13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2748

EARTHQUAKE RISK ASSESSMENT FOR PERTH, WESTERN AUSTRALIA

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SUMMARY

A probabilistic earthquake risk assessment is being undertaken as part of a multi-hazard assessment of Perth, West Australia. This major, innovative project is being implemented by the Australian government agency, Geoscience Australia (GA), to assist the West Australian government and industry stakeholders make informed decisions on risk reduction.

Geoscience Australia's earthquake risk assessment framework is focused on estimating direct financial losses caused by building damage from ground shaking. The framework is probabilistic and is designed to incorporate uncertainties in attenuation, site response and damage models. Damage is calculated by the capacity spectrum method and a simple financial loss model. The framework is designed to produce both local scale estimates of damage and financial loss as well as an aggregated loss curve for the entirety of Perth.

This paper focuses on the modeling of earthquake hazard that has been completed to date for the Perth region. A new model of seismicity for the Perth region has been prepared which includes the influential south-west seismic zone, one of Australia's most seismically active areas. The earthquake hazard on rock has been calculated using three different attenuation models from central and eastern North America. These three hazard estimates have been averaged and provide a preliminary estimate of hazard that is approximately 30 % higher than the hazard presented in the current earthquake loading standard. Moreover, the results are notably different from one attenuation model to the next emphasizing the importance of correctly choosing an appropriate attenuation model.

In addition to estimating the seismic hazard on rock, this paper also discusses modifications to the hazard model that account for local geological conditions. Finally, a GIS building database with vulnerability and

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usage attributes for each of approximately 470,000 buildings has been assembled, and cost of reconstruction/replacement data for buildings and contents have been prepared using Perth industry data.

INTRODUCTION

Geoscience Australia (GA) is currently finalizing a multi-hazard risk assessment for the city of Perth, Western Australia. This risk assessment will contrast the risk posed by a range of natural hazards including earthquake, flood, wind and coastal erosion. The final multi-hazard risk assessment will be used by the West Australian state government, various local governments as well as industry stakeholders to make informed decisions to mitigate the risk posed by natural hazards.

Geoscience Australia is completing a probabilistic earthquake risk assessment for the Perth region as part of this study. When completed, this study will represent the most detailed earthquake risk assessment published for any Australian city. The methodology used within the current study represents a significant improvement on the approach used in previous studies such as Dhu [1]. As with Dhu [1], the current study incorporates:

- aleatory variability within attenuation, site response and damage models;
- comprehensive earthquake occurrence models;
- detailed local regolith models, and;
- detailed local building inventories.

However, the current study also includes a number of additional components, specifically:

- epistemic uncertainty in attenuation models;
- improved building capacity curves developed for Australian buildings, and;
- estimates of building replacement and contents values developed specifically for Perth buildings.

This paper provides a description of the key results of the ongoing Perth earthquake risk assessment. It describes the risk assessment framework being used for the study as well as the region's "rock" earthquake hazard. It also describes the work that has been completed on site response, vulnerability and loss models for the region.

RISK ASSESSMENT FRAMEWORK

Geoscience Australia has implemented a probabilistic framework for estimating the risk posed by earthquakes. The general approach requires:

- the creation of a synthetic catalogue of earthquakes, with associated probabilities of occurrence;
- propagating the ground motion for each earthquake to sites of interest using strong motion attenuation models such as Atkinson [2], Toro [3] and Somerville [4];
- modifying this ground motion to account for local regolith (i.e. soils, geological sediments and weathered rock);
- calculating damage states via the capacity spectrum method;
- converting damage states to associated replacement and repair costs, and;
- aggregating losses across a study region to provide a loss estimate for each simulated earthquake.

A detailed discussion of the computational methodology is outside the scope of this paper. However, a brief description of some key issues/assumptions relating to the calculation of earthquake risk is included below. Dhu [5] provide a more detailed description of the risk assessment methodology, while Edwards [6] also provide a description of the methodology used for damage and risk estimation.

The calculation of earthquake hazard is based upon the general concepts of probabilistic seismic hazard assessments (PSHA) (Cornell [7]). However, unlike the classical approach, GA uses a stratified Monte Carlo simulation of events rather than the analytical solution of relevant integrals. This approach has been selected as it allows for simple, event-dependant site response factors to be incorporated into estimates of hazard and risk. Moreover, this approach allows complete response spectra to be calculated at any given site which then allows for spectral-based damage calculation.

A key component of any PSHA is the incorporation of uncertainties. Geoscience Australia's risk assessment framework has been developed to allow the separate consideration of both aleatory (i.e. random variability) and epistemic (i.e. uncertainty in the "correctness" of a given model) uncertainties. Aleatory uncertainty in attenuation, site response and damage models is incorporated into the framework. Both the attenuation and site response models are provided as probability distributions rather than as deterministic values. Consequently, the aleatory uncertainty is incorporated by sampling of this distribution rather than simply using a mean value.

