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Future Directions for the National Earthquake Hazard Map for Australia

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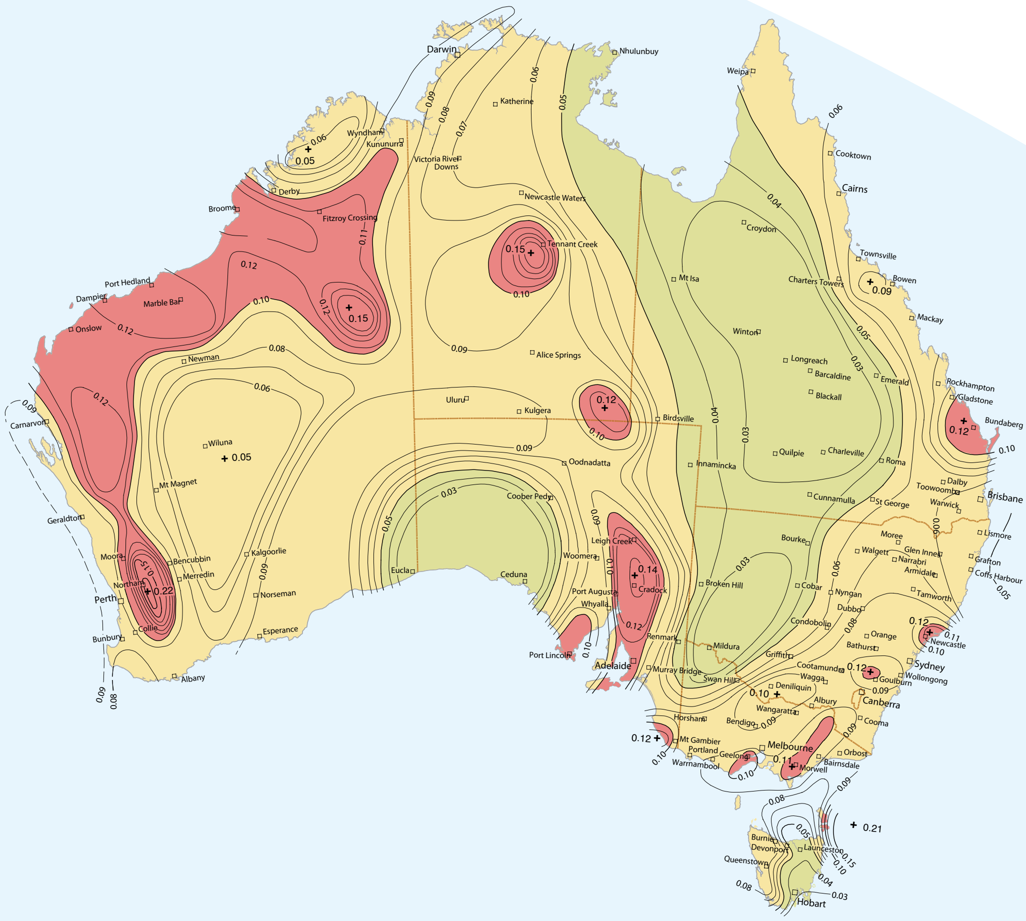

Future Directions for the National Earthquake Hazard Map for Australia

GEOSCIENCE AUSTRALIA
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by

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Glossary

Term	Definition
ABCB	Australian Building Codes Board
Aleatory Uncertainty	Uncertainty which arises from the random nature of the earthquake process (as opposed to Epistemic Uncertainty).
Annual Probability of Exceedence	The probability that a given level of ground shaking will be equalled or exceeded each year.
Attenuation	The decrease in energy of seismic waves as a function of distance from the source, usually manifested as a decrease in amplitude.
AS1170.4	The current earthquake loading standard - "Structural design actions Part 4: Earthquake actions in Australia"
^{14}C dating	A radiometric dating method which can be used to determine the age of organic material up to ~40,000 years ago. This can be used to infer the age of sediment erosion/deposition and hence fault movement.
Cosmogenic Radionuclide (CRN) Dating	A radiometric dating technique which can be used to determine when certain materials were last at the surface and exposed to cosmogenic background radiation. Like ^{14}C it can be used to infer the age of fault movement.
DEM	"Digital Elevation Model" –a grid of points depicting values of height relative to a given datum (e.g. mean sea level) for part of the Earth's surface
Earthquake Recurrence Model	An equation describing the likelihood of an earthquake of a given size or larger in a particular area.
Epicentre	The point on the Earth's surface directly above the hypocentre
Epistemic Uncertainty	The uncertainty which results from an incomplete knowledge and data about the physics of the earthquake process (as opposed to aleatory uncertainty).
Earthquake Risk Model (EQRM)	An open-source computer program developed by Geoscience Australia for calculating earthquake hazard and risk (see http://eqrm.sourceforge.net/).
EZ-FRISK™	A commercial software package made by Risk Engineering Inc to perform site-specific earthquake hazard analysis (see http://www.ez-frisk.com/).
GA	Geoscience Australia
Global Earthquake Risk Model (GEM)	A global model of earthquake hazard and risk produced by a large international public-private partnership initiated and approved by the Global Science Forum of the Organisation for Economic Co-operation and Development (see http://globalquakemodel.org/).
Global Positioning System (GPS)	A system of one or more instruments that are used to define point locations on the Earth's surface using signals from multiple geodetic satellites. High precision GPS data collected across stable networks can be used to assess crustal deformation over time.
GMPE	Ground Motion Prediction Equations – a set of equations that describes the level of ground motion expected from a given earthquake as a function of distance and the earthquake's properties (e.g. magnitude). Sometimes called ground motion attenuation equations.
GNS	GNS Science, New Zealand
Ground Penetrating Radar (GPR)	A geophysical method that uses radar pulses to image materials and structures in the sub-surface.
Gutenburg-Richter *a* and *b* values	*a* measures the rate of activity and *b* the distribution between large and small earthquakes in the Gutenburg-Richter earthquake recurrence model
Hypocentre	The spatial location of the initiation point of an earthquake, usually expressed as a latitude, longitude and depth.
Interferometric **S**ynthetic **A**perture **R**adar (InSAR)	A radar technique used in geodesy to detect centimetre scale deformation over timespans of days to years
Intensity	A number describing the severity of the ground shaking from an earthquake in terms of its effects on the earth's surface, humans and/or their structures

