The Eugowra NSW Earthquake Swarm of 1994

Gary Gibson[1], Vaughan Wesson[1] and Trevor Jones[2]

[1] Seismology Research Centre, RMIT, Melbourne, [2] Australian Seismological Centre, AGSO, Canberra

Abstract An earthquake swarm occurred at Eugowra in central New South Wales starting in late July 1994. The highest level of activity and the largest event in the swarm occurred over the period August 19-22. A high resolution network of seismographs was installed before the peak activity, allowing location of many events to a precision of 0.1 to 0.2 kilometres. The earthquakes were very shallow, with depths from near surface down to about 1.2 kilometres. The distribution of hypocentres delineated a fault plane dipping to the southwest, and a study of locations with time showed hypocentres migrating outwards from the initial events. Because of the shallow depths, very high accelerations were recorded, with high frequency motion of short duration. The maximum acceleration recorded was 0.97 g, at a site near to the epicentre of a shallow event of magnitude ML 4.1.

Introduction

In late July 1994 a number of small earthquakes were reported felt in Eugowra, a small town between Orange and Forbes in central New South Wales with a population of about 670. Current earthquake catalogues do not show significant activity about the town, but one local resident recalled a series of four or five similar events that lasted for about one day about fifty years earlier.

Earthquakes in Australia cluster in space and time. The most common patterns for clusters are the mainshock-aftershock sequence and the earthquake swarm. Other patterns include foreshock-mainshock-aftershock sequences, and multiple mainshocks.

A swarm has a number of events within a limited volume, lasting over a period from hours to months. The largest event in a swarm occurs well after the start of the swarm and has a magnitude not significantly greater than that of the second largest event.

Seismograph Network

The first reports of earthquakes at Eugowra were received from local residents by staff at the Seismology Research Centre (SRC) on 1994 July 31. The nearest seismograph with an analogue record available was over 160 kilometres to the east. This showed no events, limiting the size of the events to a maximum of ML 1.5. Additional calls were received over the next few days, and some of these events were just visible on the analogue seismogram.

On August 6, an SRC seismologist drove the 700 kilometres from Melbourne to Eugowra with a single digital seismograph. However that evening at 0903 pm EST (1103 UT), an earthquake of magnitude ML 5.1 occurred at Ellalong, south of Cessnock and west of Newcastle, so the instrument was diverted there.

The Ellalong earthquake was followed by only a few aftershocks with small magnitudes, and activity continued at Eugowra. On August 13 a digital seismograph was installed in the Eugowra office of the State Emergency Service, using the telephone for access to data. A number of small events were recorded over the next few days.

On Friday August 19, while data were being downloaded from the seismograph by telephone, the first events large enough to trigger the SRC earthquake alarm system occurred. These were of magnitude ML 2.7 and ML 3.1, and several smaller events occurred over the next few minutes. It was decided that additional instruments would be installed

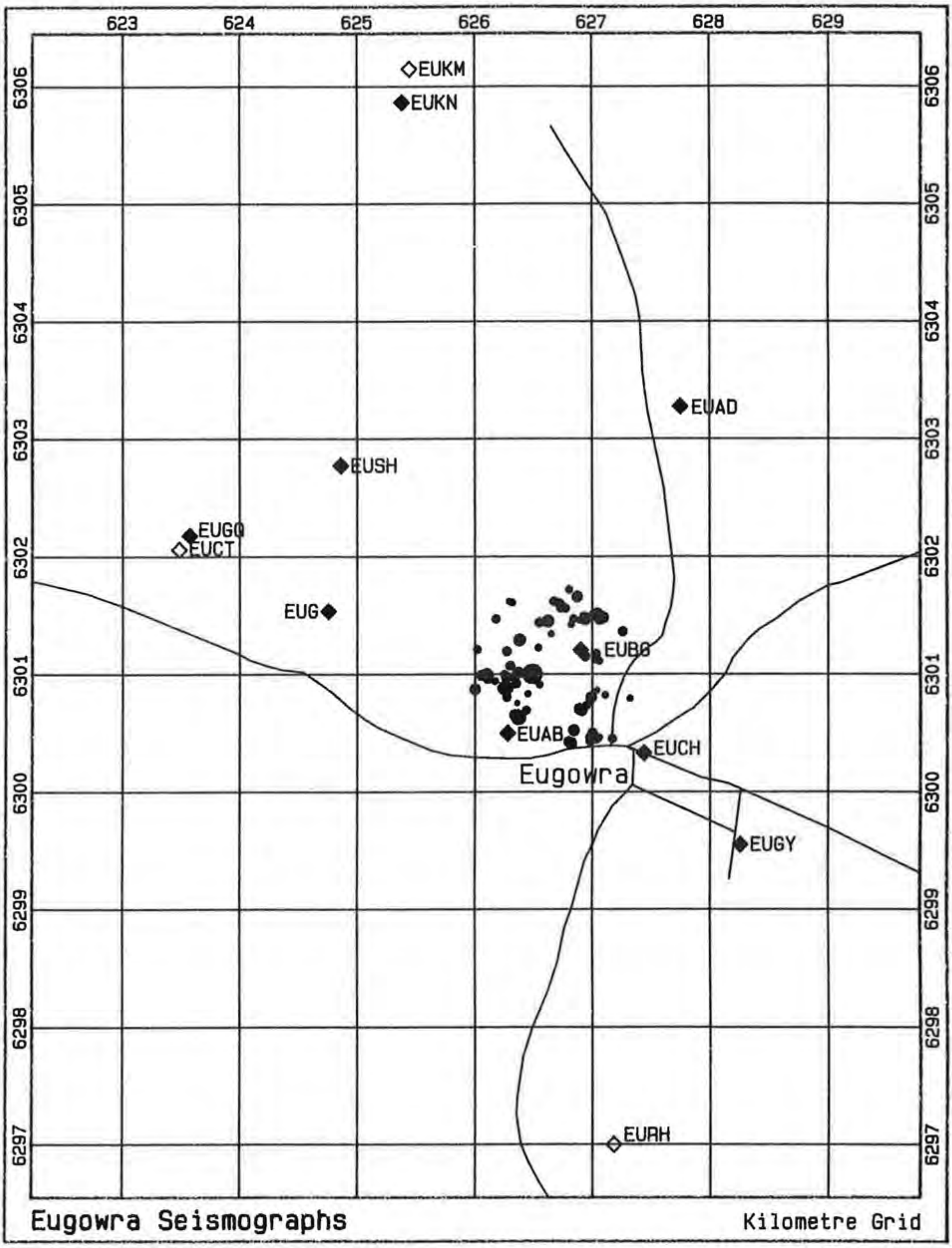

Figure 1: Seismographs and epicentres about Eugowra.

immediately, and additional instruments were sent from Melbourne, Sydney and some from Ellalong. Two digital recorders, transducers and other equipment were also provided by the Australian Geological Survey Organisation (AGSO). Both the Ellalong and Eugowra networks were operated as joint projects between AGSO and the SRC; AGSO analysed most of the data from Ellalong, while SRC analysed most of the Eugowra data.

It was clear that the earthquakes were at shallow depth because of the very small events that had been felt. It was decided to concentrate the seismographs within five kilometres of Eugowra, operate them at higher than normal sample rates, and giving special attention to high timing accuracy. Use of the satellite based Global Positioning System (GPS) was invaluable for precision timing and for locating the seismograph sites.

Swarm activity continued to increase, and six recorders had been installed by the time of the largest earthquake in the sequence on the afternoon of Sunday 21 August. A network of eight recorders, including both accelerographs and seismographs, was eventually installed within five kilometres of Eugowra.

Location Accuracy

Previous experience with monitoring swarms at Bunnaloo in southern New South Wales from 1988, and at Bradford Hills southwest of Bendigo from 1991 suggested that very high frequencies would be measured. A sample rate of 200 samples per second was adopted, and this was later increased to 250 samples per second. In future, a rate of 400 samples per second should be considered, with an anti-alias filter higher than 100 Hz. A timing accuracy of ±0.005 seconds was sought using frequent references to a master clock or GPS.

The smaller earthquakes were being felt in the area of granite outcrop north and west of Eugowra, so the network was oriented in this direction. Surface alluvium to the south and east of the town limited the availability of good seismograph sites in these directions. The seismic velocity model used for preliminary locations was based on the AGSO model DAL1, which is used for locating earthquakes in the granite outcrop of the Dalton area.

