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Results of probabilistic seismic hazard analysis assuming uniform distribution of seismicity

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ABSTRACT: This paper presents results of probabilistic seismic hazard analysis (PSHA) assuming uniform distribution of seismic activity within a broad source zone of area in the order of 10^6 km^2. When predicting ground motions affecting any designated position within the broad source zone, the computation of hazards was simplified further by considering only activities that were within 200 km from any designated position within the source. This simplified approach to modelling is considered to be reasonable for locations where no distinct seismic hot spot has been identified in the surrounding areas. The analyses were based on a range of parameter values characterising earthquake recurrences that are typical of regions of low to moderate seismicity and a list of ground motion models including the five Next Generation Attenuation (primarily for the western United States) (NGA-West2) models. The charts to be presented in the paper can be used for comparison with results from conventional PSHA and for evaluating proposed ground motion models other than the NGA-West2 models. The intention of presenting information in this generalised format is to benchmark results from PSHA and to make the probabilistic analysis process more transparent to the end users and to engineers.

1 INTRODUCTION

In the absence of a definitive emerging seismicity pattern in regions of low-to-moderate seismicity there is a great deal of uncertainty over the size and location of the earthquake generating sources and there can be episodic variations too (Leonard *et al.* 2007). Developing technologies such as space geodesy, geomorphology (neo-tectonics) and paleo-seismology can be employed to enhance the modelling but predictions derived from those studies for lower seismicity areas tend to be more relevant to very long (> 5000 years) design return period considerations than to normal design considerations for building structures. Furthermore, a very long lead time is required to deliver robust results that are considered useful for drafting structural design code provisions.

A finely divided source zone model for *probabilistic seismic hazard analysis* (PSHA) based on a few historical events would predict a high level of hazard in the vicinity of areas where earthquakes have occurred but the main concern with this style of modelling is the inherent underestimation of seismic hazard in areas where the historical database does not show any significant local seismic activity as demonstrated in Lam *et al.* (2015) and in this paper. Intraplate seismicity by definition exists in all areas away from any tectonic plate margin and earthquake events are possible at virtually any place on earth (Bird *et al.* 2010). However, many of these areas show little sign of activities if the period of observation is not sufficiently long or the catchment area is too small. It was revealed in simulation studies undertaken by Swafford and Stein (2007) that it could take thousands of years of seismological monitoring to capture the underlying spatial pattern of seismicity in an intraplate area where the rate of crustal deformation is 2 – 3 orders of magnitude lower than in interplate regions. Another issue associated with the use of a finely divided source zone model in the PSHA of a region of infrequent seismic activity is in the extrapolation of the rate of recurrence of small events to large events by several orders of magnitude (based on a best estimate of b value). This style of extrapolation of the rate of recurrence of earthquake events in PSHA is a point of contention (Wyss 2015).

The alternative *broad source zone* modelling approach is based on the assumption of a uniform level of hazard. This style of modelling (which assumes uniform seismicity over a large area) can be used to establish the minimum level of hazard in an area but fails to identify “hot spots” of relatively high seismic activities within an intraplate region. Thus, both types of source zone models when used on their own would run the risks of understating seismic hazard in certain areas. Importantly, they can be combined to produce a more representative seismic hazard model for engineering application. The assumption of a *broad source zone* also enables the level of background seismic hazard to be modelled with a simplified approach which is to be introduced in this paper. Background seismicity as a concept is well recognised but the way of quantifying the associated level of hazard is still *ad hoc*. In this paper, results from the simplified analyses are generalised for identifying the key trends in a quantifiable manner, and for benchmarking purposes for regions of low-to-moderate seismicity including Australia.

By analogy, a *source zone model* in PSHA is like a load case in structural analysis. In the structural design of building, simplified assumptions such as a uniform distribution of loading is typically made as opposed to exhausting resources to survey actual load patterns of real buildings in service. When deciding on load patterns for design purposes it is rare to seek expert opinions let alone weighting them by a logic tree (as normally done in PSHA). Yet, a safe design can be achieved by simply trying out alternative load cases and go by results obtained from the most onerous (conservative) load case.

