Chapter Nine:

Earthquake

Damage sustained by the Workers Club following an earthquake in Newcastle, New South Wales, December 1989
Photo courtesy: Emergency Management Australia.

Earthquake

Earthquakes pose a risk that is fundamentally different to those of more frequently occurring natural hazards such as tropical cyclones and floods. Australia is a tectonically stable region and has few earthquakes of any consequence in any given year. The relative rarity of large earthquakes ensures that earthquakes are not prominent in the public consciousness. However, the earthquakes in Newcastle, New South Wales, in 1989, in Meckering, Western Australia, in 1968, and in Adelaide in 1954 clearly demonstrated that moderate-sized earthquakes have the potential to tragically affect Australian communities.

Damage to a building from an earthquake in Meckering, Western Australia, October 1968
Photo courtesy: Emergency Management Australia.

A fault scarp caused by a prehistoric earthquake at Lake Edgar, Tasmania, circa 15,000 BC
Photo courtesy: Geoscience Australia.

A car damaged by falling rubble from an earthquake in Newcastle, New South Wales, December 1989
Photo courtesy: Emergency Management Australia.

A warped pipeline from an earthquake near Tennant Creek, Northern Territory, January 1988
Photo courtesy: Emergency Management Australia.

While the severity of earthquakes in Australia is not as great as at tectonic plate boundaries, the typically higher vulnerability of infrastructure can lead to severe consequences. The Newcastle experience showed how vulnerable Australian cities are to earthquakes, resulting in death, injury and substantial economic loss. The average annual cost of earthquakes in Australia is $144.5 million taken over the period from 1967 to 1999 (BTE 2001); most of this can be attributed to one key event, the Newcastle earthquake which resulted in 13 fatalities. The historical records of earthquakes demonstrate that large earthquakes do occur in Australia and there is no doubt that a large earthquake has the potential to cause massive destruction and loss of life in Australian communities.

There are still significant gaps in the understanding of earthquakes in Australia. Both government and non-government agencies have a role to play in filling these gaps, through the acquisition of fundamental data and through research into hazard and risk. Improving our understanding of earthquake hazard and the risk posed to communities and infrastructure will lead to better strategies for mitigation and emergency response. This chapter describes the process of earthquake risk analysis, and points to some of the issues that still need to be addressed.

Hazard Identification

The earth's outer shell is about 100–200 kilometres thick and is broken into nine major and several smaller plates. These plates are constantly moving away from, towards or past each other; because the continents are part of these plates, they also move. Earthquakes occur when the stresses caused by the plate movements result in the rocks fracturing along fault planes. The energy released when the rocks fracture generates seismic waves, and these cause ground shaking when they reach the surface of the earth.

Most earthquakes occur along plate edges (i.e. 'inter-plate'), where the plates meet and are forced against each other. Some 95% of earthquakes are inter-plate, with 80% of all recorded earthquakes occurring around the edge of the Pacific plate, which includes Canada, Japan, New Zealand, Papua New Guinea, South America and the United States.

Australia is situated within the Indian-Australian plate and is not on the edge of a plate, so its earthquakes are 'intra-plate' and are fundamentally different to the more common inter-plate earthquakes. The Indian-Australian plate is being pushed north and squeezed between the Antarctic, Eurasian, Philippine and Pacific plates. The stress from this squeezing builds up as compression within the Australian continent and is released during an earthquake.

Earthquake sizes are often compared using the Richter magnitude scale. This scale is based on the maximum amplitudes of the seismic waves generated by the earthquake. The magnitude of an earthquake is an estimate of the energy released by it. For every unit increase in magnitude on the Richter scale, there is roughly a thirty-fold increase in the energy released by an earthquake. For instance, a magnitude 2 earthquake releases 30 times more energy than a magnitude 1 earthquake. The difference in the energy released between earthquakes of magnitudes 3 and 1 is 900 times (30 x 30).

In populated areas, the effects seen during an earthquake depend on many factors, such as the distance of the observer from the epicentre. Even small earthquakes will be felt if very close, but generally the effects will be as shown in Table 9.1.

In Australia the principal hazard component of earthquakes is the associated ground shaking. This shaking can damage or destroy structures, which in turn can cause injuries or deaths. However, there are numerous other hazards associated with earthquakes, such as liquefaction and fault ruptures. Liquefaction occurs when shaking causes water to be expelled from the subsurface sediments and soil, leading to ground failure and loss or weakening of building foundations. Fault ruptures occur when the earthquake is shallow and the fault reaches the surface and displaces it horizontally and vertically.

