Seismological contributions to earthquake risk mitigation

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Abstract

This paper examines the risk mitigation measures (hazard studies, warnings, alarms, predictions, forecasts and alerts) that can be applied to earthquakes, and the seismological contributions required for each.

The observational seismological data used are the records of ground motion as measured by sensitive and strong motion seismic recorders. The variation in the arrival times of seismic waves is used to determine the location of the earthquake. Variation in seismic amplitude with distance (due to geometric spreading, absorption of energy and scattering) is attenuation, and empirical attenuation functions are used to estimate earthquake magnitude (size) and earthquake hazard (effect). Variation of amplitude and direction of motion with both distance and azimuth is used to determine earthquake focal mechanisms. These results are gathered in an earthquake catalogue, which may be used to investigate sources and clustering of earthquakes.

The accuracy and precision that is currently achieved and potentially may be achieved considering both random and systematic uncertainties vary greatly with the seismograph network scale (global, regional, local, mining), especially on the network density. The distance from the earthquake to the nearest seismographs and the number of recording instruments control the accuracy of locations, and whether determination of local attenuation and focal mechanisms is possible. The current and practical limits on this accuracy and precision are discussed, together with their impact on the risk mitigation outcomes.

In Australia there have been some significant improvements in seismograph systems, analysis methods and coverage over the past decade, partially offset by the reduced number of seismologists performing routine analysis. The paper concludes with some suggestions towards developments over the next few years.

Introduction

There is no doubt that the dominant factor in earthquake risk mitigation is improved building standards, and the prevention of structural collapse. Seismology has several contributions to this and other aspects of earthquake risk mitigation.

Seismology tells us much about the earth and its geological structures and processes. Knowledge of earth structure and processes is necessary for earthquake risk mitigation (the basis for much of the funding), but as with any risk mitigation there are several practical things that can also be done.

Seismological contributions to earthquake risk management

Risk mitigation actions can be associated with past, present and future earthquakes.

Past earthquakes

Our knowledge of earthquakes comes from experiences of past events and their effects. This information resides in earthquake catalogues and in publications.

Earthquake hazard studies give the average recurrence interval between the occurrence of earthquakes of a given magnitude within a given source zone, either an area, volume or on a fault, and the primary output is the recurrence of different levels of ground motion at a point. Their use in structural design is to estimate the probability that the design ground motion will be exceeded during the life of the structure. A contour map of ground motion recurrence over a region is often called an earthquake hazard map.

Present earthquakes

The earthquake of most interest to most people is the one that has just happened. In general there are two risk mitigation actions relevant for the current event.

Warnings can be issued if the event has just occurred, but its effects have not yet been felt (rain storms in a catchment allows time for flood warnings downstream, or a large shallow, dip-slip undersea earthquake gives time for a tsunami warning). There is rarely time to give a useful warning for strong earthquake ground motion, but it is attempted in Japan and Mexico.

Alarms are issued after the event has occurred, and after its effects have been felt. The purpose is to optimise the emergency response. They should advise on probable earthquake effects, and assist with emergency response actions. This is particularly important for earthquakes which, being unexpected, are followed by some chaos.

Future earthquakes

Predictions anticipate the event within relatively limited bounds of accuracy, giving the time, place and magnitude, with certainty.

Forecasts anticipate the event within wider bounds of accuracy, giving the time, place and magnitude, with some probability.

Alerts may be given when unusual activity that may be precursory to a larger event has been observed, and it may be wise to check on any preparations.

In summary, the most useful information that seismologists can give at present is in **hazard studies** and **alarms**. In the future, it may be possible to **forecast** events to allow some useful preparation to be undertaken before it occurs.

Seismological inputs to earthquake risk management

Earthquake motion

Seismographs measure the motion that results from an earthquake, usually at a point on the earth's surface, or on a structure such as a building, dam or bridge. In the past, most seismologists used sensitive seismographs to record the three dimensional (east-west, north-south and vertical) motion from distant earthquakes, while engineering seismologists used strong motion accelerographs to record the damaging motion near to large earthquakes. The full dynamic range can be measured by using a six-channel instrument with a sensitive seismometer and a strong motion accelerometer.

The study of earthquake motion is often considered in four stages – source, travel path, site, and structure.