In contrast, epistemic uncertainties are only incorporated in the choice of attenuation model(s). In this case, the hazard and risk assessment is run independently for each of the considered attenuation models. The independent results are then averaged in order to provide an estimate of hazard or risk that incorporates the epistemic uncertainties.

As mentioned earlier, GA's framework uses the capacity spectrum method to calculate damage to buildings (Freeman [8]). The capacity spectrum method essentially calculates peak displacements and accelerations of buildings in order to then calculate the probability of being in a variety of damage states. This method has the advantage over other empirical "damage-curve" approaches in that it incorporates a physical model of the damage to buildings.

REGIONAL HAZARD ASSESSMENT

Methodology

An estimate of earthquake hazard on rock requires two fundamental components.

1. A seismicity model describing the spatial distribution, magnitudes and likelihood of occurrence of earthquakes.
2. An attenuation model or models which provide ground motions as a function of earthquake magnitude and distance from the source.

Seismicity Model

The earthquake hazard in Perth is heavily influenced by a region of relatively high earthquake occurrence referred to as the south-west seismic zone (SWSZ) (McCue [9]). The SWSZ is one of the most seismically active regions of Australia and has experienced at least three earthquakes of local magnitude 5.9 or greater in the last 40 years. A sequence of more than 2000 earthquakes was recorded in the SWSZ in 2001 and 2002 (Leonard [10]; Leonard [11]). A subset of this data now forms an important element of GA's research into strong ground motion within Australia and has influenced the choice of attenuation models used in this study (Dhu [12]).

The distribution of source zones was defined at a workshop hosted by GA in December, 2002. The workshop was attended by Australian seismologists and structural geologists and was focused on reaching a consensus on the appropriate distribution of source zones for the south west of Western Australia. The workshop discussed a variety of issues related to seismicity in the region ranging from historical seismicity through to a variety of structural and tectonic issues. The final model incorporates five distinct source zones (Figure 1).

1. Zone 1, the SWSZ, modified from Gaull [13] to include the previously described earthquake sequence.
2. Zone 2, east of the Darling Fault, with boundaries modified from Gaull [13] to align with the Darling Fault and regional structural trends.
3. Zone 3, an offshore zone extending to the continental margin, modified from Gaull [13].
4. The Yilgarn Zone extending across the remainder of the Yilgarn Craton.
5. Background Zone, including the Perth Basin.

