Introduction

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Welcome to the Second Annual seminar of the Australian Earthquake Engineering Society. This is our main function for the year and I look forward to hearing our speakers today.

Our theme this year is *Earthquake Engineering and Disaster Reduction*

When I opened the first of our seminars in Sydney last year I pointed out that some of the greatest life losses due to Earthquakes had been caused by intraplate earthquakes rather than by the much better known and much better understood interplate earthquakes.

Tragically the recent Indian Earthquake is the latest devastating example of this type of Earthquake. Although of only magnitude 6.2 about 10 000 lives were lost and many more were severely injured.

Let us remind ourselves again that we still have no fundamental theory for the causation of this type of Earthquake and that this is the type of Earthquake that we have here in Australia.

With no theory there can be no basis of prediction and therefore no forewarning. Without forewarning our only means to safeguard life in damaging earthquakes is by Earthquake Resistant Design and Construction.

Here at least we are on a sounder footing; we do have an Earthquake Code. Indeed since last we met we now have a New and Revised Code, in a new Format although it is still from the same American stable and that as we shall hear is no bad thing.

We shall hear more about that code in a number of the papers to be delivered today and in the discussions arising from the presentations. In your discussions please raise any matters or areas where you consider the new Code might need some follow up action!

For example, it is a pure Loading code now. Has action been taken to make it fully workable with all materials of construction???

What is the current situation regarding adoption by Building Authorities throughout Australia? Will it be enforced everywhere? Is it being enforced yet? Will it be applied to the Olympic facilities to be built in Sydney?

By the way has anyone used it yet on real life project? Hands up.

Now these are simple and straightforward questions but such simple questions do not always and everywhere have simple answers! I spoke earlier of recent events in India.

One of the oldest Universities in the British Commonwealth teaching Civil and Structural Engineering is in India, at the University of Roorkee. They have taught the principles and practice of Earthquake Engineering at a local, National and International level for many years eg: a seismic design of large dams. Also Indian engineers have been knowledgeable and active in all aspects Earthquake Engineering for a long time, yet this knowledge did nothing to prevent the terrible loss of life in the recent tragedy!!!

It is unfortunately true that knowledge is not enough; further, Earthquake Resistant Design is not enough, even Earthquake Regulations are not enough.

Let us look for a moment at some comparative figures for loss of life and damage to property from Earthquakes in this Century so far (1900 to 1992)

The loss of life in Chinese Earthquakes is 500 times that in American Earthquakes. Yet the property damage in money terms in the US is six times more than in the Chinese Earthquakes. You don't have to be Chinese either, for example Italy in the same period had 100 times as many deaths from earthquakes as the United States.

Consideration of these figures led Hencher to say this in a recent review of Earthquake protection (book by Coburn & Spencer)

"Despite the obvious influence of relative infra-structure costs on these statistics it is clear that the US is implementing measures to prevent loss of life to a level unknown elsewhere" (is this a sound and correct conclusion?? or have the Americans just been lucky so far???)

So, on the face of it, it is no bad thing that we have adopted American design and practice in our Earthquake Codes and Regulations. But that is not enough!!! Earthquakes are unforgiving of the least fault and there is no shield or shelter.

So this work all has to be carried through and implemented to the fullest extent in the actual construction faithful to the design and even to the design intent the quality of materials even if no one sees them go into the works and of course the ongoing maintenance over the years which was perhaps the lesson of Newcastle.

Can we do all that???

Of course we CAN do it WILL we do it??? That is another matter altogether and one fully open to all the influences of economics, of education, and of POLITICS!!!

So please keep some of these issues and questions in mind throughout the day and raise them in the discussions with the speakers and with each other in and out of session, and take your decisions and conclusions home with you.

Seismic Hazard Assessment in the South West Pacific Region

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Earthquakes can inflict enormous damage and they usually attack most severely the poorest people who are least able to protect themselves. So far this century, nine earthquakes have caused more than 50,000 deaths. In fact, earthquakes cause almost 60 percent of the total number of deaths due to natural disasters. The more frequent moderate sized earthquakes, like the September 1993 earthquake in Southern India, can be just as destructive. From a seismological point of view, one of the most important inputs we can make is to develop and make available reliable methods of estimating seismic hazard.

On a global scale, the Global Seismic Hazard Assessment Program (GSHAP), which is a contribution of the International Lithosphere Program and of the International Council of Scientific Unions to the UN International Decade for Natural Disaster Reduction (IDNDR), has identified four main steps that are needed to tackle this problem.

These are :

- improve the earthquake catalogues and data bases so that they are comprehensive and consistent
- improve our understanding of the seismotectonics so that reliable models describing earthquake occurrences can be developed
- obtain records of strong ground motion so that the effects of earthquakes can be quantified
- develop and make available consistent and reliable methods for estimating seismic hazard.

These goals will only be achieved by the focusing of resources and the co-ordination of efforts. At present in the Australian/South West Pacific region some progress has been made to provide quantitative estimates of earthquake hazard but most of the main problems have yet to be tackled. The present status for Papua New Guinea, Fiji, New Zealand and Australia is outlined below (see Denham and Smith, 1993).

1. PAPUA NEW GUINEA

The seismic hazard estimates by Brooks (1965) for Papua New Guinea were the first published quantitative assessments in the region. He used a data set from 1906-1959 to estimate maximum intensities of shaking (MMI) for 25, 50 and 200 year return periods.

Jry et al. (1982), using a data base from 1900-1978, determined 20 year return period values for peak acceleration response at 5% damping for a range of natural periods and ground conditions.

Jrly et al's. (1982) work is still the basis for the definitions of the seismic zones used in the building codes. However, since 1982 there have been considerable advances in understanding the tectonic activity in the region and a whole suite of several hundred accelerograms have been captured from several sites in the country (Ripper, 1992). Significant progress can therefore be achieved on each of the four steps outlined above.

2. FIJI

Using a data set from 1850-1984, Everingham (1986) estimated the cumulative frequency of earthquake intensities in various areas of Fiji. He used these results together with the maximum recorded magnitudes for earthquakes in the region from 1961-1984. Everingham recommended that most of Fiji should adopt building standards defined for zone B (NZ Code) or Zone 2 (1979 Australian Code). Jones (1994) s has used Everingham's results to derive a preliminary Earthquake Risk Zoning Maps using the methods adopted in New Zealand.

Consequently the zones are defined in the context of a 10% chance of MM intensities being exceeded in a 50 year period.

The tectonics of the Fiji region are comparatively well understood but no strong ground motion records have been obtained from regional or local earthquakes and hence the zones are not tied in to quantitative levels of shaking.

As with Papua New Guinea, there is clearly a requirement for a proper zoning study for Fiji so that quantitative assessments of earthquake hazard be obtained.

3. NEW ZEALAND

New Zealand is situated on the boundary of the Australian and Pacific Plates. Since 1840 over 20 earthquakes with magnitude of 7 or greater are known to have taken place (Smith and Berryman, 1986). Several of these have caused significant damage and the presence of recent fault scarps in both the North and South Islands indicates the potential for major earthquakes taking place.

The first study on New Zealand was published by Smith (1976). He used a data set extending from 1840-1975 and computed cumulative frequency distributions of intensities to obtain return periods for Modified Mercalli intensities ranging from VI to IX for periods of 50 and 1000 years.

Smith assumed that the past record is representative of what will happen in the future to carry out his calculates and also determined a series of intensity/distance curves for earthquakes of different magnitudes. No attempt was made to derive ground accelerations or velocities.

Two later papers by *Smith* (1978a and 1978b) investigated the intensity decay with distance for each of the three regions defined earlier (*Smith*, 1976) and these papers contained estimates of return periods for Modified Mercalli intensities for the major urban areas. Wellington turned out to be the highest risk city with an expected return period for MM VIII of only 50 years.

Smith and Berryman's (1986) paper revised the earlier work by incorporating not only seismological data of known large earthquakes and the recent instrumental record (up to 1982) but also geological studies on Recent faults. The revision led to defining 15 characteristic regions with specific seismicity parameters and resulted in maps of revised return periods. These results show only minor changes to the earlier estimates and the table below shows the changes to the risks in some of the major cities.

TABLE 1. Return periods (years) of Modified Mercalli intensities for major cities in New Zealand from Smith (1976) and Smith and Berryman (1986).

	MMVII		MMVII	
Auckland	300	260	900	1400
Hamilton	150	9	500	420
Rotorua	80	45	250	190
Napier	30	42	80	140
Wellington	20	21	50	67
Christchurch	50	48	200	160
Dunedin	800	130	~1500	500

The left hand column for each MM intensity is from the 1976 paper and the right hand column is from the 1986 paper. A study by Matuschka et al. (1985), drew on Smith & Berryman's work prior to its publication and presented contours of response spectral accelerations (with 5% damping) for return periods of 50, 150, 450 and 1000 years. These results are currently being incorporated into the New Zealand Building Code (Hutchison et al., 1986).