	(eg Mercalli Intensity)
Light **D**etection **A**nd **R**anging (LiDAR)	An optical remote sensing technology that measures the properties of scattered light to find range and/or other information of a distant target. It can be used to produce high-resolution DEMs.
ML	"Local Magnitude", - a common magnitude scale for earthquakes in the current catalogue. Often known as "Richter magnitude", it saturates at high values.
Mmax	The maximum magnitude (according to some magnitude scale) expected in a particular area
Moho	The boundary between the crust and mantle. Named after Andrija Mohorovicic who discovered it.
Mw	"Moment Magnitude" – one of the best scales for measuring the size of an earthquake since it is uniformly applicable to earthquakes of any size.
Nakamura Method	A passive seismic method for measuring the shear wave velocity of seismic waves as a function of depth.
NEHRP soil classification scheme	The soil condition classification for ground shaking developed by the U.S. National Earthquake Hazards Reduction Program (NEHRP). The classification indicates the extent to which geological materials at a site will modify (usually amplify) earthquake energy.
NGA-East	Next Generation Attenuation Relationships for the Central and Eastern US
NGA-West	Next Generation Attenuation Relationship for the western U.S.
NRCan	Natural Resources Canada (includes the Geological Survey of Canada).
OSL	Optically stimulated luminescence is a technique for detemining when certain minerals were last exposed to sunlight. It can be used to infer the age of sediment erosion/deposition and hence fault movement.
Peak Ground Acceleration (PGA)	The maximum acceleration at a particular point from the ground shaking due to an earthquake
Peak Ground Displacement (PGD)	The maximum displacement at a particular point from the ground shaking due to an earthquake
Peak Ground Velocity (PGV)	The maximum velocity at a particular point from the ground shaking due to an earthquake
Poisson Distribution	A probability distribution that is appropriate for an event which is equally likely to happen at any point in time.
Probabilistic Earthquake Hazard Map	A map that shows a measure of the ground shaking from an earthquake which has a specific probability of being equalled or exceeded over a given period of time.
Probabilistic Risk Map	A map that shows a measure of loss or impact (e.g. cost) which has a specific probability of being equalled or exceeded over a given period of time from earthquakes.
Q	"Q" is the inverse of anelastic attenuation. The Earth's rocks are not perfectly elastic so seismic waves lose energy as they pass through them. A high "Q" value indicates low levels of anelastic attenuation.
Return Period	The average length of time between a measure of the hazard or risk at or above a given size. It is the inverse of the annual probability of exceedence.
SASW	The Spectral Analysis of Shear-Waves (SASW) method is an active source geophysical technique for determining the shear wave velocity in the Earth as a function of depth beneath the surface.
SPAC	The Spatial Autocorrelation (SPAC) method is a passive source geophysical technique for determining the shear wave velocity of seismic waves in the Earth as a function of depth beneath the surface.
USGS	United States Geological Survey

Summary

In July 2009, Geoscience Australia initiated a new project within the Geospatial and Earth Monitoring Group to update the national earthquake hazard map using the latest methods and data. This map is a key component of Australia's earthquake loading code. As part of developing the project, between 20 and 22 October 2009 Geoscience Australia hosted a workshop with a group of Australian experts in earthquake hazard assessment. The aim of the workshop was to scope out the short and long term direction of the earthquake hazard project and the national map. This report was developed from the input and advice received from that workshop.

The primary aim of Geoscience Australia's Earthquake Hazard Project is to produce a science-based quantitative estimate the level of hazard from earthquakes in Australia. Wherever possible, the outputs of the project are to be open, peer-reviewed and use the best available science.

Geoscience Australia proposes updating the current earthquake hazard map over the next two years using the best currently available data and techniques. Thereafter, regular updates of the map are broadly planned to occur every five years. The participants and contributors to the workshop generally supported this plan for the national hazard map.

As discussed in this report, Geoscience Australia proposes a range of long term, multi-disciplinary activities that could fundamentally improve the earthquake hazard map into the future (Table 1). In broad terms these activities fall into two categories:

a. the development, validation and maintenance of a range of fundamental datasets that contribute to our understanding of earthquakes in Australia. These include catalogues of Australian earthquakes, databases containing strong and weak ground motions and fault databases. Several of these datasets would be common or useful to activities other than seismic hazard assessment.
b. the development and validation of improved models of earthquake recurrence and ground motion. We expect that there will be a trend away from the current, empirical approach, towards one which relies more on numerical modelling of the earthquakes and their causes. These models will be theoretically based but empirically validated.

These activities contribute to either one or both of the major inputs into a seismic hazard assessment. A standard seismic hazard assessment requires:

1. a model which estimates the likelihood of a large earthquake in a given area and
2. a model which predicts the level of ground shaking from a given earthquake for a given area.

The various activities and the primary way they contribute to improving our understanding of either earthquake likelihood or ground shaking is shown in Table 1. Also listed in Table 1 are whether these particular areas are likely to be areas of focus over the short, medium and/or long terms. For the purposes of this document, "short" means that this area is likely to be particularly important for the next hazard map produced in a few years time. "Medium" means that it is likely to be important for the hazard map produced in seven years time and "Long" term activities are ones which are likely to remain important areas of active research indefinitely into the future. The various areas shown in Table 1 are discussed in more detail in the rest of the document.

Table 1 The scientific research areas and the main way they contribute to national earthquake hazard map. The timeframe indicates whether this area is expected to will be a main area of research over the next two years (short), seven years (medium) or indefinitely into the future (long).

Research Activity ...	**Primarily improves our estimates of…**	**Timeframe…**
Earthquake Catalogue	Earthquake Likelihood	Short/Medium/Long
Earthquake Recurrence Models	Earthquake Likelihood	Short/Medium/Long
Source Zonation	Earthquake Likelihood	Short/Medium
Fault catalogue	Earthquake Likelihood	Medium/Long
Strain rate data	Earthquake Likelihood	Long
Geodynamic Models	Earthquake Likelihood	Long
Neotectonics	Earthquake Likelihood & Maximum Magnitude	Short/Medium/Long
Seismic velocity and Q models	Earthquake Likelihood & Ground Shaking	Medium/Long
Earthquake waveform data	Ground Shaking	Medium/Long
Ground Motion Prediction (a.k.a. Attenuation) Equations	Ground Shaking	Short/Medium
Local Site response	Ground Shaking	Medium/Long
Strong Motion Numerical Models	Ground Shaking	Long
Software development	Earthquake Likelihood, Ground Shaking & Hazard Assessments	Short/Medium/Long

Introduction

The current national hazard map's primary use is in the Australian Standard AS1170.4 "Structural design actions Part 4: Earthquake actions in Australia". This Standard is prepared by Committee BD-006, General Design Requirements and Loading on Structures of Standards Australia. The objective of this standard is to "provide designers of structures with earthquake actions" to use in the design of certain classes of buildings. The earthquake actions that have to be considered are all based on the level of shaking shown by a hazard map and listed in a Table at the front of the standard. The last edition of the standard was produced in 2007. However, the earthquake hazard map within this version of the standard was almost identical to the map from the previous 1993 standard (McCue *et al.*, 1993). The McCue *et al.* (1993) map was constructed using modified source zones of Gaull *et al.* (1990), based on an additional 6 years of earthquake data and about a hundred independent site hazard estimates. Since these maps have been produced, many more earthquakes have occurred within Australia (which will improve the reliability of our estimates of the likelihood of an earthquake) and we also have a much better idea of how much the ground-shaking will attenuate with distance from the earthquake source. Consequently, even an update based only on the latest earthquake catalogue and set of ground motion relations could significantly improve the map and hence the standard.