Although earthquakes are nowhere near as common in Australia as on plate boundaries, Australia has a long history of earthquakes. The first recorded event occurred near Sydney Cove on 22 June 1788, just five months after European settlement began. Many of the first settlers mentioned the event in their diaries. Their descriptions help us understand the source and magnitude of the earthquake.

One diarist, Blackburn, wrote (Cobley 1987, p. 167):

> ***'The shock did not last more than two seconds. It came from the (southwest) like the wave of the sea, accompanied by a noise like a distant cannon. The trees shook their tops as if a gale of wind was blowing.'***

Another noted that (Bradley 1802, p. 115):

> ***'This shock was distinctly felt on board the ships in the cove and by several people on shore, who supposed it to be the shock of an earthquake.'***

Adelaide has the highest earthquake hazard of any Australian capital city (AS 1170.4-1993), having had more medium-sized earthquakes in the past 50 years than any other. South Australia is slowly being compressed at an estimated rate of 0.1 millimetres each year (Leonard in review); the stress builds up in the rocks over many years, until they break and cause an earthquake. Earthquakes cannot be predicted, but measuring these changes, in the context of Adelaide's earthquake history, helps researchers to estimate the likelihood of earthquakes in the region around Adelaide.

MAGNITUDE	EFFECTS
< 3.4	Recorded only by seismographs
3.5–4.2	Felt by some people who are indoors
4.3–4.8	Felt by many people, windows rattle
4.9–5.4	Felt by everyone, dishes break and doors swing
5.5–6.1	Causes slight building damage, plaster cracks and bricks fall
6.2–6.9	Causes much building damage, houses move on their foundations
7.0–7.3	Causes serious damage, bridges twist, walls fracture and many masonry buildings collapse
7.4–7.9	Causes great damage, most buildings collapse
> 8.0	Causes total damage, waves are seen on the ground surface and objects are thrown in the air

Table 9.1: Earthquake magnitudes and typical associated effects
Note: Events between magnitudes of roughly 2.0 and 3.4 may be felt within a few kilometres of the epicentre.

Australia's largest recorded earthquake occurred in 1941 at Meeberrie, Western Australia. Its magnitude is estimated to be 7.2 but, fortunately, it occurred in a remote area. The magnitude 6.8 earthquake that occurred at Meckering in 1968 caused extensive damage to buildings and was felt over most of the southern part of the state. Earthquakes of magnitude 4 or more are fairly common in Western Australia, with one occurring approximately every five years in the Meckering region. For four years, Burakin, 150 kilometres east of Perth, has been Australia's most active earthquake region. A magnitude 5.0 earthquake in September 2001 was followed by 18,000 much smaller earthquakes over the next six months.

Cost of Earthquakes

Earthquakes pose a particularly challenging risk to Australian communities in that they are relatively rare events but have the potential to cause catastrophic losses. This can be seen from an analysis of historic earthquake losses in Australia (as shown in Figure 9.1). The average annual cost of earthquakes in Australia is $144.5 million (BTE 2001); over the period from 1967 to 1999, there is only one decade with losses due to earthquakes in excess of $250 million. However, the losses in the decade from 1980 to 1989 are almost entirely from a single, catastrophic event, the earthquake in Newcastle in 1989 which resulted in 13 deaths and injured 130, and had an overall cost of around $4.5 billion.

Risk Analysis

The general approach to estimating earthquake risk is to model numerous earthquakes and to estimate the consequences associated with each event as well as the probability of such an event occurring. This process requires five key models:

- an earthquake source model that describes the likelihood of an earthquake of a given magnitude occurring in a given location
- a ground motion model that defines the ground shaking experienced at a given distance from a simulated earthquake of a specific magnitude
- a site response model which estimates the level of local ground amplification
- an exposure model that describes the number of structures exposed to earthquake-induced ground shaking
- a vulnerability model that characterises the nature, magnitude and economic cost of the damage that structures will experience when exposed to ground shaking.