One problem with the New Zealand zoning effort is that the many hundreds of strong ground motion records obtained in recent years do not appear to have been incorporated into the zoning process. However, a large effort will be required to undertake this task.

4. AUSTRALIA

Compared with countries situated in tectonically active regions like Indonesia and Papua New Guinea, Australia is relatively aseismic. However, in the last 50 years seven earthquakes have taken place which have caused the equivalent of more than $1 million damage and five earthquakes have been associated with surface faulting (BMR, 1992). The seismicity in the Australian continent is typical of that experienced in intra-plate environments (Denham, 1988). All the earthquakes occur within the crust (<40km) and all the focal mechanisms are consistent with a compressed crust. In situ stress measurements, quarry floor pop-ups and borehole deformation observations confirm this compressive environment.

The first published earthquake risk study was by McEwin et al. (1976). The earthquake risk maps from this work were prepared from a very short data set (1960-1972) and extreme value methods were applied to obtain 50-year return periods for acceleration, velocity and intensity. The standard Kanai scaling rule was used with the Esteva and Rosenblueth (1964) coefficients.

The results from this work were used to derive four zones in the earthquake zoning map of Australia, which was incorporated with the Australian Building Code (AS 2121-1979).

Gaull et al. (1990) published a revised set of maps using the standard Cornell-McGuire methodology. This technique starts by defining source zones, then adopting seismicity parameters and attenuation relations for each zone, to prepare the earthquake risk maps. The expanded data base (1873-1988) enabled risk estimates to be obtained for a larger area of the continent.

The risk estimates for the capital cities were also modified as a result of this analysis. Table 2 compares the Gaull et a.l (1990) estimates with those of the earlier McEwin et al. (1976) results.

Table 2. Estimated peak acceleration for 500 year return period in m/s^2

City	1990	1976
Adelaide	0.60	0.9
Brisbane	0.25	<0.3
Canberra	0.55	0.3
Darwin	0.53	<0.3
Hobart	0.25	<0.3
Melbourne	0.40	<0.3
Perth	0.44	0.4
Sydney	0.50	0.3

The largest change is for Melbourne where the 500 year peak acceleration increases from less than $0.3 m/s^2$ to $0.40 m/s^2$ Adelaide is still the capital with the highest risk.

After the Gaull et al. (1990) work was completed major earthquakes took place near Tennant Creek (1988) and Newcastle (1989). These events forced further amendments to the hazard maps which now emphasise that no part of the Australian continent is free from the possible occurrence of earthquakes. The new map indicates that the risk has been 'smeared' over the whole continent and the amplitudes of 'bulls eyes' around areas of high seismicity in the recent past are reduced.

In Australia many strong motion records have been obtained but these have mostly been from small earthquakes. Consequently, it has not been possible to usefully apply these data sets into the hazard assessment process.

5. CONCLUSIONS

This review has revealed that for each country, where earthquake risk assessments have been made, the methods used are different. Furthermore, the parameters plotted on the risk maps are invariably different. These differences include the return periods selected and the parameters plotted (intensity, acceleration or velocity).

One of the problems in carrying out the studies outlined above is that, for the most part, local strong ground motion recordings were not included in the analyses. This was probably due to their unavailability. In the last few years this situation has changed and in Papua New Guinea, New Zealand and Australia there is now a good data set of these recordings. It would therefore seem appropriate for the risk assessment to be re-evaluated using these recordings and also consistent sets of attenuation relations. This does not mean that these must be the same in each region, rather that is possible to compare easily risk levels from country to country. At present this is very difficult and causes major problems in standardising and comparing building codes. We also found that many of the countries in the South West Pacific, while having a high earthquake risk, have no quantitative risk assessments. It is important that these assessment be carried out for the whole of the Australian/Pacific plate margin from Papua New Guinea through to Macquarie Island.

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Seismicity and Earthquake Hazard in Australia

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ABSTRACT

This paper summarises the seismicity of Australia and the world since the last AEES meeting in Sydney in September 1992. The frequency of earthquakes is compared with established recurrence relationships which show it to have been an average 12 month interval worldwide but the seismicity level was below average in Australia. The appropriateness of using imported attenuation models in earthquake hazard analyses is questioned. Lastly, the locations of the larger earthquakes are compared with the zones of known seismicity, both interplate and intraplate and the ramifications for loading codes discussed

1. INTRODUCTION

Models are an essential tool for the evaluation of earthquake hazard. The distribution of source zones and recurrence and attenuation relationships are all amenable to modelling. For interplate regions, models based on plate tectonics may appear to be reasonably robust, there is at least a theory which explains the cause of these earthquakes. So the informed occupants of Wellington New Zealand, San Francisco United States of America, and Tokyo Japan, know that a 'great' magnitude 8 earthquake will strike their city at some time in the future. The theory does not predict when that event will occur.

However plate tectonics does not account for intraplate earthquakes, and continental Australia is entirely intraplate. In any single place, with a few notable exceptions, earthquakes are relatively rare or of low intensity; few building owners of Sydney or Melbourne would be sufficiently concerned about the possibility of earthquake damage that they would retrospectively strengthen them to satisfy AS1170.4. But large earthquakes do occur within the plates and without the benefit of an explanation for their cause, and without a dataset spanning several tens of thousands of years, future earthquakes in Australia are likely to surprise even the most informed pundits.

2. ATTENUATION RELATIONSHIPS

In North America, there is some debate about whether intraplate earthquakes in the east have a higher stress drop (Ds) than interplate earthquakes of similar size (seismic moment M_o) in the west (Somerville & others, 1987). This influences the relative amplitude of ground motion at high frequencies through a relationship of the form

$$\Delta\sigma \propto M_o f_c^3$$

where f_c is the corner frequency of the displacement spectrum below which the amplitude is frequency independent and above which it decays at a rate of f^{-3} in this constant stress drop model (Brune, 1970). A systematic analysis of stress drops has not yet been made in Australia but in-situ measurements of crustal stress at shallow depths (Denham, Alexander & Worotnicki, 1979), have found high horizontal compressive stresses, and observed co-seismic faults have been thrusts.

Published attenuation relationships rely heavily on data recorded in the western United States because it is the most voluminous dataset and freely available. However they may not be an appropriate nor conservative predictor of near field ground motion in Australia, especially at high frequencies.

3. RECURRENCE RELATIONSHIPS AND SPATIAL DISTRIBUTION SEPTEMBER 1992 TO AUGUST 1993

A magnitude/frequency relation of the form $\log N = a - bM$ fits the observed frequency of earthquakes in either tectonic setting, where N is the cumulative number of earthquakes per year above some magnitude M. Simple relationships that hold over the limited magnitude range stated are given by

- the world:

$$\log N = 8.0 - M, \quad 6 \leq M \leq 8$$

- and Australia:

$$\log N = 5.3 - M, \quad 4 \leq M \leq 7$$

For N = 1, the once-per-year earthquake is magnitude 8 or more worldwide and 5.3 in Australia. The difference of 2.7 magnitude units between the once-per-year earthquakes may not sound much but a magnitude 8.0 earth-quake may have a fault length of several hundred kilometres compared to the ML 5.3 Australian annual event with a fault length of only a few kilometres; and there is an energy release difference of more than 10^4. The areas of high intensity and potential damage are vastly different.

Interplate seismicity The world recurrence relation predicts that in an average year there will be a single earthquake of magnitude 8 or more, 10 of magnitude 7 or more and about 100 of magnitude 6 or more.

Reference to the monthly seismological reports published by the Australian Seismological Centre reveals that there was one great earthquake in the period September 1992 to August 1993. And like most great earthquakes it occurred on the Pacific Plate boundary, though in an unexpected location.

This Ms 8.0 earthquake on the Mariana Trench near Guam on 8 August 1993 was the world's largest earthquake since the magnitude Ms 8.1 earthquake on the Macquarie Ridge in May 1989. Both the Macquarie Ridge and Guam earthquakes were the first known on the respective plate boundary segments (Figure 1). No lives were lost in either earthquake but 48 people were injured and there was considerable damage in central Guam.

In the same period there were 10 earthquakes of magnitude 7 or more (neglecting aftershocks) and 90 of magnitude 6 or more which makes this a very average 12 month period.

More than half of the 3055 earthquake related deaths occurred in the magnitude Ms 7.5 earthquake and ensuing tsunami that struck the Indonesian Island of Flores on 12 December 1993. It was reported that some 90% of the buildings at Maumere were destroyed and 50 to 80% of those on Flores damaged or destroyed making it the worst disaster of the period. This earthquake fatality rate is well below the average for this century of 10 000 deaths per year (Figure 2).

Intraplate seismicity Of more immediate relevance to us are those earthquakes that occurred well clear of the plate margins. The largest was a magnitude 6.7 earthquake in

Zaire on 11 September. Some buildings were destroyed and 8 people killed and another 37 injured.

Cairo, Egypt seemed an unlikely site for the damaging magnitude ML 5.3 earthquake on 12 October but the grim statistics of 541 dead, 6500 injured and $300M damage are testimony to the damage potential of relatively small earthquakes, if the basic tenets of earthquake engineering are neglected. A moderate earthquake there in 1955 reportedly collapsed 12 schools, crushing 11 children and injuring another 120 people, 60 of them children.