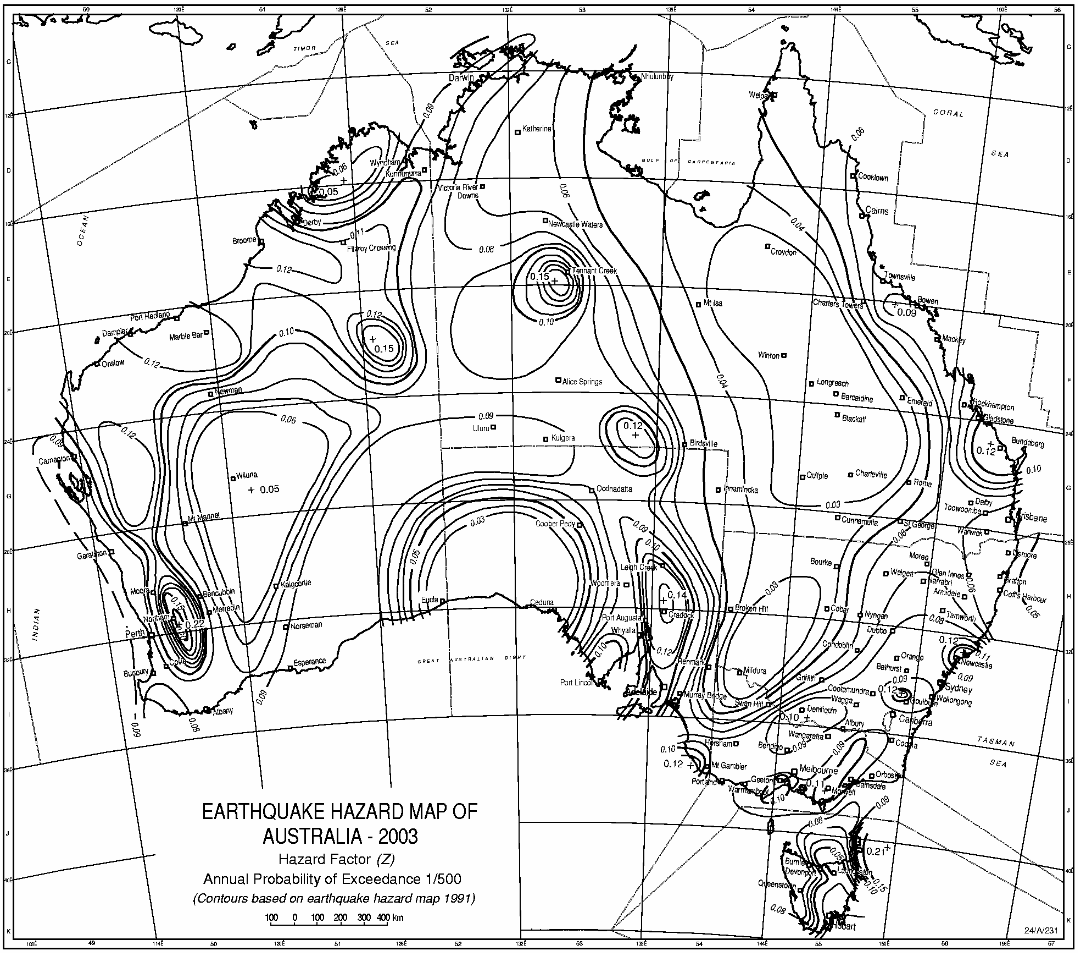

Figure 1 The current earthquake hazard map for Australia in AS1170.4. The map shows the peak ground acceleration (PGA) with a 10% chance of being exceeded per annum. This is equivalent to the PGA with about an annual probability of exceedence of approximately 1/500 (Building Seismic Safety Council, 2004).

DEFINITION OF AN EARTHQUAKE HAZARD MAP

A probabilistic earthquake hazard map shows the ground shaking which has a specific probability of being equalled or exceeded over a given period of time. Currently the map in AS1170.4 is a probabilistic hazard map showing the peak ground acceleration (PGA) from earthquakes with a 10% probability in 50 years of being exceeded on hard rock across Australia based on a Poisson distribution (Figure 1). This probability has a return period of 475 years, rounded to 500 years in AS1170.4. Future hazard maps for the code may wish to also show other measures of ground shaking, for example the peak ground velocity (PGV), or the acceleration at periods which are more likely to cause damage to residential structures. In the current standard, if the designer wishes to include site effects or consider the acceleration at different spectral or return periods, the hazard given by the map is multiplied by one or more scaling factors given by tables specified in the standard. In the future it could be expressed as maps for a series of different measures of ground shaking (e.g. PGA, PGV, PGD, the shaking with a period of 1s etc) and for different return periods. It could also be expressed for different rock or site conditions.

A scenario earthquake hazard map shows the level of ground shaking from a specific earthquake. Such maps are not used in the current standard; however they are often used by emergency managers for planning and preparation. Many of the inputs to a scenario hazard map are the same as a probabilistic one, thus developments in one help the other. However, since the standard does not currently include such maps, and is unlikely to do so in the future, they will not be discussed any further herein.

EDITIONS

The earthquake loading standard goes through an approximately 10 year cycle of updates. Therefore, Geoscience Australia proposes updating the national hazard map in a cycle tied to updates in the standard. The current proposal is that updates to the map should occur about twice every update cycle of the standard (i.e. every five years). In order to bring the current map into this cycle, Geoscience Australia proposes producing a new, updated map in about 2012, five years after the last major update of AS1170.4. Future updates to the map would then occur every five years thereafter (i.e. 2017, 2022, 2027, etc). Given the short timeframe, the map produced in a few years will be based on existing methods but with improved data. Maps produced beyond 2012 could involve much more significant changes to the methods used and thus to the maps.

The 2012 map will be submitted to Standards Australia for inclusion as an amendment to the existing standard, AS1170.4. It will be an updated map showing the PGA (equivalent to a response spectral period of 0s), on hard rock, with a 10% chance in 50 years of being exceeded (or equalled). Geoscience Australia will also produce at least two other maps at response spectral periods of 0.2s and 1.0s. This was suggested by the workshop in order to make the standard more consistent with world's best practice (i.e. the International Building Code).

Before the map is included in the code, both the map and associated assumptions will be submitted for international peer review in an appropriate scientific journal. The journal paper will include the maps designed for the code, but could include other measures of the hazard as time permits. For example, maps of other return periods, spectral periods or on different site conditions could also be included in the paper, even if such maps are not currently required for inclusion in the standard. The maps showing the hazard at other return periods in particular could be used to update the scaling factor tables which adjust the level of ground motion to one appropriate for return periods or spectral periods other than that shown in Figure 1.

In future years (2017 onwards) broadly the same process will occur. Namely the maps will be peer reviewed via publication in the scientific literature before submitted for consideration into updated versions of the Standard.

Preferred Time Frame

It is proposed that each map (2012, 2017, etc.) goes through a staged process of release:
1) Internal iteration within GA and the Australian earthquake hazard community
2) External iteration which will include feedback from external geological agencies (e.g. GNS, USGS and/or NRCan) and/or external peer review via a journal publication
3) Submission of the map or maps for inclusion in the next release or update of AS1170.4.

An outline of the approximate timelines for each activity that goes into a hazard map will be given in the following sections. When reading the timelines the following points should be borne in mind:

1. The work for the 2012 edition of the map is based on work done to date plus the assumption that current GA staffing numbers, skill sets and resources are maintained at current level for that period. Given the timeframe, the 2012 map will be a relatively small improvement over the current map.
2. The 2017 map will address all the major concerns with the current input data, particularly the current catalogue and the lack of a thorough validation of the existing ground motion equations. However, while this map will still be based on historic seismicity, greater input will come from the other areas listed here (neotectonics, site effects etc). Again, this is based on the assumption that current GA staffing numbers, skill sets and resources are maintained at current level for that period.
3. For the maps at 2022 and beyond, the science is much more aspirational. Consequently, the results of the basic research between now and then may greatly change the type of map produced from what is described here.

It is important to note, that if there are additional resources, either in GA, other agencies or universities, the science plan listed can be brought forward but the release schedule will remain the same (i.e. a new map every five years). If more resources are available, the new maps every five years will instead have much richer content and could involve much larger changes than those suggested here.

PRIORITY AREAS

Since Australia is large, some prioritisation of areas on which to focus efforts is required. In the short to medium term, the following broad regions will be Geoscience Australia's main areas of focus:

1. Southeast Australia – Victoria, the ACT and eastern NSW.
2. Southeast Queensland - including SE Queensland and northern NSW
3. South Australia - Adelaide region.
4. Southwest WA – Perth region

These were chosen on the basis of population density and the level of hazard expected in each area. The areas chosen have been the most active ones over the last hundred years and all include major cities and other critical infrastructure. In the long term, other areas may be added to this list depending on population growth, presence of critical infrastructure (e.g. lifelines) and/or economic importance.