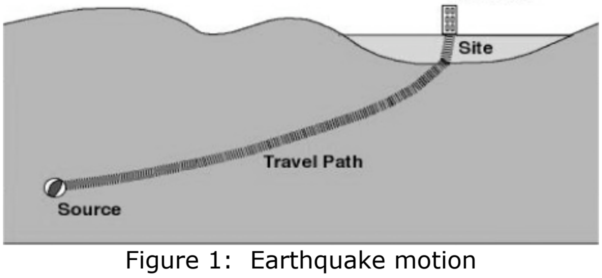

Figure 1: Earthquake motion

The motion recorded by seismographs is affected by at least both source and travel path, and measurements are often affected by site response. Motion recorded on structures is affected by the dynamic response of the structure. To separate the effects of the different stages, almost all seismological analysis is done by comparing motion recorded at different locations.

Earthquakes are located by comparing the arrival times of seismic waves in a surrounding network. Attenuation, and thus magnitudes require comparison of amplitudes with distance. Site response is measured by comparing motion recorded at the surface with motion on nearby bedrock or in a borehole. Structural response is measured by comparing motion recorded on the building with motion at the foundation and with a nearby surface motion reference point. Focal mechanisms inherently require measurements at points that vary in both distance and magnitude.

Determining both attenuation functions and focal mechanisms require measurement of ground motion from a set of earthquakes, each recorded by as many seismographs as possible over a wide range of distances and azimuths, preferably distributed as the logarithm of distance (e.g. 2, 4, 8, 16, 32, 64, 128 km). For each earthquake, the ratio of the greatest distance to the closest distance should be at least one order of magnitude (e.g. 20 to 200 km), ideally more, and preferably two orders of magnitude (e.g. 5 to 500 km).

Seismographs placed around a planned blast or for aftershocks can be arranged in logarithmic distribution with distance, preferably with one or more instruments at considerable distance in each of two orthogonal directions. However, it is not possible to anticipate most earthquake locations to allow a logarithmic distribution. To monitor an earthquake with seismographs ranging in both distance and azimuth it is necessary to have a high density of seismographs.

Earthquake focal mechanisms

The focal mechanism is used to relate the earthquake to local geology, to obtain an estimate of the orientation of the stress field that generated the earthquake, and to refine the estimated seismic wave radiation pattern expected for this earthquake, especially directivity effects near to the fault rupture as required for next-generation earthquake alarm systems and future hazard studies.

When the local stress field is known, as given on the World Stress Map (Figure 2) or locally, faults that are susceptible to failure may be distinguished from those that developed when the stress field was different and are unlikely to reactivate. When other earthquake source parameters are estimated, such as stress drop and rupture dimension, it is possible to characterise local earthquake hazard.

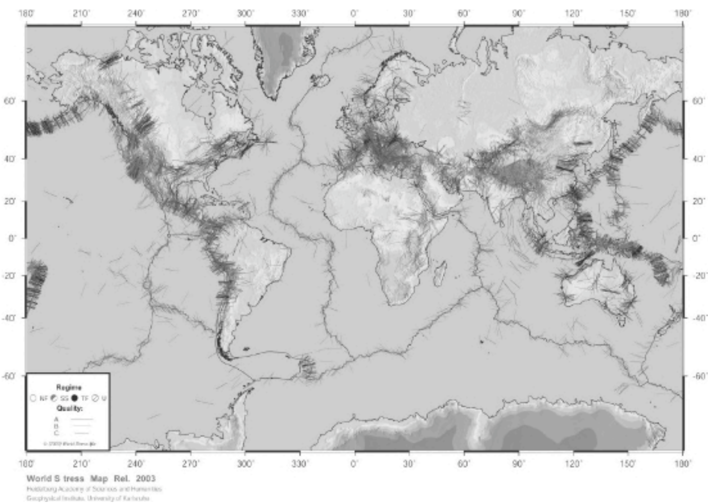

Figure 2: The World Stress Map shows the direction of the maximum horizontal stress, coloured depending on the fault type – blue for reverse faulting, red for normal faulting and green for strike-slip faulting.
Note regional variations; such as extensional normal faulting in Africa, and compressional reverse faulting in Australia, and the dependence on azimuth of normal and strike-slip faulting along oceanic ridges. Such features occur on smaller scales.

