Seismic hazard mapping in Australia, the Southwest Pacific and Southeast Asia

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Abstract
Where available, regional assessments of earthquake hazard were compiled into the final map and elsewhere a knowledge of the tectonics and site specific studies, often for dams or mines, were cobbled together to produce a regional map. Cornell's method was used with a variety of attenuation relationships chosen for their suitability depending on the tectonics. Various versions of McGuire's program FRISK88 or similar programs including the USGS SEISRISK and the Seismology Research Centre's GMREC were used for the computations.

Key words *earthquakes – Australia-South Pacific-Southern Asia – seismic hazard assessment – UN/IDNDR*

1. Introduction

After the initial GSHAP proposal had been adopted, an additional regional centre was established at AGSO Canberra, region 10, which included intraplate Australia, and surrounding interplate countries including New Zealand, Fiji, Vanuatu, Solomon Islands, Papua New Guinea, Indonesia and the Philippines. Region 10 country representatives were invited to a meeting convened by the regional coordinator David Denham and held at the Seismology Research Centre, Melbourne 23-24 November 1995. David Denham agreed to seek resources to carry out the GSHAP goals identified by the meeting.

AGSO hired a mapping specialist for 6 months and produced a series of maps of Australian epicentres superposed on digital geophysical data sets of the continent; gravity, magnetics, elevation, geology and crustal elements. This exercise demonstrated that there was no obvious correlation between the seismicity and the geology of crust and upper mantle in the region which was disappointing. Checks were done that FRISK88 and GMREC produced the same results with the same model, which they did, and sensitivity studies were done to assess the influence of different values of standard deviation in attenuation on the results.

Due to lack of resources, further progress was slow with some of the individual countries preparing their own hazard assessments until the GSHAP meeting during IASPEI in Greece when the deadline loomed nearer and compilation of these various separate activites commenced. Many of the developing countries had no resources to compile the maps so they were collected and digitised at AGSO as described above and the files concatenated into the world map by Kaye Shedlock at the USGS.

2. Tectonic setting

In the following brief summary of the tectonics of the region we follow the tectonic style from the Macquarie ridge in the southeast to the Indonesian arcs in the northwest around the core of the Australian plate occupied by conti-

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nental Australia. The earthquakes, volcanoes, ground deformation and tsunamis that can be so destructive in the region all result from the interaction of four major plates; the Pacific, Australian, Philippine and Eurasian plates (fig. 1). The tectonic setting is beautifully illustrated in a series of maps of the circum-Pacific region (Halbouty, 1981).

The circum-Pacific seismic and volcanic belt extends from the Macquarie ridge through New Zealand to Fiji, and from Vanuatu to the Solomon Islands and Papua New Guinea. This is a convergent boundary with a pole of rotation for the Pacific/Australian plate interaction near the triple junction south of Macquarie Island resulting in 4 to 5 cm/yr of shortening at the latitude of New Zealand increasing north to 10 cm/yr at the latitude of Bougainville. This belt is characterised by long seemingly linear trench segments offset by transform faults and/or back arc basins with reversal of subduction from one trench segment to the next.

Southwest of New Zealand the Puysegur trench marks subduction of the Australian plate