Short term Activities for the 2012 hazard map

This section will list the achievable short term goals for the 2012 map. They are broken up into three streams: the earthquake recurrence model, the ground motion model and local site effects.

STREAM 1 – EARTHQUAKE RECURRENCE MODEL

The earthquake recurrence model is used to estimate the likelihood that an area will experience an earthquake at or above a given magnitude. For the 2012 map the model will be entirely based on statistical analysis of the existing earthquake catalogue, with as many improvements to the catalogue as can be completed in the time available.

Inputs

The Earthquake Catalogue

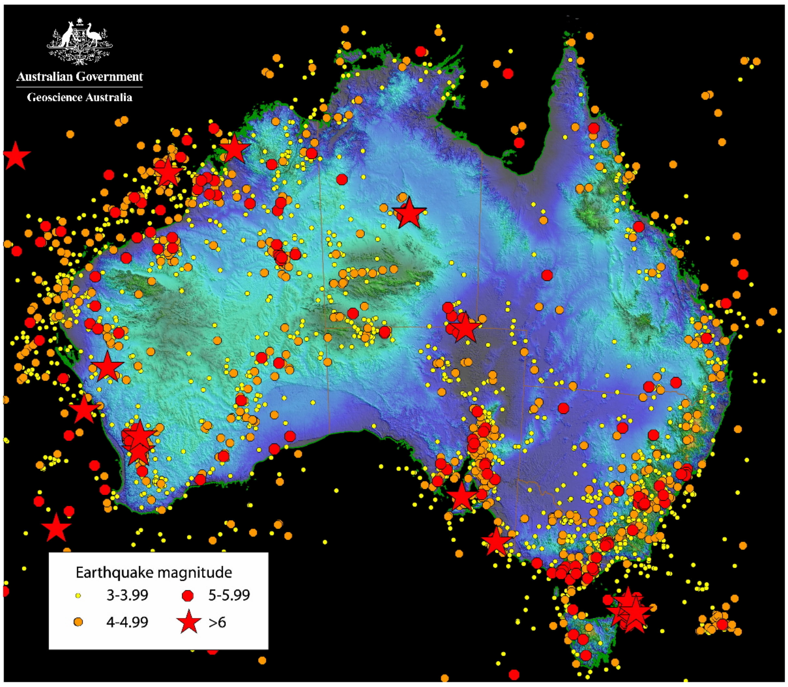

Figure 2 Australian earthquakes in the GA catalogue between 1800 and 2000.

For the 2012 map the catalogue will simply be a list containing the longitude, latitude, depth, date and preferred magnitude for all known Australian earthquakes in the historic catalogue. The workshop proposed that the 2012 map use a merged version of Gary Gibson's catalogue and the most up to date version of Geoscience Australia's own catalogue (Figure 2).

One of the more important requirements for this catalogue is that the magnitude scale used for all earthquakes is consistent. The majority of magnitudes in Australian earthquake catalogues are "local magnitudes", ML. They use either Richter's (1935) original definition for earthquakes in California or use equations that were later modified to be more appropriate for Australia. Consequently, magnitudes listed in the catalogue have been estimated using different local magnitude attenuation formulae for earthquakes in the same area depending on when the earthquake occurred. Given the time limitations, recalculating the magnitudes for the entire earthquake catalogue from raw data will not be possible. Instead a first-order (6-12 month) study should be undertaken to determine the extent to which this is required and whether it is possible to produce straight-forward corrections to revise magnitudes of older events (if needed). If this is not required then the current magnitude values can be used as they are. Earthquakes in priority areas will be considered first. The purpose of these corrections is twofold:

1. to mitigate apparent distance biases in existing local magnitude formulae, and
2. to enable the conversion of as many of the earthquakes as possible to an `approximate' Mw scale instead of the current mix of magnitude scales used in existing catalogues.

Source Zones

The 2012 map will use the source zone method for calculating the likelihood of an earthquake. In the source zone method Australia is divided into zones based primarily on the seismicity. A recurrence model (Gutenberg-Richter *a* and *b* values and the maximum magnitude, Mmax) is then calculated for each zone based on the observed rate of earthquakes within the zone. However, the workshop did not agree on the best source zone subdivision to use. Therefore, over the next few years, Geoscience Australia will select or create one or more subdivisions of Australia for the 2012 map. While the zones will be primarily based on the contemporary seismicity, other information may also be taken into consideration. One possibility would be to start with an existing source zonation such as Gaull *et al* (1990) or Brown & Gibson (2004) and then to refine one or the other. It was suggested at the workshop that whatever subdivision is used, each zone should have:

1. a minimum of 20 earthquakes,
2. at least one earthquake above 5.0,
3. a Gutenberg-Richter *b* value of at least 0.7 and
4. a correlation coefficient (which measures the fit to the Gutenberg-Richter equation) above 0.95.

An additional decision that needs to be made for each zone is the maximum possible earthquake magnitude that could occur within that zone. This will be based on the maximum size of any earthquake as determined from any neotectonic feature in a geologically similar area, as well as the maximum historic earthquake that has occured in that zone.

STREAM 2 – GROUND MOTION PREDICTION EQUATIONS

Ground-motion prediction equations (GMPEs) relate a specific measure of the expected ground shaking to earthquakes, typically based on magnitude and distance. They are also sometimes called ground motion attenuation equations or simply attenuation equations. In active crustal regions with an abundance of recorded ground-motion data, GMPEs are typically derived from empirical regressions of the observed data. However, in stable continental regions, like Australia, the observed ground-motion dataset is not generally sufficient to develop reliable GMPEs based on recorded data alone. Consequently, in these regions, we often rely on ground-motion models that use source and attenuation properties derived from smaller, more abundant earthquakes, and use physical assumptions (or source scaling) to extrapolate observed ground-motions to larger earthquakes through stochastic simulation.

At present, only southeast Australia has enough earthquake recordings to estimate the frequency-dependent attenuation of weak-motion seismograms. High-quality digital datasets recorded over a range of distances and azimuths is more limited for South Australia and Western Australia and is very rare for the rest of Australia. Due to the limited number of large magnitude earthquake recordings, the magnitude scaling for GMPEs for much of the country is presently quite uncertain.

Somerville *et al* (2009) employed earthquake source models representative of Australian earthquakes and regional crustal velocity models to simulate broadband strong-motion records for several tectonic elements across Australia. These simulations were subsequently regressed to develop regionally specific GMPEs. The Somerville et al (2009) approach provides an alternative method to develop GMPEs in regions of low seismicity.

The use of GMPEs, which have been developed for other regions (e.g., eastern North America), may be beneficial for incorporating epistemic uncertainty into the hazard model. However, the usage of these models may introduce biases owing to differences in crustal structure (i.e., velocity profile) and source characteristics of the earthquakes (e.g., stress drop and depth distribution). Differences in crustal structure will tend to have a more dominant effect on ground-motion amplitudes at larger source-receiver distances. Furthermore, the distribution of earthquake focal depths will become a significant variable in Western Australia, which is typically characterised by very shallow seismicity (focal depths generally less than 3 km) and subsequently, a higher contribution of long-period ground-motions. An alternative approach for ground-motion prediction is to modify GMPEs developed in other regions so that they can be applied in Australia. This "hybrid empirical model", first introduced by Campbell (2003), uses the ratio of stochastic or theoretical ground-motion estimates to adjust empirical ground-motion relations developed for a *host* region to use in a *target* region. This technique could potentially be used to modify GMPEs developed for the NGA-West program, for example, so that they are consistent with ground-motion characteristics for Australia.