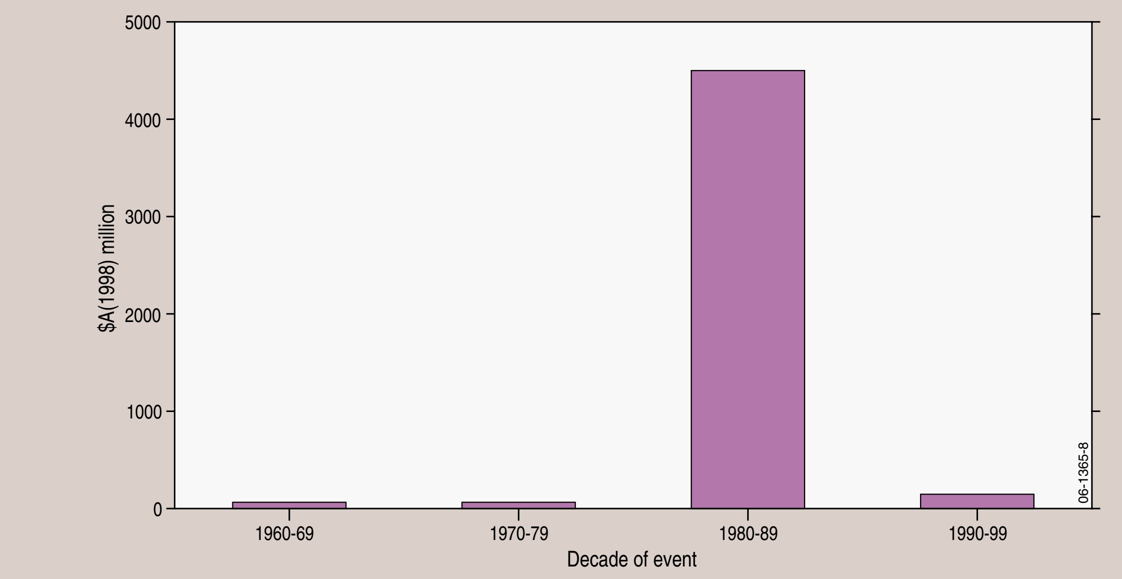

Figure 9.1: Total cost of earthquakes in Australia by decade, 1967 to 1999
Source: BTE (2001), Figure 3.24.

Police rescue squad looking in the rubble for survivors following an earthquake in Newcastle, New South Wales, December 1989
Photo courtesy: Emergency Management Australia.

Likelihood Analysis

A likelihood analysis for earthquakes is aimed at determining the chance of an earthquake occurring at a specific location. Because of the relative rarity of earthquakes in Australia, it is not yet possible to identify the specific faults on which earthquakes will occur in future. Therefore, an earthquake likelihood analysis is generally conducted through the use of source models which divide Australia into regions that are considered to have a consistent rate of earthquake occurrence. The aim is to identify broad regions that are more or less likely to have earthquakes. These regions are typically derived from an interpretation of the historical earthquake records within Australia, combined with an understanding of regional geology.

An earthquake likelihood analysis can be extended to produce an earthquake hazard map that can be used to underpin building codes. An earthquake hazard map for Australia is shown in Figure 9.2. The development of an earthquake hazard map requires not only an understanding of the occurrence of earthquakes, but also a ground motion model that describes how the intensity of ground shaking decays as distance from an earthquake increases. For example, in the regions of Australia which are geologically old such as Western Australia, the rocks are hard, so there is relatively little absorption of energy and earthquakes are felt over unusually long distances. These models are very region dependent, and to date very little is known about what the appropriate ground motion model for Australian conditions should be.

Local soils and shallow geological sediments (collectively known as 'regolith') affect the ground motion, and models must be modified to account for these effects. The shaking by a seismic wave that moves from hard rock into regolith is amplified because of several factors which significantly increase the risk of damage from an earthquake. These include the increased amplitude required to transmit a given amount of energy and the resonance effects within surface layers. It is possible to develop detailed models that account for the effect of regolith; however, this requires detailed geological and geotechnical data, such as shear-wave velocity and regolith thickness, which are generally available only for urban centres.

Data requirements

Determining the likelihood of earthquakes relies on the availability of a consistent, high-quality record of the magnitude and location of earthquakes in Australia. Until the late 1970s, Richter's formula was generally used to calculate the local magnitude at all Australian observatories. In the late 1980s and early 1990s most observatories developed their own local magnitude scales, with several observatories changing their approach more than once.

The use of different magnitude scales has resulted in magnitudes for same-sized earthquakes recorded prior to 1990 and since 1990 differing up to 0.5 magnitude units, though this is also partly the result of seismograph instrumentation changing from traditional pen recorders to digital recorders. This is equivalent to a factor of 10 in energy release. Producing a comprehensive earthquake catalogue with consistent magnitude, both between regions and in time, is a key requirement, and requires high-quality seismic data to develop regional earth models.

