transition between a single phase, fluid vapour to a two phase, liquid-gas as the temperature of a fluid is decreased below its critical temperature. Another well-studied example is the spontaneous demagnetisation of a paramagnet when heated above its Curie temperature.

A theory known as Renormalisation Group Theory was developed in Statistical Physics to describe the physics of extended dynamical systems near a critical phase transition. Very near the critical transition, there is a progressive formation of long-range correlations in a physical property of the system associated with fractal clusters of regions with similar physical properties. For fluids, the physical property of interest is fluid density, while net magnetisation is the important property for spontaneous demagnetisation.

Sornette and Sammis (1995) [9] derived a Renormalisation Group Theory for earthquakes and proposed the Critical Point Hypothesis. This hypothesis asserts that an earthquake may only occur when there exists sufficiently long-range correlations in the tectonic stress field. These long-range correlations are formed by the action of tectonic loading and stress transfer during smaller earthquakes in the vicinity of the impending earthquake. The occurrence of an earthquake destroys the long-range correlations, diminishing the likelihood of another earthquake of comparable size until the long-range correlations can be reformed. Thus, the preparation of the Earth's crust for a large or great earthquake involves the occurrence of moderate earthquakes in the surrounding region. Static stress changes during these moderate earthquakes and tectonic loading, promote the formation of the long-range stress correlations necessary to produce a large event.

Occurrence of a large or great earthquake destroys long-range correlations in the region, decreasing the likelihood of moderate to large earthquakes. As tectonic loading and smaller earthquakes reform long-range correlations, moderate to large earthquakes become progressively more likely. Thus, an increase in the rate of moderate earthquakes prior to a large earthquake is predicted by the CP Hypothesis. Renormalisation Group Theory predicts power-law accelerations in energy release prior to the large or great event, which follow the form of Equation 1. A fractal distribution of earthquake hypocentres and power-law frequency-magnitude distributions are also predicted by the Renormalisation Group Theory.

Stress transfer and Coulomb Failure Analysis

Despite predicting accelerating moment release, fractal distributions of hypocentres, and the Gutenberg-Richter law, it remains unclear whether the CP Hypothesis is a good theory of regional seismicity. The major prediction of the hypothesis, namely evolution of stress field correlations, cannot be confirmed using the currently available observational methods. However, indirect evidence exists which supports the proposition that stress transfer during an earthquake may promote the occurrence of a subsequent earthquake.

Coulomb Failure Analysis is a technique developed to approximate the static stress changes due to a given earthquake. Empirical data such as the slip distributions, fault orientation, and earthquake magnitude for a given event, is used to model the earthquake as an elastic dislocation in a uniform continuum. The static stress changes in the medium due to the dislocation may then be computed. This data is used to determine the change in Coulomb Failure stress on optimally oriented faults within the medium. The change in Coulomb Failure stress for a given fault is defined by

$$\Delta CFS = \Delta\tau - \mu\Delta\sigma_n \quad , \tag{2}$$

where $\Delta\tau$ is the change in shear stress and $\Delta\sigma_n$ is the change in normal stress on the fault due to the nearby earthquake, and μ is the coefficient of friction of the fault. A positive ΔCFS implies that the fault has been brought closer to failure due to static stress transfer. Conversely, a negative ΔCFS implies that the fault has been unloaded by the nearby earthquake.

Stein (1999) [10] reviews Coulomb Failure Analysis and its implications for stress triggering and seismic hazard assessment. Lobes of off-fault aftershocks are commonly found to correspond to regions where Coulomb Failure stress has increased due to the mainshock (see Harris, 1998 [4] for a review). The correlation between Coulomb stress increases and off-fault aftershocks is insuffient evidence to demonstrate that stress change due to a mainshock had any effect on off-fault seismicity. To demonstrate this, Coulomb stress increases and seismicity rate changes must be compared. A spatial regression of stress change on seismicity rate change for the 1995 $M_w = 6.9$ Kobe, Japan earthquake revealed that a 1-bar increase in Coulomb stress resulted in a 10-fold increase in seismicity rate for shocks with $M_l \geq 2.6$; a 5-bar increase in stress resulted in a 100-fold increase in seismicity rate [10]. Parsons *et al.* (2000) [8] performed Coulomb Failure Analysis for seven large earthquakes on the North Anatolian fault since 1939. These events displayed a largely westward progression since 1939. Stress triggering is held responsible for this progression; all but one event appeared to promote the occurrence of the next event.