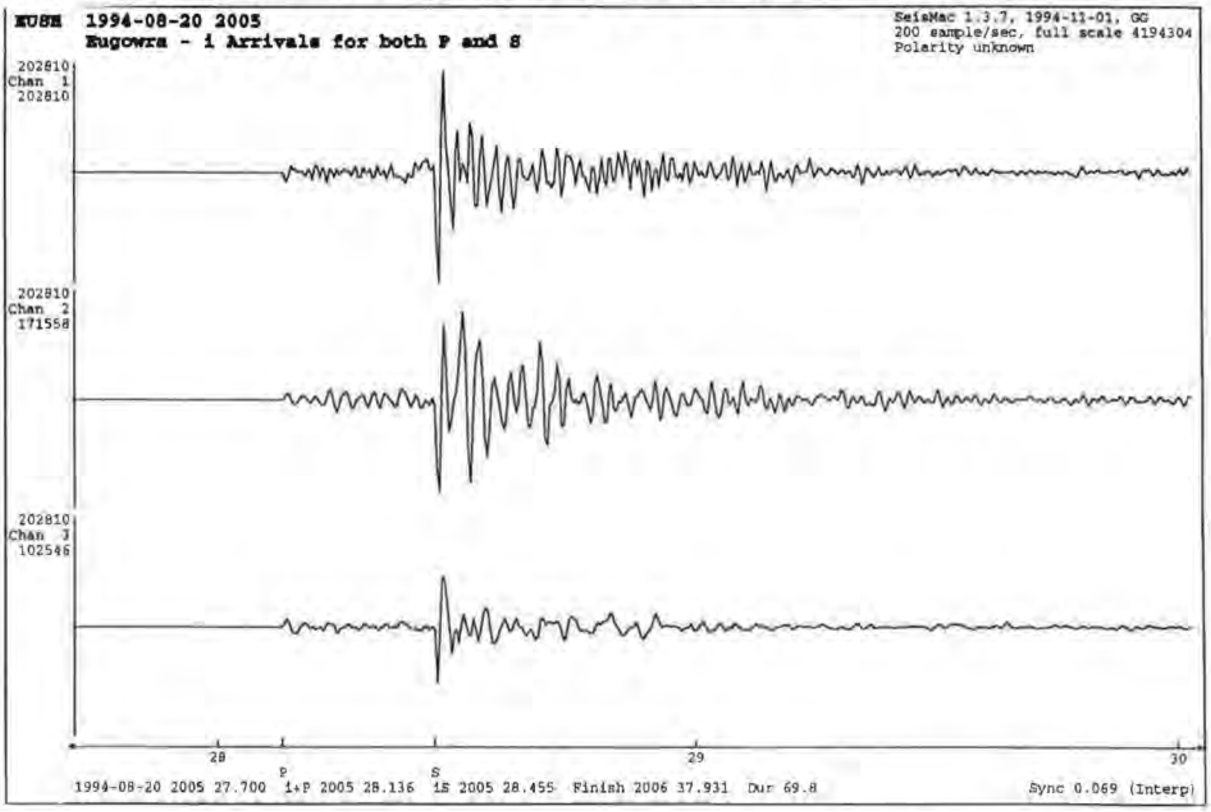

Figure 2: Typical seismogram, showing very sharp P and S arrivals

Epicentres and Depths

Because there were up to three seismographs within a kilometre or two of most epicentres, each with timing to a precision of about 5 milliseconds, earthquake depths have been determined with high accuracy. Many of the depths have been determined with an uncertainty of 0.3 km or less, and some with an uncertainty approaching 0.1 km.
It was soon found that the deepest events were to the south west, at depths down to 1.2 km beneath mean sea level.

The topography in the area consists of the valley of the Lachlan River to the south west at an elevation of about 0.28 km. A range of hills with outcropping granite extends to the north northwest of Eugowra, and rises to about 0.55 km above mean sea level. There is a creek valley north of the town down to 0.29 km, and to the north east is another range of granite hills rising to 0.50 km. Some of the events were located in granite above sea level.
Figure 3 shows plots of epicentres for events in a series of depth ranges. The maps show the epicentres of those events that occurred between the surface and 0.5 km below mean sea level, 0.5 km to 1.0 km, and deeper than 1.0 km respectively.

A cross section with earthquake locations projected onto a vertical south west to north east plane, azimuth 228°, shows that the events fit near a plane dipping at about 38° to the south west. This plane does not correspond to a known fault.

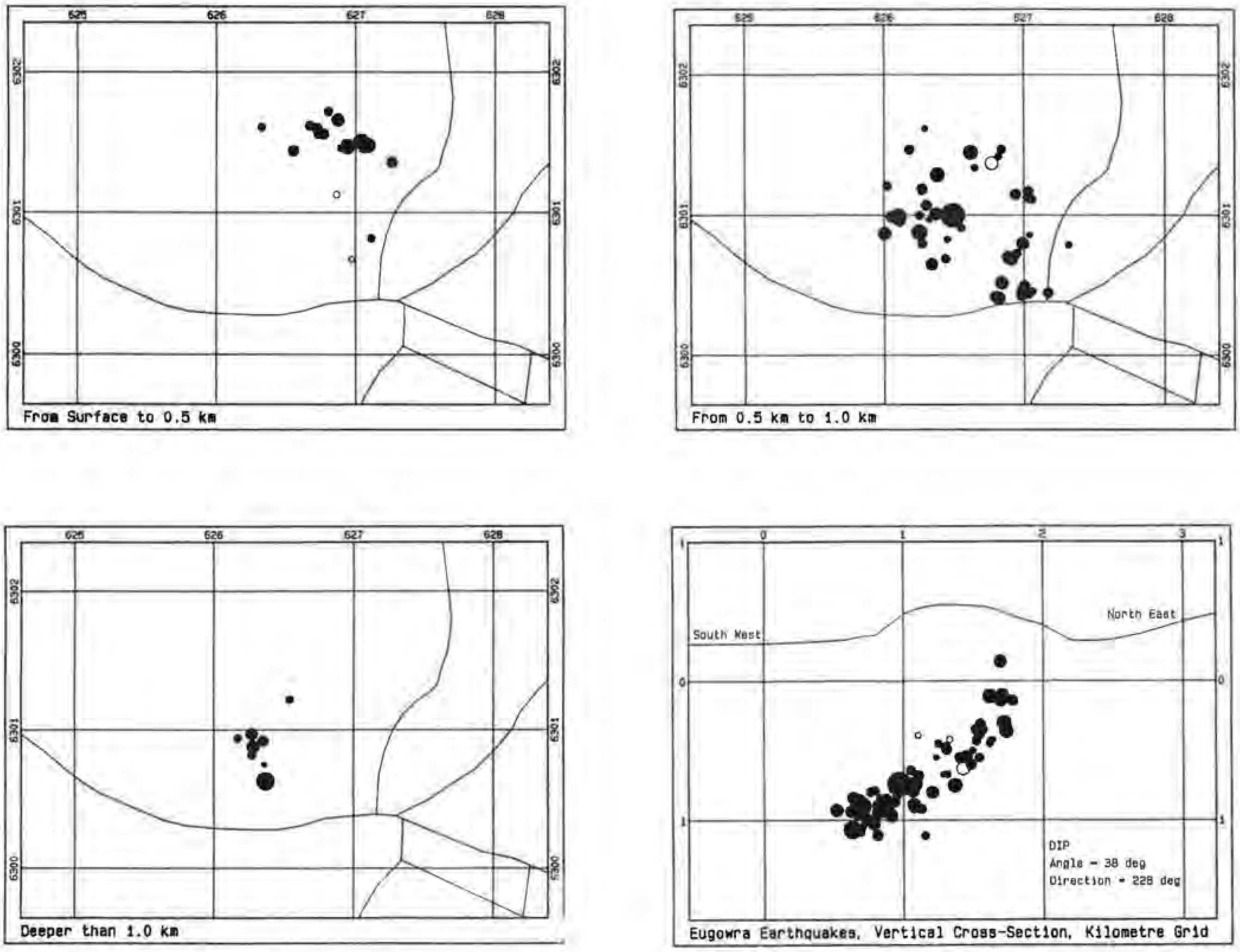

Figure 3: Variation with Depth. The size of the earthquake symbol increases with magnitude, the largest event being of magnitude ML 4.1. Open circles represent earthquakes with higher uncertainties in their locations than those with solid circles.

Migration of Hypocentres

Because of the precise earthquake locations, it was possible to trace the development of the swarm through time. The first events to be located after the seismograph network installation began were in two clusters. The larger of these was about one kilometre north west of the centre of the town, and the smaller cluster was just 0.5 km north west of town.

The largest event occurred near the location of the larger cluster. The magnitude of ML 4.1 can be expected to produce a rupture of about one square kilometre, so it is likely that it ruptured the entire central area between the two clusters. The activity in the next ten days, from August 22 to August 31, occurred in the same general area, but with few events within the central area.

From September 1 to October 31, activity continued to move away from the original rupture area, including deeper events to the south west, and shallower events to the north east.

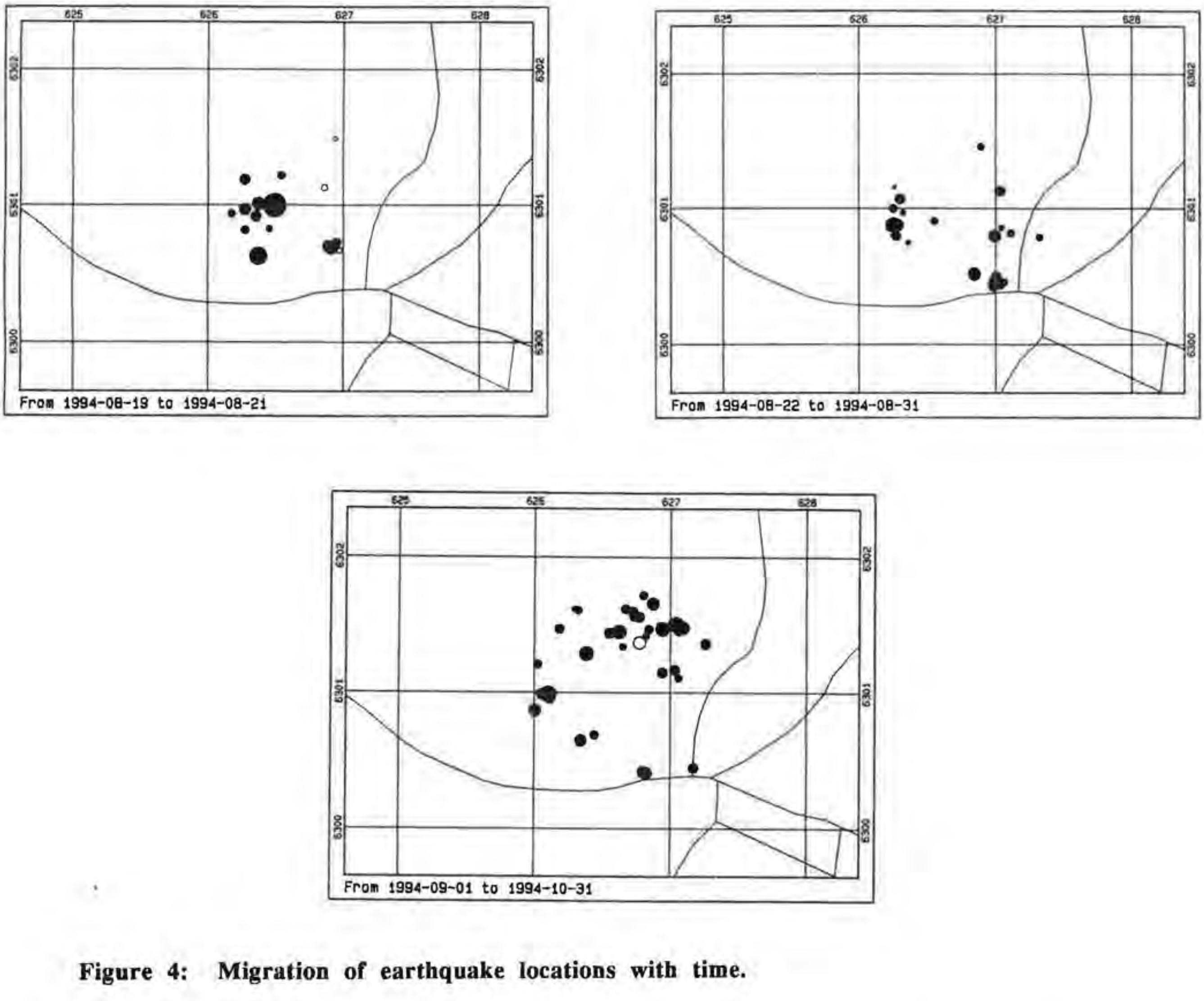

Figure 4: Migration of earthquake locations with time.