Inputs

Existing Ground Motion Prediction Equations

The workshop agreed that the 2012 map should use existing published and well accepted GMPEs. The two latest GMPEs for Australia are the Somerville ground motion equations produced for GA in 2008/09 (Somerville 2009) and the equations produced by Geoscience Australia internally (Allen et al, 2006 and Allen et al, 2007). The Next Generation Model for western North America (NGA-West) may also be considered for zones in eastern Australia. For western Australia, previous studies by Hao and others should also be taken into consideration (Gaull et al 1995, Hao & Gaull, 2004a-d, Sinadinovski et al 2005 and Liang et al 2007). As time permits, these equations will be validated by checking them against existing Australian ground motion data records in the priority areas. The results of this validation will determine whether only one of these GMPEs is chosen or whether the map includes several of them by using a weighted logic tree (similar to what is used in the US Earthquake Hazard Map, see Petersen *et al.*, 2008).

STREAM 3 –SITE RESPONSE

This stage converts the bedrock or hard rock shaking into the shaking that would actually be experienced by a building due to the effect of the underlying regolith (i.e. soils). Including the effect of regolith can thus produce a more realistic estimate of the actual level of ground-shaking that a building could experience in an earthquake. Local site data at seismic stations is also useful when improving future GMPE since it assists with accurately removing the effect of local site conditions from a seismic record. Currently there are two national scale site models that use proxy information to define earthquake site response, one based on mapped geology (McPherson & Hall, 2007) and one based on topographic slope (Allen & Wald, 2007; Wald & Allen 2007). Both require validation and both currently have a relatively coarse spatial resolution.

Inputs

For the 2012 hazard map, an improved site response map will not be required since the map in the AS1170.4 is only calculated to a single site class, B. However, work on the long term incorporation of site effects into the map will continue. For example, the proposed 2010 joint USGS-GA shear wave survey will collect additional data in order to validate the existing national site class maps. Data collected at the seismic stations from this survey will also assist with validating the GMPE mentioned above. The effect of the site conditions should also be validated against observed seismic data where available, such as was done by Gaull *et al*, 1995.

STREAM 4 – SOFTWARE DEVELOPMENT

Given the timeframe, Geoscience Australia's preference is to use the existing code, EQRM, for the production of the hazard map. EQRM is discussed in Robinson *et al* (2006) and can be downloaded from http://eqrm.sourceforge.net/. The current version of EQRM needs to be modified to include the new GMPE but it otherwise does not require further changes. Cross-validation with other codes would be desirable if time allows but is not critical. Some additional code may also need to be obtained or written for the statistical analysis of the earthquakes within each source zone (outlined above) depending on the method finally chosen.

STREAM 5 – PUTTING IT TOGETHER

The combination of all these activities should result in a significantly improved hazard map overall. The earthquake catalogue has grown considerably, and new estimates of earthquake activity should be much better constrained. The earlier maps were based on ground motion prediction equations that did not use any Australian data. This need not be the case since new equations are now available which do include Australian data. Overall, these two aspects alone justify updating the map.

Long Term Activities for the Map (2017 onwards)

STREAM 1 – EARTHQUAKE RECURRENCE MODELS

As our understanding of earthquake hazard becomes more sophisticated, the number of inputs needed will grow and cover more diverse scientific disciplines than those traditionally used for seismic hazard assessment. There will be an increasing trend to more data which describe not only the earthquakes but also faults, the Australian continent and the stresses acting upon it. For the purposes of this section, “long term” refers to activities for any hazard map from 2017 onwards.

Inputs

Earthquake Catalogue

No matter what other information is used for hazard assessment in the future, there will always be a need for a catalogue containing all known information about earthquakes that have occurred in Australian history. However, as our models become more complex, more information than just the magnitude and location will need to be incorporated into the catalogue. For example, the earthquake’s focal mechanism, the uncertainty ellipsoid and the isoseismal intensity maps from the earthquake can also provide much useful information about an event. At a minimum the catalogue needs to contain our current best estimate of the spatial location of the hypocentre and the time at which the rupture began. As our methods and data (particularly the seismic velocity model) improves, this will need continuous updating to ensure that the information in the catalogue is as accurate as possible. A consistent magnitude (Mw) is also needed, preferably one calculated from the initial raw data (i.e. waveforms). As mentioned, the magnitudes in the current catalogue were calculated using a range of different scales depending on when the earthquake occurred and which agency calculated it (Leonard, 2008). It will be important that exactly the same, repeatable method for location and magnitude is used consistently for all earthquakes in the catalogue. This will require metadata, such as the instrument response for seismic stations, going back as far as possible. The feeling at the workshop was that ensuring the consistency and quality of the catalogue is one of the key requirements for the map and will be a main driver for many years.

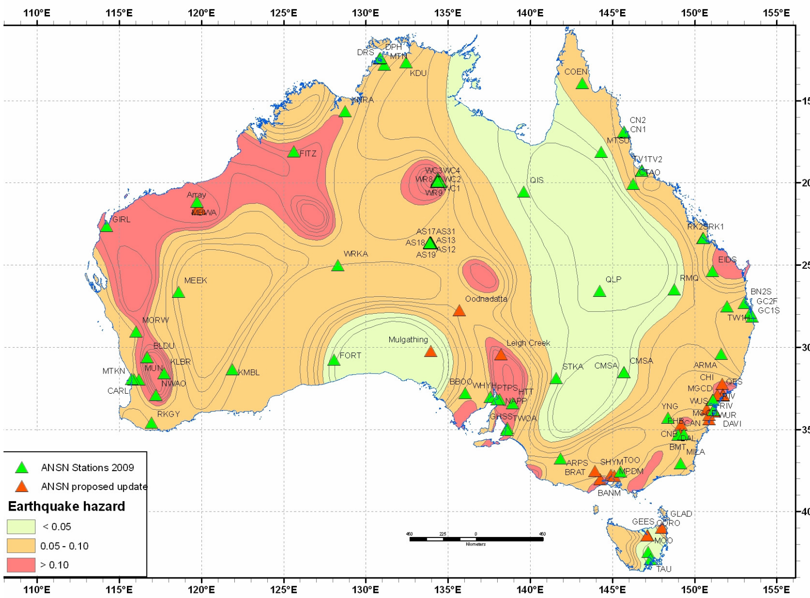

Figure 3 The current Australian National Seismic Network (ANSN) shown as green triangles on top of the McCue *et al* (1993) national earthquake hazard map.

Another area in the catalogue that could be improved is completeness. A catalogue is "complete" for all the earthquakes above a given magnitude when it captures all the earthquakes in an area that have happened over a given period of time above that magnitude. The magnitude value at the cut off is called the threshold magnitude for the catalogue. We would expect to capture all the earthquakes above the threshold and only a fraction of those below it. Lowering the threshold for at least the priority areas would increase the number of earthquakes in that area and greatly improve the statistical reliability of the earthquake recurrences model derived from the catalogue for that area. It was pointed out at the workshop that since the 1990s there has been a decrease in the number of local earthquakes detected, located and added to the catalogues, possibly because of an increase in the threshold magnitude for some regions due to some local networks closing or changing observatory practices. Reversing this trend would be of great use to the earthquake hazard maps which are based on catalogue data. The current national network is shown in Figure 3.