Numerical simulations and the plausibility of the theory

The results of Coulomb Failure studies indicate that the stress changes due to an earthquake affect the seismicity rate in the surrounding region and may promote the occurrence of subsequent events. However, such evidence is insufficient to confirm the assumption of the CP Hypothesis, that stress changes due to smaller earthquakes prepare a region for a large earthquake. Given the present capabilities for measuring the stress field of the crust, it is difficult to confirm the validity of this assumption via direct observations.

One means available to explore the plausibility of this assumption is to study physics-based numerical models of earthquake fault systems. Significant advances in both numerical methods and computational speed have been made in the last decade. These advances offer the possibility of simulating the elastodynamics of a complex system of faults embedded in a 3D elastic continuum. One advantage of numerical simulations is that all physical parameters of the system are available for analysis. Recent simulations of a complex fault zone using the Lattice Solid Model have shown stress correlation evolution consistent with the CP Hypothesis (Mora and Place, 2000 [7]). Further study of stress transfer using macroscopic models of fault systems may confirm whether stress correlation evolution is an important factor determining regional seismicity. Simulations using simplified Statistical Physics models have shown that critical point systems may display a variety of behaviours (Weatherley *et al.*, 2000 [13]). Such results offer the hope of explaining both cases of accelerating moment release and cases where no acceleration was observed within a common framework.

Preliminary results from 2D, two-fault models indicate that a rupture on a given fault may cause static stress changes on nearby faults. Work is in progress to study stress transfer within systems of faults of differing lengths, frictional properties, and orientations. It is hoped that such a study may provide insight into the role of stress transfer in determining subsequent seismicity, and provide an indication of the applicability of the CP Hypothesis as a theory of regional seismicity.

Implications for prediction of macroscopic failure

The phenomenon of accelerating seismic moment release has clear implications for seismic hazard assessment. Identification of an accelerating sequence of earthquakes in a given region offers the possibility of forecasting the occurrence of a large or great earthquake in the intermediate term. Although is is doubtful that an accuracy better that a few months can be achieved, such intermediate-term forecasts provide a useful indication of the probability of a strong, damaging earthquake in a given region.

The Critical Point Hypothesis is perhaps the most promising advancement towards a comprehensive theory of macroscopic failure. Implicit in the theory is the concept of self-similarity; similar physical processes preceed ruptures of quite difference scales. The time-to-failure relationship, Equation 1, has been successfully employed for several decades to predict the failure time for stressed materials, landslides, and volcanic eruptions. Although some assumptions of the theory are still under contention, the possibility of predicting macroscopic failure is an enticing prospect, particularly for the mining industry.

Capabilities in numerical simulation continue to improve at an astounding rate. Comprehensive physics-based models of geophysical processes, both in the microscopic and macroscopic domains, may soon be a reality. Such models will be vitally important to the mining industry in particular. Physical models of the Earth's crust such as the Lattice Solid Model [7], combined with the geophysical data available in the mine environment, will permit the construction of "virtual mines". A virtual mine which may be continuously updated as ore extraction occurs will provide a means to assess the changing stress state within the mine. By employing the Critical Point Hypothesis or a similar theory, it may be possible to provide sufficient warning of catastropic failures such as rock-bursts and cave-ins to minimise both economic and human losses.

References

[1] Bowman, J. R., 1992, *The 1988 Tennant Creek, Northern Territory Earthquakes: A Synthesis,* Aust. J. Earth Sci. **39**, 651–699.