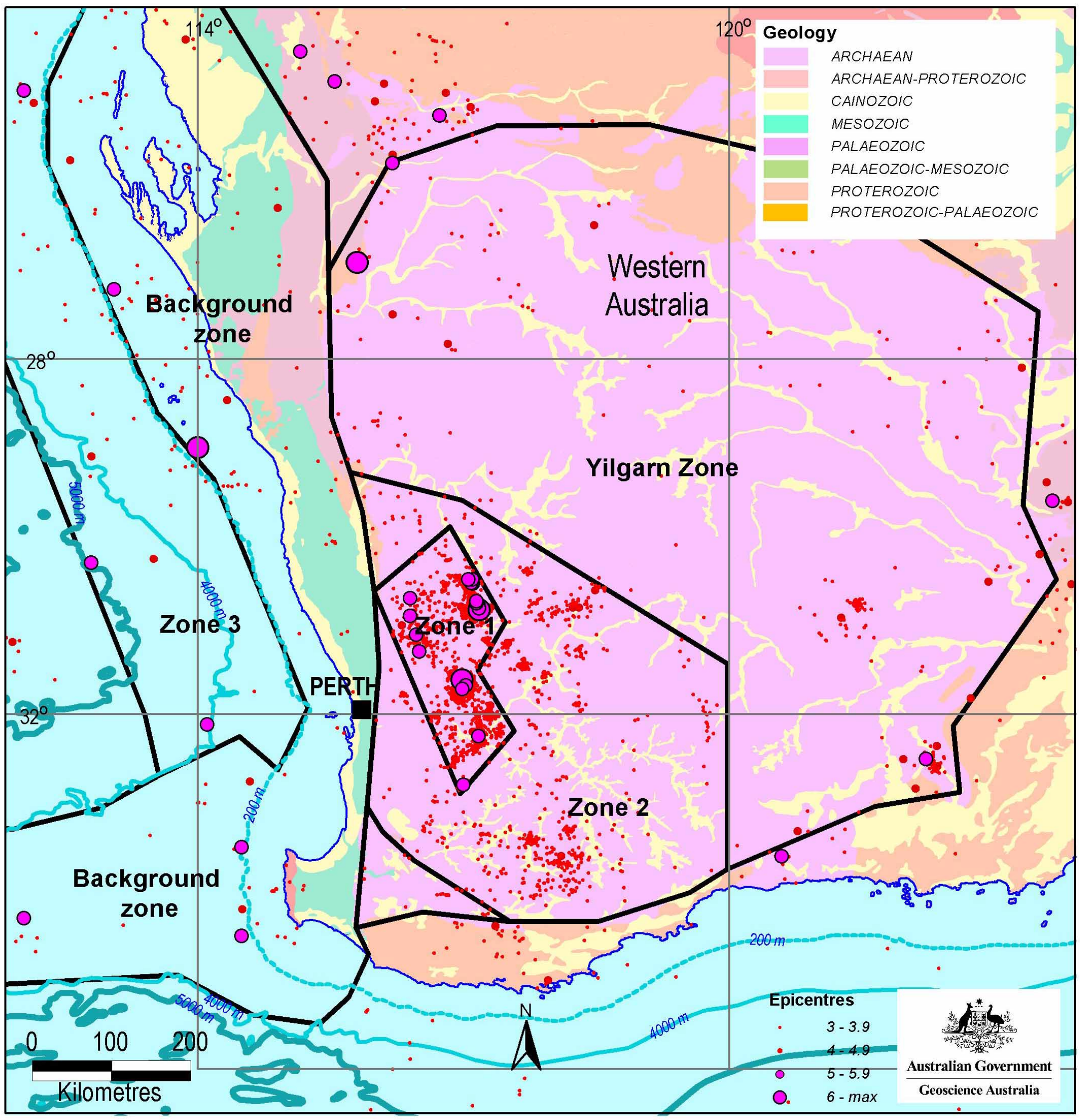

Figure 1: Earthquake source zones in south-west Western Australia.

Statistical analysis of historical seismicity was used to determine parameters such as likelihood of occurrence and maximum magnitude for each of the source zones (Table 1). This analysis was restricted to time intervals in which the seismic network was able to consistently record all earthquakes of the specified magnitude in the Australian continent, with a minimum magnitude threshold of 3. The catalogue of historic events was also declustered by removing identifiable foreshocks or aftershocks using the procedure described by Sinadinovski [14]. Table 1 describes the parameters used in this paper, however there is a significant amount of uncertainty associated with these parameters. For example, alternate seismicity models could incorporate maximum magnitudes as large as 8 and/or b values that vary from the global average. These alternate seismicity models are not currently included in GA's risk assessment. However, future work will focus on attempting to incorporate this uncertainty.

Table 1: Summary of seismicity parameters for south-west Western Australian source zones. M_{min} is the minimum moment magnitude, M_{max} is the maximum moment magnitude, and A_{min} is the number of earthquakes per year with $M \geq M_{min}$, normalized to 100,000 km^2.

Source zone	Area (km^2)	M_{min}	M_{max}	b	A_{min}
Zone 1	25,365	3.9	7.5	1	1.29
Zone 2	134,344	3.9	7.5	1	0.02
Zone 3	330,916	3.9	7.5	1	0.11
Background	373,291	3.9	7.5	1	0.05
Yilgarn	460,465	3.9	7.5	1	0.04

The GA workshop also determined a number of other key parameters relating to the seismicity in south-west Western Australia. For example, all of the earthquakes simulated in this study are assumed to occur in the top 20 km of the crust and upper mantle, with higher probabilities of occurrence in the upper 5 km. Earthquake mechanisms are assumed to be predominantly reverse faulting with the principal stress axis normal to the regional north-north-west structural trend. Faults are assumed to dip at 35 degrees east or west of this trend with equal probability.

Attenuation Models

Earthquake risk assessments in Australia are often hampered by the lack of a robust spectral attenuation model derived for Australian earthquakes and crustal conditions. One of GA's key research priorities is the development of an attenuation model for Australia. However, this work is in its early stages and has not yet produced an Australian model. Consequently, previous earthquake risk assessments in Australia have used spectral attenuation models from other intra-plate regions such as central and eastern North America (CENA) (eg. Dhu [1]).

Geoscience Australia's research has provided some quantitative support for the use of attenuation models from CENA over models developed for western North America (Dhu [12]). However, Dhu [12] were not able to provide any recommendations as to which, if any, CENA model would be the most appropriate for Australian conditions. Consequently, this study has incorporated three different CENA attenuation models into its estimates of earthquake hazard, specifically:

- Atkinson [2];
- Toro [3] (mid-continent), and;
- Somerville [4] (non-rifted).

These three models were all derived using similar crustal velocity structures; however they contain different assumptions about source and path effects. These assumptions result in different predicted response spectral accelerations (RSAs) for any given magnitude-distance combination. The various predicted RSAs for a magnitude 5.5 event at 100 km distance are shown in Figure 2 in order to demonstrate the differences in these models for an earthquake typical of the SWSZ that would be expected to affect Perth. The Toro [3] and Somerville [4] predictions are essentially the same for periods less than 0.2 s. In contrast, the Atkinson [2] predictions are approximately twice the predictions of the other two models for periods less than 0.2 s. All of the models predict similar RSAs for periods between 0.1 s and 0.4 s. However, the Toro [3] model predicts the largest RSAs for periods greater than 0.4 s.