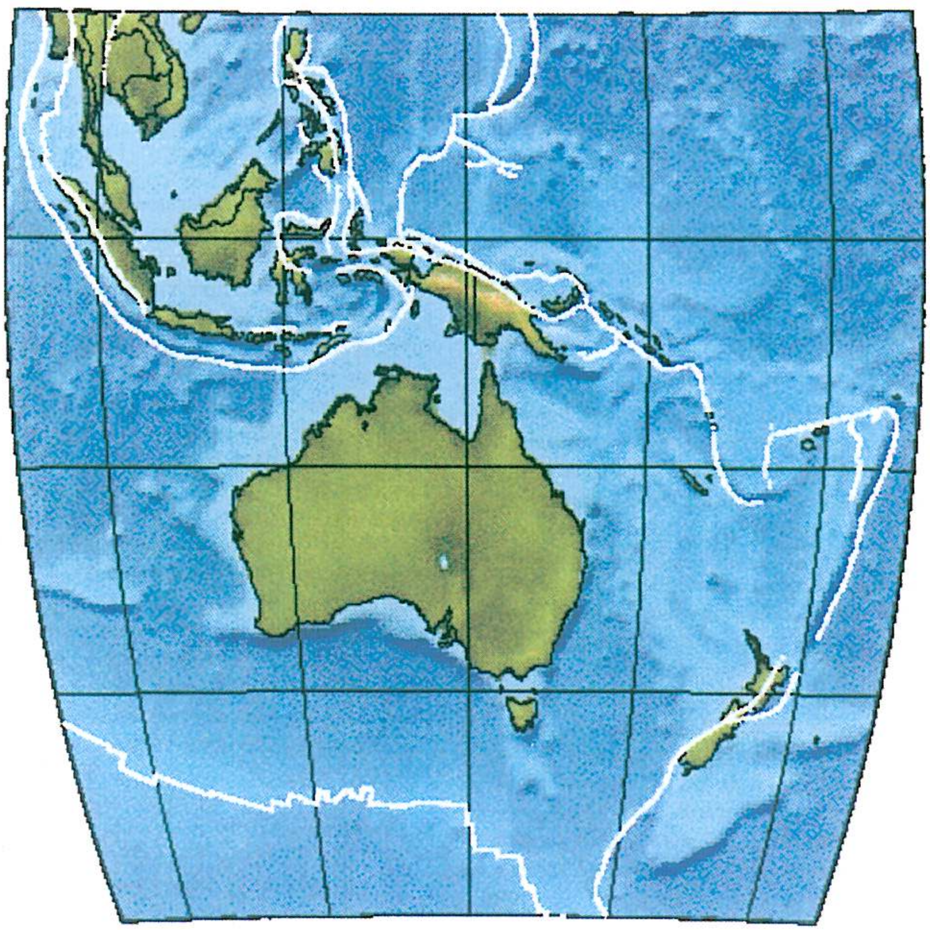

Fig. 1. Geographical coverage and main tectonic features and plate boundaries for the GSHAP Region 10: Australia-South Pacific-Southeast Asia.

beneath the Pacific plate but in the south island relative motion is taken up on the Alpine transpressive fault (notable for the lack of large earthquakes this century). The Alpine fault splays into a system of predominantly dextral faults including the Wellington fault which extend from the north of the south island through the north island. The Hikurangi trench east of the north island reverses the subduction polarity *i.e.* Pacific dipping under the Australian plate with active back-arc spreading above the Benioff zone in the Taupo volcanic zone (Walcott, 1978). Great shallow earthquakes have occurred in the last two decades along segments of the plate boundary both north and south of New Zealand but none in the intervening segment through New Zealand, not since the 1855 earthquake on the Wairarapa fault (Eiby, 1989).

The Kermadec and Tonga trenches absorb the collision, Pacific plate subducted under the Australian plate to Samoa where a larger version of the Alpine fault/Taupo volcanic zone transfers plate convergence west through Fiji to the New Hebrides and Solomon trenches. The Australian plate is again subducted beneath the Pacific plate. Fortunately for Fiji the main islands of Viti Levu and Vanua Levu are south of the active transform fault which does not contribute greatly to the hazard onshore (Hamburger and Everingham, 1986). Intraplate earthquakes are the dominant hazard in Fiji so the hazard is comparable to that in Australia and Kalimantan.

In Papua New Guinea the most active plate boundary is that through Bougainville, New Britain and then along the north coast of New Guinea where the earthquake hazard is very high (Denham, 1969; Everingham, 1974; Ripper, 1975). Johnson (1979) published a useful review of the tectonics of Papua New Guinea. Between Bougainville and New Guinea are four small plates, the Solomon Sea and Woodlark basin plates south of New Britain and the North and South Bismarck Sea plates to the north of New Britain. Many of the large earthquakes are offshore, west of Bougainville and south of New Britain, so the tsunami hazard around the Solomon Sea is very high, as it is along the north coast of New Guinea (Everingham, 1977) as demonstrated so tragically for the villagers in the Sissano Lagoon region on 17 July 1998.

The western edge of the Solomon Sea plate along the Papuan peninsula and a continuous zone of shallow thrust faults along the southern side of the Central and Southern Highlands which marks the northern edge of the Australian plate (Ripper and McCue, 1983), are hazardous earthquake zones in Papua New Guinea. The largest earthquake in the Southern Highlands seismic zone was the M 7.5 Kikori earthquake in 1922 and there was another M 7 earthquake near Tari in 1954. The Bismarck Sea seismic lineament seems to continue to the west through New Guinea joining the extension of the Southern Highlands seismic zone at the neck of the Bird's Head (Vogelkop) and continuing to the Outer Banda arc.