2 CIRCULAR SUB-SOURCE MODELLING APPROACH

This section is concerned with explaining how ground motion intensities are derived as function of the return period and parameters which characterise a broad source zone in the presented simplified approach. Given that ground motions generated by an earthquake with magnitude of up to M7 from distances exceeding 200 km are expected to have been attenuated to a negligibly low level the aggregation of hazards for any position within the broad source zone (BSZ) was based on considering a generic circular sub-source of 200 km radius. Thus, the analysis of seismic hazard at a pre-defined location only needs to consider this generic sub-source which is circular and centred at the site under consideration. The radius of the circle needs not exceed value $R_{\max}$ (maximum source-site distance) which is the distance limit beyond which the intensity of the transmitted ground motions is deemed negligible. The probability density function for source-site distance R (spatial distribution of seismicity) within the sub-source can be expressed as follows:

$$f(R) = \frac{2R}{{R_{\max}}^2} \tag{1}$$

The earthquake recurrence relationship assuming a doubly-truncated exponential function can be expressed as follows:

$$N(M) = \upsilon \frac{\exp[-\beta(M - M_{\min})] - \exp[-\beta(M_{\max} - M_{\min})]}{1 - \exp[-\beta(M_{\max} - M_{\min})]} \tag{2a}$$

where $N(M)$ is the number of earthquakes with magnitude greater than M, occurring in a fixed time interval and within the circular source area of radius $R_{\max}$. υ is the total number of earthquakes with magnitude greater than $M_{\min}$, occurring in a fixed time interval and within the circular source area. $\beta = 2.303b$, in which b is the slope of the Gutenberg-Richter relationship.

The corresponding probability density function is defined as follows:

$$f(M) = \frac{\beta \exp[-\beta(M - M_{\min})]}{1 - \exp[-\beta(M_{\max} - M_{\min})]} \tag{2b}$$

For every combination of M and R, seismic intensities are predicted by employing some selected ground motion prediction equations (GMPEs). Finally, the total seismic hazard of the site encompassing all the considered M-R combinations can be computed using the conventional *Cornell-McGuire* approach (Cornell 1968; McGuire 1976) which is represented by the following integral:

$$P\left[Z > z\right] = \upsilon \int_R \int_M P\left[Z > z \middle| M, R\right] f(M) f(R) dMdR \qquad (3)$$

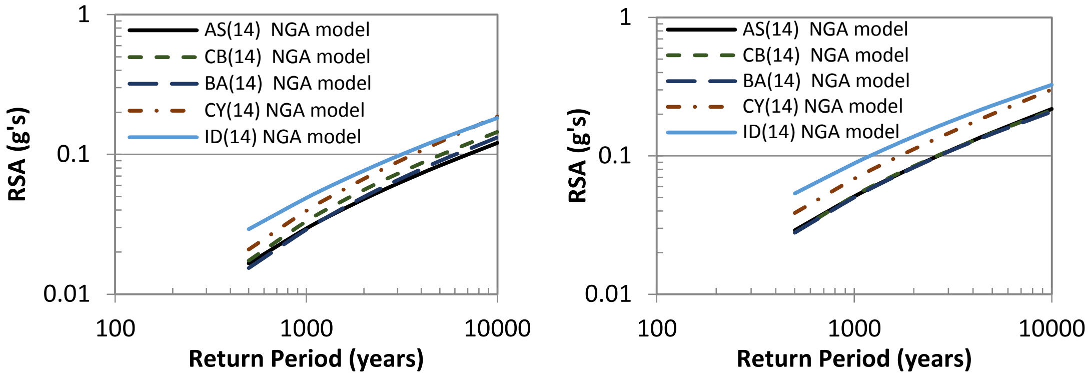
The implementation of the computational algorithm on EXCEL spreadsheet has been demonstrated in Lam *et al.* (2015).

3 SENSITIVITY STUDIES ON RETURN PERIODS AND RATE OF RECURRENCES

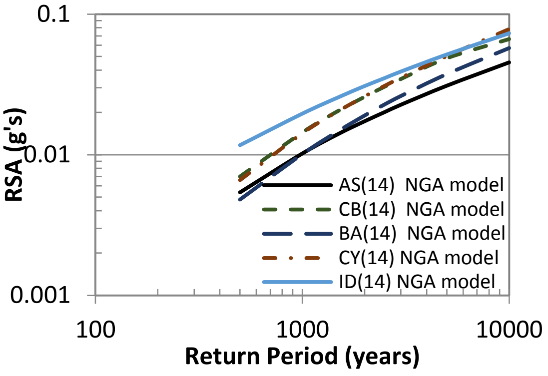
Results from PSHA as derived using equations (1) – (3) can be presented in the form of response spectral acceleration (RSA) values as function of return period for given level of seismicity which can be defined in the Gutenberg Richter form (equation 4).