A magnitude 5.2 earthquake in the Sudan on 1 August caused damage in Khatoum which left 2 dead and 9 injured. The largest earthquake ever recorded in Sudan was on 20 May 1991, about 1000 km north of this epicentre. It had a magnitude of Ms 7.1.

Australia's largest known earthquake (at Meeberrie WA on 29 April 1941) had a magnitude of Ms 6.9.

Australian seismicity The recurrence relationship summarising the seismic activity of Australia predicts an average of 2 earthquakes of magnitude 5 or more and 20 of magnitude ML 4 or more per year, with the once-per-year earthquake at magnitude ML 5.3.

Magnitude ML 5.3 was the size of the largest earthquake in the year. It occurred on the Lord Howe Rise, ESE of Sydney NSW on 30 September but went unnoticed. Few earthquakes have been recorded on the Norfolk Ridge and this is the largest.

An equally unusual location was that of the ML 5.1 earthquake off the coast of Arnhem Land NT on 30 August which was strongly felt at Maningrida and Gove, and barely felt at Darwin (Figure 3). What was most unusual about this earthquake was its focal depth, determined from depth phases at 38 ±2 km which is near the crust/upper mantle boundary, the deepest known earthquake in Australia.

Of the 9 earthquakes of magnitude ML 4 or more, 4 were on the Lord Howe Rise, 3 in the Northern Territory (2 of them at Tennant Creek) and one each in South Australia (in the Musgrave Ranges) and Western Australia (SW of Exmouth).

Only 78 of the located earthquakes were of magnitude ML 3 or more compared with an expected 200, and of the 78, 12 were at Tennant Creek. The Australian National Network is not yet capable of detecting earthquakes down to magnitude 3 throughout the continent but there were significantly fewer small earthquakes than expected in the 12 months period.

4. DISCUSSION

There is great variability in the observed frequency of both interplate and intraplate earthquakes. Indeed this is to be expected if they are, as modelled, Poisson events (independent, non-simultaneous, stationary). The mean frequency should be time invariant but events cluster in time because their inter-arrival times are exponentially distributed.

Intraplate earthquakes keep happening in unexpected places, ie outside the modelled source zones. Local examples include; the Tennant Creek NT sequence of January 1988, where thousands of earthquakes occurred among which were three large earthquakes of magnitude Ms 6.3, 6.4 and 6.7, and the ML 4.9 earthquake near Nhill Western Victoria on 27 December 1987. The most recent example was last month's destructive Ms 6.1 earthquake in central India on 30 September which resulted in almost 10 000 fatalities. The location of the next large Australian earthquake is unknown, but on the relative frequency of such earthquakes over the last 100 years it is most likely to occur in Western Australia and least likely in Eastern Australia. The pattern of seismicity of the last decade would point to a location in Central Australia.

Few accurate focal depth determinations have been possible in the past so knowledge of their crustal depth distribution, so critical in the hazard analysis, is not known. Digital recording and a denser seismograph network make this a more tangible goal. By enabling unambiguous identification of depth phases (Figure 4), as was possible for the 1989 Newcastle earthquake, the focal depth can be computed within about 2 km.

In parts of New Zealand and western North America the 500 year design ground motion may well be the ultimate ground motion but the acceleration coefficients specified in the Australian Standard AS1170.4 may fall far short of ground motions in a close moderate earthquake. The Standard specifies minimum design precautions, and compliance with the Standard should at least prevent building collapse and will reduce damage but not prevent it.

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6. FIGURES

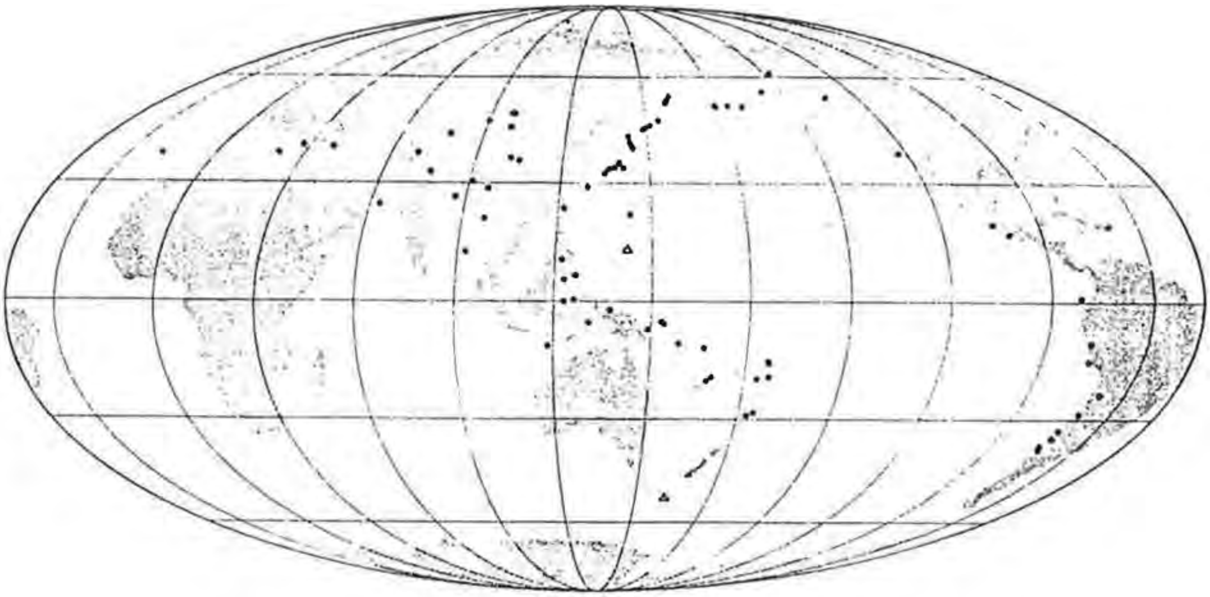

Figure 1: Great earthquakes of the world 1904 - 1993 M≥ 8.0; dots for pre-1989 earthquakes, triangles for the 1989 Macquarie Ridge and 1992 Guam earthquakes.

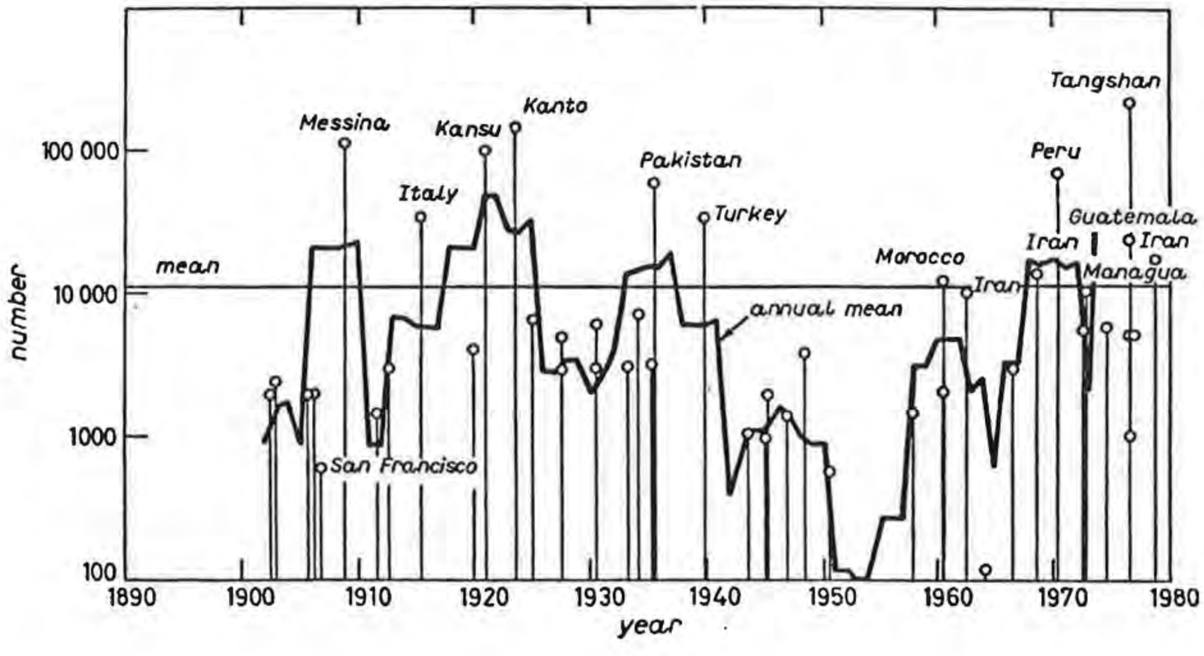

Figure 2: Loss of life caused by major destructive earthquakes. The vertical bars are for the individual event and the solid curve shows the annual average (unlagged five-year running average).