Hamilton (1979) published a comprehensive account of the tectonics of the Indonesian area. A series of island arcs and offshore trenches mark the boundary between the Australian and Eurasian plates from Sumatra, Java, Sumba, Timor and Banda Sea to the Tanimbar Islands south of the Bird's Head in Irian Jaya. North of the Bird's Head the Philippine plate subducts to the west under the Eurasian plate through the Philippines but the sinistral Sarong fault zone along the north coast of the Bird's Head cuts through to Sulawesi north of the Banda arc which folds right around the Banda Sea. Hamilton (1979) suggests that Northeastern Sulawesi is a separate small clockwise-rotating plate. Australian continental crust abuts against the Banda arc from Timor to Seram under the Arafura Sea and Bird's Head complicating the tectonics.

Kalimantan is an intraplate craton within the Earasian plate where seismic hazard is low. Similarly continental Australia is wholly within the Australian plate and like Kalimantan is a melange of blocks of differing ages, Archaean in the west to Mesozoic in the east. Though intraplate the Australian continental crust is under high compressive stress from the plate boundary stresses; subduction in the east, seafloor spreading though the Southern and Indian Oceans south and west of the continent, and collision with the Pacific and Eurasian plates through Papua New Guinea and Indonesia in the north.

3. Australia

Entirely intraplate, the causes of continental Australia's seismicity are inexplicable. In the last 100 years there have been 20 earthquakes of magnitude 6 or more, seven of which have ruptured the crust. The most damaging earthquake in the last 200 years was the moderate magnitude 5.6 earthquake near Newcastle NSW on 28 December 1989 which resulted in 13 deaths and $AUS 1.2 billion damage. A similar sized earthquake near Adelaide South Australia in 1954 caused $ 100 million damage though there were no deaths.

The largest known continental Australia earthquake was a magnitude 7.2 event in 1906 off the central west coast of Western Australia which was felt over one third of the continent. Only after the magnitude 6.8 Meckering WA earthquake on 14 October 1968 did engineers accept that even in the middle of the Australian plate earthquake hazard could not be neglected and this led to the development of the first Australian earthquake code.

Most earthquakes are very shallow, less than 15 km focal depth, and cause strong ground shaking in the epicentral region, just as strong as an earthquake of similar size anywhere. A number of regional hazard studies were done and incorporated into AS2121 - 1979, the first Earthquake Building Code written in Australia. They all used Cornell's (1968) method. The deficiencies of the hazard analyses became apparent with each new earthquake in Zone 0 (defined to be where earthquakes were so infrequent that they could be neglected for design purposes) so revision was soon required for a rewrite of the code.

Cornell's (1968) method was adopted by Gaull *et al.* (1990) to map earthquake hazard throughout Australia using an early program of McGuire's (1976). They contoured the peak ground acceleration, velocity and *MM* intensity at the 475 year return period (10% in 50 year lifetime) using data from 1900 to 1986.

They developed local attenuation relationships for intensity using an extensive set of isoseismal maps. The authors then converted the intensity values to ground velocity and acceleration using empirical relationships developed in the Western U.S. and Papua New Guinea respectively.

Their map was used as the basis for a Standards Australia committe review of earthquake hazard in Australia for the Australian Building Code AS1170.4. Additional earthquake data to 1992 was considered by the committee, as well as historical data and limited Australian strong motion data. Source zones were modified on the basis of the new data and some consideration of the geology and the map was incorporated into the current Loading Code and used in the GSHAP World map. The results are sensitive to the chosen source zone boundaries and to the attenuation relation and its standard deviation.

The map (fig. 2) illustrates that the seismicity of Australia is low compared with that of surrounding interplate countries such as Papua New Guinea and New Zealand as expected.

4. New Zealand

(contributed by Graeme McVerry, IGNSNZ)

New Zealand peak ground accelerations are shown on the accompanying map for a return period of 450 years for «average» ground conditions, *i.e.* typically firm-stiff deep alluvium.

The seismicity, model is the 1992 version of the Smith and Berryman model, first published in 1983, with modifications in Canterbury as discussed in the recent paper on *Earthquake Hazard in Christchurch* by Dowrick *et al.* (1998). As for the Smith and Berryman model, the Canterbury seismicity is all modelled by distributed source zones, without individual faults represented (*i.e.* the second model discussed on page 12 of the above paper). As depth is both a parameter of the attenuation model, and enters into the distance definition, the Smith and Berryman seismicity was also apportioned among a number of layers at different depths.

The attenuation model was an interim one produced during the course of the study that led to the model published by Zhao *et al.* (1997). The model was similar to Model 5 of their paper, derived without site condition, earthquake type or mechanism terms.