$$\log_{10} N = a - bM \qquad (4)$$

The charts shown in Figures 1a – 1c are RSA (g's) values at 0.3s, 0.5s and 1.0s for *a*=5.2 and *b*=0.9. The "*a*" value of 5.2 was derived from estimates of the world average of the global rate of recurrence of intraplate earthquakes based mainly on counting the number of *M*>5 events occurring on land in an intraplate area for a normalised area of 1,000,000 sq. km and a 50 year period of exposure (Lam *et al.* 2015). Results presented in this paper are based on a *b* value of 0.9 which is consistent with recommendations by the literature for low-to-moderate seismicity regions; refer Lam *et al.* (2015) for a brief review of this area of the literature. Provided that the source area is large enough to capture a significant number of M>5 events and that intraplate earthquakes exceeding M6 is rare (though it is possible) the predicted level of hazards should be less sensitive to variations in the assumed *b* value than the case of a finely divided source zone (for which predictions are typically based on very small magnitude events). Results of each member of the five Next Generation Attenuation – West2 (NGA-West2) models are shown. Refer Table 1 for a listing of the literature references in which various Ground Motion Prediction Equations (GMPEs) are introduced.



(a) 0.3s period **(b) 0.5s period**

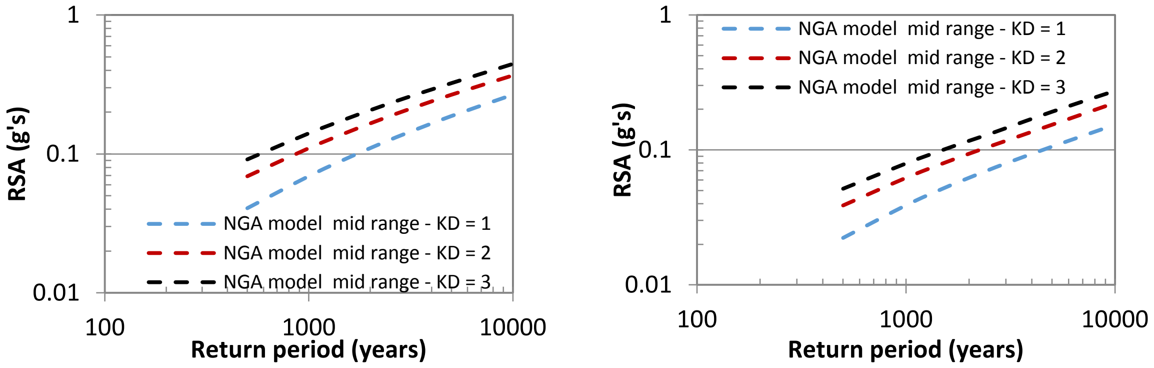


(c) 1.0s period

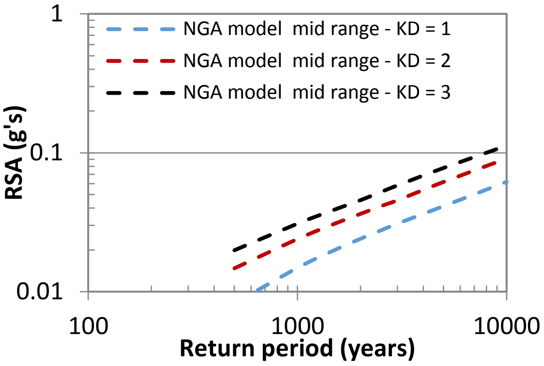
Figure 1. Results of PSHA on rock for $a = 5.2$, $b = 0.9$ (K_D=1) given $M_{\min} = 4$ and $M_{\max} = 7$

Response spectral values shown in Figure 1 are based on the assumption of random occurrence of intraplate earthquakes. In reality, earthquakes including intraplate earthquakes occur in clusters and not completely random. A survey undertaken in the Eastern United States (Kafka 2007) revealed such clustering phenomenon which results in most of the seismic activities occurring in about one-third of the area within an intraplate region. The rate of recurrence of earthquakes within such relatively active areas is accordingly 3 times the average rate of recurrence on the global scale or continental scale. In the case of Australia the average rate of recurrence (of M>5 events) across the entire continent has been found to be broadly consistent with the global average; being about 5 events for every million sq. km in the past 50 years (Lam *et al.* 2015). However, clustering of activities can result in a significant increase in the rate of recurrence in certain areas within a region. A K_D parameter is introduced herein to characterise the rate of recurrence for comparison with the global average (Lam *et al.* 2015). For example, K_D=1 when a = 5.2 and K_D = 3 when a = 5.7 approximately (being 5.2 + $\log_{10}(3)$).