[2] Bufe, C. G., Nishenko, S. P., and Varnes, D. J., 1994 *Seismicity Trends and Potential for Large Earthquakes in the Alaska-Aleutian Region,* Pure Appl. Geophys. **142**, 83–99.

[3] Gutenberg, B. and Richter, C. F., 1954, *Seismicity of the Earth and Associated Phenomena,* (Hafner, New York, 1954).

[4] Harris, R. A., 1998, *Introduction to Special Session: Stress Triggers, Stress Shadows, and Implications for Seismic Hazard,* J. Geophys. Res. **103**, 24347–24358.

[5] Jaumé S. C. and Sykes, L. R., 1999, *Evolving Towards a Critical Point: A Review of Accelerating Seismic Moment/Energy Release Prior to Large and Great Earthquakes,* Pure Appl. Geophys. **155**, No. 2-4, 279–305.

[6] Keylis-Borok, V. I. and Malinovskaya, L. N., 1964, *One Regularity in the Occurrence of Strong Earthquakes,* J. Geophys. Res. **69**, No. 14, 3019–3025.

[7] Mora, P. and Place, D., 2000, *Microscopic simulation of stress correlation evolution: implications for the Critical Point Hypothesis for earthquakes,* abstract submitted to Second Int. ACES Workshop, Japan.

[8] Parsons, T., Toda, S., Stein, R. S., Barka, A., and Dieterich, J. H., 2000, *Heightened odds of Large Earthquakes near Instanbul: An Interaction-Based Probability Calculation,* submitted to Science.

[9] Sornette, D. and Sammis, C. G., 1995, *Complex Critical Exponents from Renormalisation Group Theory of Earthquakes: Implications for Earthquake Predictions,* J. Phys. I France, **5**, 607–619.

[10] Stein, R. S., 1999, *The Role of Stress Transfer in Earthquake Occurrence,* Nature, **402**, 605–609.

[11] Varnes, D. J., 1989, *Predicting Earthquakes by Analyzing Accelerating Precursory Seismic Activity,* Pure Appl. Geophys. **130**, 661–686.

[12] Voight, B., 1989, *A Relation to Describe Rate-dependent Material Failure,* Science, **243**, 200–203.

[13] Weatherley, D., Xia, M. F., and Mora, P., 2000, *Correlation length evolution in cellular automata with long-range stress transfer,* abstract submitted to Second Int. ACES Workshop, Japan.

EARTHQUAKE FORECASTING: RETROSPECTIVE STUDIES IN AUSTRALIA - THE NEWCASTLE AND BURRA EARTHQUAKES - AND NUMERICAL SIMULATION OF THE PHYSICAL PROCESS

PETER MORA[(1)], DAVID PLACE[(1)], YUCANG WANG[(2)], XIANGCHU YIN[(2,3)], KEYIN PENG[(3)] AND DION WEATHERLEY [(1)]

(1) QUAKES, DEPARTMENT OF EARTH SCIENCES, THE UNIVERSITY OF QUEENSLAND, BRISBANE, QLD,.
(2) LNM, INSTITUTE OF MECHANICS, CHINESE ACADEMY OF SCIENCES, BEIJING,
(3) CENTER FOR ANALYSIS AND PREDICTION, CHINA SEISMOLOGICAL BUREAU, BEIJING,

AUTHORS:

Peter Mora is a Professor at The University of Queensland, Director of QUAKES and Executive Director of the APEC Cooperation for Earthquake Simulation. He obtained a BscHons from Adelaide University and a PhD from Stanford. He has worked as a researcher at Thinking Machines Corporation and as a Professor of the IPG in Paris.

David Place is a Senior Research Officer at QUAKES. He obtained a MSc in parallel computer science and earthquake simulation in France at Lille University and at IPG in Paris. He obtained a PhD in earthquake simulation from The University of Queensland.

Yucang Wang is a Research Fellow of the Laboratory of Nonlinear Mechanics of the Chinese academy of sciences. He will join QUAKES as a Research Fellow end 2000.