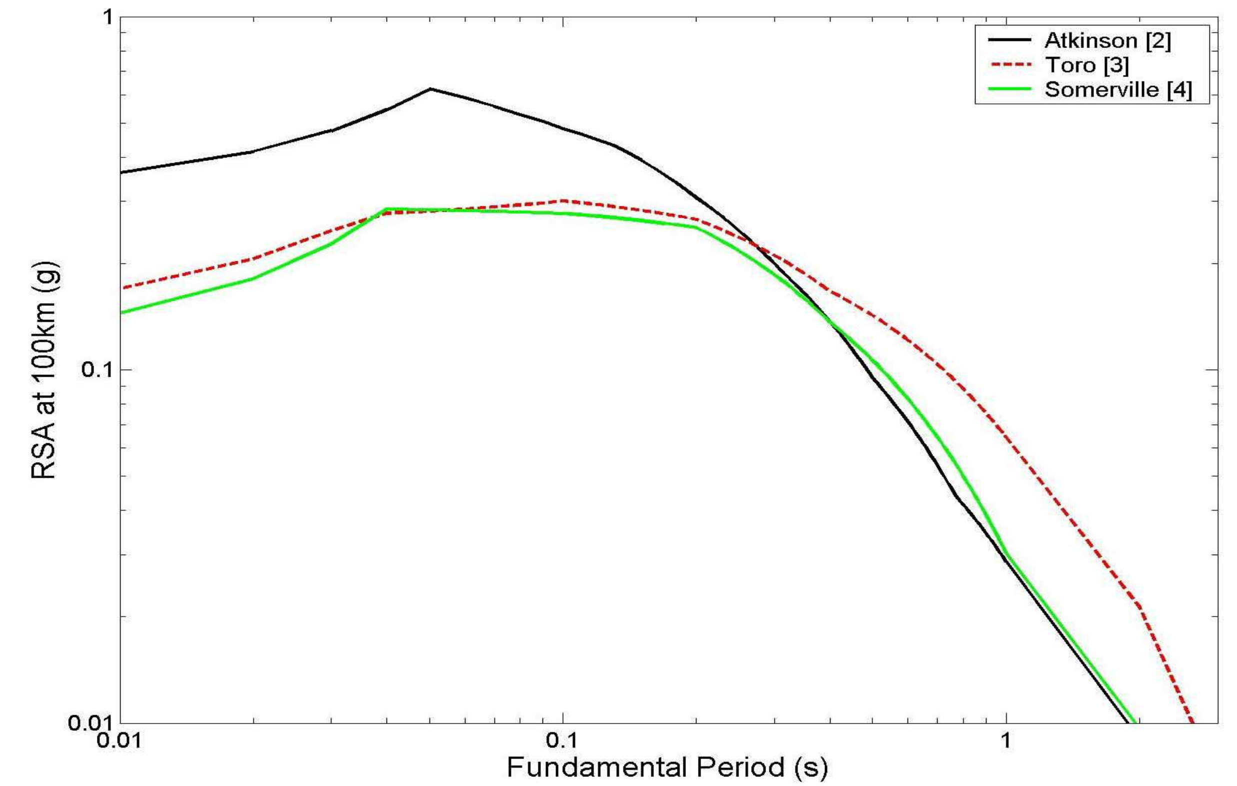

Figure 2: Predicted RSA for a magnitude 5.5 event at 100 km for all three of the attenuation models considered in this study.

The three models used in this study all have subtly different approaches for incorporating uncertainties. For example, Toro [3] incorporate and separate two distinct types of variability, specifically epistemic and aleatory. In contrast, Atkinson [2] and Somerville [4] only capture aleatory uncertainties. As mentioned previously, this study has used the three selected attenuation models independently and then averaged their respective hazard estimates. Consequently, only the aleatory component of uncertainty has been used when applying the Toro [3] model.

Earthquake Hazard on Rock

We calculated the PGA on rock in Perth with a 10 % probability of being exceeded in 50 years in order to demonstrate the outputs of the hazard model and to highlight issues arising from our approach. The current Australian earthquake loading standard considers earthquake hazard in terms of an equivalent PGA with the same probability and gives the bedrock hazard in Perth as 0.09 g (Standards Australia [15]). In contrast, the use of the Atkinson [2] model leads to notably higher estimates of hazard ranging from PGAs of 0.22 g in the north-east through to 0.16 g in the south-west (Figure 3).

The Toro [3] attenuation model generates estimates of earthquake hazard that are only marginally higher than the current Australian standard (Figure 4). In this case the estimated PGA ranges from 0.12 g in the north-east down to 0.09 in the south-west. Similarly, the Somerville [4] estimates are marginally lower than the current Australian standard with values ranging from 0.09 g in the north-east to 0.07 g in the south-west (Figure 5).