Source parameter summary

The limiting factor in the accuracy and precision of earthquake locations is the number of seismographs recording the event, and the distance to the nearest seismographs. Local attenuation functions can only be reliably determined if the event is recorded over a logarithmically distributed range of distances, preferably in orthogonal directions. Earthquake focal mechanisms can only be reliably determined if the event is recorded over a logarithmically distributed range of distances and over a range of azimuths.

To determine all of these parameters to high precision would require a seismograph/ accelerograph network with the same density as is currently installed in Japan, even in places with relatively few earthquakes such as Australia. Rather than installing an observational network that does not work particularly well anywhere, we will probably need to concentrate on populated areas and on more active areas. A very rapidly deployed aftershock network will be highly productive providing very precise location information, and the opportunity to optimise the seismograph network for local attenuation determination and focal mechanism determination.

Earthquake clustering

Clustering must be examined in hazard studies to use independent events for recurrence calculations, and for forecasts.

Earthquakes and geology

The relationship between earthquakes and local geology requires precise locations from a high-resolution network, together with determination of focal mechanisms and estimates of the orientation of the local stress field.

The relationship is bi-directional, in that earthquake data can be used to help decipher the geology, and geological information can be used to explain the earthquakes.

The earthquake seismicity information is limited by the duration of the data available, as only relatively imprecise parameters are available for those few earthquakes before 1960 that were large enough to be reported or recorded. In most parts of the world the seismicity data is still limited by poor precision and accuracy.

Application to earthquake risk mitigation

Earthquake hazard studies

Earthquake hazard studies are based on past earthquakes and their effects. This information is best included in an earthquake catalogue, which includes **locations**, **magnitudes**, **mechanisms**, earthquake **effects**, **clustering** details, any relationship to **geology** (faults or structures), relevant **publications** listed, all with information on accuracy and precision.

Many current generation hazard studies are still computed from simple seismotectonic models based on seismicity alone, and do not incorporate geological information or active faults. Studies range from “flat-earth” models where earthquakes are assumed to occur with equal probability at any location within large regions, resulting in little or no variation in estimated hazard from point to point. The opposite extreme would be where earthquakes are only anticipated on known active faults, resulting in highly variable estimates of hazard with maximum value near to the faults, and very low values elsewhere. Brown (2003) developed a series of models including some active faults, and volume sources tending towards higher resolution in regions where more geological, geophysical and seismicity data was available.

Quantification of earthquake recurrence in areas of low seismicity can be significantly affected by earthquake clustering. The largest earthquake in a cluster sequence will give the strongest and most damaging motion. If other members of the cluster are included in earthquake magnitude studies, these dependent events result in a higher ratio of small to large earthquakes (Gutenberg-Richter b value), and an underestimation of the recurrence of large events. Earthquake catalogues must be declustered for earthquake magnitude recurrence estimates.

One of the most significant limitations on earthquake hazard studies at present is the non-availability of local frequency-dependent ground motion attenuation functions. This affects both the magnitudes being calculated, and the resulting ground motion estimates. Attenuation depends significantly on local geology, with young, soft or hot rocks attenuating motion rapidly with distance, and old, hard, cold rocks giving very low attenuation. In the absence of local measurements, consideration of the geology, particularly the age of rocks in the upper half of the crust, is a very useful guide.

Earthquake alarms

The implementation of an earthquake alarm first requires determination of the earthquake location and magnitude as soon as possible after the event, preferably within minutes. Most alarm systems have an automatic calculation of location and magnitude, which is checked by a seismologist and often modified before the alarm is issued.

Useful alarms require more than just the location, origin time and magnitude of the earthquake (Peck et al, 1996). They need an estimate of the probable effects of the earthquake so that appropriate responses are made. This requires estimation of the ground motion at a number of locations or throughout an area, which needs a local strong motion attenuation function, possibly using site response estimates. The alarm system usually requires estimates of the vulnerability of structures (provided by engineers).

Well-designed emergency response plans should anticipate the actions to be taken, such as inspecting a structure, and taking measurements that will indicate normal or abnormal operation. Communication tasks are the most common, ensuring that all relevant people are informed as soon as possible.