The map gives the correct impression of the general level of PGAs and relative hazard in

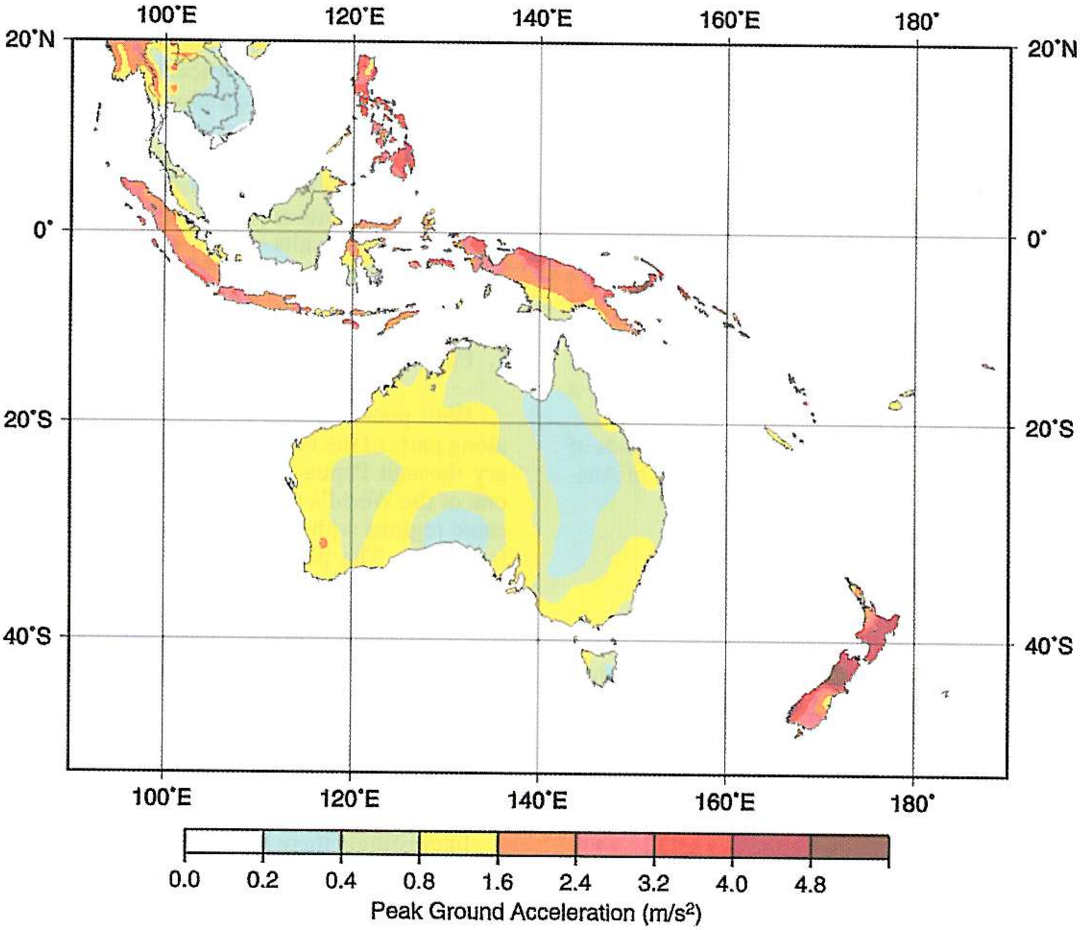

Fig. 2. Seismic hazard map for the Australia-South Pacific-Southeast Asia region, depicting peak ground acceleration for an exceedance probability of 10% within 50 years.

different parts of the country, but site-specific studies for particular locations in New Zealand using our best estimates of seismicity (including individual faults as well as distributed regional seismicity) and the Zhao *et al.* (1997) PGA attenuation model could well produce estimates considerably at variance with those shown in some cases. The map should therefore be used only for general comparison purposes with other parts of the world, rather than as current best estimates for specific locations in New Zealand.

5. Fiji

Recent studies of the seismicity and tectonics of the Fiji region (Hamburger *et al.*, 1988, 1990) and a timely unpublished thesis concerning an earthquake hazard analysis of a dam site (Singh, 1997) and other consultancy reports (*e.g.*, Somerville, 1997) form the basis of this hazard analysis. In common with other parts of region 10 there is insufficient (a single record) strong motion data available because of the lack of instruments.

Singh did a sensitivity analysis using a number of different attenuation relationships including both U.S. and N.Z. attenuation relationships.