Xiang-chu Yin is a Professor of the Centre for Analysis and Prediction and the China Seismological Bureau and of the Laboratory of Nonlinear Mechanics of the Chinese Academy of Sciences, He is founder of the LURR earthquake prediction method.

Keyin Peng is a Professor of the Centre for Analysis and Prediction of the China Seismological Bureau. He has worked extensively in development and practical application of the LURR earthquake prediction method.

Dion Weatherley is a PhD student at QUAKES. He is conducting his research on the physics of earthquakes.

ABSTRACT:

Mitigation of the earthquake hazard requires an ability to reliably predict the level and variability in space and time of the hazard. The key to such an ability, particularly the time variability aspect, is an understanding of the phenomena. We present retrospective intermediate-term earthquake forecasting studies for the Newcastle and Burra earthquakes using Accelerating Moment Release and Load-Unload Response Ratio observations. The results suggest both events could have been forecast and point to a common physical origin for the observations. A new numerical simulation tool for solid earth processes - LSMearth provides a predictive modelling capability that allows the underlying mechanism to be studied. The simulation results are consistent with the observations and point to a physical mechanism for forecasting. An international cooperation has been established to simulate the entire earthquake process and provides an opportunity to develop a new earthquake anaylsis system based on modelling the phenomena.

Paper No. 28

Introduction

The Centre for Analysis and Prediction (CAP) of the China Seismological Bureau – which has responsibility for forecasting earthquakes in China – has made successful predictions resulting in life saving evacuations (Hui and Kerr, 1997). While such results intrigue western scientists, there has been limited overall success in earthquake forecasting to date so risk management practitioners have tended to rely on probabilistic hazard assessments. This method assumes the frequency-magnitude statistics of recently recorded low-level seismic activity provide a reliable basis to extrapolate the long-term earthquake hazard. However, this hypothesis is not born out by observations which indicate both the seismicity and hazard can vary strongly in time. Progress towards taking this time variation into account requires a thorough understanding of the physical process. A predictive modelling capability for earthquake phenomena would provide such an understanding and the basis to develop a new generation of earthquake analysis and forecasting system. Recognition of the need for simulation in the international community has led to establishment of a multi-lateral research cooperation (ACES[1]) to develop numerical simulation models for the entire earthquake generation process (see http://www.rist.tokyo.or.jp/ACES_WS2 for information on the 2nd ACES workshop). Here, we present results of collaborative research under ACES involving QUAKES, CAP and the Laboratory of Nonlinear Mechanics, Chinese Academy of Sciences.

Retrospective earthquake forecasting studies

Observations of increasing seismic energy release rates prior to large earthquakes have led researchers to suggest that fitting the cumulative energy (or Benioff strain) release to a power-law time-to-failure function such as $E(t) = A + B(t_f - t)^c$ may provide a means for intermediate-term earthquake prediction (Bufe and Varnes, 1993). AMR has successfully been used to predict the 1996 M=7.9 Aleutian Islands, Alaska earthquake (Bufe *et al.*, 1994; Bufe *et al.*, 1996) and is being observed in an increasing number of cases prior to large earthquakes (Bowman et al, 1998). A physical basis for the AMR observations has been proposed (Sornette and Sammis, 1995, Rundle et al, 1999) and is consistent with observations of changes in the frequency-magnitude distributions of earthquakes in the lead-up to large events (Jaumé, 2000). Namely, that the Earth's crust acts as a critical point system. If so, then AMR would provide a means to forecast a critical point when the Earth's crust is primed for a large earthquake (see Weatherley and Mora, 2000, for a detailed review of the Critical Point Hypothesis). Hence, this kind of forecast provides the time after which a large event is likely to occur.