Alarm systems require databases of structure vulnerabilities and responses (actions or tasks to be undertaken) to be prepared in advance, and checked regularly.

First-generation alarm systems estimate ground motions using a simple radially symmetric attenuation function. High precision earthquake locations are not particularly needed for this alarm function, and the existing seismograph system with gaps in coverage filled is adequate. Second generation alarm systems will also estimate ground motions by computation, but will include site response and seismic wave radiation pattern, so will need focal mechanisms and more precise earthquake locations (e.g. as in California). Third generation alarm systems actually measure ground motion over a dense network (e.g. as in Japan).

Earthquake forecasts and alerts

Most earthquakes occur without any indication that it is imminent. A study of earthquake clustering may reveal precursory behaviour.

Precursory activity seems to be more apparent in the stable continental regions, where there are few earthquakes, faults rarely fail, and stress levels reach much higher values than in active areas.

Some earthquakes are preceded by multiple sequences of smaller earthquakes, any one of which is comparable with normal small earthquake sequences that often occur, but together may suggest an oncoming major event.

Two perspectives on seismological monitoring

Seismologists tend to polarise into two groups, depending on the distance between the earthquakes they are studying and the seismographs recording the ground motion.

Global or broadband seismology

Global seismology is concerned with world earthquakes, usually recorded at distances of hundreds of kilometres to thousands of kilometres.

Local or high resolution seismology

Local seismology is concerned with earthquakes within a seismograph network, often covering a country or state, where distances are from hundreds of kilometres down to less than a kilometre. Because seismic wave travel distances are short, travel times are low, and major changes in geological structure are limited. The small area means that large earthquakes are rare, but relatively small earthquakes can be detected and analysed.

However, the strong motion from large nearby earthquakes is one of the most significant aspects when working at this scale because this is what causes earthquake damage. Most of the data used comes from individual networks, but it is very useful to share data between neighbouring networks (local collaboration). Table 1 compares some of the aspects of global and local seismology. It shows that the shorter distances, higher frequency motion, and smaller earthquakes considered on a local scale leads to more precise locations. To emphasise this point the name high-resolution seismology is used instead of local seismology

Global seismology and high resolution seismology

	Global seismology	High resolution seismology
Travel path distances	Hundreds of km to world wide.	Less than 1 km to hundreds of km
Magnitudes	Usually from magnitude 4 to over 9, with some smaller events but rarely less than magnitude 3.	Depending on network size, from ML 0 to 2 and above for earthquakes, or down to magnitude -2 or -3 for events in mines. Strong motion from large nearby earthquakes provides invaluable hazard information.
Minimum frequency motion	From less than 0.01 Hz for very large events, and from 0.05 Hz for magnitudes from Mw 4.0.	From 0.2 Hz for large events, 1 Hz for small earthquakes, and 10 Hz for very small events.
Maximum frequency motion	Typically several hertz for events at thousands of km, up to 10 Hz at hundreds of km.	Tens of hertz for earthquakes at 100 km distance, to 100s or 1000s of hertz closer than 1 km.
Sample Rate (samples per second)	20 to 50 /s.	100 to 200 /s for larger local networks, 500 /s for aftershocks, to 20000 /s or more in mines.
Data per day (compressible for storage and telemetry, all saved for continuous, some for	16 to 39 megabyte	155 to 300 megabyte for local networks to 1.6 gigabyte in mines