The development of ground motion models depends upon high-quality recordings of the ground shaking from earthquakes. Ideally, recordings from large earthquakes are used directly to produce models to predict the ground shaking from future earthquakes. However, due to the rarity of large earthquakes in Australia, there are virtually no high-quality recordings of ground motion for large earthquakes at distances closer than hundreds of kilometres. An alternate approach is to use the ground shaking recorded from small earthquakes to help predict the shaking that would be associated with large earthquakes, but this is complicated by differences in the vibration frequencies from small and large earthquakes.

The final dataset required to understand the hazard associated with earthquakes is detailed information on the regolith. In particular, it

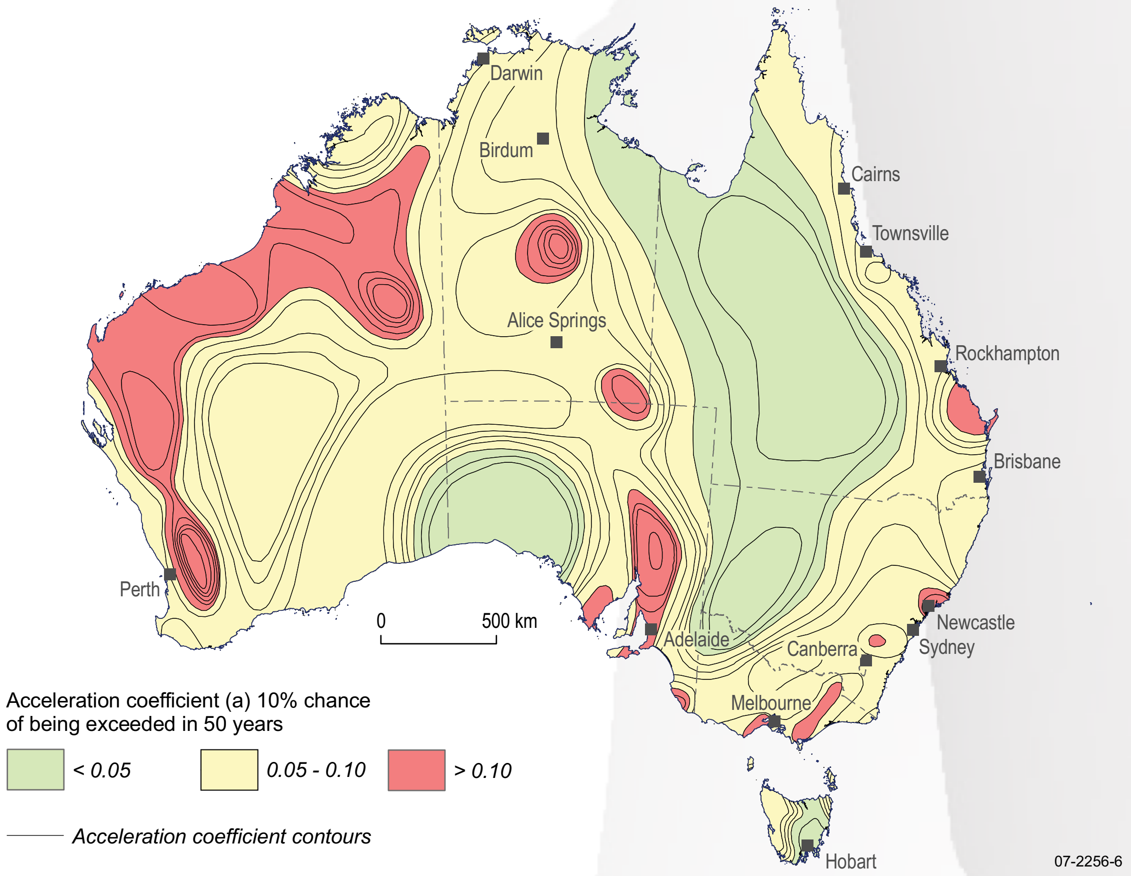

Figure 9.2: Earthquake hazard map of Australia
Source: Geoscience Australia.

is necessary to have data on the thickness and shear-wave velocity of the regolith in order to accurately understand its effect on earthquake hazard. These data can be collected by a variety of methods, ranging from geotechnical studies, including seismic cone penetrometer tests, through to passive monitoring techniques that use seismic noise (generated by cars, pedestrians, ocean waves etc.) to determine the regolith's properties. However, it is critical to recognise that regolith can be very spatially variable. Therefore, the required data need to be captured at a high spatial resolution in order to accurately model the hazard.