Strong Motion

Because of the very close distance from earthquake to seismograph, very strong ground motion was recorded, especially from the ML 4.1 event on 1994 August 21 at 0553 UTC (0353 pm EST). Figure 5 shows the record from a six channel instrument about 5.3 km to the northwest of this event. This had a triaxial sensitive seismometer and a triaxial strong motion accelerometer in parallel. The output from the seismometer was full scale for over 15 seconds, but the acclerometer gave a very clear record with peak acceleration of 0.108 g.

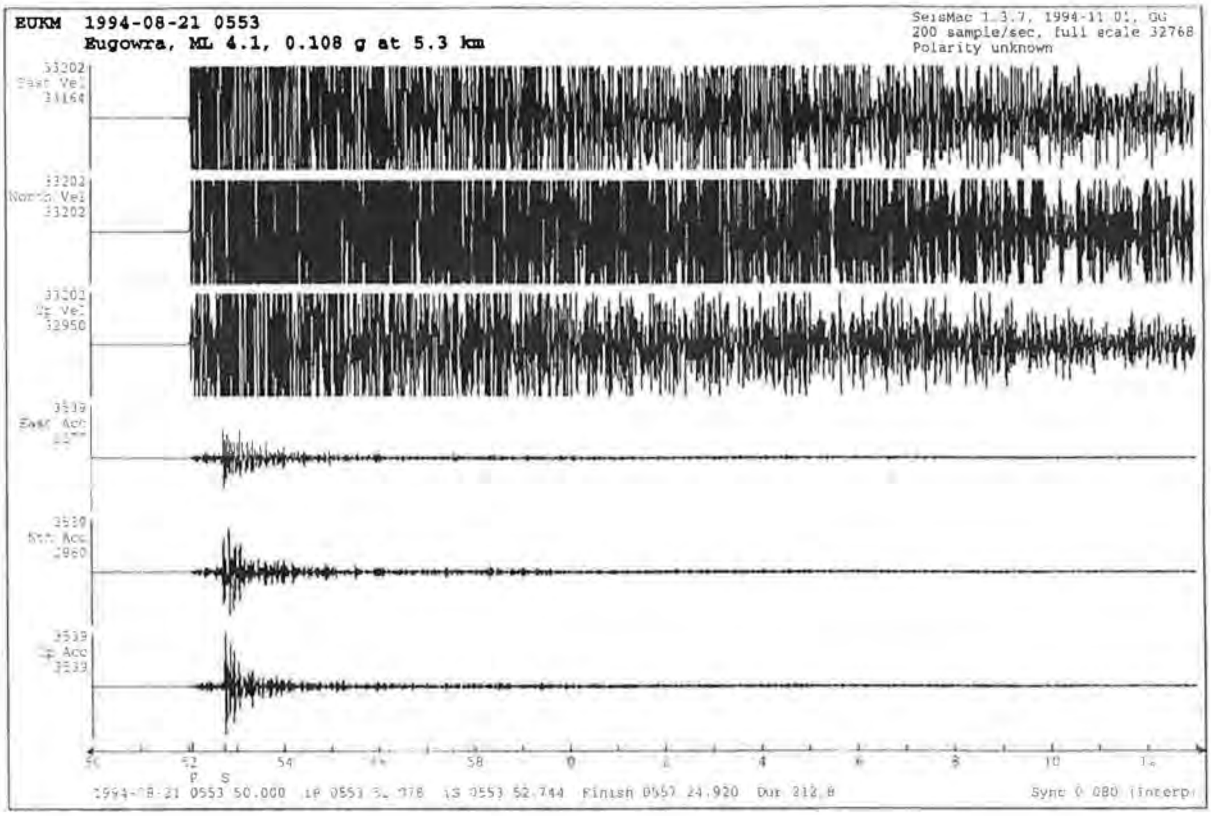

Figure 5: Ground motion recorded by a 6-channel instrument with a trixial seismometer and a triaxial accelerometer.

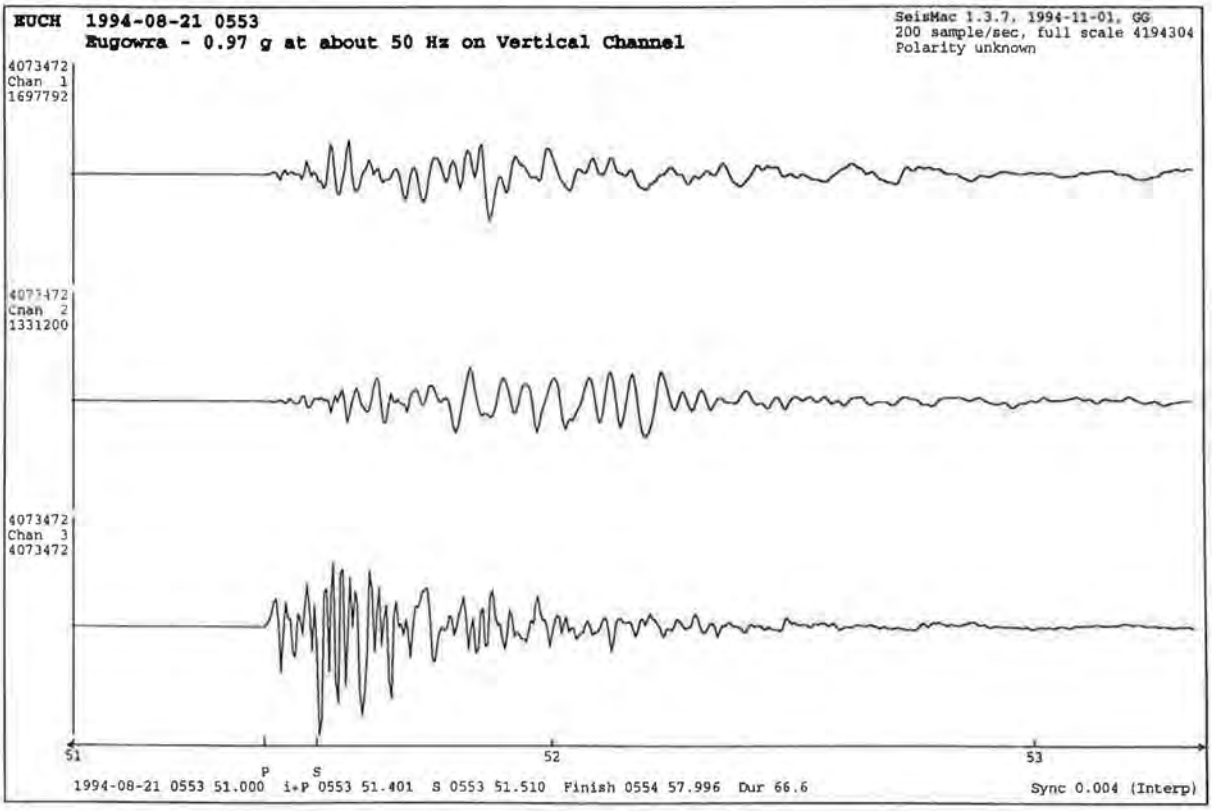

Figure 6: Strong Motion recorded at the Central Hotel in Eugowra, with a peak ground acceleration of almost 1g.

The strongest motion recorded was 0.97 g, about 1 km from the rupture of the magnitude ML 4.1 event. This was on the vertical component at a frequency exceeding 50 Hz.

Effects on Buildings

Only very minor damage was observed during the swarm. The high acceleration shown in figure 6 was recorded adjacent to the Central Hotel in Eugowra. This is a traditional two storey hotel, built in 1920 of mixed concrete and timber construction. The damage was limited to items fallen from shelves, a mirror fell from a wall, and broken figurenes, all in the upper floor.

For a short period, a six channel accelerograph was installed in the Central Hotel to record its response. One triaxial transducer was placed on the floor at ground level, and another was placed on a window sill in the south wall on the top floor. This clearly showed the amplification of the motion by the building, especially the north-south motion of the south wall.

Figure 7 shows the response to an earthquake to the northwest, with dominant horizontal response of the wall. Figure 8 is from a smaller earthquake near to vertically under the hotel, with dominant vertical motion and with vertical amplification.