The Load-Unload Response Ratio (LURR) method (Yin et al, 1995) is one of the methods being applied in China to predict earthquakes. An increasing number of cases are being documented in which high LURR or *Y*-values precede earthquakes (Yin et al., 2000). The physical concept underlying LURR (Yin et al., 2000) is that when a system is in a stable state, the response to a small loading is nearly the same as the response to unloading, but when the system is near failure or in an unstable state, they are quite different. LURR is defined according to this difference as $Y = X^+ / X^-$, where X^+ and X^- are response rates during loading and unloading. When a system is in a stable or linear state, $X^+ \approx X^-$ so $Y \approx 1$. When a system lies beyond the linear state,

[1] The APEC Cooperation for Earthquake Simulation (ACES) – http://quakes.earth.uq.edu.au/ACES.

$X^+ > X^-$ and $Y > 1$. Hence, LURR can be used as a criterion to judge the degree of stability of a system. In the practice of earthquake prediction using LURR, loading and unloading are decided by calculating the effective shear stress induced by the earth tidal forces along certain fault orientations or tectonic stress directions, and LURR is often defined as ratio of Benioff strain release during loading compared to unloading periods. In retrospective studies, high LURR or Y-values have been observed a few months or years prior to most events (Yin et al., 2000) and some successful intermediate-term earthquake predictions have been made.

The Burra and Newcastle earthquakes

Power law time-to-failure curves and LURR were calculated for the 1997 M=5.0 Burra SA earthquake and the 1989 M=5.7 Newcastle earthquakes (Figure 1). In the case of the Burra SA earthquake, the LURR rises sharply just prior to the event and the AMR based forecast is quite precise (M=5.1 mainshock predicted with the crust reaching a critical state a few weeks before the event – see also Mora et al., 1999). In the case of the Newcastle earthquake, the LURR anomaly peaks a few years early and remains high until just prior to the event. The AMR forecast is again quite accurate (M=5.5 predicted but with the critical point reached a few years prior to the event). These results suggest that both events could have been forecast in the intermediate-term (months to years time frame) using AMR and LURR. Observational studies demonstrate that the critical region around the epicenter where AMR fits are optimal is similar to that in which LURR anomalies are maximized (Yin et al, 2000). This provides evidence that both AMR and LURR have the same physical origin.