Consequence Analysis

Consequence analysis is focused on examining the elements that are subjected to a specific hazard, and their associated vulnerability.

It is important to recognise that it is inappropriate to determine the consequences of earthquakes, unlike hazards such as riverine flood, from a hazard map. The extent of a flood is largely constrained by the geometry of the river channel and floodplain being considered. Therefore, a flood hazard map is generally representative of a single flood event, and it is realistic to determine the consequences of such an event from a hazard map. In contrast, earthquakes can occur anywhere, meaning an earthquake hazard map is not representative of any single earthquake. An earthquake risk map is normally produced by modelling the damage caused by a large number (e.g. thousands) of synthetic earthquakes, and weighting them according to their magnitude and source zone.

Earthquakes are like many other hazards in that they have great potential to disrupt communities. Seismic events do this directly through damage to buildings and, less directly, through the damage they cause to the infrastructure that communities rely upon. Damage to building contents causes further impact on residents and a disruption to business activity, through the loss of stock and damage to the means of production. The direct damage to structures is typically estimated through the use of engineering models that relate the likely degree of structural damage to the severity of ground shaking (Robinson and others 2005).

For discrete residential buildings, these vulnerability models are typically associated with the wall and roof type. Residential house walls usually brace the building for lateral loads. Some wall types, such as unreinforced double brick, have been associated with greater losses from earthquake damage than other types, such as framed wall systems (Edwards and others 2004). Analysis of insurance claim data derived from the Newcastle earthquake in 1989 revealed that the repair costs for unreinforced masonry buildings were double those for timber-framed constructions exposed to the same intensity of ground shaking. Heavier, tiled roof construction also influences damage outcomes by accentuating inertia loads, while much lighter sheet metal–clad roofing reduces the demands on the bracing walls.

For commercial and industrial buildings the vulnerability model is generally related to the structural system and the nature of infill walls. Australian reinforced concrete frame systems, while massive, inherently possess a degree of ductility that has been shown to be generally adequate for the Australian seismic hazard. However, in some instances stiff infill walls have not been separated from the structural elements, leading to a compromised resistance.

Building vulnerability research is by no means mature in Australia, and an improved understanding of susceptibility of buildings to earthquake hazard is challenged by a lack of well-documented historical data. Consequently, damage model research is now more focused on developing an understanding of the engineering system than on using actual loss data to produce empirical models. Furthermore, engineering models validated against the available data can be used to identify mitigation options for more vulnerable structures, and to quantify their effectiveness.

One of the main indirect effects from earthquakes is their potential to disrupt essential utility services, such as electricity, water and gas supply, along with transportation systems. This has been illustrated in recent damaging Australian earthquakes. An earthquake in Tennant Creek, Northern Territory, in 1988 severely damaged the main gas pipeline from Tennant Creek to Darwin, although there was no disruption to supply in that case. The Newcastle earthquake caused significant damage to high-voltage circuit breakers at the Kilmore electrical substation, thereby disrupting supply. There are considerable lead times for the replacement of some vulnerable asset types, such as high-voltage transformers.

The widespread impact of damage to critical infrastructure assets has highlighted the need to better understand their vulnerability. The disruption of major highway corridors was the subject of work by Dale and others (2005) in which an approach from the HAZUS-MH tool (National Institute of Building Sciences 2003) was used to model the damage caused by representative earthquakes. Similar models that separately examine the individual components of more complex assets are under development and are aimed at predicting the damage to other critical infrastructure assets, such as large storage tanks, thermal power stations, electrical substations and telephone exchanges. This work will lead to a more complete picture of the vulnerability of Australian communities to earthquake hazard.

Data requirements

A consequence analysis has the same data requirements as the likelihood analysis described above. In particular, it is essential that realistic models of earthquake likelihood and associated ground shaking are used in order to accurately model the consequences of earthquakes. If a site-specific study is going to be conducted (e.g. for critical facilities or infrastructure), it is also important to have accurate, detailed geotechnical information at the site of interest.