Most of the shallow earthquakes are off shore from the two major islands of Vitu Levu and Vanua Levu and pose a relatively low threat to the islanders. The most damaging known earthquake of the last 90 years was that of 1953, an intraplate earthquake. Its magnitude was M_S 6.7 and eight people were killed, three of them in the resulting tsunami (Singh, 1997). Larger but less damaging earthquakes have occurred, the largest the 1979 Taveuni earthquake with a magnitude of M_S 7.0.

Earthquake hazard in the two large islands of Fiji is comparable to that in many parts of Australia.

6. Samoa

(extended abstract from Boyce, 1998)

As part of the design process for a Hydropower project in Western Samoa it was necessary to determine appropriate design loadings to account for earthquake effects.

Current practice in Western Samoa is to design structures to the requirements of the New Zealand loading code (SANZ, 1984) using Zone B coefficients although there is a 1974 recommendation from the New Zealand Department of Scientific and Industrial Research to use Zone A coefficients. Practice in American Samoa is to use UBC Zone 3. The Applied Technology Council guidelines (ATC, 1984) give an acceleration coefficient of 0.20 for American Samoa.

It was deemed necessary to carry out a seismic hazard analysis for the site to determine acceleration coefficients for use in the design of the project. There were severe constraints on time and cost and the analysis was carried out within these constraints. These constraints are common for engineering consulting work but are often not recognised by the wider engineering, scientific and general community.

The seismic hazard analysis was based on the probabilistic method of Cornell (1968) and McGuire (1976), encompassed in the computer program EQRISK using data from NGDC and the Esteva-Villaverde attenuation relationship. A plot of acceleration coefficient contours has been produced and it is concluded that reasonable design coefficients are 0.20 for Western Samoa and 0.15 for American Samoa.

Again Boyce's data were used with a tectonic model to contour hazard throughout the region and the results were included in the regional map.

7. Papua New Guinea

With plate motions of more than 10 cm/yr along parts of the Pacific/Australia plate boundary through Papua New Guinea this region is one of the World's most active seismic and volcanic regions with accompanying tsunamis and landslides. The plate and subplate boundaries are well defined and the rates of activity can be well determined using a much shorter observation period than in regions like Australia. There are about 10 to 12 earthquakes of magnitude 6 or more and one of magnitude 7 or more per year. The main source of uncertainty is the attenuation relationship because of the lack of strong motion data, and the lack of analysis of the analogue data that does exist.

Interestingly there have been no documented fault ruptures on shore despite the high level of activity which contrasts starkly with recent history in intraplate Australia.

Two studies have been made to zone PNG in terms of earthquake hazard, for bridges and for buildings (Beca *et al.*, 1976; Jury *et al.*, 1982). A number of individual studies have been done for special facilities or structures *e.g.*, the Ramu Dam site and the Bougainville Copper Mine (McCue, 1974, 1984), and for the major towns of PNG (Gaull, 1969). A number of different attenuation relationships were used for these studies including those of Esteva and Rosenblueth (1964) and Gaull (1969). Somerville (*personal communication*) also did some hazard analyses for the Solomon Islands and Bougainville using a variety of attenuation models. A number of PNG Geological Survey reports of hazard analyses for particular sites were also consulted (*e.g.*, Ripper and Anton, 1995).

All computed 475 year ground accelerations were plotted on the seismicity/plate boundary map of Ripper and Letz (1993) and the results contoured to produce the adopted map.

8. Indonesia

One of the World's more active seismic regions, Indonesia is at the junction of the colliding Australian and Eurasian plates. The Philippine plate is also a minor player in this tectonic drama. The seismic zones highlight the Sunda, Banda and Andaman arcs where earthquakes extend to 650 km down the subduction zones beneath the islands and most of the shallow seismicity is well offshore. An exhaustive study of the tectonics of the Indonesian region was published by Hamilton (1979).

In 1978, the New Zealand Engineering firm Beca *et al.* (1978) prepared a loading code for Indonesia which incorporated an earthquake hazard map upgrading the zoning map of Soetadi (1962). Inexplicably this is incompatible with the later one they compiled for Papua New Guinea, the maps do not meet seamlessly across the border of PNG and Irian Jaya.

A recent report by Shah and Boem (1996) contains a 475 year PGA map which has been digitised for this mapping project though it omits Kalimantan and Sulawesi. An independent study by Thenhaus *et al.* (1993) did cover the north part of Sulawesi and has been included.

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