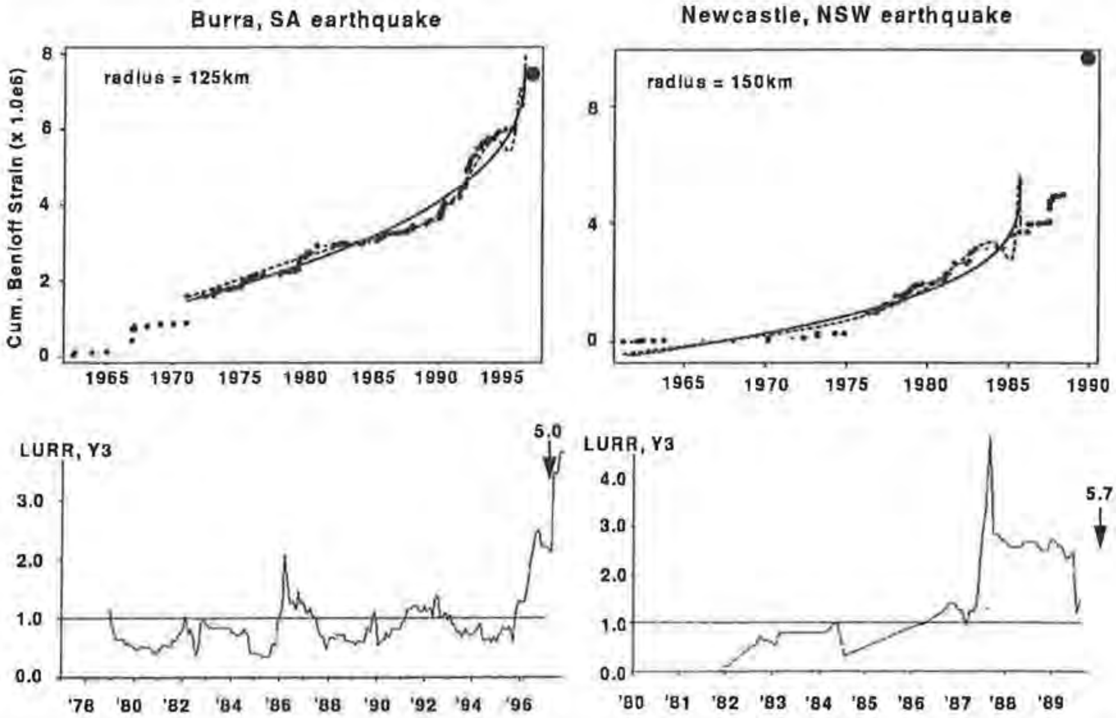


Figure 1. **Top:** Cumulative Benioff strain and power law time-to-failure fits calculated from data within 125 km of the Burra earthquake and 150 km of the Newcastle earthquake. Small circles depict earthquake data, large circles on each plot are the Burra & Newcastle earthquakes, and solid and dashed lines are respectively the power law time-to-failure fits without and with log-periodic fluctuations. **Bottom:** LURR anomalies for the two earthquakes.

Predictive modelling of the earthquake process – LSMearth

The lattice solid model is a particle-based numerical model that was developed to simulate the nonlinear dynamics of earthquakes (Mora and Place,1994; Place and Mora, 1999). The lattice solid model has been applied to the study of the heat-flow paradox (Mora and Place, 1998; 1999), rock fracture, and localisation phenomena (Place and Mora, 2000). In its present form, the LSM is capable of simulating physical processes such as friction, fracture, granular dynamics and thermal effects including thermo-mechanical and thermo-porous feedback (Abe et al., 2000). A modular approach and software system (Place and Mora, 2000; Figure 2) has been developed that allows the LSM to be easily applied to a range of disciplines including earthquake studies, engineering & construction, geomechanics, and materials engineering. Here we make use of the LSM to probe the underlying mechanisms of the AMR and LURR observations.

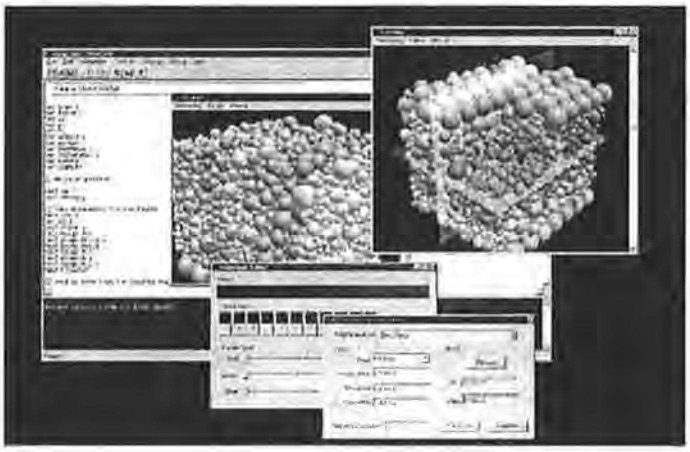


Figure 2: The LSMearth modelling software system showing a random lattice of particles representing a model rock structure being subjected to compression.

Numerical simulation studies of the AMR and LURR mechanism

The key to developing a reliable forecasting capability in practice is understanding of the physical phenomena in question. Only such knowledge provides a sound scientific basis for forecasting. The LSM provides a means to study the earthquake process and develop such a scientific basis for earthquake forecasting. Simulations involving a granular system subjected to shear have been conducted. Since the model simulates an elasto-dynamic system in which ruptures may occur on any internal surface of the granular system, the model simulates the dynamics of a simplified interacting fault system. The simulation results indicate that as in earthquake observations, large events are frequently preceded by a period of accelerating seismic moment release and changes in simulated earthquake frequency-magnitude statistics (Mora et al, 2000). More importantly, the stress field shows a consistent evolution in correlation lengths in the lead-up to a large system-sized rupture (Mora and Place, 2000), providing clear evidence of a physical mechanism for earthquake forecasting and prediction of failure of granular systems. Recently, the LSM has been applied to the study of the LURR mechanism (Wang et al, 2000). In this work, a 2D model rock is subjected to uniaxial compression from rigid driving plates on the upper and lower edges of the model. Stress on the upper and lower plates is increased gradually until the sample fails. A sinusoidal disturbance to stress or driving rate is applied as the system is loaded, in order to simulate the loading and unloading induced by tidal forces. Figure 3 shows kinetic energy and LURR. The results show that LURR values are high immediately prior to the initiation event for the catastrophic failure at around 212,000 time steps. This demonstrates that LURR provides a good predictive parameter for failure in the numerical experiment, and that the LSM can be used to probe the underlying mechanism for LURR observations.