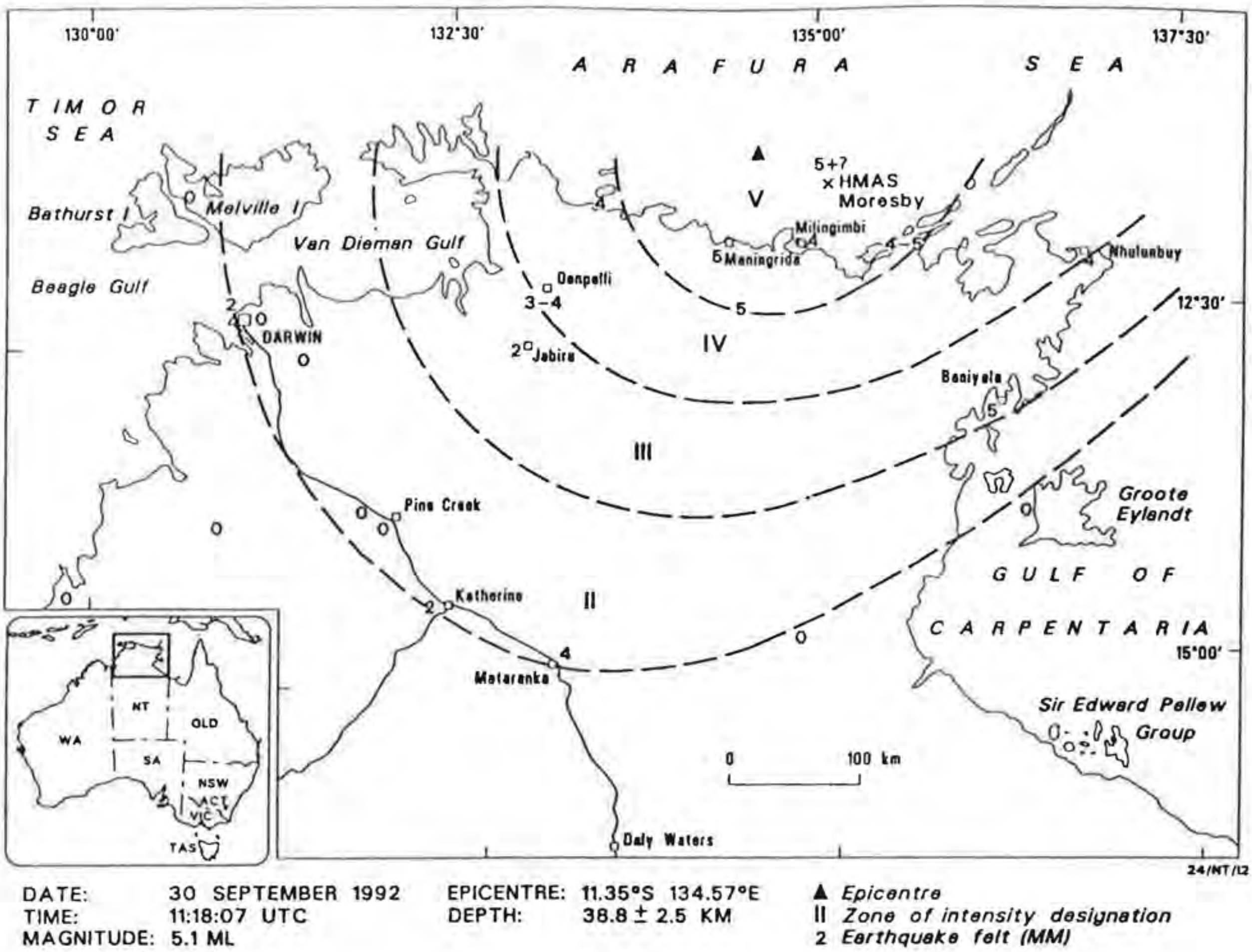

Figure 3: Isoseismal map of the Arnhem Land earthquake, 30/9/1992

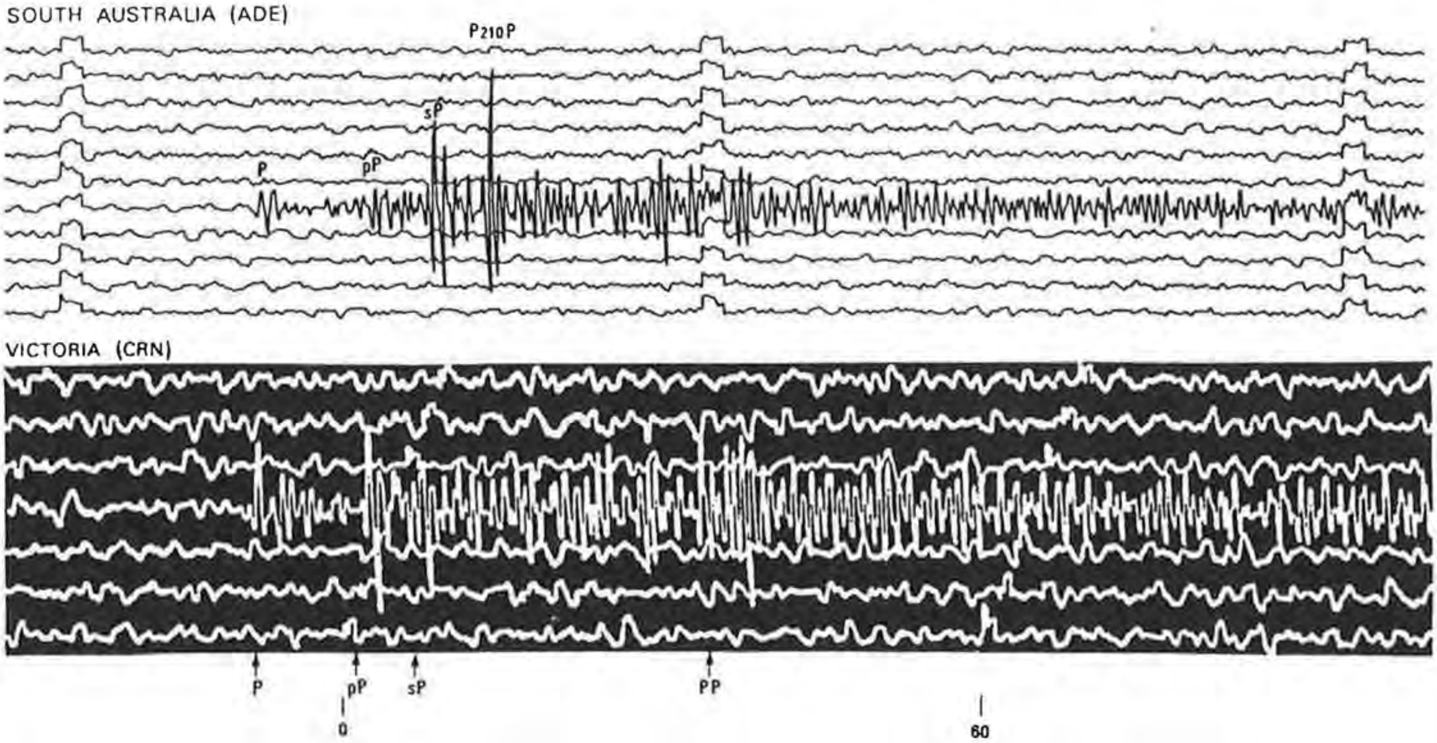

Figure 4: Depth phases, pP & sP, from the Arnhem Land earthquake

Earthquake Instrumentation in Australia

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1. INTRODUCTION

Two types of seismic instrument are in common use, sensitive seismographs or strong motion accelerographs. The names refer to the transducers used to detect motion, seismometers measuring velocity or sometimes displacement and accelerometers measuring acceleration.

Seismograph networks obtain details about earthquakes including their location, size and mechanism. It is normally necessary to have a network of seismographs surrounding an epicentre to obtain an accurate location. To accurately determine the earthquake depth it is necessary to have one seismograph at a distance near to the epicentre (relative to the depth).

Accelerographs measure stronger motion and are have two main uses. Bedrock mounted accelerographs are used to determine attenuation functions giving the reduction in seismic wave amplitude with distance. Accelerographs mounted on structures or on soft sediments measure the response of the structure or site to earthquake motion.

Seismologists studying world earthquakes and the large-scale structure of the earth measure low frequency motion. This may require the use of very sensitive and expensive broad-band seismometers.

Engineers interested in damaging strong motion at sites or structures, and seismologists studying local earthquakes both measure higher frequency vibrations. Precise location of nearby earthquakes requires very accurate seismograph timing, preferably with times accurate to 0.01 seconds.

There are many more small earthquakes than large, so a sensitive high density seismograph network may be used to delineate active faults relatively quickly (perhaps within years instead of centuries).

2. SEISMOGRAPH NETWORK DENSITY

The density of a seismograph network depends on the desired earthquake location accuracy and the minimum magnitude to be located. The accuracy of an earthquake depth depends on the epicentral distance to the nearest seismograph. It is desirable to have a seismograph within an epicentral distance not greater than about twice the earthquake depth.