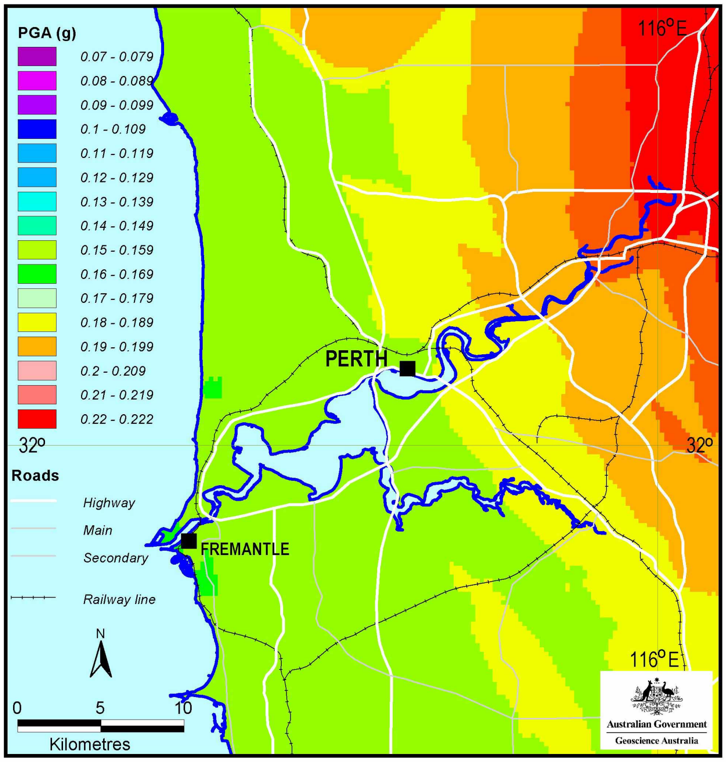

Figure 3: Rock PGA in Perth with a 10% chance of being exceeded in 50 years, derived using Atkinson [2].

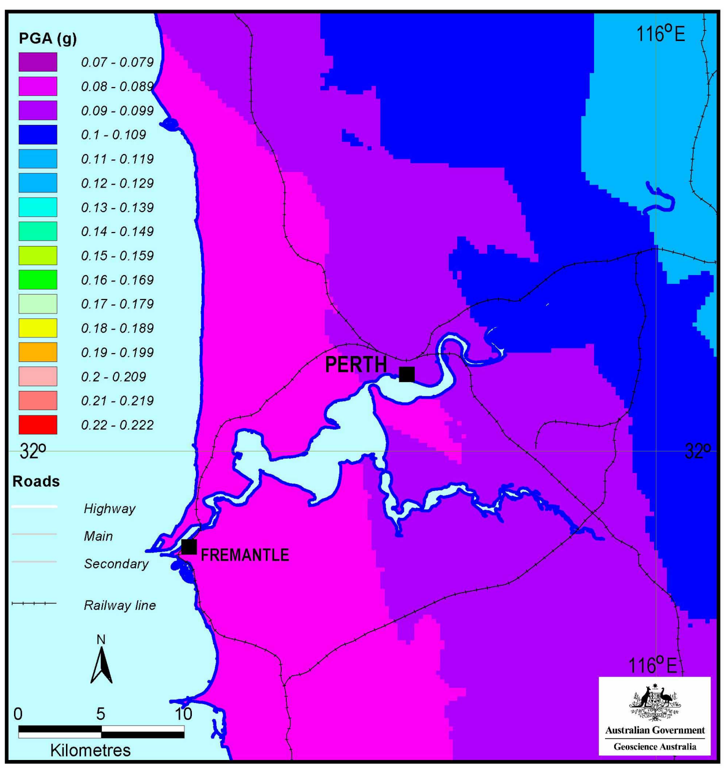

Figure 4: Rock PGA in Perth with a 10% chance of being exceeded in 50 years, derived using Toro [3].

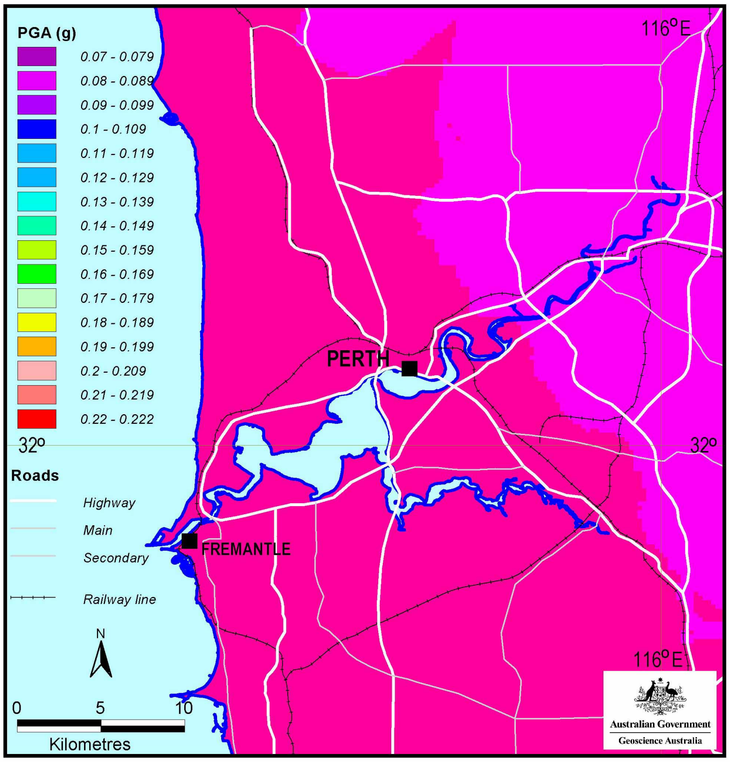

Figure 5: Rock PGA in Perth with a 10% chance of being exceeded in 50 years, derived using Somerville [4].