Earthquakes are not point sources; they have a spatial extent and can have complex rupture histories. In the much longer term, to validate our rupture models we will need even more information (wherever available) about the earthquake including its rupture length, width, slip distribution and rupture time histories. This information is sometimes called a finite fault model for the earthquake (as opposed to a point source model). Globally, finite fault models are becoming routine observatory practice for large events. The workshop recommended that this should also be done for the large historic events where enough data is available.

In order to produce this extra information, we need to put in place instruments and software that can collect data of the right quantity and quality, at least for the priority areas. The workshop recommended that a high density sensor network (i.e. strong and weak motion seismometers, GPS sites, etc) should exist in areas of greatest need (the priority areas) and/or those with the greatest chance of success (e.g. aftershock sequences or areas of ongoing seismicity) so that sufficient data can be collected to improve our models of both earthquake recurrence and ground shaking.

Timeline

2017:

- Routine calculation of Mw for new earthquakes where appropriate should be in place.
- The workshop recommended that retrospective Mw and hypocentre estimates be produced for all events in the current catalogue (where the necessary data is available) and that consistent retrospective ML values for all other events are calculated as well. The latter can then be converted to an `approximate' Mw to make the catalogue as consistent as possible.
- Data (including waveforms) and metadata accessible and discoverable, preferably online.
- The workshop proposed a "Did You Feel It?" website similar to the USGS to encourage more intensity data to be collected, specifically with a mechanism for providing near-real time feedback to encourage use. Ideally, this should be place well before 2017.

Beyond 2017

- Finite fault models for important historic events should be undertaken and routine processing should be in place for future (large) earthquakes.
- Continual maintenance and updating of the catalogue will be needed as new techniques and methods become available to extract new or better information about earthquakes in the past and present.

Fault catalogue

Most seismologists agree that earthquakes occur on pre-existing faults. Therefore, the more information we have about faults the more we can learn about why earthquakes occur where they do. This catalogue should contain information about faults known to be active (according to some specified definition) and those which have been shown (e.g. through field work and/or numerical modelling) to be inactive. The likelihood of activity could be expressed as a probability from say 0 to 1. The numbers of faults (including blind ones which have little to no surface expression) across Australia is very large, so the process of creating this database will be substantial. As with other areas, focus will initially be on large faults in priority areas. Currently some fault information exists but it is somewhat scattered rather than contained in a single catalogue.

In summary, the fault catalogue should at least include the following information:

- 3D fault geometry (where known)
- Activity probability
- Known rupture history (e.g. average recurrence interval, any evidence for episodic behaviour)
- Displacement per event plus total displacement in the current stress field

Timeline

2017

- The fault database should exist and begins to be populated. The focus will be on large faults in priority areas.

Beyond 2017

- The fault catalogue should by now be well-developed for the priority areas. This catalogue is likely to be critical for finite fault modelling and geodynamic modelling, both of which are expected to become increasingly important for the hazard maps from 2022 onwards.
- Faults will continue to be added to the catalogue as more information becomes available.

Stress data

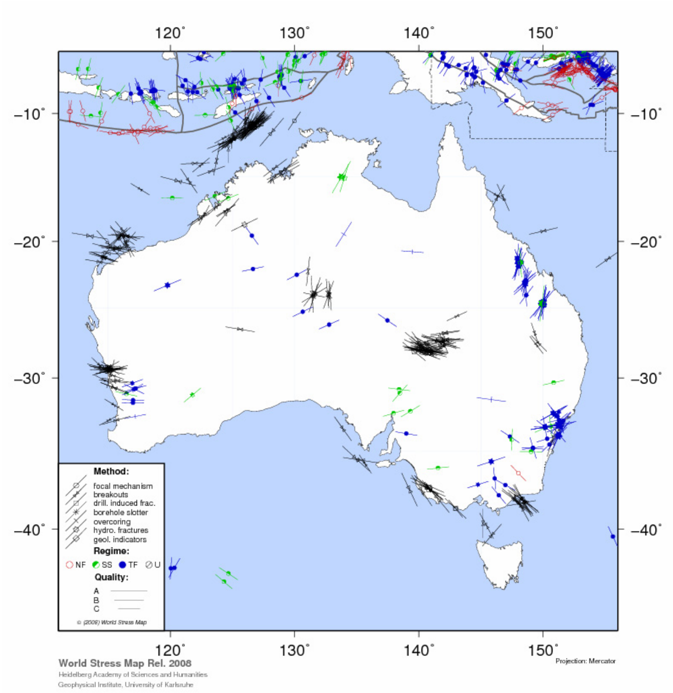

Figure 4 The direction of maximum principal stress across Australia (Heidbach *et al*, 2008).

The direction and magnitude of the stress (the stress tensor) drives the deformation of the plate and thus the earthquakes. Current stress data is generally sparse and the data that does exist is heavily concentrated in specific areas (Figure 4). National (the Australasian Stress Map, http://www.asprg.adelaide.edu.au/asm/) and international (the World Stress Map http://dc-app3-14.gfz-potsdam.de/) stress databases already exist, therefore there is no need to replicate them.

However, there does remain a need to populate them, particularly in priority areas with sparse data.

Timeline

Beyond 2017

- In order to fill in the gaps in our knowledge of the stress field, focal mechanisms of earthquakes can be a useful constraint. Inverting for stress within priority areas should begin by 2017 and, like fault data, is likely to become increasingly important from 2022 onwards. This is an area which an enhanced Geoscience Australia's seismic network can make a major contribution to understanding the stress in the continent.

Strain rate data

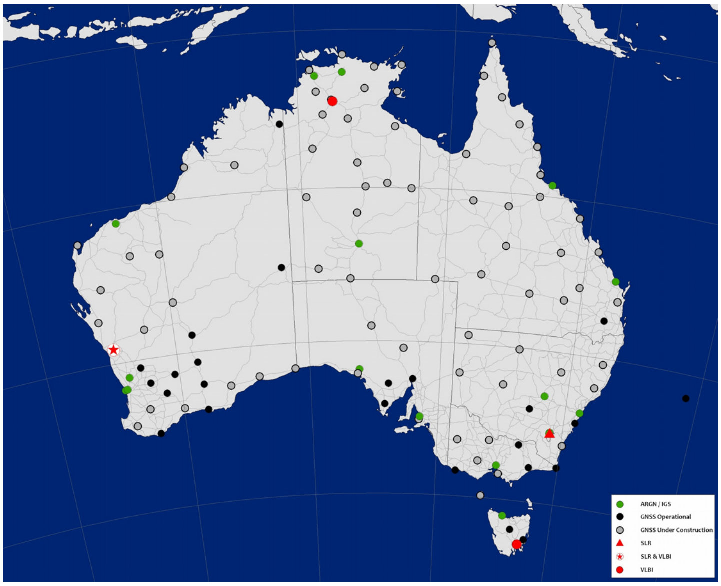

Figure 5 The current (coloured circles) and proposed (grey circles) network of continuously operating geodetic stations across Australia.

Geodetic data (GPS, InSAR, etc.) is a direct measure of the rate at which the plate is deforming, albeit over short timescales (years to decades). The current and proposed network of continuously operating geodetic stations is shown in Figure 5. Currently there are also high density networks of GPS monuments in southwest WA (Figure 6) and in southern South Australia (Flinders and Mt Lofty Ranges, Eyre and Yorke Peninsulas). Another network of monuments is currently being installed in Victoria (Otway and Gippsland Basins). Each monument is reoccupied every four years on a campaign basis. The rate of deformation within the plate is likely to be too low for very reliable direct measurements over short timescales (i.e. between campaigns). However, as measurements are taken over much longer timescales the amount of deformation will eventually become large enough to measure accurately.