	Global seismology	High resolution seismology
triggered)		
Triggered or Continuous	Normally continuous on all channels.	Usually continuous on one or three channels, plus triggered on all channels
Transducers required to detect target bandwidth	Broadband seismometer is ideal for moderate to low frequency motion.	The smaller the network the higher the frequency of motion. Short to moderate period seismometers, geophones and accelerometers cover the range.
Dynamic Range	Significant distances may limit dynamic range requirements.	Wide variation in amplitudes requires large dynamic range. Often requires triaxial seismometer plus a triaxial accelerometer.
Seismometer installation	Expensive vault needed	Vault not needed. Relatively simple weather and security protection is adequate.
Power Requirement	Moderate, often dominated by communications, especially VSAT sites	Low without telemetry (single small solar panel and battery). Moderate when telemetry is used.
Data Collection	Continuous data normally telemetered to observatory, with on site storage used during communication failure.	Can use on site storage manually collected by exchanging discs or memory cards, and/or telemetry of either triggered or continuous data.
Best case earthquake location uncertainty: (many seismographs, and epicentre inside network, and one or more seismographs near epicentre, and simple geology)	Location accuracy usually limited by seismic wave velocity model. Random uncertainty of 2 km, plus systematic uncertainty of several km.	Location accuracy usually limited by the number of seismographs recording each event. Random uncertainty from less than 1 km, plus systematic uncertainty of less than 1 km.
Typical poor quality location uncertainty (few seismographs, or epicentre outside network, or no seismograph near epicentre, or complex geology)	Random uncertainty of ten to hundreds of km, plus systematic uncertainty up to tens of km.	Random uncertainty of ten to hundreds of km, plus systematic uncertainty up to several km.
Cost of each site including installation and operation, excluding analysis (A$, 2006, ±30%)	$50,000 plus $8000 to $12000 per year (assuming alarm reliability needed).	$10,000 plus $3000 to $8000 per year depending on telemetry (assuming no alarm function).
Number of seismographs	Typically tens to hundreds – the current global network (global collaboration).	Depends critically on the local network, plus help from neighbours (local collaboration).
Major contribution to	Global tectonics, nuclear monitoring, tsunami warning, global earthquake hazard and risk.	Local earthquake hazard and risk.

Tennant Creek aftershocks, 1988

Aftershocks of the Tennant Creek earthquakes from January 1988 illustrate the difference between global seismology results and high-resolution seismology. Figure 3 shows earthquakes located using global data. On a map covering Australia or the world, these would all be at almost the same point, but on the scale of this figure, they can be seen to spread over tens of kilometres. Most of the depths are assigned values of 5 or 10 km, so there is no significant depth dimension to the plot. Figure 4 (at the same scale as Figure 3) and the enlarged Figure 5, were produced using results from a local network of 10 to 15 seismographs in a high-resolution network. Despite being before the advent of GPS timing, the typical uncertainties in longitude, latitude and depth were often from one to two kilometres, and the relationship between the earthquakes and the fault is very clear.

A mapped fault is drawn oriented WNW to ESE. This corresponds to the main fault rupture in the earthquake sequence. The southern block was the upthrown block on the south dipping reverse fault. There was also a smaller steeply dipping conjugate fault to the northwest, giving some deeper events that can be seen on Figure 5.

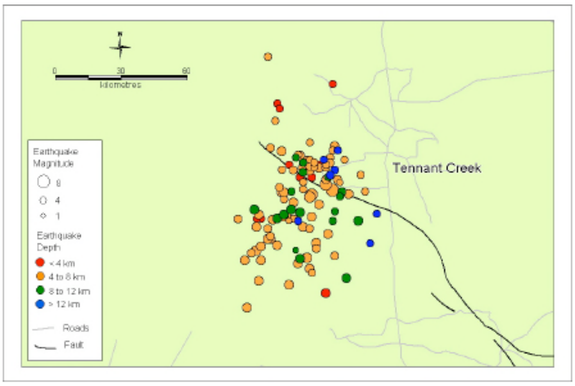

Figure 3: Aftershocks of the 1988 Tennant Creek earthquakes as located by the International Seismological Centre show considerable scatter, with uncertainties of tens of kilometres. There is no obvious relationship between the depths of events and the fault.

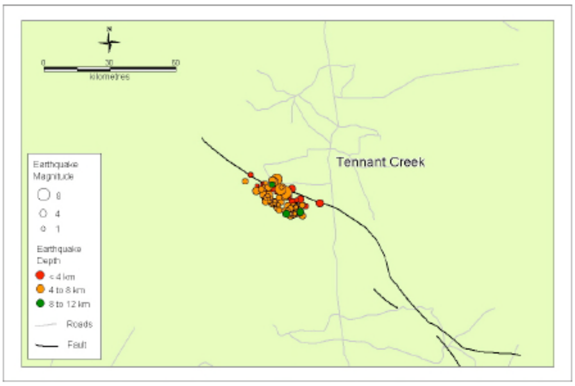

Figure 4: Aftershocks located by a local network have location uncertainties an order of magnitude less, measured in kilometres, and are much more closely related to the fault.