Results of PSHA for different K_D values are presented in Figures 2a – 2c. Only lines representing the *mid-range* estimates are shown in these figures whereas lines associated with individual GMPEs are not shown (*mid-range* means half way in between the upper and lower limits). The *mid-range* estimates can be exceeded by results derived from one of the five GMPEs by some 25%. Values of the *Effective Peak Ground Acceleration* (EPGA) which is defined herein as value of RSA at 0.3s period divided by 2.5 are listed in Table 2 for K_D values of 1 - 3 and return period of 2500 years, with and without the 25% allowance. Recent surveys undertaken by the authors revealed K_D = 1 for Sri Lanka, K_D = 2 for the Korean Peninsula, K_D = 3 for Sarawak and K_D = 3 along the eastern seaboard of Australia as demonstrated in a later section of the paper. Return period (k_P) factors based on the assumption of uniform seismicity are also shown (refer Table 3).



(a) 0.3s period **(b) 0.5s period**



(c) 1.0s period

Figure 2. Results of PSHA on rock for K_D = 1, 2 and 3 given $M_{\min}$ = 4 and $M_{\max}$ = 7

4 EXAMPLE APPLICATION

On the Australian eastern seaboard as shown in Figure 3a which has an area of 447609 km^2 *some* 60 seismic events have been recorded during the 50 year period: 08/1965-08/2015 according to information shown on website of *Geoscience Australia* http://www.ga.gov.au/earthquakes/. The distribution of earthquake magnitudes is also shown (Figure 3b). It is noted that the distribution of earthquake events within the considered magnitude range is consistent with the assumed *b* value of 0.9. As shown in Table 4 seven M>5 events where *M* is in the moment magnitude scale have been recorded in the area in the past 50 years. The normalised count based on a reference area of 1 million sq. km is equal to 40 $\left(\text{being}\ \frac{1{,}000{,}000}{447{,}609}\times 7 = 15.6\right)$. The value of K_D is accordingly about 3 (being 15.6/5).

The *Effective Peak Ground Acceleration* (*EPGA*) value for a return period of 2500 years is 0.09g – 0.11g, being the *mid-range* and *upper limit* estimates respectively from the five considered GMPE's (refer Table 2). The reference design *PGA* value (i.e. *EPGA* for notional return period of 500 years) is accordingly 0.06g – 0.08g, being 2/3 of the values for return period of 2500 years.

Table 1. Literature references to ground motion prediction equations

Literature citations	Acronyms in legends	Remarks
Abrahamson *et al.* (2014)	AS(14)	NGA-West2 model
Boore *et al.* (2014)	BA (14)	NGA-West2 model
Campbell & Bozorgnia (2014)	CB (14)	NGA-West2 model
Chiou & Youngs (2014)	CY (14)	NGA-West2 model
Idriss (2014)	ID (14)	NGA-West2 model
Akkar & Bommer (2007)	AKB(07)	Europe & Middle East

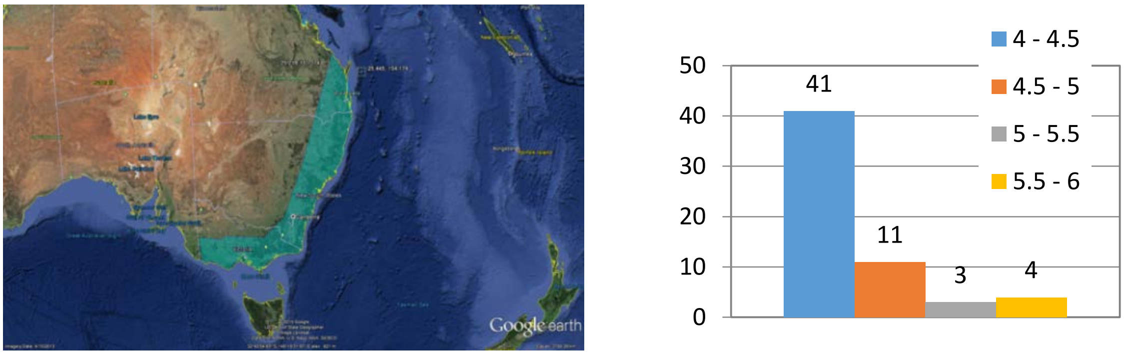
Table 2. *Effective Peak Ground Acceleration* (EPGA) for 2500 years Return Period