All three attenuation models demonstrate a common trend of decreasing hazard towards the south-west of metropolitan Perth (Figure 3 - Figure 5). This common trend is due to all three models using the same simulated catalogue of events. However, the different models have notable differences in the range of hazard predicted across the study region. For example, the Atkinson [2] results have a range of approximately 0.06 g in contrast to the ranges of 0.04 g for the Toro [3] model and 0.01 g for the Somerville [4] model. This difference in range is due to differences in the rate of RSA decay with distance.

As mentioned earlier, there is currently no quantitative evidence to support the preferential use of any of the three CENA models (Dhu [12]). Consequently, the three hazard maps (Figure 3 - Figure 5) were averaged with equal weighting in order to provide a combined estimate of hazard for the Perth region (Figure 6). This averaged hazard tends ranges from 0.14 g in the north-east to 0.1 g in the south-west, which is higher than the level of 0.09 g prescribed by the current Australian earthquake loading standard (Standards Australia [15]) (Figure 6).

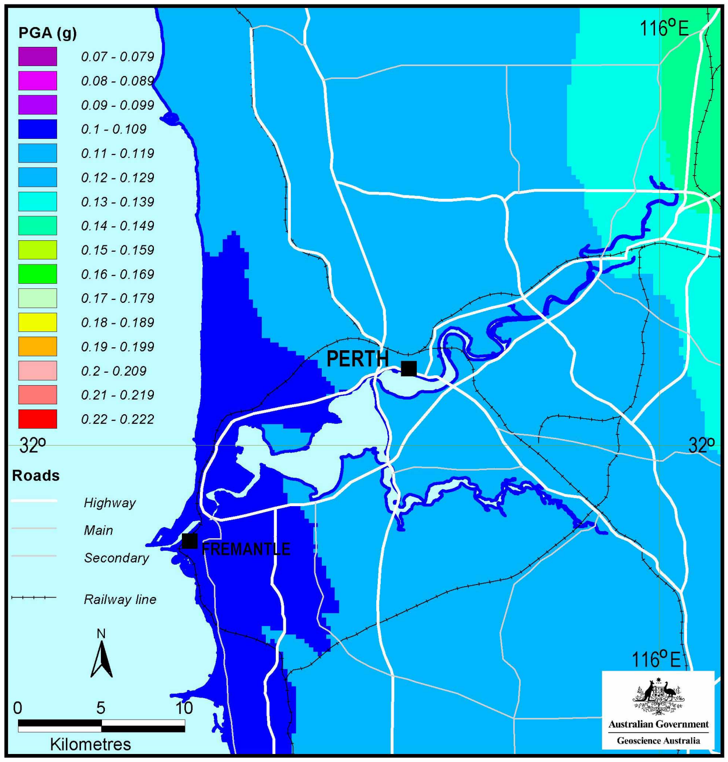

Figure 6: Rock PGA in Perth with a 10% chance of being exceeded in 50 years as derived from averaging the hazard results generated using the three CENA attenuation models.

Discussion

The hazard in Perth is strongly influenced by the SWSZ which is located, at its closest, approximately 100 km to the north-east of the study region. The estimated hazard decreases towards the south-west due to increasing in distance from the SWSZ. This suggests that the pga with a 10 % probability of being exceeded in 50 years is probably being driven by small-to-moderate sized earthquakes at distances of around 100 km or more.

The averaged hazard results tend to be slightly higher than the level prescribed by the Australian earthquake loading standard. This is due primarily to the higher PGAs predicted by the Atkinson [2] model. Atkinson [16] explicitly state that their model "grossly overpredict[s] … amplitudes of small-to-moderate earthquakes at distances greater than 30 km". This was a deliberate compromise of their model to ensure that their simple functional form adequately described spectral shapes that displayed complicated magnitude dependence (Atkinson [16]). Similarly, both Toro [3] and Somerville [4] focused their work on accurately describing larger earthquakes that were seen to be important to the earthquake hazard in CENA. However, neither of these two models claims to grossly over-predict small-to-moderate earthquakes, and they both predict notably lower hazard than that predicted by Atkinson [2].

The variability in the three sets of results emphasizes the point that Australian earthquake risk assessments are heavily influenced by the appropriate selection of attenuation model(s). Geoscience Australia has recognized the importance of developing a robust spectral attenuation model for Australian earthquakes and conditions in order to reduce the uncertainties in its risk assessments. Consequently, this work has become one of GA's key earthquake related research priorities over the coming years.

LOCAL GEOLOGICAL EFFECTS

The previous section of this report described the earthquake hazard in Perth without incorporating the effect of local geological conditions. There are two key aspects of Perth's geology that need to be incorporated into any realistic earthquake risk model.