Global networks use seismographs all over the earth to locate earthquakes down to magnitude ML 4.0 to 4.5. The accuracy of locations determined by a global network is sometimes better than ±10 to 20 kilometres, but is quite often much worse. This means that global networks cannot be used to delineate active faults. However, larger earthquakes can be recorded on the opposite side of the earth, sometimes with reflected wave phases that constrain the earthquake depth.

Regional seismograph networks cover an area with diameter from about 500 to 3000 kilometres, such as the seismograph network over Australia. A suitable aim for a regional network is to locate all earthquakes within the network exceeding magnitude ML 3.0. Seismic waves recorded at distances from a few hundred kilometres to a couple of thousand kilometres are often more complex and difficult to read than those recorded either closer or further from the earthquake, so this scale is not easy for seismological analysis. Because of the large area covered by a regional network, many earthquakes occur at considerable distances from the nearest seismograph so earthquake depths can be very difficult to determine. Many events are simply assigned a "normal" depth of 10 or 33 kilometres. This means that regional networks cannot usually be used to delineate active faults. The regional network gives the large scale distribution of epicentres essential for computation of earthquake hazard.

Local seismograph networks locate earthquakes from smaller than ML 1.0 to a precision that will eventually delineate active faults. In a given area these networks can locate up to 100 smaller earthquakes for each earthquake of magnitude ML 3.0 or larger. High density networks allow accurate earthquake depth estimates. These networks may also include accelerographs for attenuation studies, or for measurement of site and structure response.

On a smaller scale there are microearthquake networks such as those used to record small earthquakes about dams and reservoirs, or on a mining seismology scale where rockbursts in mines are being located.

The specifications and requirements of seismograph networks vary widely, but the following table shows some typical network parameters.

TABLE 1. Seismograph network parameters

Network	Network Diameter (km)	Minimum Magnitude ML	Time Accuracy Required (sec)	Event Location Precision (km)
Global	20000	4.5	1.0	20
Regional	1000 to 3000	3.0	1.0	20
Local	200 to 500	1.5	0.1	5
Microearthquake	10 to 80	0.0 to 1.0	0.01	1
Mining	0.1 to 5	-3.0 to -1.0	0.001	0.01 to 0.1

3. LOCAL SEISMOGRAPH NETWORKS

A seismograph uses precise timing to determine the distance to an earthquake. A network of at least three seismographs is normally required to precisely locate an earthquake epicentre and focal depth. The more recordings used, the more precise the location.

Earthquake depths can only be precisely determined if the distance to the nearest seismograph is not greater than about twice the earthquake depth or about 10 kilometres, whichever is the larger. Australian earthquakes usually occur at depths between 1 and 20 kilometres.

To delineate faults in three dimensions, earthquake depths must be determined precisely. This could be done with a seismograph within about 10 kilometres of the epicentre, plus two others within 50 kilometres in two directions at right angles (an L shaped network). Seismographs in a triangle (Δ shaped network) up to about 30 kilometres apart will give reasonable depths for all earthquakes within the triangle except for shallow events near its centre. An additional seismograph at the centre of the triangle (giving a Y shaped network) will constrain these events and provide a degree of redundancy in case of instrument failure. More complex configurations (X shaped arrays, etc) provide better quality locations over a wider area. Introducing redundancy into the network can also reduce its operating costs by increasing the routine time interval between seismograph service visits.

The rate at which earthquakes are located depends on the seismograph separation distance and the background noise level. The following table gives an approximate minimum magnitude that can be recorded by a typical sensitive seismograph at a good location, and by a good quality high dynamic range accelerograph. This minimum recordable magnitude will be higher for noisy sites, lower for very good sites and the values listed may vary by ±1 magnitude unit or more.

TABLE 2. Seismograph and accelerograph sensitivity

Distance (km)	Seismographs	Accelerographs
1	ML -1.6	ML 0.5
10	ML 0.0	ML 2.2
100	ML 1.6	ML 4.0
1000	ML 3.2	ML 5.8

Note that the difference between seismographs and accelerographs exceeds 2 magnitude units, or a factor of over 100 in ground motion. This means that seismographs have the potential to record 50 to 100 times more earthquakes than accelerographs will record. In active areas, such as the epicentral area of a large earthquake, accelerographs can be used both to locate earthquakes and to record strong ground motion (refer figures 1 and 2).

To determine the epicentre of an ML 1.6 earthquake, it must be inside a network of three or more seismographs all within 100 kilometres of the epicentre. To determine its depth requires that one seismograph is nearby.

4. ACCELEROGRAPH NETWORKS

Accelerographs are used for two purposes. They give the attenuation of strong ground motion on bedrock, and they measure the response of sites or structures to this motion.

Most accelerographs are set to give full scale motion at 1g. However, a number of recent earthquakes have given peak accelerations greater than 1g, and consideration is now being given to decreasing instrument sensitivity so that peak motion is perhaps 2g.

5. ATTENUATION

The attenuation of strong ground motion with distance from an earthquake varies depending on the geological structure. There is high attenuation in areas of young active rock, and low attenuation in old stable continental shields.

Attenuation is not easy to determine because earthquake magnitude itself is computed from the ground motion amplitude corrected for distance with an implied attenuation function. Seismic wave radiation patterns vary with direction around the earthquake, and many earthquakes are not recorded over a wide range of distances and directions, so it is not easy to separate magnitude and attenuation.

Attenuation studies require records from a number of earthquakes, each earthquake being recorded at a wide range of distances. The quantities measured may include peak ground motion, effective peak acceleration (defined to avoid the effect of an odd random high peak, refer figure 3), spectra, or ground motion duration.

Accelerographs used for attenuation are normally mounted on bedrock, preferably on a flat surface but certainly without very steep topography. A recent development is to install an accelerometer and a seismometer at the same site using the same digital recorder, thus giving measurements from background noise level through to strong ground motion.

6. SITE OR STRUCTURE RESPONSE

In engineering applications accelerographs are used to compare motion on structures, their foundations, on the earth's surface and on bedrock. Such comparisons inherently require multiple detectors. These may be recorded either separately or preferably on a common multi-channel recorder.

Accelerometers are normally triaxial, to measure east-west, north-south and vertical motion. For most structural applications the horizontal motion is more critical than the vertical, so a number of single component horizontal accelerometers may be used. For example, the upstream-downstream motion of a dam may be measured at several points on the structure.

Torsional motion can be estimated by recording translational motion at different parts of a structure with well calibrated accelerometers. Very sensitive torsional transducers have not yet been developed.

7. AUSTRALIAN SEISMOLOGICAL OBSERVATORIES

The Australian Seismological Centre at the Australian Geological Survey Organisation operates the Australian National Seismograph Network. This aims to give epicentre estimates for all Australian earthquakes larger than magnitude ML 3.0. It also includes stations in Australian Antarctic Territory and on Macquarie Island.

The ASC is also the Australian authority for most matters relating to routine international seismology, and it supports epicentral networks after major earthquakes, and co-ordinates local seismograph networks within Australia. It produces the Australian Seismological Report each year.

The ASC administers the urban monitoring program. The 1992/93 Commonwealth Budget committed $1.5 million over three years to improve earthquake monitoring in Australia. Most of this is being used to improve monitoring facilities in the major urban areas, where the potential for future earthquake damage is greatest. At least 24 new digital accelerographs are being installed as part of this program. The program is funding the purchase and installation of the equipment, and operating costs are to be met by the local state networks.

The Mundaring Geophysical Observatory near Perth is a section of the ASC, and maintains the western half of the Australian National Seismograph Network. It also operates a more dense network of seismographs in southwest Western Australia and over twenty accelerographs within the state.

The Research School of Earth Sciences at the Australian National University in Canberra operates seven permanent seismographs in southeast Australia, a broadband seismograph near Canberra, and the Warramunga seismograph array near Tennant Creek in the Northern Territory. Several portable seismographs are used, mainly for studies of large scale earth structure.

The Seismology Research Centre at RMIT University in Melbourne operates a network of 83 seismographs and accelerographs in southeast Australia. The work of the centre concentrates on seismology at a microearthquake to local scale, particularly for engineering and geological applications. It is actively developing seismograph instrumentation and analysis software, and is working on earthquake hazard evaluation methods.

The Sutton Earthquake Centre at the South Australian Department of Mines and Energy (SADME) operates a local network of 16 seismographs and 6 accelerographs in South Australia. The centre is conducting a detailed zonation study of earthquake hazard in the Adelaide area.

The Department of Earth Sciences at the University of Queensland operates a local network of 26 seismographs in Queensland, plus 8 accelerographs. It also operates a broadband digital seismograph in Charters Towers as part of the global network. It is working on earthquake hazard evaluation in the Brisbane area, and has studied the relationship between the seismicity and geology in southeast Queensland.

The Department of Applied Physics at the University of Central Queensland in Rockhampton has recently installed a small network of three seismographs and two accelerographs. The Department is undertaking research into analysis of digital seismograph data recorded at close distances, from aftershocks of large earthquakes and from mining seismology. Research in co-operation with the CSIRO on the applications of seismology in coal mining is being developed.