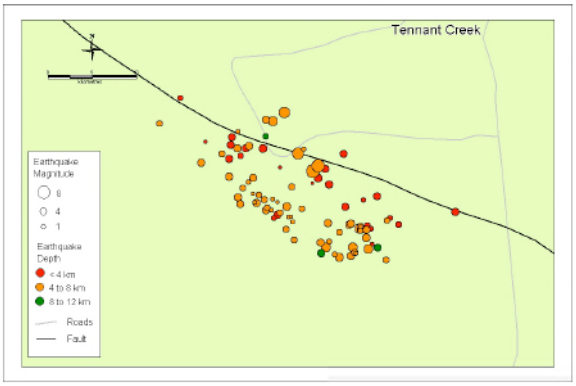

Figure 5: At a larger scale, the aftershocks located by the local network outline the fault rupture, showing the main fault as a south dipping reverse fault, with a smaller conjugate fault dipping to the northwest.

Recent developments in applied earthquake seismology in Australia

Earthquake alarms

When the Newcastle earthquake occurred in 1989, relatively few of the seismographs throughout Australia were telemetered to observatories. Initial locations using data predominantly from the southwest showed the epicentre well inland, but with very high uncertainty because it was well outside the network. It took some hours before the estimates began to indicate a Newcastle location.

This lead to the introduction of automatic telemetered seismograph networks with automatic event detection and automatic preliminary locations at Geoscience Australia in Canberra and the Seismology Research Centre in Melbourne. The other major network in Australia, operated by Primary Industries and Resources South Australia, in Adelaide, also now has an alarm system. The Seismology Research Centre operates independent alarm systems in Brisbane and Melbourne to ensure reliability of the system, especially in the case of an earthquake occurring at either location. The alarm systems operated by Geoscience Australia and PIRSA operate independently but all systems cooperate closely, so automatic locations for most Australian earthquakes are available within minutes of an event, and seismologist revised solutions are usually available within tens of minutes of the event.

Routine earthquake monitoring

The new alarm systems have seen digital recording totally replace analogue recording at most observatories. Most of the analogue drum recorders still operating are only used for educational and public display purposes.

This has been a major change to observational seismology in Australia, and the accuracy and precision of the analysis of larger events has improved. However, it has brought some disadvantages with its advantages. The extensive use of digital recording has meant that many smaller earthquakes remote from seismographs do not trigger the system and are not detected.

Examination of continuous digital data on a screen could be used to manually detect these events, especially in the format with all stations recording in parallel rather than all data from one station on a simulated helical recorder. Correlation between records from different instruments should attract the eye of the observer similar to an automatic multi-channel earthquake trigger. However the resolution of modern computer screens is still not as good as high quality analogue records, and the number of smaller events currently being located per year is about half of that in the past, despite the increase in number of seismographs.

Magnitude and attenuation

Magnitude estimates have always shown inconsistencies. Within a network, calculated magnitudes often vary with recording distance, indicating that the attenuation function used in the calculation is not valid.

Even when magnitudes computed by a given network are consistent, they may vary relative to estimates given by neighbouring networks.

Allen (2004, and related publications) has made steps towards developing attenuation functions that can be used for both:

1. correcting ground motion measurements for distance to calculate earthquake magnitude estimates, and

2. using earthquake magnitudes to estimate the ground motion at a point some distance away, normally for hazard studies.

These functions are empirically determined, and ensure that magnitudes do not vary with distance, and they are related to motion near to the earthquake source rather than at an arbitrary distance, such as 100 km, so magnitudes recorded in areas of high and low attenuation should be equivalent.

Site response

Over recent years, Geoscience Australia and others have placed considerable emphasis on the significance of site response to earthquake hazard. Detailed microzonation maps have been produced that incorporate amplification due to soft surface sediments.

Asten (2005, and earlier papers) has developed the spatial auto-correlation (SPAC) method of determining the shear wave velocity profile at a site using ambient vibrations recorded on a small array. Although not yet being applied extensively, this method shows a considerable advancement over methods using horizontal/vertical motion ratios at a point (Nakamura method).