Timeline

2017

- The southwest WA array will have been reoccupied again and a well-constrained geodetic estimate of strain rate for the area should be available (depending on the size of the signal relative to the measurement uncertainty). The other arrays will also have been revisited and initial results may be available from them as well.

Beyond 2017

- As the existing networks are re-occupied, at some point a well-constrained estimate of the strain rate will become available for all of them (again depending on the size of the signal). The strain rate estimates can then be directly included as a constraint on the geodynamic modelling and/or as a direct input into the hazard map. The strain rate values will continue to be refined over time and as techniques improve.

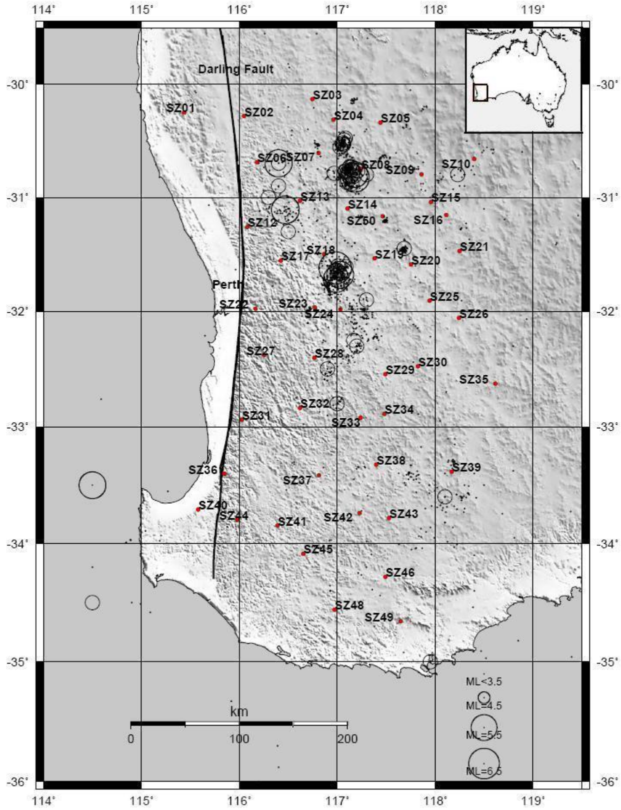

Figure 6 The network of GPS monuments in the southwest seismic zone to the east of Perth (red dots) . Also shown are the earthquakes for this area (open circles).

STREAM 2 – GROUND MOTION PREDICTION

Inputs

Waveform (time-series) data

The full time-series data from seismic stations needs to be routinely stored so that earthquake waveforms can be extracted as needed for research. This time series database will need to link into the earthquake catalogue mentioned earlier. This database should include all seismic data collected by all stations, including strong motion data. This database should be in place by 2017 and will need to be regularly updated and maintained. Both the waveform and hypocentre databases will also need some simple tools for ingesting and accessing the data so that they are easy to use both internally and externally to GA.

Refined Ground Motion Prediction Equations (GMPE)

More work can be done to refine the existing GMPE, particularly testing against recorded data in WA, Qld and SA. This should lead to a much better model, or suite of models, for each priority area. In addition, two international initiatives, the Global Earthquake Risk Model (GEM) and the Next Generation Model of Eastern North America (NGA-East), should be released in the next 5-10 years. Both will provide a new set of tools, relations and recommendations that could assist with improving the existing, Australian specific, GMPE.

Timeline
2017

- Validation against recorded data for WA, Qld and SA should be completed. Any additional earthquakes that occur in this period could also be included in the validation process. This, plus the international initiatives mentioned above, should lead to an updated set of GMPEs for Australia by 2017.

Beyond 2017

- Research will continue into improving the GMPEs, possibly by including previously unconsidered factors such as basin or topographic effects (based on 3D numerical models - see below). Careful validation of the GMPEs against a wide range of observations (including teleseisms, local earthquakes, isoseismals and strong motion records) will continue to be needed in the future.

3D Numerical Models of Ground Motion

One of the fundamental problems facing GMPE is that it is unlikely there will ever be enough observational data to completely constrain the ground motion empirically across the whole of Australia or even just the priority areas. One solution to this problem is to move towards including fully 3D numerical models of the ground motion based on the best available data. These models would complement the existing methods based on using GMPE. The 3D models will be computationally intensive and require large amounts of data, but they are likely to be the long term future of ground motion modelling. The actual ground motion is a combination of a variety of factors (e.g. basin and topographic effects) which will never be completely captured in an equation but could be captured by a full numerical model.

Timeline

2017

- Initial numerical models with the capability of modelling ground motion should be in place. These models would be useful for relocating earthquakes and reassessing magnitudes, as well as modelling the ground motion. Validation of this model is likely to be the main focus up to 2017.

Beyond 2017

- Depending on the above and the availability of data, it may be possible to have well-constrained fully 3D models for the priority areas (or for a small, important section such as a major city). This is similar to what has been developed for California and is used in programs such as "Cybershake" (Graves *et al.*, 2008). The model could be used to generate a priority area scale hazard map where the ground motion for all earthquakes in the earthquake forecast or synthetic catalogue is numerically calculated instead being derived from a set of GMPE.
- At an even later date, a 3D model will eventually become possible for use in ground motion prediction and earthquake location/magnitude estimation for the entire nation. From here on, the main effort will be on further improving and refining this model.

Seismic Velocity and Q models for Australia

Velocity models will be a required input for both the 3D models of strong ground motion and for improved earthquake locations. These models can be derived by inversion of seismic data, thus they depend on the earthquake waveform database. Work will focus of both evaluating and enhancing existing 1D velocity models for Australia and move over time to more elaborate models, ultimately to fully 3D ones. Models of Q (a measure of the anelastic attenuation of seismic energy in the Earth) will also be important for modelling the ground motion at large distances and at certain frequencies. Both velocity and Q models will be critically important for several of the other areas already mentioned (earthquake location, magnitude estimation and strong ground motion modelling).

Timeline

2017

- The 1D models for each of the priority areas should be completed. Some preliminary work on 2D or 3D models for key areas should have started

Beyond 2017

- Key areas (e.g. major cities) should have a 3D velocity model available for use in the numerical modelling so that factors such as the effect of basins on ground motion can be included.

STREAM 3 – SITE RESPONSE

Local site effects are currently included in the code as a multiplier to the hazard on bedrock. Work on improving the multipliers will initially be the main focus. In the long term, national scale maps with validated site response will become available and should be considered for direct use in the standard. Note that, ultimately, local governments and the private sector will need to conduct the site response measurements for their particular communities or engineered structures.

Inputs

Timeline

2017

- The national maps will be updated to a much higher spatial resolution than the current ones, particularly in priority areas. Testing and refinement of topographical- and geological-based classifications may contribute to this improvement. This work will include quantifying the relationship between geology/topography and the seismic velocity structure for different areas of Australia. There is scope to use these data sources in tandem, with geological information potentially being used for validating topographic classifications. The workshop recommended that these new national site classification maps use an expanded NEHRP scheme (Building Seismic Safety Council, 2004; Wills *et al.*, 2000) which includes site classes A and AB.
- The workshop also recommended that passive or active (e.g. SASW/Nakamura/SPAC). V_s^{30} (average shear wave velocity to 30m) measurements should be established as a rolling program so that these national and regional maps have more data for validation. Rather than trying to measure V_s^{30} everywhere, an approach that defines a distribution of values for each site class is likely to be taken.
- The workshop further suggested that State Government and private sector geophysical and geotechnical data should be compiled so that it can also be used for validation. Another two sources of validation data are the seismic waveforms observed at stations from actual earthquakes and intensity data.
- In brief, the main area of work over this period is testing of the national site classifications schemes with as much measured near-surface data as possible.