The University of Tasmania operates a network of eight seismographs and two accelerographs. The seismograph signals are telemetered to the laboratory in Hobart. The group also maintains a USA funded broadband digital seismograph in Hobart as part of the global network.

8. CONCLUSION

One of the most significant factors regarding seismological instrumentation in Australia over the past ten years has been increased co-operation between the seismological observatories. Regular contact between neighbouring networks is maintained to ensure that earthquakes that occur between the networks are not missed. Data is now shared using electronic mail.

One of the main differences between seismological instrumentation in Australia and that in USA or New Zealand is that seismograph and accelerograph operations are fully integrated. In those more active areas, seismologists traditionally operated seismographs and engineers operated accelerographs. The original analogue seismograph and accelerograph recorders were quite different, with seismographs recording on continuous helical drums and accelerographs producing triggered recordings on photographic film. The limited dynamic range of each meant that seismographs reached full scale well before an accelerograph at the same site could detect any motion.

With digital recording the same recorder can be used for both seismometers and accelerometers. A six channel recorder can have three seismometer channels (east-west, north-south and vertical) plus three accelerometer channels. Before the seismometers reach full scale, the accelerometer channels will give a usable signal (see figure 3).

Integrated operation of seismographs and accelerographs provides a number of advantages. Financially, only one operating infra-structure is required. Accelerograph data recorded with precision timing can be used to help locate earthquakes, especially nearby earthquakes which would drive seismometers to full scale. Attenuation studies using both seismograph and accelerograph data will cover a greater range of distances from the earthquake, and will ensure that the magnitude attenuation functions usually used by seismologists, and the strong motion attenuation functions usually used by engineers are consistent.

9. REFERENCES

AGSO, 1991: Earthquake Monitoring in Australia: A Plan for the Future, AGSO, Canberra.

Gary Gibson, 1992: Seismic Instrumentation, Proc of Conf on Earthquake Resistant Design and Insurance in Australia, AEES and SGSG, 25 Sep 1992, Sydney, 7-20.

10. FIGURES

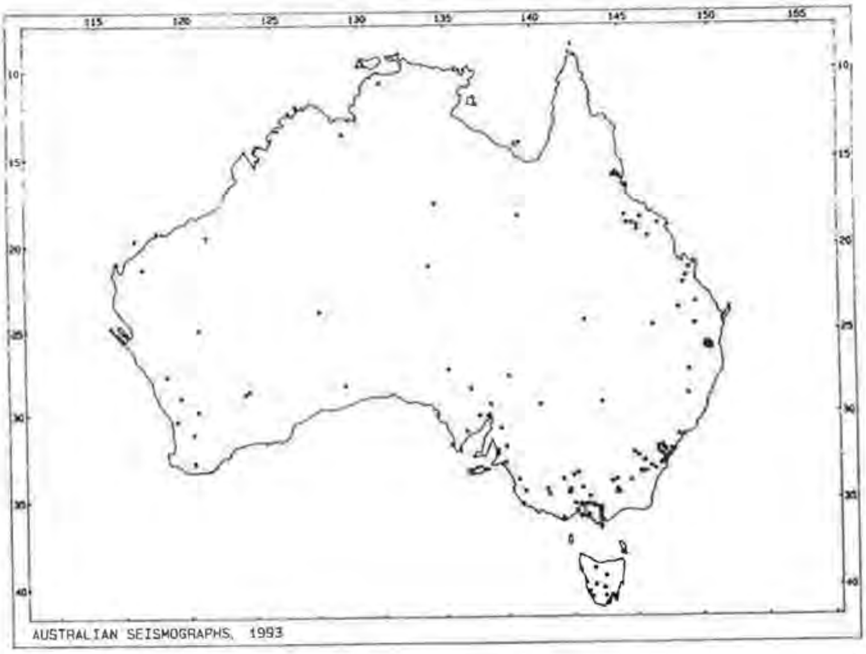

Figure 1: Seismographs in Australia, 1993. To allow a precise location, an earthquake should be recorded by three or more surrounding seismographs. When used with table 2, this map shows a significant variation in the sensitivity of seismograph coverage over Australia. In most states there is much better coverage of dams and reservoirs than of the major cities.

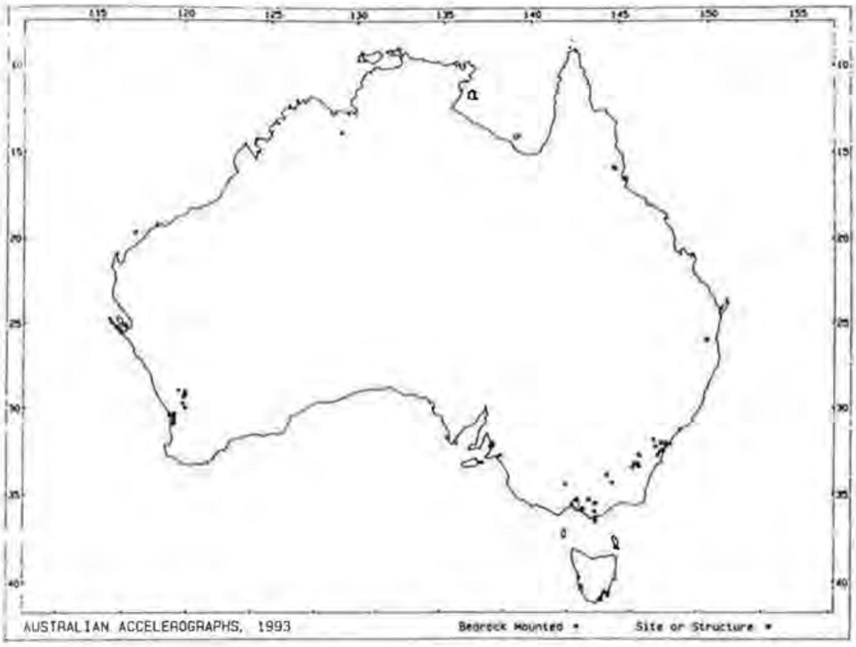

Figure 2: Accelerographs in Australia, 1993. Determination of attenuation functions requires that strong motion from large earthquakes be recorded over a wide range of distances. The only areas where this is possible are in the southeast and in southwest Western Australia.

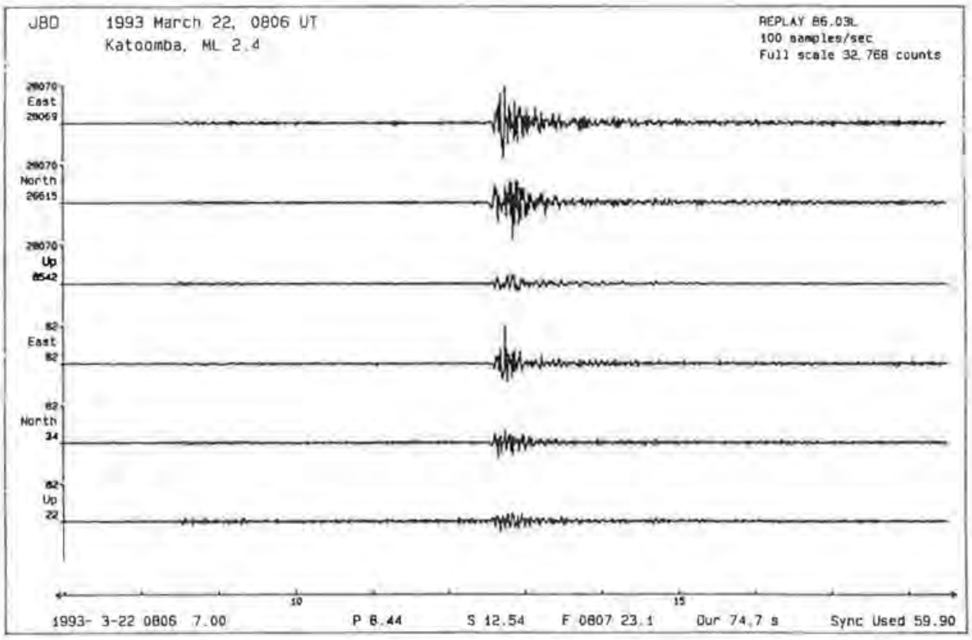

Figure 3: A six-channel digital seismogram and accelerogram recorded 33 kilometres from an earthquake of magnitude ML 2.4. The top three seismograph channels are approaching full scale of 32768 counts, while the lower three accelerometer channels are resolving the motion, showing a peak acceleration of 82/32768 = 0.0025g.

The New Australian Earthquake Loading Code

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1. INTRODUCTION

Standards Australia has recently published the Earthquake Loading Standard, AS1170.4 - 1993. This document will not only effect structural engineers but also architects, building services engineers, designers and others involved in the design of new buildings and existing structures undergoing renovations.