In addition to the information on the earthquake hazard, current earthquake damage models for buildings typically require information such as each structure's construction type (i.e. wall and

A collapsed house following an earthquake in Meckering, Western Australia, October 1968
Photo courtesy: Emergency Management Australia.

Damage sustained to the Workers Club following an earthquake in Newcastle, New South Wales, December 1989
Photo courtesy: Emergency Management Australia.

roof material), number of storeys, floor area and replacement value. Structural information is also required for critical infrastructure in order to model the impact of earthquakes.

Information Gaps

A fundamental problem in Australia is the limited availability of the basic physics and engineering models that underpin any earthquake risk analysis. The development of these models has been particularly difficult in Australia because of the rarity of large earthquakes and the associated lack of data. The following section describes the gaps in earthquake source and ground motion models and vulnerability research, as well as the research required to address these gaps.

Earthquake Source Models

Earthquake source models are generally produced from an interpretation of the historical record of earthquakes in Australia. However, there is no clear consensus as to how the limited historical record should be interpreted. There are at least three published source models available (Leonard in review; Gaull and others 1990; Brown and Gibson 2004). The underlying assumption for most of these models is that the history of earthquakes in the past century is an accurate indicator of the likely occurrence of earthquakes in the future.

The zonation for the Brown and Gibson (2004) model is based on regional geology. Although geological deformation and faulting was considered in quantification of the zones, the activity estimates rely heavily on the short period of historical earthquake activity. However, this fundamental assumption has not been rigorously tested. Furthermore, there is some indication that seismicity in a given region, and on individual faults, is highly episodic (Crone and others 1997; Crone and others 2003; Leonard in review).

The rarity of earthquakes in Australia means it would take thousands of years to record enough events to confidently understand the distribution of future earthquakes. However, a careful study of the Australian landscape can provide evidence of prehistoric earthquakes that can be used to improve earthquake source models. This neotectonic evidence can be used to extend our understanding of the history of earthquakes in Australia back tens of thousands of years (Clark 2006).

In addition to identifying prehistoric earthquakes in the landscape, it is possible to use precise measurements of the deformation in the Australian crust, combined with numerical modelling, to try to identify regions that are more likely to experience earthquakes in the future. This work requires repeated observations of landmarks to detect sub-millimetre movements over the course of many years. Given time, this work will provide a more realistic understanding of the deformation of the Australian crust that can be used to improve our earthquake source models.

Ground Motion Models

The first ground motion model developed for Australia using only Australian data was the Gaull and others (1990) model. This model is based entirely on seismic intensity data, which are obtained from personal perceptions of shaking and damage. Because engineering damage models typically need more information than seismic intensity, earthquake hazard and risk assessments in Australia generally adopt ground motion models from other stable continental regions, such as eastern North America (e.g. Dhu and Jones 2002).

However, there has been very little analysis undertaken to show whether these models are applicable to Australian conditions. For example, an analysis of data recorded during the earthquake sequence at Burakin, Western Australia, in 2001 and 2002 (Allen and others 2006) suggests that, at small distances from the earthquake, higher ground motions are observed compared with eastern North America. This results in ground shaking in southwest Western Australia that decreases at a lower rate with distance compared to ground shaking in eastern North America for an earthquake of the same magnitude. However, this may also be due to the influence of surface waves from these shallow events.

As the quality of seismic data recorded in Australia continues to improve, there is a continuing need to use these data to develop Australia-specific ground motion models. The current lack of data will result in large uncertainties in these models; however, this will improve over time as modelling techniques are refined and the amount of data increases.

As mentioned previously, there is also a need to develop models that describe the effect of regolith on earthquake ground shaking. The development of these models is fundamentally limited by the availability of detailed geotechnical data. These data are particularly crucial in urban areas where consequence analyses are usually conducted. In many urban areas significant amounts of data are held by local councils, industry and the state government, but no urban area has a single comprehensive database of this information. Another potential source of such data is the datasets acquired for the development of infrastructure such as bridges and tunnels. These projects often require geotechnical studies as part of the construction process.

Vulnerability Research

Building vulnerability research in Australia is challenged by a lack of well-documented historical data. Sufficient structural damage and loss data do not exist to permit the development of empirical models. There are further difficulties in assessing the local hazard that caused damage, due to a lack of strong motion records. This is unlikely to change in the near future. Therefore, damage model research is now more focused on developing an understanding of the engineering system.