Although the swarm caused very little damage, it it did affect many local residents. Even very small events, smaller than magnitude ML 1.0, could clearly be heard. They sounded like a short sharp explosion. Events larger than ML 2.0 were quite loud, larger than ML 3.0 were very loud and the vibration was quite apparent, and the ML 4.1 event caused

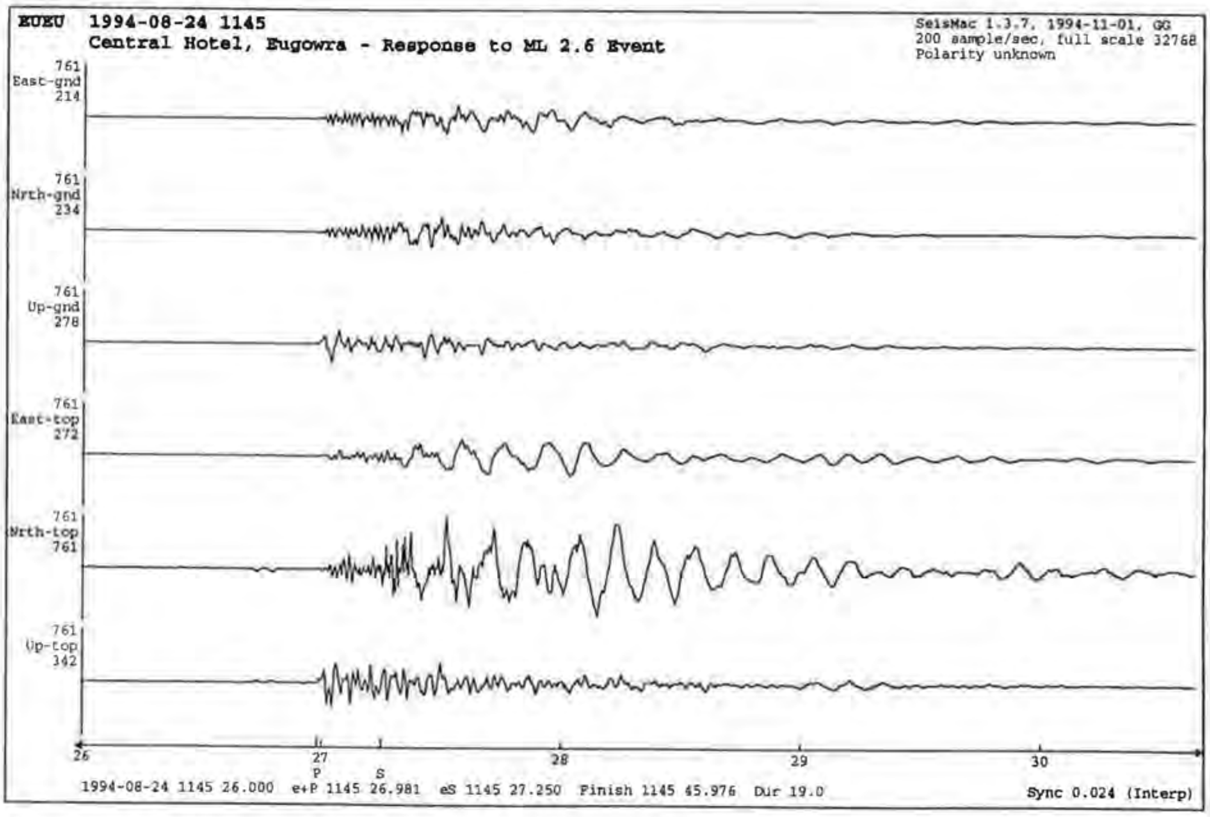

Figure 7: Top floor wall motion and ground floor motion of the Central Hotel for an earthquake of magnitude ML 2.6 about 1.3 km to the northwest and 0.9 km deep.

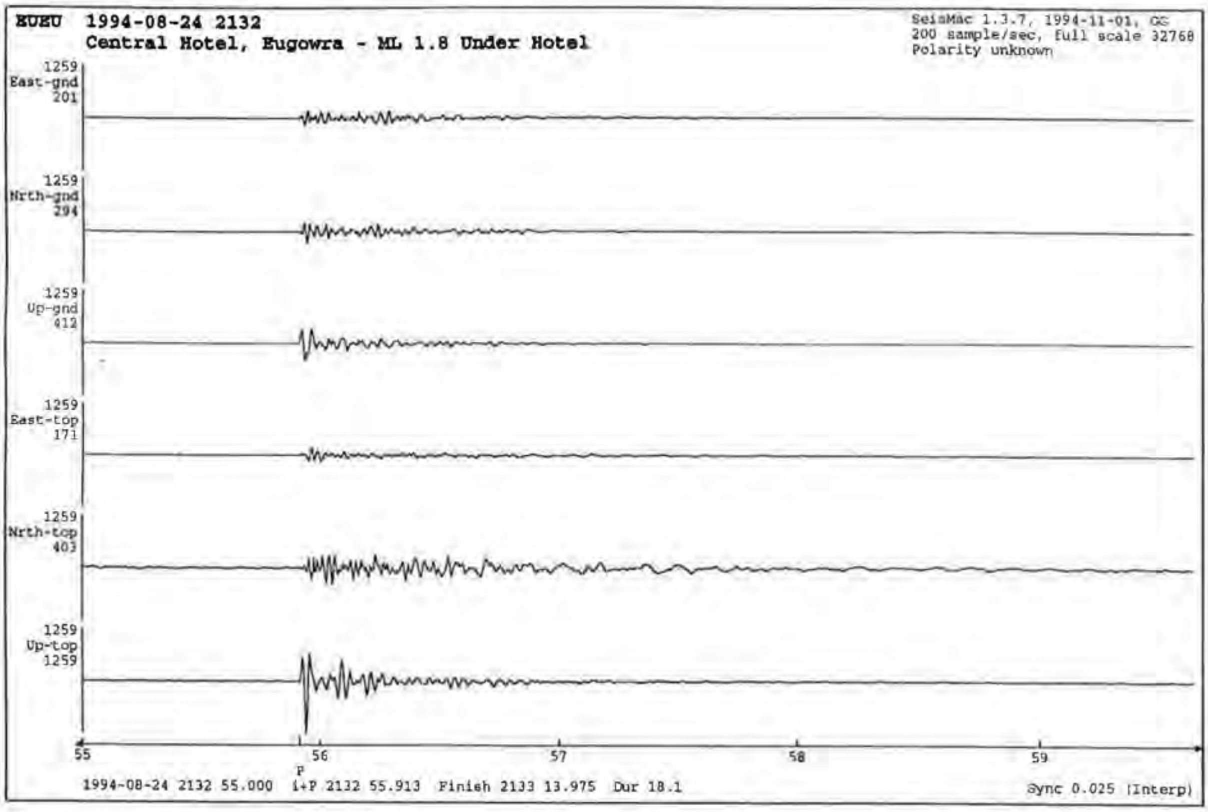

Figure 8: Top floor wall motion and ground floor motion of the Central Hotel for an earthquake of magnitude ML 1.8 about 1.0 km under the hotel.

Effects on People

each day, with many events loud enough to waken sleeping people. The novelty of being woken several times each night quickly lost its appeal.

The sound and vibration from the events was normally much more pronounced at the western end of the town. Granite outcrops north west of the town, and the high frequency motion (30 to 70 Hz) could easily be heard. The alluvium to the south east of the town filtered out the higher frequencies and gave dominant motion in the range 10 to 20 Hz. Together with the greater epicentral distances, this gave a lower emphasis on sound but a proportionally greater emphasis on felt vibration compared with the effects to the north west.

One of the main concerns of local residents was whether the swarm would produce an even larger event. Previous experience with swarms at Bream Creek in Tasmania in 1987, at Bradford Hills near Bendigo from 1988, and at Bunnaloo in southern NSW from 1991, suggested that the swarm would probably have an exponential decay in frequency of events over a period of weeks or months. Seismologists presented this opinion to the local population through the media and at public meetings, together with the possibility that a larger event could occur.

Talks were given to local schools and other groups. As expected in an area with low seismicity, many people did not have knowledge or experience of earthquakes in Australia, and many had ideas of fissures opening up to produce chasms. A more realistic portrayal of earthquake effects seemed to be comforting to many residents. The State Emergency Service and police in Eugowra played a key role in the education program.

Discussion

Traditional correlations between peak ground acceleration (PGA) and earthquake hazard have primarily been derived from earthquakes of magnitude 6 to 7 at distances of 10 to 100 kilometres, mainly from California.

Small nearby earthquakes can give very high accelerations without causing any damage. This motion is at high frequencies (short period), well above the natural frequencies of most buildings. Large distant earthquakes will produce longer period (lower frequency) vibrations with very low accelerations, but which can cause considerable damage, such as following the Mexican earthquake of 1985.

Peak ground acceleration is a very poor measure of earthquake hazard. Without frequency or duration information it gives little or no indication of possible damage. Earthquakes smaller than about magnitude ML 5.0 rarely cause much damage, even if they are shallow, because the duration of strong motion is short. The larger the magnitude of an earthquake, the longer the rupture time and the longer the duration of strong motion. Long rupture times of large earthquakes produce a higher proportion of low frequency seismic energy than experienced from smaller earthquakes.

Peak ground displacement is high for long period vibrations, and is very low for short period vibrations. Its use as a measure of hazard would over-estimate the effect of large distant earthquakes, and under-estimate the effect of moderate magnitude nearby events. Earthquake magnitudes are measured using displacement.

For structures with natural periods between 0.2 and 4 seconds (natural frequencies between 5 Hz and 0.25 Hz), earthquake vibration hazard correlates better with peak ground velocity than either displacement or acceleration. It is a matter of definition that earthquake vibration hazard correlates with intensity. Intensity inherently includes the effects of vibration amplitude, frequency content and duration. This is probably one of the best arguments in support of continued use of intensity.

The Fourier amplitude spectrum of a seismogram clearly indicates both amplitude and frequency content, but does not give a clear measure of the duration.

A response spectrum also includes the effect of duration of motion for a damped harmonic oscillator. However, it does not normally incorporate nonlinear behaviour of the structure.

Static analysis methods for design of structures, such as included in Australian Standard 1170.4, incorporate an "acceleration co-efficient", a. This is not a peak ground acceleration. It is a measure of ground motion, empirically determined, that is appropriate for use in analyses of this type. The value of a static analysis for appropriate structures is not affected by the statement that peak ground acceleration is a poor measure of earthquake hazard.

Conclusion

1. A dense network of seismographs with high precision timing can be used to locate shallow events with an uncertainty of 100 metres or less. Uncertainties reduce significantly if there are six or more recorders in the network.

To constrain earthquake depths it is essential that one of the seismographs should be near to the epicentre, preferably at a horizontal distance not greater than the earthquake depth

2. Seismographs used for aftershock and swarm studies can use either seismometers or accelerometers. Seismometers have the disadvantage of going to full scale for larger events, but the advantage that they do not require power. Wide dynamic range accelerometers used with digital recorders will record both small and large earthquakes, but usually use considerable power. For aftershock monitoring we suggest that accelerometers should be used when possible, and appropriate solar panels should be provided.

3. Results of this study confirm that peak ground acceleration is a very poor measure of earthquake hazard. PGA values recorded close to the earthquake are higher than were previously expected. However, for small earthquakes with high frequency short duration motion, high PGA will cause little damage. High PGA values should not significantly affect the acceleration co-efficient values used in static analysis.