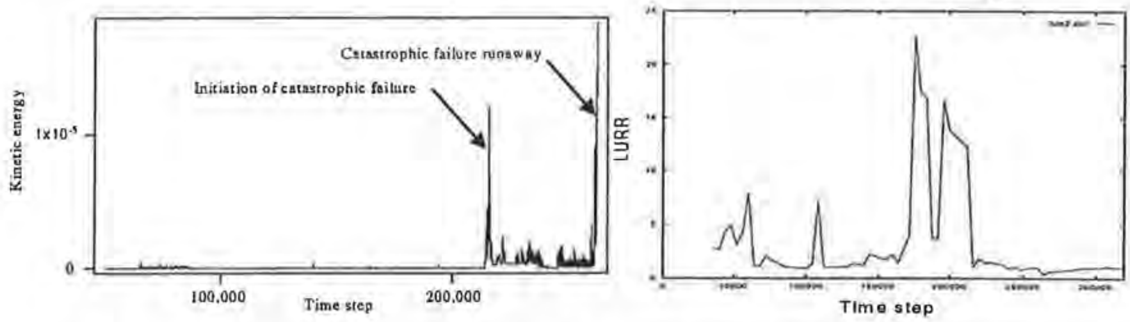


Figure 3: **Left:** Kinetic energy. **Right:** LURR values versus time for the model system.

Conclusions

Observational studies suggest that both the 1997 Burra SA and 1989 Newcastle earthquakes could have been forecast using AMR and LURR observations. Knowledge of the mechanisms underlying these promising observations would provide a scientific foundation for earthquake forecasting. A particle-based numerical model has been developed which provides a means for predictive modelling of earthquake phenomena, solid earth processes and failure of complex systems. Simulation studies with the model suggest that the AMR and LURR observations have a physical origin. These results are encouraging and motivate an increased emphasis on development of predictive modelling capabilities and earthquake forecasting.

Acknowledgments

This research was funded by the Australian Research Council (ARC), The University of Queensland, the ARC International Researcher Exchange Programme 2000 (IREX), the National Natural Sciences Foundation of China (Grant No. 19732060), the Centre for Analysis and Prediction of the China Seismological Bureau, and the Laboratory of Nonlinear Mechanics of the Chinese Academy of Sciences. The authors wish to thank the Australian Geological Survey organization and Kevin McCue for provision of the Australian Earthquake Catalog, and Russell Cuthbertson for assistance in data provision and formatting.

References

[1] Abe, S., Mora, P., & Place, D., 2000, *Extension of the lattice solid model to incorporate temperature related effects*, PAGEOPH **157**, in press.

[2] Bowman, D.D., Ouillon, G., Sammis, C.G., Sornette, A. & Sornette, D., 1998, *An observational test of the critical earthquake hypothesis*, J. Geophys. Res. **103**, 24,359-24,372.

[3] Bufe, C. G., Nishenko, S. P. & Varnes, D. J., 1994, *Seismicity trends and potential for large earthquakes in the Alaska-Aleutians region*, PAGEOPH **142**, 83-99.

[4] Bufe, C.G. & Varnes, D.J., 1993, *Predictive modeling of the seismic cycle in the greater San Francisco Bay region*, J. Geophys. Res. **98**, 9,871-9,833.