The Standard (AS1170.4 - 1993) provides data and sets out procedures for determining the minimum loads induced in structures by earthquakes. It also sets out minimum detailing requirements for structures.

The Standard does not consider other phenomena which may be related to earthquakes. For example settlement, landslides, subsidence, liquefaction and localised faulting are not considered.

It is intended that the Standard be applied to structures, particularly buildings, non-buildings structures, fixings and non-structural components including building services and architectural elements. So called 'special structures' such as nuclear reactors, dams, transmission towers, piers and wharves are not covered by this Standard. Structures may be classified as special if their failure under earthquake induced loading must be avoided at all costs or if they have a particularly non-uniform vertical and horizontal distribution of mass and stiffness.

The earthquake induced loadings calculated using this Standard are ultimate loads and must be combined with other relevant loadings expected to be applied to the structure at the time of an earthquake.

2. GENERAL REQUIREMENTS

Whether or not it is necessary to design a given structure to specifically resist earthquake induced loading depends primarily on the location of the structure, the structural configuration and the importance of the structure. If it is necessary for the structure to be designed to resist earthquake induced loading, the loadings may be determined either by an equivalent static analysis or a dynamic analysis. The Standard provides detailed guidance on an equivalent static analysis method in Section 6 and appropriate criteria to be used in the conduct of a dynamic analysis in Section 7.

The design requirements depend on the structure configuration and ductility and the earthquake design category.

2.1 Structure Configuration and Ductility

The structure configuration, in both the horizontal and vertical planes determines whether or not the given structure is classified as regular or irregular. Considering plan configurations, a structure may be deemed irregular because of such things as torsional effects, re-entrant corners, discontinuity in diaphragms, discontinuity in horizontal force path and non-parallel horizontal resisting systems. Similarly, in considering the vertical configuration a structure may be deemed irregular because of attributes such as 'soft storeys' which cause stiffness irregularities, 'weak storeys' which cause strength irregularities, irregularity in the distribution of gravity loads between floors and geometric 'set backs'.

Using guidelines provided in the Appendices of the Standard, the designer must ascertain whether or not the structure under consideration is deemed regular or irregular.

The ductility of a structure or element is a measure of it's ability to undergo repeated and reversing inelastic deflections beyond the point of first yield whilst maintaining a substantial portion of its initial load carrying capacity. In effect the ductility of a structure or element is a measure of the energy absorption capability of the system.

The method of analysis used to determine the earthquake induced loading in a structure is influenced by the inherent ductility of the structure. It is necessary for the designer to ascertain the ductility of the structure being designed and this will depend on the load carrying structural system chosen and the materials used for construction. Detailed guidance concerning ductility and structural systems is provided in Appendix B of the Standard. It should be noted that once a particular structural system is selected for use it is essential that the structure be designed and detailed to ensure that the system will behave in the way intended. Nominally non-load bearing elements must not interfere with the action of the structural design.

2.2 Earthquake Design Category

The earthquake design category depends on the structure classification, the acceleration co-efficient and the site factor.

- **Structure Classification**

  For the purposes of earthquake resistant design, structures are classified as either domestic structures or general structures. Domestic structures are detached single dwellings, terrace houses, town houses and the like which lie within dimensional constraints specified in the Standard. All other structures are considered to be general structures.

  General structures are further classified into structure types I to III. Type III structures include buildings that are essential to post-earthquake recovery or are associated with hazardous facilities. Type II structures include buildings that are designed to contain a large number of people, or people of restricted or impaired mobility. Type I structures include all general structures that do not fall into the other categories. Detailed examples of structure classifications are provided in Appendix A of the Standard.

- **Acceleration Coefficient**

  The acceleration coefficient (a) depends on the geographic location of the structure. An appropriate value of acceleration coefficient may be obtained in the first instance from the table provided in the Standard, or if necessary from the detailed contour maps provided. Linear interpolation between contours is permitted.

  The acceleration coefficient is an effective peak ground acceleration corresponding to a return period of approximately 500 years.

- **Site Factor**

  The site factor (S) must be established from substantiated geotechnical data. It ranges from 0.67 for rock to 2.0 for very soft clays and silt.

  The earthquake design category is determined from the product of the acceleration coefficient (a) and the site factor (S) as shown in Table 1

TABLE 1. Earthquake Design Category

Product of acceleration coefficient and site factor (aS)	Design Category			
	Structure Classification			
		General Structures		
	Domestic Structures	Type III	Type II	Type I
$aS \geq 0.2$	H3	E	D	C
$0.1 \leq aS < 0.2$	H2	D	C	B
$aS < 0.1$	H1	C	B	A

3. DESIGN REQUIREMENTS

Design requirements vary with each earthquake design category. Detailing requirements as specified for each category are outlined in Section 4 of the Standard. Further the Standard specifies deflection and design storey drift limits for structures which must be adhered to in any design.

For each earthquake design category the design requirements can be summarised as follows:

- **Category A**

  No analysis is required

- **Category B**

  No analysis required for regular, ductile structures, all other structures require static (or dynamic) analysis. Restriction on unreinforced loadbearing masonry components.

- **Category C**

  Static (or dynamic) analysis, detailing requirements, restrictions on unreinforced loadbearing masonry.

- **Category D**

  Static (or dynamic) analysis for regular structures and dynamic analysis for irregular structures, further restrictions on the use of unreinforced loadbearing masonry.

- **Category E**

  Restrictions on structural systems, static (or dynamic) analysis for regular structures, detailing requirements and reinforced masonry components only.

3.1 Summary of Procedure to Establish Design Category

1. Establish if standard is applicable
2. Determine whether the structure is regular or irregular from the structural configuration
3. Determine whether the structure is ductile or non-ductile
4. Determine the structure classification
5. Determine the appropriate acceleration coefficient
6. Determine the site factor
7. Establish the earthquake design category
8. Determine the design requirements. These depend on the earthquake design category, the structure regularity and the structure ductility.

4. STATIC AND DYNAMIC ANALYSIS

The design requirements for a given structure and the type of analysis required have been established using the method outlined in the previous section.

4.1 Static Analyses

An equivalent static analysis procedure is outlined in Section 6 of the Standard. This form of analysis enables a static load to be calculated for each floor level in the structure. In theory this loading is equivalent to that which would be obtained using a three dimensional dynamic analysis. The approximation is quite adequate for structures with uniform vertical and horizontal distributions of mass and stiffness as such structures respond primarily in their first mode of vibration which may be described by a simple equation.

Structures must be designed to resist earthquake induced forces applied in any horizontal direction and these forces may be assumed to act non-concurrently in the direction of each principal axis except for certain cases including some irregular structures. In such cases the structural components and footings must be designed for the additive effect of 100% of the horizontal earthquake forces in one direction and 30% in the perpendicular direction.

- **Earthquake Base Shear**

  At the heart of the equivalent static analysis is the earthquake induced base shear estimate (V) which is given by:

$$V = I\,(CS/R_f)\,G_g$$

within the limits $V \geq 0.01\,G_g$ and $V \leq I\,(2.5a/R_f)G_g$

where:

I = importance factor (either 1.0 or 1.25 depending on structure classification)

CS = product of earthquake design coefficient (C) and site factor (S) which must not exceed 2.5a, where a is the acceleration coefficient.

R_f = structural response factor which reflects the energy absorbing capabilities of the chosen system. R_f varies from 1.5 for unreinforced masonry to 8 for special moment resisting frames.

G_g = gravity load which consists of the dead load plus a proportion of live load that can be reasonably expected at the time of the earthquake.

- **Vertical Distribution of Horizontal Earthquake Induced Forces**

The earthquake induced base shear force is distributed up the structure in accordance with height and vertical mass distribution. For a very stiff regular structure the distribution of earthquake induced forces will take the form of an inverted triangle.

- **Torsional Effects**

The resultant of the earthquake forces induced at a particular storey is assumed to act though the centre of mass of the floor. The resultant of the resisting forces provided by the structural elements acts through the centre of stiffness. As these two centres are rarely coincident a torsional loading is induced at each storey. The Standard provides guidance on the calculation of these torsional moments.

- **Stability Effects**

The overturning stability of the structure under earthquake induced forces must be assessed. Special requirements are placed on structures that take the form of an inverted pendulum.

- **Drift Determination**

The overall deflection of a structure is calculated as the product of the static deflection and a deflection amplification factor (K_d) to account for inelastic effects under the ultimate limit state earthquake event.

4.2 Dynamic Analysis

A dynamic analysis may take the form of a time history analysis or a response spectrum analysis using the modal analysis technique. A time history analysis requires an input consisting of an acceleration versus time record of an earthquake. As earthquakes are random events, and no two earthquakes are the same, this approach is not appropriate for most structures. The Standard recommends the use of the response spectrum method.

- **Response Spectrum Method**

  The normalised response spectrum provided in the Standard has been derived from an ensemble of earthquake records for a number of different soil conditions. Most standard commercially available dynamic analysis software packages are able to utilise a response spectrum in a modal analysis.