Acknowledgements

Tony Corke, Adam Pascale, Mark Carter, Wayne Peck, Cameron Bricker and Ken Marshall assisted with installation and operation of the seismograph network. Much assistance has been provided by Anne Bray, by Kevin, Jeannette and David Norris at the Central Hotel with support from Blossom, Greg and Marie Augustine and the Eugowra State Emergency Service, Doug and Leonie Greenhalgh, John and Ro Andrews, and many other residents of Eugowra.

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Effects of Intraplate Earthquakes on Structures

John Wilson, Nelson Lam, and Graham Hutchinson

Department of Civil and Environmental Engineering, The University of Melbourne, Parkville Vic 3001

Introduction

Australian earthquakes are associated with relative slip between geological faults within a tectonic plate and are known as intraplate earthquakes. These faults are generally smaller than the faults associated with a plate boundary and result in maximum credible earthquakes that are smaller in; magnitude, frequency of occurrence, peak ground acceleration, duration of shaking and area of influence than interplate earthquakes. In addition, the fault mechanism of Australian earthquakes is reverse faulting compared with the strike slip faulting that is commonly associated with Californian interplate earthquakes. Consequently Australian earthquakes tend to have a high stress drop and contain a large proportion of high frequency energy resulting from numerous short duration acceleration pulses. The seismic hazard in Australia is principally associated with the near field ground motions of relatively shallow medium sized earthquakes. (Mag 5-7)

In contrast, the earthquake hazard in California is from both near and far field large earthquakes (Mag 6-9) and consequently the earthquake design parameters recommended in these regions have been developed from an ensemble of earthquakes that reflect both the low frequency energy associated with far field events and the high frequency components of near field earthquakes.

ARC Research Project

The new Australian earthquake loading standard, AS1170.4-1993, (Ref 1) is based primarily on Californian experience (Ref 2, 3) and consequently involves a number of seismological and engineering extrapolations for Australian conditions. The most significant extrapolations are associated with the calculation of earthquake forces which essentially comprises two parts:

i. Selection of the earthquake ground motion in the form of an elastic response spectrum.

ii. The construction of an inelastic response spectrum from the elastic spectrum using the "Structural Response Factor", or 'R' factor.

Preliminary studies suggest that the UBC (Ref. 3) normalised design response spectra used in AS1170.4 are conservative for the design of buildings greater than three stories in height (Figure 1). Further, the inelastic demand experienced by structures is dependent on both the duration of strong motion shaking together with the size, shape and sequence of acceleration pulses.

Since Australian earthquakes are generally smaller in magnitude, shorter in duration and contain a greater proportion of high frequency components than Californian earthquakes, further investigation is needed to determine the suitability of using Californian based 'R' factors in Australia.

A three year research project, funded by the Australian Research Council, has been initiated which brings seismologists and engineers together to investigate Australian engineering seismological parameters (Ref. 5). Specifically the project aims to:

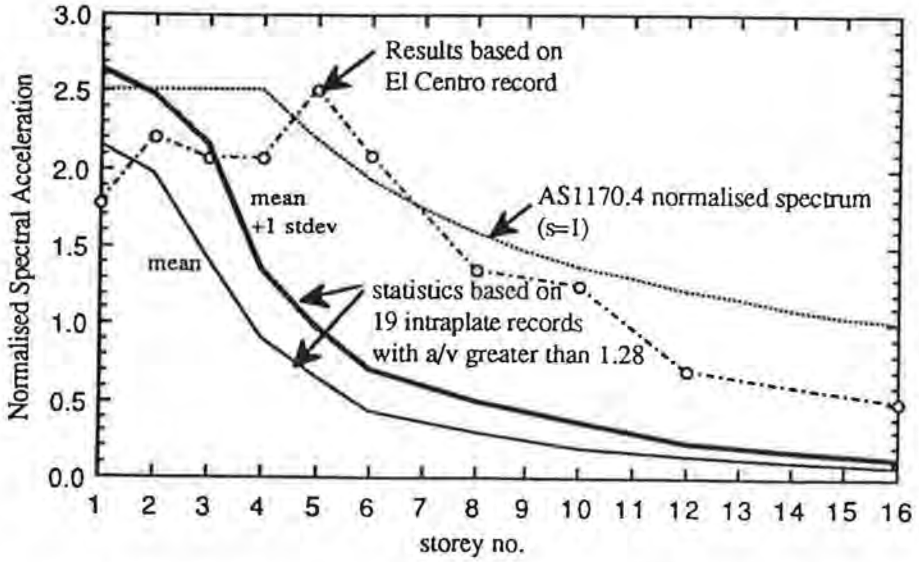

Figure 1 Intraplate earthquake and design response spectra (after Ref. 10)

i. Develop appropriate earthquake ground motions and response spectra for Australian conditions for rock and a range of soil profiles, and

ii. Investigate the overstrengths and energy absorption capabilities of commonly used Australian framing systems when subjected to typical Australian earthquakes. (These structural response parameters are measured in the new Earthquake Standard using the 'R' factor).

Elastic Design Spectra

This ARC funded research project will develop Australian spectral attenuation functions which present displacement, velocity and acceleration components of ground vibration as a function of frequency for bedrock motion.

From these ground motion spectra, linear elastic design response spectra for Australian conditions will be developed using a number of methods including:

i. The use of existing Australian data from the 80 seismographs installed and maintained by both the Seismology Research Centre (SRC - RMIT) and the Australian Seismological Centre (ASC - AGSO). The SRC and ASC have been developing the Australian seismograph network using digital seismographs for the past fifteen years and now have a significant collection of small earthquake ground motions (Mag<4).

This data combined with similar overseas data and supplemented with new data recorded from ambient vibrations, artificially induced vibrations and vibrations from blasts and earthquake aftershocks will be processed and extrapolated to develop appropriate Australian ground motion spectra.

ii. The small data base of recorded ground motions for larger intra plate events (Mag>5) in Australia and overseas will be compared with similar sized interplate earthquake ground motions that have been recorded in the near field.

iii. The development of synthetic ground motions using programs such as SIMQKE (Ref. 6) and other methods which use the actual fourier phase components of recorded ground motions combined with specified fourier amplitude components of ground spectra (Ref. 7).

b. Soil effects

Another aspect of the research will focus on the effects different soil profiles have on filtering earthquake ground motions. In general soft soils tend to amplify low frequency components and attenuate high frequency components. Analytical studies will be undertaken considering various soil profiles using typical Australian bedrock earthquake ground motions to develop suitable response spectra for different soil profiles for Australian conditions. Specialist software packages such as 'SHAKE' (ref. 8) will be used in the analytical study.

Inelastic Response

The 'structural response factor' or 'R' factor is used to modify results obtained from a linear elastic analysis to approximately account for both structural overstrength and the energy absorption capacity of the structural system (commonly measured using the ductility factor). The 'R' factor is independent of structural period and is based on the 'equal displacement' observation whereby the maximum displacement of a single degree of freedom (SDOF) system responding in the inelastic range is assumed equal to a similar system responding purely elastically (Figure 2).

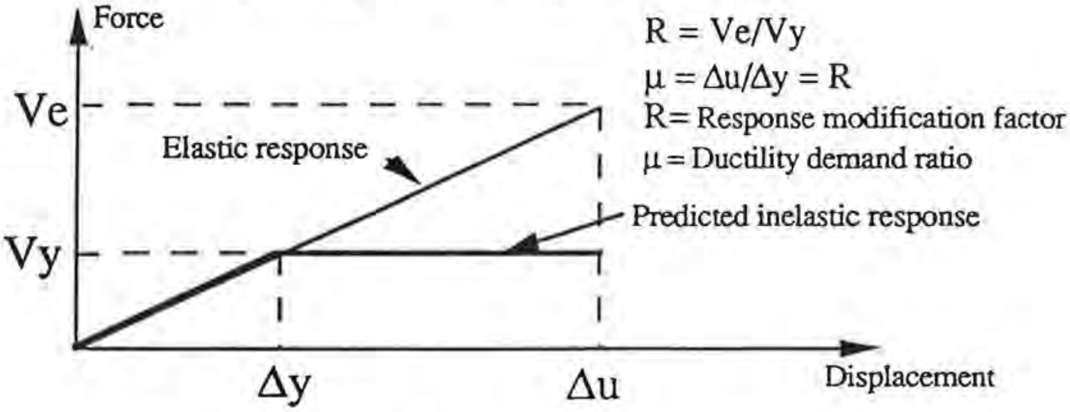

Figure 2 Equal Displacement Response

Miranda (Ref. 9) carried out some 31,000 inelastic analyses using 124 interplate ground motions and concluded that the 'equal displacement' method was reasonable for structures with periods greater than about 0.7 seconds.

Preliminary studies carried out using 19 intraplate earthquakes with an 'R' factor of 4 suggested the 'equal displacement' method was reasonable for structural periods greater than about 0.3 seconds although the results showed large scatter (Figure 3). Of particular interest is the exceptionally high ductility demand associated with the short duration M_L 4.9 aftershock recorded at Tennant Creek (Ref. 11). The high ductility demand was attributed to the sequence of the pulse arrivals.

It should be noted that the aftershock at Tennant Creek was not strong enough to yield buildings above 6 storeys in view of the low elastic response spectral accelerations over that range. (Figure 4). However, this high ductility demand could be of practical significance if a larger earthquake event had a similar but amplified waveform.