Seismology and geology

The link between seismicity and geology is best made using high-resolution seismograph networks, especially with earthquake focal mechanisms. Temporary high-resolution networks have been deployed about the Burakin earthquake swarm in Western Australia by Geoscience Australia, and in the Flinders Ranges of South Australia by Geoscience Australia, PIRSA and the ANU. Discussions have been held regarding a temporary high-resolution update on activity in the Tennant Creek region.

Geoscience Australia have developed studies of earthquake geology throughout Australia, and have significantly increased the number of recognised examples of neotectonic activity, particularly in southwest Western Australia (Clark, 2005 and other publications).

Challenges facing us over the next decade

There have been many improvements in seismograph systems and analysis methods over the past two decades. The global scale is now well-covered (apart from oceanic regions) and moderate magnitude earthquakes are usually well located, and have reliable magnitudes and mechanisms. However, resolution remains limited by the velocity or travel time model used, and many earthquake locations have both random uncertainties and systematic uncertainties of tens of kilometres. It is approaching a level that can be regarded as adequate for earthquake alarm systems.

The local scale has many applications for hazard and risk in particular areas. Precise locations of earthquakes delineate faults, recording ground motion over a wide range of logarithmically spaced distances determines attenuation and thus reliable magnitude estimates, and focal mechanisms reveal links between earthquakes and geology. However it is limited by the seismograph/accelerograph network density.

Future routine earthquake monitoring

To improve earthquake locations, magnitudes, and focal mechanism, a high seismograph network density is needed, and the dominant limiting factor in Australia is cost. The challenge is to develop instrumentation with low capital and operating cost that can be deployed widely. The cost of seismograph recorders has significantly reduced over recent years, especially on a local scale.

If trends can be extended to the transducers required (short period and strong motion accelerometers are appropriate for high-resolution monitoring), and costs can be reduced by the economies of larger scale deployment, then much higher seismograph network densities should become economically feasible. It would be a useful and achievable aim to reduce the capital and operating costs by another factor of two.

The current seismograph array in Australia has almost enough instruments telemetering near real-time for earthquake alarm purposes.

If the capital cost plus operating cost of communications is significant (e.g. telephone, mobile telephone, radio modem or VSAT), then remote operation is an option for some or many of the instruments. Modern seismographs have sufficient data storage space for many months of operation, and are sufficiently reliable to allow remote operation with infrequent field visits for data collection.

Despite the increasing deployment of small, relatively low-cost, six-channel instruments, the existing strong motion network in Australia is extremely sparse. Attenuation functions are determined by comparing motion on bedrock sites over a range of distances, so records from a single isolated instrument have limited value.

Very few strong motion instruments are installed on buildings or other structures in Australia, and most of these are on large dams. Give the reductions in cost over the past decade; it is now much easier to instrument a range of typical structures to gather vulnerability data appropriate for earthquake engineering. The multiple locations required to compare motion of the structure, foundation and bedrock could use low-cost wireless connections.

Site response

There is no doubt that earthquake damage is greater on soft surface sediments than on hard rock sites, and that this is due to resonant amplification of the seismic wave motion at the natural frequencies of sites.

Current site response methods, both H/V (Nakamura) methods and SPAC methods, apply to horizontally layered sediments and do not consider three-dimensional structures such as valleys. Site response methods should develop beyond horizontally layered structures, and include valley edge effects.

A challenge that will involve both site response and structural engineering dynamics is to minimise the possibility of multiple resonance. If the natural frequency of a site corresponds to the natural frequency of a structure, the site will first amplify the earthquake motion by some factor, then the structure will further amplify this motion by another factor. This can be avoided by ensuring that the structure does not have the same natural frequency as the site. The natural frequency of the site cannot easily be changed (although it may vary a little with ground-water variations), but the natural frequency of the structure can be varied depending on its mass and stiffness, and particularly on its height. Multiple resonance is not considered in the current version of Australian Standard AS1170.4, although it was considered in the previous SAA Loading Code AS2121-1979.

Seismotectonic models, seismicity and geology

Traditionally, the seismotectonic source models used for earthquake hazard studies were based solely on the limited available seismicity data. This is not a great problem in active areas where the average return period between major earthquakes is of the order of hundreds of years. However, in stable continental regions like Australia, where return periods of large earthquakes may be tens or hundreds of thousands of years, the seismicity record is similar to a jigsaw puzzle with many missing pieces.