[5] Bufe, C.G, Varnes, D. J. & Nishenko, S.P., 1996, *Time-to-failure in the Alaska-Aleutian region: an update*, EOS Trans. AGU 1996 Fall Meeting Suppl. **77**, F456.

[6] Jaumé, S. C., 2000, *Changes in earthquake size-frequency distributions underlying accelerating seismic moment/energy release prior to large and great earthquakes*. in: The Physics of Earthquakes, eds. Rundle, J.B., Turcotte, D.L. & Klein, W. (Am. Geophys. Union, Washington), in press.

[7] Hui, L., and Kerr, R.A., *Warnings precede Chinese Tremblors*,Science, **276**, 526.

[8] Mora, P.,Place D.,1994, *Simulation of the frictional stick-slip instability*, PAGEOPH **143**, 61-87.

[9] Mora, P., Place D., 1998, *Numerical simulation of earthquake faults with gouge: towards a comprehensive explanation of the heat flow paradox*, J. Geophys. Res. **103**, 21,067-21,089.

[10] Mora, P. & Place, D., 1999, *The weakness of earthquake faults*, Geophys. Res. Lett. **26**, 123-126.

[11] Mora, P., Jaumé, S., and Place, D., 1999, *Evolution of earthquake statistics and forecasting the earthquake hazard*, in: Proc. Aust. Eng. Soc. 1999 conference.

[12] Mora, P., Place, D., Abe, S., & Jaumé, S., 2000, *Lattice solid simulations of the physics of earthquakes: the model, results and directions*, in: The Physics of Earthquakes, eds Rundle, J. B., Turcotte, D. L. & Klein, W. (Am. Geophys. Union, Washington), in press.

[13] Mora, P., and Place, D., 2000, *Microscopic simulation of stress correlation evolution: implication for the Critical Point Hypothesis for earthquakes*, in: 2nd Int. ACES Workshop Extended Abstracts, Japan (Oct 15-20)..

[14] Place, D. & Mora, P., 1999, *A lattice solid model to simulate the physics of rocks and earthquakes: incorporation of friction*, J. Comp. Phys. **150**, 1-41 (1999).

[15] Place, D., Mora, P., 2000, *A random lattice solid model for simulation of fault zone dynamics and fracture processes*, preprint.

[16] Rundle, J.B., Klein, W. & Gross, S., 1999, *A physical basis for statistical patterns in complex earthquake populations: models, predictions and tests*, Pure Appl. Geophys. **155**, 575-607.

[17] Sornette, D. and Sammis, C.G., 1995, *Complex critical exponents from renormalization group theory of earthquakes: implications for earthquake prediction. J. Phys. I.* **5**, 607-619 (1995).

[18] Wang, Y.C., Mora, P., Place, D., and Yin, X.C., 2000, *Simulation of the Load-Unload Response Ration using the Lattice Solid Model*, in: 2nd Int. ACES Workshop Extended Abstracts, Japan (Oct 15-20).

[19] Weatherley, D., and Mora, P., 2000, *Accelerating seismic moment release, the Critical Point Hypothesis and predicting macroscopic failure*, in: Proc. Aust. Earthquake Eng. Soc. 2000 conference.

[20] Yin, X. C., Chen, X. Z., Song, Z. P. ,Yin, C. ,1995, *A new approach to earthquake prediction: the Load\Unload Response Ratio (LURR) theory*, PAGEOPH **145**, 701-715.

[21] Yin, X. C., Mora, P., Peng, K. Y., Wang, Y. C., and Weatherley, D., 2000, *Load-Unload Response Ratio, accelerating moment release, and earthquake prediction*, in: 2nd Int. ACES Workshop Extended Abstracts, Japan (Oct 15-20).

[22] Yin, X.C., Wang, Y.C., Peng, K.Y., Bai, Y.L., 2000, *Development of a new approach to earthquake prediction: Load/Unload Response Ratio (LURR) theory*, PAGEOPH **157**, in press.