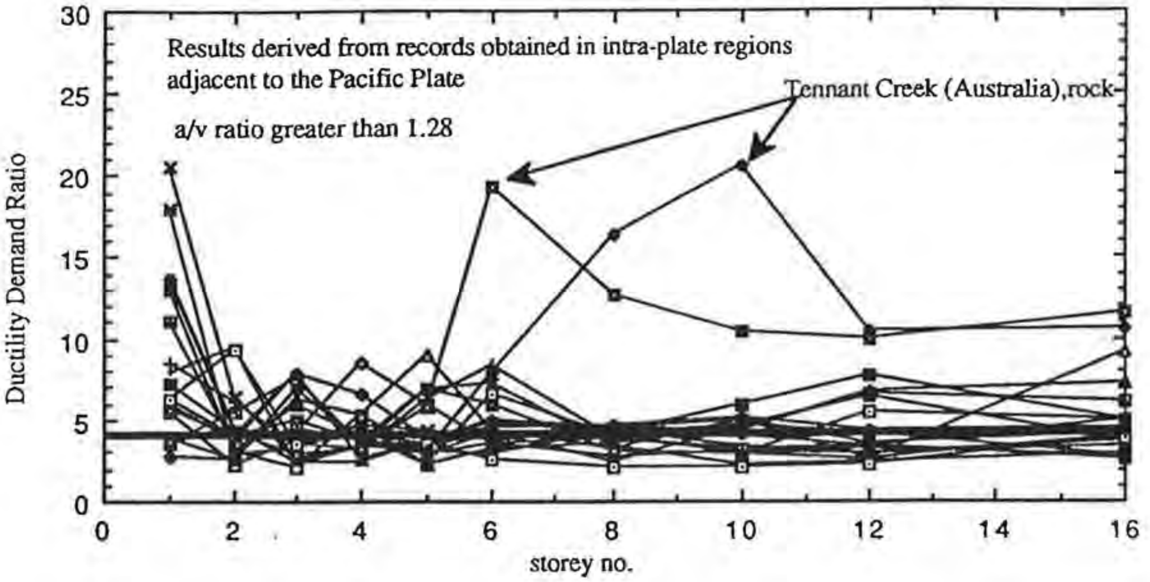

Figure 3 Displacement Ductility Demand (After Ref. 10)

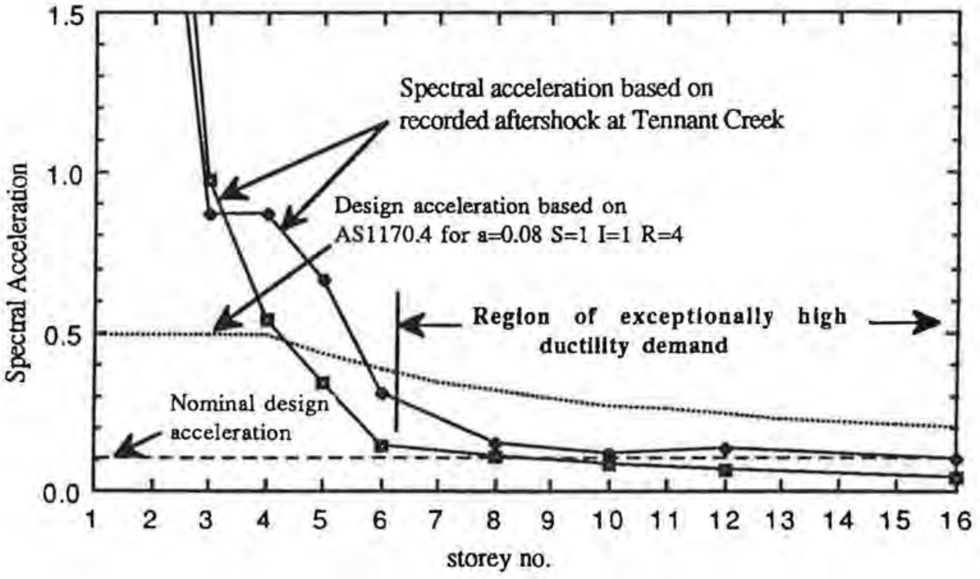

Figure 4 Tennant Creek and Design Response Spectrum

The investigation into the response of SDOF to both intraplate and interplate earthquakes is continuing and will be extended to include:

i. multidegree of freedom systems

ii. overstrength factors associated with typical framing systems.

iii. appropriate detailing to reduce earthquake vulnerability

Conclusions

This paper has described an ARC funded research project between seismologists and engineers which aims to provide appropriate earthquake loading and detailing provisions for Australian conditions.

In particular, the research has two primary objectives:

i. Develop appropriate earthquake ground motions and response spectra for Australian conditions for both rock and a range of soil sites.

ii. Investigate the overstrengths and energy absorption capabilities of commonly used Australian framing systems when subject to typical Australian earthquakes.

In addition, the research project will examine appropriate detailing measures to improve the earthquake resistance of structures in a cost effective manner.

Acknowledgements

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Pipeline Earthquake Survival
Tennant Creek Australia 1988

S A M Dykes and J K McDonald

AGL Pipelines Limited, GPO Box 2179, Canberra ACT 2601

Abstract N. T. Gas Pty Limited, a subsidiary of AGL Pipelines operates the Amadeus basin to Darwin Natural Gas Pipeline. Over 1600 kms in total length, the pipeline was considered to traverse a seismically stable region. This belief was shared by the Australian Geological Survey Organisation who operate a substantial seismic recording array approximately 50 kms from the site of the earthquake.

Three intraplate earthquakes escalating to 6.7 on the Richter scale occurred near Tennant Creek on Friday 22 January 1988.

The discovery of a reverse slip fault which transgressed the Amadeus to Darwin pipeline at right angles led to concern over the integrity of the pipe. Subsequent investigations revealed concertina type failure of the pipe without cracking or rupture.

Although historical records show little activity before 1986, two small earthquakes in that year were followed by a series of over 150 events to January 1987. The largest four of these occurred in January 1987 and were recorded at magnitudes in the range between 5 and 5.5. Seismic activity continued throughout 1987 with no further single events of significance.

The paper will address:

(1) N.T. Gas Pty Limited, the location details of the Pipeline and its major functions.

(2) A description of the January 1988 earthquakes and their regional and local effects.

(3) A description of and explanations for the pipe performance during and subsequent to the earthquakes.

(4) The magnitude of seismicity in the Northern Territory and its threat to pipeline integrity in the future.

(5) Suitable actions to reduce the risks of pipeline failure due to seismic activity.

Brief History of N.T. Gas Pty Limited

Early in 1981 the Northern Territory Electricity Commission saw a need to replace the ageing Stokes Hill power station in Darwin. The question of continuing with the oil fired option using oil imported from Singapore was considered prohibitive by world oil pricing forecasts at the time. Several fuel alternatives were looked at, and from an economic point of view the coal fired option was most favoured. This would allow satellite power stations to continue to run on diesel until a grid system could be established.

The natural gas option using Amadeus basin gas discovered in the 1960s was discounted due to an apparent lack of reserves.

The gas proposal required more definition and, whilst planning for the coal fired option continued through 1983, a consortium of Australian companies forming N.T. Gas Pty Limited, progressed a feasibility study into the gas option. The result, submitted to the Northern Territory government in April 1984, showed that gas piped from the Amadeus basin did in fact provide a more economical power generating basis and had the gas reserves to sustain it. Furthermore, by utilising indigenous resources with a pipeline extending the length of the Territory, the scope for industrial development would be increased substantially.

The coal project was abandoned and negotiations continued resulting in a committal to gas turbine generating facilities in December 1984. Construction began in July 1985 and the pipeline was commissioned in November 1986. Gas for power generation flowed into the Channel Island turbines in December 1986 successfully completing one of the most time constrained projects in the history of the Australian hydrocarbon industry.

The Pipeline System

Gas is drawn from two producing fields; Palm Valley 140 km west of Alice Springs and Mereenie 100 km further west. Pipelines from the two gas fields meet at Tylers Pass 40 km north west of Palm Valley. In addition to supplying gas to the Power and Water Authority in Darwin through the main trunk line, the system supplies gas to power stations in Tennant Creek, Elliott, Katherine, Pine Creek and Cosmo Howley through lateral pipelines. Another 100 km pipeline supplies gas to Power and Water Authority Alice Springs powerhouse and a 280 km pipeline delivers crude oil to Alice Springs from Mereenie.

N.T Gas as operator of the pipeline is responsible for over 1600 km of pipe ranging in diameter from 3 inches to 14 inches. The trunk line is grade 5LX60 with 3 different wall thicknesses appropriate to class location and code requirements. The pipeline operates at a maximum allowable pressure of 9650 kPa for the Mereenie to Tylers Pass Section.

The entire pipeline is monitored from Palmerston Control Centre utilising the supervisory control data acquisition (Scada) system. Remote access terminals allow 24 hour surveillance of pipeline operating parameters.

The Tennant Creek Earthquake

On Friday 22 January 1988, a series of strong earthquakes occurred about 36 km south west of Tennant Creek. Three mainshocks of surface wave magnitudes 6.3, 6.4 and 6.7 were recorded at 1006, 1327 and 2135 hrs local time respectively, and were followed by an aftershock of magnitude 5.3 at 0624 hrs on Saturday morning.

Although historical records show little activity before 1986, two small earthquakes in that year were followed by a series of over 150 events to January 1987. The largest four of these occurred in January 1987 and were recorded at magnitudes in the range between 5 and 5.5. Seismic activity continued throughout 1987 with no further single events of significance.

The epicentres of the January 1987 events, located by a three station AGSO portable network and the Australian National University's Warramunga Seismic Array near Tennant Creek, were in the same area as the 1988 events.

Earthquakes greater than 5.9 Richter in Australia

Although there has been substantial reduction in the daily rate of earthquakes, Tennant Creek residents continue to experience tremors. These earthquakes make up the strongest and most prolonged earthquake sequence seen in Australia this century rivalling the 1941 Meeberrie earthquake east of Carnarvon in W.A. for intensity. It was almost as large as the 1968 Meckering W.A. earthquake which levelled the small wheat town.

Damage to the Tennant Creek township was relatively minor with no reports of severe structural damage. Local goldmines at Warrego and nearby were virtually unaffected.

The earthquakes produced a number of complex surface faults which totalled 30 kilometres in length. The two major faults trended east-south west with the southern block thrust over the North. A smaller fault trending east-northwest moved the Northern block over the south. The reverse slip faulting was produced by north-northeast to south-southwest compression. Vertical displacements of 1m along the fault line were common.

Pipeline Damage

Vertical cracks running parallel to the pipeline on both sides indicated upward movement of the pipe to the south of the fault line intersection. The uplift occurred about 30-40 metres to the south of the fault indicating very closely the natural curvature of a 14" diameter pipeline under compressive forces.

The fault scarp had a vertical displacement directly over the pipe of about 600mm. Horizontal movement could not be measured and therefore any calculation of residual compressive stress was impossible. However, it was obvious that some residual stress was present and with this in mind, excavation commenced to relieve this. A backhoe exposed each side of the pipe alternatively, moving south towards the fault from a point 50m to the north. At this time the pipeline was still holding 8,000 kPa pressure and reducing slowly with demand. Movement of the pipe in the trench indicated severe residual stress and at that point the entire 75 kilometre section was isolated and blown down.