These problems can be minimised by the use of geological and geophysical data to provide a framework for the seismotectonic model, use of geological fault slip rates to confirm earthquake magnitude recurrence rates, and using palaeoseismology data to confirm maximum credible magnitude estimates.

Seismotectonic models have traditionally varied between flat-earth models, where the likelihood of earthquakes is uniform over large areas, and the active-fault models, where all future earthquakes are assumed to lie on active faults that have already been delineated. There seems to be little doubt that proximity to an active fault is the major consideration for earthquake hazard, and that future earthquake hazard maps will show more variations at scales of tens of kilometres than the smoothed “fault-less” hazard map used in the current loading code, Australian Standard AS1170.4. The challenge is to identify and quantify all major active faults in Australia.

It is possible that time variant hazard maps will become more apparent in the next decades. The existing AS1170.4 map already includes some time-variant features. The Tennant Creek earthquakes of 1988 have lead to a prolonged period of adjustment activity in the region, and after more than 18 years the region still experiences a significant proportion of Australian earthquake activity. It is possible that more moderate to large events may occur as part of this sequence, and the hazard map reflects this possibility. When this sequence is over, perhaps after about 100 years, the region may experience a long period of quiescence, giving a long-term average fault slip-rate consistent with geological data.

Seismology and geology

Until a dense permanent network of seismographs is installed, temporary deployments of dense networks, either for aftershock sequences or in selected regions, will provide a link between earthquake activity and geology. Aftershock sequences are particularly useful because they occur at a known place, so the seismographs or accelerographs can be deployed with increasing density towards the epicentre.

We are coming up to the 20th anniversary of the Tennant Creek earthquake, and the next major earthquake in Australia may not be very far off. We must be prepared for a very rapid deployment. In the meantime, we should be alert for repeated sequences of small earthquakes that may be precursory events.

Public education

There can be little doubt that one of the best ways to mitigate risk is through a public education program. The program in the Philippines covering geohazards, including earthquakes, volcanoes, tsunamis and landslides, is world leading. It has produced a good level of awareness and sophistication, primarily through its schools program. Seismology can be used as a means of teaching the basics in many school subjects, including physics, geology, geography, mathematics, environment, and social studies.

School seismograph systems have been installed in several regions, and have proved useful, although results are sometimes disappointing and recording systems require too much attention. Development of a reliable school seismograph with adequate long-period response for large distant earthquakes could reduce current limitations. Perhaps this could plug into the USB port of a standard desktop computer with a large LCD screen and appropriate software to handle display, data storage and data exchange. The major problem would be the development of an inexpensive transducer with fair long-period response, a specification that would be appropriate for this application but not adequate for a seismic observatory.

A similar recorder, but with short period and strong motion transducers, could be used by schools and the growing number of amateur seismologists to supplement the local seismograph network.

Conclusion

Both global scale, and high-resolution local monitoring are important. It is easier to fund global monitoring because it deals with larger damaging earthquakes, which occur relatively often about the earth, and is supported by nuclear monitoring and tsunami warning functions.

Permanent monitoring seismicity at high-resolution requires a dense network. A sophisticated network of sites that all have real-time communications, as deployed throughout Japan, is economically unfeasible in Australia. The unit cost (both capital and operating) for seismographs and accelerographs in a dense Australian network will need be minimised. Incorporation of communications by telephone, radio or satellite would be too expensive at many or most sites, and is not necessary for the scientific purposes of the network.

Of the current earthquake risk mitigation measures in Australia, earthquake alarms are approaching a satisfactory level. The large size of Australia means that earthquake hazard studies are limited by the low seismograph network density. Earthquake location precision does not allow fault delineation, and local attenuation functions (and thus magnitudes) and focal mechanisms usually cannot be determined. The high stress drop of many Australian earthquakes suggests that earthquake forecasts or alerts, considering earthquake clusters and possibly other precursors, may have a higher chance of being useful than in more active regions.

The most appropriate extension to current monitoring is to emphasise areas of highest earthquake activity (hazard) and risk (those with high vulnerability and exposure - that is, relatively populated regions), and to be prepared for rapid deployment of instruments for aftershock studies.

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