The use of engineering models can provide the opportunity to identify and assess the effectiveness of mitigation options where vulnerabilities exist. Additional research needs to be done to better predict physical damage and to include economic cost. Furthermore, the detailed analysis in some of this work needs to be generalised so that reliable assessments of damage and cost can be made for large populations of building structures.

The vulnerability of critical infrastructure to earthquake is less well understood than that of building structures. Critical infrastructure can comprise extremely complicated systems with many components that are all vital to successful operation (e.g. the complex systems comprising a coal-fired thermal power station). The components within a system each have their own seismic vulnerability, and knowing each of these is essential to an understanding of the overall vulnerability and prognosis for restoration of the asset.

Roles and Responsibilities

Management of earthquake risk cuts across all levels of government, non-government agencies and groups, and the general community. The analysis of earthquake hazard and risk requires collaboration between these sectors as each has their own responsibility and role.

Australian Government

The Australian Government's overarching goal in the management of earthquake risk is to ensure the sustainability and prosperity of Australia's communities. It provides financial assistance to help achieve this through its funding programmes aimed at reducing the risk of natural disasters. The Australian Government also operates a national seismograph network which monitors earthquakes in the region and maintains the Australian Earthquake Database. It also provides earthquake information and undertakes research into reducing risk through improved understanding of the earthquake hazard and risk in Australia. However, numerous other collaborators also have crucial roles in this process.

State and Territory Governments

State and territory governments play an important role in earthquake risk management in Australia. Historically, the state and territory governments have been involved in the preparation of emergency management plans for earthquakes, the mitigation of earthquake risk, and responses to earthquakes that have affected Australian communities. In addition to these roles, some of the fundamental data required for risk analysis can only be acquired in collaboration with state and territory agencies.

Local Government

Local government agencies are involved in planning and mitigation, as well as emergency response at the local level. An accurate understanding of earthquake risk requires some components that are very site specific, such as an understanding of the local regolith and a comprehensive building inventory.

Industry, Coordinating Groups, Professional Bodies and Research Institutions

A few professional bodies, coordinating groups and industry bodies have an advocacy and/or coordinating role in earthquake risk mitigation. For example, the Australian Earthquake Engineering Society, a technical society of Engineers Australia, promotes the practices of engineering seismology and earthquake engineering. Similarly, the Australian National Committee on Large Dams Incorporated has supported research into earthquake hazard and arranged for earthquake data collected by its members to be made available for research purposes.

The University of Queensland undertakes some research into earthquake hazard assessment as part of a wider programme of investigating the physics of earthquakes through the use of computer simulations. The Australian National University has a major seismic research programme in observational and theoretical seismology, with a focus on understanding the earth's structure and processes, but undertakes minimal research into earthquake hazard.

Several universities in Australia (University of Adelaide, Curtin University, University of Melbourne and University of Western Australia) undertake neotectonic geological investigations, and several universities in Australia (University of Adelaide, University of Melbourne, Monash University, University of Newcastle and Swinburne University of Technology) undertake research into the structural vulnerability of buildings to earthquakes. No university in Australia has a major programme of earthquake hazard research.

The Seismology Research Centre within Environmental Systems and Services, Melbourne, monitors seismic activity in eastern Australia with its own networks, and undertakes hazard studies both within Australia and overseas.

Conclusion

The earthquake hazard risk is low in Australia compared to more seismically active regions of the world, but there is potential for a disastrous and costly event. Historically the average annual economic loss caused by earthquakes has been low at $144.5 million per year or about 13% of the cost of natural disasters; however, events such as the Newcastle earthquake which resulted in 13 deaths and a total loss of about $4.5 billion, demonstrate the potential for very significant overall cost to the community.

An understanding of earthquake risk in Australia requires an understanding of the fundamental characteristics of earthquakes in Australia, how their associated ground shaking propagates, the effects of local site conditions, the vulnerability of buildings, and the exposure of buildings and people to the ground shaking.

To develop new and improved models in these areas requires high-quality earthquake and ground motion data, along with comprehensive building and infrastructure performance data and inventories. By combining these models it is possible to understand the risk, and to minimise the chance of catastrophic losses by improving the design of structures through appropriate building codes.

Gaps in the knowledge and information that is required to achieve these outcomes, particularly in the areas of earthquake source models, ground motion models and vulnerability research, need to be addressed, and the three levels of government, as well as industry and academia, all have important roles to play.

A fault scarp caused by an earthquake in Meckering, Western Australia, October 1968
Photo courtesy: Geoscience Australia.