Excavation continued toward the scarp allowing continued movement of the pipe in the trench. Tolerable bending stresses were exceeded, since the trench walls resisted free movement of the pipe, and finally the failed section was discovered directly beneath the fault intersection. A total of 300m of pipe was exposed with evidence of movement along the pipe bedding indicating that the original premise of pipe uplift to the south of the fault was correct.

A total of 93m of thin wall pipe was removed and replaced with heavy wall. The new section was 970 mm shorter than the original.

In addition to replacing the section of pipe four adjacent field wells were inspected with gamma ray and showed no sign of stress cracking. Two additional sites to the south were excavated and two wells at each site inspected. The coating showed signs of horizontal movement but the welds were intact. These sites were backfilled.

The major excavation was left exposed, the new section wrapped with tape and pointed to reduce ultra violet degradation of the coating. The pipeline resumed normal operations at midnight on Saturday 30 January 1988.

Pipeline Performance

Trench Geometry and Soil Conditions The failed section was found at the exact point where the fault crossed the pipeline. The failure occurred next to a field weld, with the steel flowing plastically to accommodate some of the forces caused by the fault. The rest of the force was absorbed through displacement of the pipe.

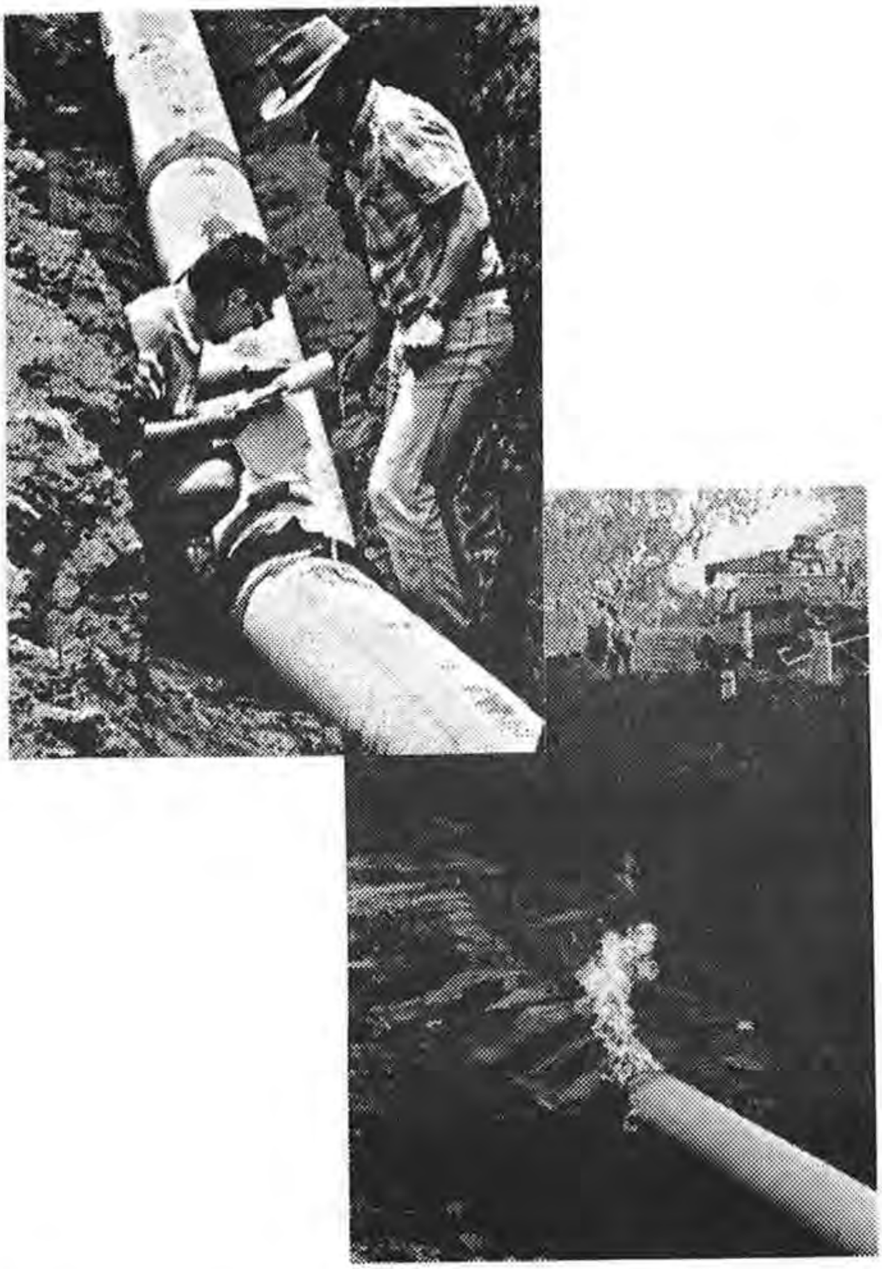
The process by which the pipe failed was not by bucking. For this to have occurred, unrestricted lateral movement of the pipe would have to have been possible. The process was more a telescoping effect whereby the pipe flowed plastically in a concertina manner.

The pre-requisites for this mode of failure are:

a) An internal hydrostatic pressure, the resultant radial component of which acts to increase the axial rigidity and stiffness.

b) External pressure provided by the trench geometry and backfill soil conditions, which acts to prevent lateral and vertical displacement.

c) An external force acting such that the resultant axial stress on the pipeline exceeds the yield strength of the material. Rupture will occur locally at a point where the stress in the yielding portion of the pipe exceeds the ultimate tensile strength.



In a paper given in 1985 entitled "A Refined Seismic Analysis and Design of Buried Pipeline for Fault Movement" Leon Ru Liang Wang demonstrated that there are critical parameters for the design of pipelines crossing known fault zones. Dealing with a compressive regime, he was able to show that for each diameter pipe:

(i) There is a critical fault displacement beyond which rupture will occur.

(ii) There is a critical crossing angle at which axial pipe stress will exceed design parameters and the larger the crossing angle the less the chances of rupture.

(iii) There is a critical pipe/soil frictional angle beyond which axial pipe stress increases rapidly given the critical crossing angle and fault displacement.

(iv) There is a critical burial depth at which displacement can be accommodated but when exceeded, the weight of soil is greater than the inherent strength of the pipe and failure, followed by rupture may occur.

N.T. Gas was fortunate that the pipe did not rupture for a number of reasons.

(a) The fault displacement was less than critical and the axial stress caused in the pipe, although greater than the yield strength, was not greater than the ultimate tensile strength of the pipe.

(b) The crossing angle was reasonably high at about 40^0 which resulted in a reduced axial stress component than had the angle been more acute.

(c) The pipeline was operating very near to its maximum allowable operating pressure. The radial component of the hoop stress was at its maximum and acting to keep the pipeline straight.

(d) The backfill was loose, uncompacted desert sand with a low frictional angle allowing vertical displacement within the trench confines to occur, relieving some of the axial stress.

(e) The burial depth, a nominal 900 mm was sufficient to prevent the pipe from springing out of the ground and failing by buckling.

Steel Metallurgy Consideration Measurements taken of radial expansion indicate an approximate strain in the failed section of 20%. This is further supported by a series of hardness tests of the steel, utilising the Vickers method, on the same shown.

The Vickers hardness tests also confirmed that the heat affected zone (H.A.Z) extended 10 mm from the weld and did not contribute to the adjacent failure.

The graph shows an actual stress strain curve completed from tensile tests on an unaffected portion of the pipe taken some 5 metres away from the failed section. Through extrapolation the stress required to cause a 20% strain is approximately 500 mPa. This is equivalent to an instantaneous force of some 22,000 tons. Since the pipe did not arrest the earthquake and some of its force was absorbed through displacement of the pipe, this would be the minimum instantaneous force caused by the earthquake at the failure site.

A comparison of the chemical composition between a sample taken across the failure and a sample taken at an adjacent weld showed little difference, and was within the manufacturer's published tolerances.

In an attempt to find other pipelines which had suffered similar compression failure from earthquake, contact with the Southern California Gas Company revealed some startling facts.

A similar 16" line subjected to compressive forces in the 6.4 magnitude San Fernando earthquake in 1971 failed through a concertina type compression. Rupture of the pipeline occurred through cracking of the steel. Strain measurements were of the order of 15%.

Displacement of the pipe in the trench also allowed absorption of some of the force. The Tennant Creek earthquake was a magnitude 6.8 and although there is no linear relationship between magnitude and displacement, the amount of movement along a fault does increase with earthquake intensity.

Further reason that the N.T. Gas pipeline did not similarly rupture may be explained through a consideration of steel quality. Modern Australian manufactured linepipe has high inner cleanliness. The presence of sulphide, silicate and aluminate inclusions interferes with the stress carrying capability of a steel. Processes such as vacuum degassing and use of argon shrouds in casting operations has had a marked effect on increasing the inner cleanliness.

The steels are also of low carbon equivalents. Fine grain size is the main contributor to high yield strength steels but carbon content is the main contributor to tensile strength. It is the high yield strength of the 5LX 60 linepipe used in the Amadeus basin pipeline that allowed for 20% strain without fracture. High tensile strength steels produced with increased Carbon and Manganese content have low fracture toughness and lower yield strengths.

The ability of steel to survive such forces is in its capacity to yield without reaching the ultimate tensile strength. It is a common misconception that high tensile strength will result in good yielding properties. The two requirements have very different metallurgical needs.

Seismicity in the Northern Territory

As can be seen from the histogram in an earlier slide, the seismicity in the Northern Territory prior to 1986 was of little consequence. Most events recorded were of minor significance i.e. of surface wave magnitudes less than 4 to 4.5.

The increase in seismicity post 1986 in the Tennant Creek area culminated in four significant events in January 1987 and these occurred in the same region as the major events in January 1988. In a report tabled by Gary Gibson of the Phillip Institute of Technology Seismology Research Centre and Roger Bowman of the Australian National University, aftershock activity is expected to continue for a long time. Although the level of activity will diminish, small events will occur at a rate above average for many years. The chances of another major earthquake occurring at the same place will diminish with time. However, major earthquakes might occur at either end of the existing fault lines, and if large enough could cause further movement along the rupture.