Beyond 2017

- As the 2D/3D numerical modelling aspect develops it will eventually have the spatial resolution to directly include the site effects. This means that the site classification data will need to be ready to feed into those models once that happens. These models will require V_s profiles down to at 100m (or to the depth to hard rock whatever is greater), rather than just the average in the top 30m.
- The workshop also suggested that a borehole array in the priority areas should be considered in the long term. This would allow ground motion level as a function of depth to be measured and would provide excellent, albeit expensive, data for validation.
- Beyond 2017 there will be need to continually refining and validate the national site class map as new data becomes available. Updates to the national site class map will be published as needed.

STREAM 4 - NEOTECTONICS

Another way to bypass the problem caused by the relatively short length of the catalogue is through neotectonic research. This program seeks evidence of prehistoric earthquakes in the landscape, and then progressively trenches and dates those structures to understand more about the earthquake history of Australia. One of the main contributions in both the short and long term is the ability of this method to improve our estimates of the maximum possible magnitude earthquake (M_{max}) for a given area. The largest possible earthquake in an area must be at least as large as what has been observed, and neotectonics allows us to look back tens of thousands of years or more. The neotectonic features can also be used to define different domains in Australia which have consistent properties such as rupture length and vertical displacement (c.f. Shyu *et al*., 2001). Geoscience Australia currently maintains a database of neotectonic features internally.

Inputs

- High-resolution Digital Elevation Models (DEMs) for the priority areas (e.g. LiDAR)
- Near-surface geophysics data (ground penetrating radar, resistivity, high resolution seismic refraction/reflection, electromagnetics)
- Palaeo-seismological investigations of faults
- Dating (OSL, ^{14}C, Cosmogenic Radionuclide, etc.)

Timeline

2017

- The main focus up to 2017 will be to refine the statistics defining the different neotectonic domains. An updated version of the domains model should be completed by 2017.
- Features in the neotectonic database will be ranked in order of importance and progressively trenched. Ranking may include data from geodynamic modelling, the neotectonic confidence index and seismic hazard assessments. Features which may make a large difference to the earthquake hazard in a few key cities or to key infrastructure should be targeted first.

Beyond 2017

- The results from the neotectonics program will ultimately be directly included in hazard assessments on a routine basis. The results will be particularly important for maps at the longer return periods where large earthquakes on specific faults can make a significant contribution to the hazard.
- The neotectonic domains model will continue to be refined and updated every five years or so.
- Validation of whether or not features in the landscape are actually caused by an earthquake will remain the main focus of this activity.

STREAM 5 - GEODYNAMIC MODELLING

Geodynamic modelling refers to the process of modelling the stress and consequent strain rates acting on the plate and using those models to estimate the likely future rate of deformation and thus the seismicity. One advantage of such modelling is that it allows a seismic hazard map to be created which does not (directly) depend on having a long seismic catalogue to calculate the earthquake probability empirically. The main disadvantage of the method is the large amount of data needed for such a calculation and the amount of software and hardware needed to do the calculations. Such modelling is still in its infancy and the main focus for the medium term is on developing such models and validating them. A pilot 2D geodynamic model of the strain rate across the Australian plate based was published in 2004 (Burbidge, 2004). However that model had a relatively coarse resolution. Work from here on will be focussed on improving the 2004 model.

Inputs

Geodynamic modelling uses many of the inputs already described but also needs additional data to help constrain the temperature and rheology of the plate, and the magnitude of the forces acting upon it. The model requires information such as the heat flow, heat production with depth, data constraining the lithological layering thickness and properties (e.g. depth to the Moho, density profile of the crust) and properties of the nearby plates and the underlying mantle (e.g. plate velocity). At its core this modelling aims to improve out understanding of the basic principles of why earthquakes occur in Australia in the places that they do.

Timeline

2017

- A more sophisticated plate-scale geodynamic model than the 2004 model should have been developed for the whole plate by about 2017 (i.e. one with a higher resolution and better input data). More detailed "pilot" models of the high priority areas should also have been completed by this stage.

Beyond 2017

- As this activity continues, more advanced time-independent models focussing on the priority areas will become available. Once they are sufficiently validated, they can be used as a direct input into long return period hazard maps for those areas and eventually the continent.
- In addition, work will continue on adding time-dependency to the models (so the strain-rate goes up or down through time). Such models will need to include factors such as the elasticity of the crust, stress interactions between faults and fault healing processes which may lead to temporal clustering of large earthquakes. To some extent, these models can be validated against the patterns observed in the Australian earthquake catalogue. However, the catalogue is unlikely to long enough to see these patterns clearly (hence the need for modelling). More active areas, with a more comprehensive catalogues in geological similar environments, may also need to be used for validation purposes. If these time dependent models can be sufficiently validated, then they could also then be included into hazard assessments for the shorter return periods as well as the longer ones.

STREAM 6 – IMPROVED RECURRENCE MODELS

In order to put the map together, there needs to be, in parallel, continual development and refinement of the computer codes required to produce the hazard maps. This includes a code which ultimately directly includes faults, time dependency and more sophisticated ground motion models as required. This will be obtained by a combination of code development of existing programmes (e.g. EQRM or EZ-FRISK™) and/or their replacement with new codes developed locally or by international efforts in this field (for example the Global Earthquake Risk Model, GEM).

One of the most important questions is how to go from a catalogue of earthquakes (and possibly other data) to a recurrence model which estimates earthquake likelihood. Currently most methods assume earthquakes have a Poisson probability distribution (i.e. are independent so that one earthquake does not change the probability of the next) and use some method to smooth the seismicity from a catalogue, usually into source zones. However, there is no consensus on the "best" way to do this.

Another theory is that earthquakes are not Poissonian but occur in clusters. Future hazard maps are likely to become time dependent (see above) and require much more sophisticated earthquake forecast and activity models. The inputs required for this are unclear but probably include all of the above data plus other data describing the faults and/or fluid pressures across Australia. More fundamentally, including time dependency into hazard assessments requires some major advances in our understanding of earthquake behaviour. If the uncertainty in the time dependency is large, then the probability will effectively become Poissonian again.

Timeline

2017

- A numerical hazard assessment code which includes faults and 3D source zones should be developed or obtained externally and be in regular use. The model needs to integrate with all the component datasets and the output should be compatible with risk assessment codes.

Beyond 2017

- From here on there needs to be continual refinement and validation of advanced hazard codes and recurrence models. This will include a move towards time-dependent models and away from the current time-independent ones.
- Fundamental research into earthquake likelihood will continue up until 2022 and well beyond.

Conclusion

In summary, there are a large range of inter-disciplinary activities that can be undertaken in both the short and long term to improve our understanding of the level of earthquake hazard faced in Australia. These activities have in common the need for additional data, validation and research. Many of the issues here will require many years or decades of research and testing. However, by progressively releasing updated maps at regular intervals tied to the standard, these issues can gradually be addressed over time. There is still much uncertainty about some fundamental issues around earthquake likelihood and the propagation of the seismic energy. However, these uncertainties can be reduced over time. Focus will initially be on determining which of the numerous input parameters contributes the most to the uncertainty and focusing on them one by one. Over time, this will ultimately lead to a much more sophisticated, accurate and detailed understanding of the true level of the earthquake hazard faced by Australian communities and infrastructure.

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