  The steps in a dynamic analysis are as follows:

  1. develop a realistic finite element model of the structure accurately reflecting the stiffness and mass distributions

  2. scale the normalised response spectrum provided in the Standard by the factor (aI)

     where a is the acceleration coefficient and I is the importance factor.

     This is effectively providing a linear elastic response spectrum for the ultimate limit state earthquake event.

  3. further scale the linear static response spectrum by $1/R_f$ to account for inelastic behaviour

  4. analyse structure using the inelastic spectrum obtained in Step 3

  5. check horizontal base shear force and compare it with the value obtained from an equivalent static analysis. For irregular structures the Standard requires that the results obtained from the dynamic analysis be scaled such that the base shear force equals that obtained from an equivalent static analysis. Similarly, for regular structures the dynamic base shear force must not be less than 90% of the equivalent static analysis base shear force.

  The adjustment in Step 5 is specified in the Standard to acknowledge the uncertainty associated with calculating the earthquake induced forces. The earthquake base shear force, V, has been developed from a combination of theoretical, experimental and field data and is considered a realistic maximum force that a particular structural system could resist in the inelastic range. The dynamic analysis is primarily carried out to provide a more accurate distribution of the earthquake induced forces and a better estimate of the building's natural periods of vibration.

- **Other Considerations**

  - As with the equivalent static analysis earthquake directional effects must be accounted for using the 100% and 30% rule described above.

  - In a full three dimensional analysis the dynamic amplifications associated with horizontal effects are automatically accounted for. The finite element model must, however, be adjusted to account for the effects of accidental eccentricities. For a two dimensional dynamic analysis, torsional effects are not included and an equivalent static torsional analysis must be conducted.

- The displacements calculated from a dynamic analysis must be multiplied by the deflection amplification factor (k_d) to account for inelastic behaviour.

5. CONCLUDING REMARKS

Minimum design loads on structures Part 4: Earthquake Loads (AS1170.4 - 1993) represents a major step forward in Australian structural design procedures in that it provides a simple but effective procedure for earthquake resistant design. It has been particularly developed for Australia which, in earthquake terms, is considered a "low risk, high consequence" region.

Earthquake Resistant Design in Australia - Concrete Structures

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1. INTRODUCTION

AS 1170.4 - Minimum design loads on structures - Earthquake Loads was published by Standards Australia in 1993 and supersedes AS 2121.

The new Code applies to all of Australia and represents the current state of collective knowledge. It is a major step forward in seismic design. It is a loading code in limit state format and specific requirements for materials are in to be revised codes such as AS 3600 and AS 4100.

Appendix A of AS 3600, with additional requirements for building subject to seismic action, is currently being revised and should be available later this year.

The design of buildings for earthquake loads may be new for many engineers and designers but when AS1170.4 is included in the Building Code of Australia and gazetted by the various states, then all new buildings will be required to be designed to this Code. In many cases only limited design will be required particularly for the smaller regular buildings on firm soils.

2. EXPERIENCE TO DATE

The previous earthquake code AS 2121 published in 1978 has been used in a limited way in South Australia, Western Australia and by the Commonwealth Government Departments. For a variety of reasons seismic design was not part of the normal design for buildings in the major cities of Australia. For those engineers not familiar with seismic design, the new Code will come as a bit of a shock and will take some time in getting used to the necessary design concepts. However, once the principles are understood then the design is not too difficult.

Experience in construction in Adelaide with seismic design has indicated some changes will be required and will be new to the building industry. This will provoke some comment and relearning of steel fixing techniques but they can be done.

3. USING AS 1170.4

AS 1170.4 has been arranged so that for all structures a logical approach is taken in using the new Code to establish the design loads. Designers must determine the following:

- Type of structure i.e. domestic or general
- For general structures determine whether it is Type I, II or III or for domestic structures determine whether it is H1, H2 or H3
- Acceleration Co-efficient a
- Site Factor s
- Importance Factor I

From Table 2.6 determine the earthquake design category i.e. A, B, C, D or E for general structures.

For general structures then determine:

- Is the building regular or irregular i.e. configuration
- Is the structure ductile or non ductile (NOTE: reinforced concrete is ductile)
- The structural system

Four structural systems are allowed:

- Bearing wall system which consists of load bearing walls for vertical loads and shear walls or braced frames which provide the horizontal restraint for earthquake loads.
- Building frame system - a moment frame supports the vertical loads and shear walls or braced frames provides the horizontal restraint for earthquake loads.
- Moment resistant frame system, where the moment frame resists both vertical and horizontal forces by flexure.
- Dual system - where a moment resistant space frame provides all of the vertical and at least 25% of the horizontal force restraint and shear walls or braced frames provides the rest.

For reinforced (or prestressed) concrete the following design criteria will apply for AS 1170.4.

- Design Category A
  - No structural analysis
  - No structural detailing
  - No non-structural detailing
- Design Category B
  - Structural analysis only for irregular building (static)
  - Structural detailing
  - Non structural detailing
- Design Category C
  - Structural analysis
  - Structural detailing
  - Non-structural detailing

Note for Design Category D and E vertical effects on cantilever including prestressed must be considered.

4. STRUCTURAL DETAILING

Section 4 of AS 1170.4 sets out the requirements for all general structures (if required) which include load paths, ties and continuously wall anchorage, diaphragms and footing ties.

Reinforce concrete structures of design category A have no specific structural detailing requirement.

Concrete Detailing

While reinforced concrete is regarded as a ductile material, the approach in AS 1170.4 is that if the structures has better ductility then that structure attracts a lower earthquake force for the same design category.

From the point of the view of the designer this means by using the special concrete detailing in Appendix A of AS 3600, this will increase the ductility and result in lower earthquake forces to be designed for.

This increased ductility is obtained at an increased cost of both design and construction so designers will have to make a cost benefit analysis of the alternatives. Experience will be the best judge of this. However, ductility is a very important part of resisting earthquake loads.

Concrete Member Design

Reinforced members of a building of earthquake design category A have no specific concrete design or concrete detailing. For irregular concrete structures of design category B, design of the structure is required to be designed for the lateral earthquake forces but no specific concrete detailing is required.

Buildings of design categories C, D and E have to be designed for lateral earthquake forces and may have specific concrete detailing also.

For concrete buildings of design categories C to D exterior walls of precast concrete will need to be designed for racking movements and connections have to be ductile.

The Earthquake Loading Code allows for structural systems to resist lateral loads as previously stated. These systems are now discussed in detail below.

5. STRUCTURAL SYSTEMS

Bearing Wall Systems

This is a system of load bearing walls carrying the vertical load and shear walls or braced frames providing the lateral restraint for earthquake forces. AS 1170.4 requires the system to carry approximately 33% greater horizontal loads than a building frame system and the reinforcement to resist the forces is higher and is considered sufficient without special detailing i.e. no special detailing is required for this structural system to Appendix A of AS 3600.

Building Frame System

This is a structural system in which an essentially complete space frame supports the vertical load and shear walls or braced frames provide the lateral loads.

i. Shear Walls

In addition to designing for forces as determined by the load combinations, there are additional provisions for boundary elements at edges and openings of shear walls.

Boundary elements do not necessarily mean increase in thickness of wall. Boundary elements, if required for buildings up to 4 storeys will be deemed to comply type details and will require no specific design. Above 4 storeys, design will be required for these boundary elements.

ii. Braced Frames

Because members of a braced frame resist lateral earthquake axial forces in both alternating tensions and compression, the longitudinal reinforcement requires lateral restraint by vertical ties or closed ligatures. The Code will provide clauses to determine the amount of helical or rectangular ligatures required

Moment Resisting Frames (MRF)

This is a structural system in which an essentially complete space frame resist both the vertical and horizontal earthquake loads by flexural actions. Here the designer has a choice of three types of frames:

- Ordinary Moment Resistant Frame - this has the highest lateral forces and no additional detailing for ductility other than members shall be designed to AS 3600 excluding Appendix A. There is a height limit of 50m where as > 0.1

- Intermediate Moment Resistant Frame - this has lower lateral force than an OMRF in accordance with AS 1170.4 but requires additional detailing in beams, slabs and columns in accordance with Appendix A to provide a higher level of ductility.

- Special Moment Resistant Frames - this has the lowest lateral force in accordance with AS 1170.4 but requires special detailing of beams, slabs and columns in accordance with the ACI Code. The number of buildings designed using SMRFs in Australia will be very limited.

Intermediate Moment Resistant Frames

i. Detailing for Beams

- Top and bottom faces have to continuously reinforced

- Positive moment at support not less than 1/3 of negative moment strengths than 20% of the maximum moment strength provided at the face of either support.

- Longitudinal reinforcement shall be continuous through the support.

- Lapped splices shall be confined

- Shear reinforcement is greater at reduced centres and closer spacings at supports.

ii. Detailing of Slabs

This is similar for beams except for the shear reinforcement. Flat slab will have special requirement

iii. Columns

Columns have closely spaced ligatures at their top and bottom to improve their ductility

iv. Column/beam joints

May require ligatures to provide full confinement.