This in fact did take place with an earthquake recorded on the 18 March 1988 registering magnitude 4.6. This event was further to the south east of the January earthquakes indicating continued activity to the eastern end of the existing fault line. This event caused a further 52 mm compression along the pipeline route and was absorbed by the pipeline in lateral displacement. The decision to leave the pipeline exposed proved to be a crucial one.

Although the Tennant Creek area for a long time has been considered seismically stable, the events of 1988 have left us with the prospect of future movement across this fault line. As the location of the fault is known, measures have been taken to assure pipeline integrity at this particular intersection.

How can we be certain then that the rest of the pipeline is safe from seismicity in the future? Basically we cannot. Unlike other difficulties that face the pipeline industry such as stress corrosion cracking where the necessary conditions for its onset are defined and can be precluded from the design, seismic phenomena cannot. The conditions for the occurrence of seismic events have not been defined beyond a recognition that an increase in activity may be the precursor of catastrophic failure.

Most engineering structures are only at risk when their dynamic response to ground vibrations caused by an earthquake is not favourable. Buried pipelines are most in danger where significant and localised surface displacement occurs.

Since a pipeline generally traverses long distances over varying and unique geological formations, the task of fault definition is an arduous and costly exercise. Even if it is completed, how do we as engineers design an earthquake proof pipeline. From seismic records taken in an area seismologists can statistically generate synthetic earthquakes of maximum magnitude that can be expected during the design life of a pipeline. This data can be used to set the general stress tolerance parameters.

Seismic risk analysis is cheap insurance if applied to buildings extending over small areas but with the significant distances covered by pipelines the cost is prohibitive. The decision to incorporate risk analysis as part of the design phase is generally only made from an assessment of recent seismic activity along its route.

This in itself is not an adequate rationale behind whether seismic risk analysis is necessary or not. Since pipelines are prone to possible failure by surface disturbance the delineation of localised faults is paramount to the pipeline having effective resistance to earthquake activity. This is supported by the fact that the fault where rupture took place in the January 1988 events pre-existed and is clearly visible on magnetic maps available from the Bureau of Mineral Resources.

For N.T. Gas it is likely that the big event has occurred along the Tennant Creek fault. Statistically it is more probable that future activity will occur along other faults crossing the line. For the moment the location of these faults remains unknown, and seismological information is scare.

In the light of our experience it may be prudent to pay more detailed attention to the delineation of local faults along a pipeline route in the design phase, and consider some of the techniques applicable to minimising the danger to the pipeline should movement occur along them.

Solutions to Traversing Active Fault Zones

Once a fault line has been located along a proposed pipeline route, avoid it if possible. If you can avoid it, then be sure that it is not likely to extend beyond its present length only to affect the re-routed pipeline.

If you can't avoid it, then the following considerations must be taken:

1. A geological analysis of the faulting mechanism is crucial to effective earthquake design. Complex mechanisms require more elaborate crossing techniques than simple ones.

2. A reasonable assumption of possible displacement must be made. These can normally be calculated from physical observations along the fault scarp itself.

3. The crossing design can be such as to allow displacement along the fault to be absorbed by increased axial stress or torsion in the pipe or by allowing strain to occur. This can be determined by the choice of steel and the crossing method used. High yield strength steel has more ductility and will absorb significant displacement by strain before rupturing. Torsion is more easily accommodated by a pipeline than axial stress, and will occur if the pipeline is zig zagged across a complex fault.

   Increasing the strength of the pipeline crossing by either using thicker wall pipe or by splitting the pipeline into two or three Mr smaller diameter lines for the same volume of gas is not recommended. Increased strength steels are more brittle, and have the least fracture toughness.

4. For simple fault lines the crossing should be made as close to right angles as possible. Failure by buckling, or by yield phenomena such as concertina, is more likely if the plane of movement of the fault increases axial, rather than shear, stress. Pipelines are inherently stronger in shear and should be designed to uplift or cut through backfill in the event of displacement.

5. Preferably leave the pipeline above ground but if you do bury it, use loose, friable and sandy backfill with low friction angles, and bury it with minimum cover.

   A compromise should be achieved between allowing displacement to occur to relieve axial stress while preventing extensive movement to the point of buckling.

6. Vertical trench walls restrict displacement of the pipe to the vertical plane only. Grade of 1 in 3 to 1 in 5 should be applied, to allow stress relief through some displacement.

7. If the pipe is designed to cross a fault above ground, the question of vertical acceleration must be addressed. Displacement occurs at a speed of 3 kilometres per second. In the event of movement along a fault in a reverse slip direction, the pipe will accelerate vertically, come to rest at a certain height above the ground and then accelerate back again. It is important that the impact on contact with the ground is not concentrated at a single point. Crossing mechanisms designed to allow movement in the vertical direction require that the impact be spread as evenly as possible over the pipe. Alternatively impact absorbing pipe coatings such as rock shield should be considered.

Pipeline or lifeline earthquake engineering is a rapidly developing science. As the pipeline grid across continents becomes more dense, the frequency of pipelines crossing active fault zones will undoubtedly increase. The application of simple techniques will serve to give some security however, we have no control over intensity and timing of earthquake phenomena. Ultimately our best endeavours in safeguarding against disaster may be fruitless.

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Emergency Management in the ACT

Greg R James

Director ACT Emergency Service
Executive Officer ACT Emergency Management Committee

The Australian Capital Territory (ACT) has had a Disaster Plan in place since 1984. That Plan provided for the co-ordination of all the necessary resources within the ACT to respond to the perceived hazard impacts of that time. The Plan was based upon the Chief Police Officer of the ACT acting as the Emergency Operations Controller supported by a small executive that provided specialist advice and links to Government. The Plan had been prepared by a Committee that was appropriate for the times. That Committee lay dormant for some years after the production of the Plan.

With the advent of self Government, many of the provisions of the Plan were inappropriate as they related to Commonwealth Government resources and facilities. It was, therefore, necessary and appropriate for the ACT Government to recreate a Disaster Planning Committee to prepare a new Emergency Management Plan for the ACT.

The ACT represents an interesting situation when compared to other States in that when self Government was granted, not all land and buildings within the ACT were handed over to the ACT. They, in fact, remained Commonwealth Government property and were excluded from the ACT. This has produced some very interesting challenges in disaster planning and has been the subject of a recent workshop in an effort to rationalise the relationship and determine the inclusion and exclusion of these areas and resources from emergency management planning in the ACT. The ACT is also different to other States and Territories in that there is only one level of Government, with the ACT Government performing all the services and functions that are normally performed elsewhere by Local Government.

The new Emergency Management Committee is chaired by the General Manager of the ACT Emergency Management Group, which is a newly created amalgam of the ACT Fire Brigade, ACT Emergency Service and the ACT Rural Fire Service. The Chief Police Officer of the ACT retains the function of Emergency Operations Controller and holds a position on the Committee. The Director of the ACT Emergency Service holds the position of Executive Officer to the Emergency Management Committee. These three people also form the Emergency Management Executive. All other emergency services within the ACT are represented on this committee together with the prime Government organisations and departments that would be involved in emergency management. These include the ACT Health Department, City Services Branch of the Department of Urban Services, ACT Electricity & Water, ACT Community Services Bureau, Department of Environment, Land & Planning together with the ACT Treasury.

It should be noted that the ACT Emergency Management Committee like all other State and Territory Emergency Management Committees is only responsible for planning for the co-ordination and optimisation of the resources that are actually owned by that State & Territory. Whilst there are many Commonwealth resources resident in the ACT, they are not involved nor included in the planning arrangements as the ACT has no direct control over those resources. There are, however, adequate Federal arrangements in place to co-ordinate and utilise Commonwealth resources in the event of the Territory resources being fully committed or incapable of performing a particular function. Because of the extensive Defence Department establishment within the ACT and to assist all planning for the families of serving Defence members, there is a Defence Department Observer accredited to the ACT Emergency Management Committee.

At this time there is no legislation that provides for Emergency Management as in other States and Territories. The Emergency Management Committee has been charged with the responsibility of preparing such legislation for consideration by Government.

To facilitate the working of the ACT Emergency Management Committee, a sub committee structure has been established. These committees are based upon functional requirements where services are provided by more than one particular Government Department or service. One particular Government Department is appointed as Chair and Co-ordinator of a committee with representatives of all Departments or community bodies that have a capacity in that particular functional area. The sub Committees include Medical & Health, Disaster Welfare & Recovery, Communications and media. There are also sub Committees looking at specialised areas that will provide the necessary advice on matters as part of the planning process including hazard analysis.

Emergency Management Planning in the ACT is different to that in many other areas by virtue of the topography and the community composition of the area. There are many factors, such as the highly mobile population and a population that predominantly has family ties in other states and territories, that all impact upon the planning process.

Natural hazards within the ACT include bush fires, which can develop in any of the surrounding forest areas and impact upon the community, storms, which regularly impact upon the developed residential area and, to a lesser extent, there is the possible hazard of earthquake. One of the more active earthquake areas in Australia lies directly to the north of Canberra and Canberra itself is criss-crossed by several fault lines.

Technological hazards in the ACT have been greatly mitigated by virtue of the planning considerations that have been exercised upon the placement of industry relative to the residential population. There is an increase in volume of hazardous material loads traversing the ACT which could represent a hazard.

Of some concern in the Planning process is the necessary consideration for the maintenance of the lifelines for the community. All of the ACT's power supply enters the Territory through one set of lines, gas likewise enters the ACT through a single piped point and whilst water supply can be drawn from several sources, its networking is limited and centralised through a single point.

One hazard that must be considered within the planning process is that which would result from terrorism. The ACT as the seat of Federal Government, together with the numerous diplomatic premises and Federal Government office buildings in the area all represent possible targets that could have an impact upon the surrounding community.

The topography of Canberra requires special consideration in planning in that the city is basically bisected by Lake Burleigh Griffin and there are only four means of crossing that waterway and moving from north to south, all of which are also used to carry water, gas, electricity and telephone lifelines. The loss of any one of these access ways would cause great problems that need to be addressed as part of the planning process.

The Emergency Management arrangements that are in place in the ACT are similar to those that exist in most States and Territories and follow nationally practices and principles.