1. A crustal velocity structure that is notably slower than the structure assumed for the various attenuation models.
2. The presence of 10 to 70 m of soils, geological sediments and weathered rock (collectively referred to as regolith).

Current work is focused on the development of site response factors that can be applied to the RSAs predicted by the various attenuation models to incorporate these geological factors.

Crustal Velocity Structure

The crustal velocity structure in the Perth Basin has been interpreted from deep seismic refraction work (Mathur [17]; Dentith [18]) (Figure 7). This shear wave velocity structure has been interpreted from the P wave velocities using a Poisson ratio of 0.25. All of the CENA attenuation models used in this work were derived using the mid-continent crustal velocity structure defined by Electric Power Research Institute [19]. This velocity structure is notably faster than the interpreted Perth Basin structure, especially for depths less than ~7 km (Figure 7). In the absence of the increased damping that would be expected in the region, this difference in velocity structures will cause the rock motions in Perth to be larger than those predicted by the three CENA attenuation models considered in this paper.

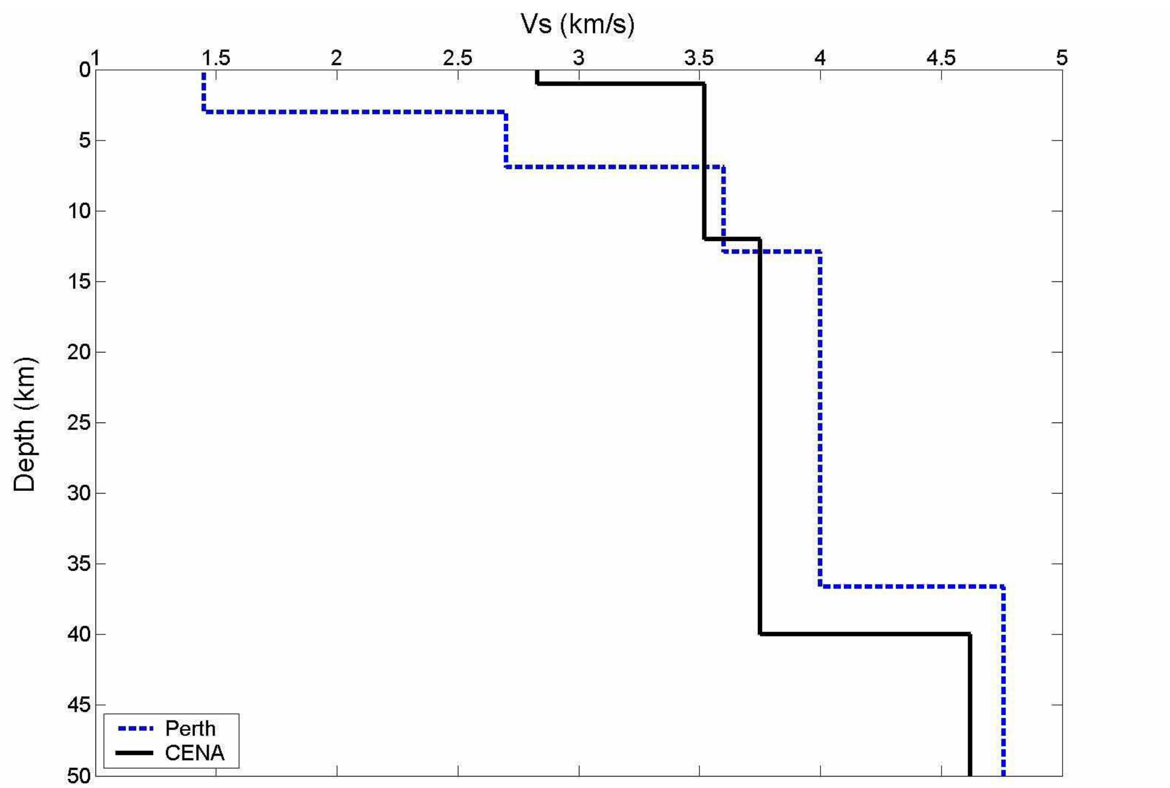

Figure 7: Crustal shear wave velocity structures for Perth and for CENA. The Perth velocity structure has been interpreted from Mathur [17] and Dentith [18] with a Poisson ratio of 0.25 and the CENA (mid-continent) velocity structure is from Electric Power Research Institute [19].

Regolith Models

A 10 – 70 m thick veneer of regolith covers the majority of metropolitan Perth (Playford [20]). This regolith consists mainly of sand, silt, clay and limestone in varying proportions. Along the eastern margin of the coastal plain the sediments are more clayey than those in the central area, which are predominantly sandy. To the west, the sandy sediments pass laterally into limestone, which borders the coastal strip. This relatively thick regolith will have a significant influence on the ground shaking experienced in Perth during an earthquake.

Geoscience Australia is currently modeling the response of this regolith through an equivalent linear methodology similar to the approach used in Dhu [5]. Geotechnical models are being finalised based on seismic cone-penetrometer testing and natural period measurements acquired by GA over the last two years. These detailed data are being combined with boreholes collected by the West Australian Water and Rivers Commission. The final geotechnical models will be combined with transfer functions that account for the previously described differences in crustal velocity and damping between the Perth Basin and the CENA mid-continent models to provide detailed site response factors for the Perth region.

BUILDING EXPOSURE AND VULNERABILITY

A detailed understanding of the exposed building stock is required in order to estimate the risk posed by earthquakes. The city of Perth has some 681,000 separate building occupancies located in approximately 466,000 discrete structures which in turn have a range of structural forms. A detailed database of this building inventory has been created based on the Western Australian Valuer-General's Office (VGO) building database. The VGO database provided detailed, basic information on occupancy types, indicative floor areas (in many instances) and building construction materials used. This information was further supplemented with approximately 420,000 building footprints provided by the WA Department of Land Information. Geoscience Australia used aerial photography to convert these building footprints from CAD files in order to provide improved measures of building floor area.

The interpretation of these data was verified by GA through ground-truth surveys in May 2002 and December 2003. Construction details and occupancy type of approximately 3,200 buildings in the Perth CBD and Swan and Canning floodplains were recorded using GPS/GIS data acquisition techniques and palm top computer equipment. In part, the field data have permitted the gross roof areas (building footprints) to be reduced to net floor areas, and one and two storey dwellings to be identified. This valuable data set has been mapped to structural and occupancy type according to the classification of the Australian Bureau of Statistics. Table 2 presents a summary of the principal building occupancies and structural types in the Perth Metropolitan area as extracted from the GA database.

Table 2: Summary of the building inventory in Perth, Western Australia

Structural Type	**Usage Type**			
	Residential	**Commercial**	**Industrial**	**Other**
Unreinforced masonry with tiled roof	372843	4751	130	1629
Unreinforced masonry with metal roof	19560	5541	345	871
Timber clad with tiled roof	16978	113	21	22
Timber clad with metal roof	14034	64	251	21
Steel frame with unreinforced masonry infill walls	0	4732	8148	1523
Brick veneer with tiled roof	11826	5	2	7
Brick veneer with metal roof	2978	17	5	2
OTHER	0	30	0	110
TOTAL	438219	15253	8902	4185

The assessment of earthquake risk also requires an understanding of the vulnerabilities of the defined building stock. Vulnerability models are used to calculate the direct damage to buildings for each simulated earthquake following the approach of the National Institute of Building Sciences [21]. This methodology is based on an engineering knowledge of building behavior that permits the maximum spectral displacements and accelerations experienced by the representative structures across the city to be predicted. Fragility relationships for both drift and acceleration sensitive building components are then employed to determine the probability that the building is in one of several damage states. Response prediction is achieved using a capacity spectrum formulation similar to that proposed by Freeman [8] that requires representative push-over behavior, effective viscous damping, and fragility relationships for the building stock modeled. The HAZUS manual presents parameters that are considered representative of typical US construction that GA has used as a default for some building types (National Institute of Building Sciences [21]). However, GA has undertaken research to revise these parameters to better reflect Australian reinforced concrete frame type structures and residential buildings.

A series of building replacement cost models were developed that covered over 95 percent of the city's building stock to reflect the reconstruction costs in Perth (Reed Construction [22]). The models specifically address a wide range of usage types including residential, industrial, commercial and government. The models are also a function of construction type, gross floor area and number of storeys. The value of building contents is described as a function of both floor area and average household income of the suburb being assessed. As with the building replacement cost models the contents models are specifically tailored to building usage.

In the risk assessment process the direct damage loss sustained by a number of representative structures is calculated for a suite of simulated earthquake events. The losses and are aggregated across the region to obtain an overall financial loss for each event. This information can then be used to estimate either probable maximum loss (or exceedence probability) curves as well as estimates of the annualized loss associated with earthquakes.

CONCLUSIONS

The results-in-progress presented in this paper generally suggest that the earthquake hazard on rock in Perth is moderately higher than currently predicted in the Australian earthquake loading standard. Actual hazard estimates for the built environment in Perth will be higher again when local geological effects due to crustal velocity differences and the presence of extensive regolith are taken into account.

There are significant uncertainties within the hazard results presented in this paper. Epistemic uncertainties within seismic source models as well as questions over the appropriateness of the CENA attenuation models used are yet to be fully addressed. Nonetheless, the hazard results represent the most thorough assessment of the earthquake hazard published for the Perth region.

An understanding of hazard is an important element of any attempt to understand the risk posed by natural hazards. However, this understanding must be combined with the exposure of the built environment and an economic loss model in order to realistically describe the risk. This understanding of risk is essential to making appropriate decisions on the mitigation and management of the risk posed by natural hazards. The Perth building database developed for Perth is sufficiently detailed and accurate to allow sensitivity tests and cost-benefit analyses to be undertaken in the risk assessments.

ACKNOWLEDGEMENTS

We are grateful to our West Australian collaborators for providing data and advice that have assisted this study. We also wish to thank Ingo Hartig and Neil Corby for preparing the GIS figures, and Justin White for providing information on the building database.

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