K_D	1	2	3
EPGA (g's)[1]	0.05	0.08	0.09
EPGA (g's)[2]	0.06	0.09	0.11

1 – *mid-range estimates (meaning half way in between the upper and lower limits) derived from the five GMPE's*
2 – *upper limit estimates out of the five GMPE's*

Table 3. Return Period Factor (k_p)

Return Period (years)	$K_D = 1$			$K_D = 3$		
	$RSA_{0.3s}$	$RSA_{0.5s}$	$RSA_{1.0s}$	$RSA_{0.3s}$	$RSA_{0.5s}$	$RSA_{1.0s}$
500	1.0	1.0	1.0	1.0	1.0	1.0
1000	1.7	1.8	1.8	1.5	1.5	1.6
1500	2.2	2.3	2.4	1.9	1.9	2.0
2000	2.7	2.8	2.9	2.3	2.3	2.3
2500	3.1	3.2	3.3	2.5	2.5	2.6
3000	3.5	3.6	3.7	2.8	2.8	2.9
5000	4.6	4.7	5.0	3.5	3.7	3.9
10000	6.5	6.9	7.5	4.9	5.3	5.7



(a) Area of study (b) frequency of earthquake occurrences

Figure 3. Case study of Australian eastern seaboard

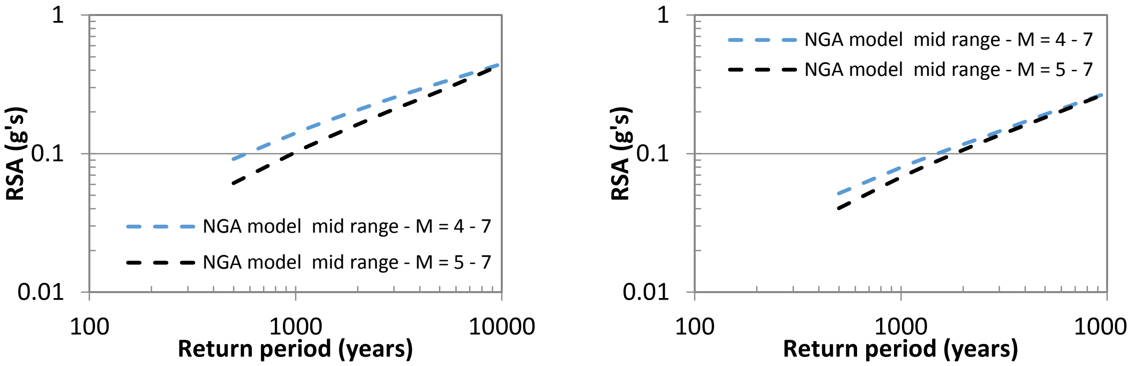
Strictly speaking, the dimension of the BSZ should exceed the diameter of the circular sub-source in order to have it fully accommodated. Should the dimension of the BSZ be not large enough there can be errors in the predicted level of hazard. In the presented example the predictions have errors on the conservative side given that areas external to, and surrounding, the source has a lower level of average seismicity than within the source.

5 SENSITIVITY STUDIES

Sensitivity analyses have also been carried out to reveal the significance of the range of magnitudes that have been included in the PSHA. It is shown that results derived from considering events in the magnitude range of M = 4 – 7 and M = 5 – 7 give very similar predictions of the response spectral accelerations in probabilistic terms at return period of 2500 years except for values of $RSA_{0.3s}$ (Fig. 4). It is shown by further analyses that results derived from considering events in the magnitude range of M = 4 – 6 and M = 4 – 8 are also very similar at return periods of up to 2500 years (Fig. 5). Charts have also been produced to show predictions by PSHA when GMPEs other than the NGA-West2 models were employed in the analyses (refer Table 1 for the listing). It is shown that results of PSHA employing the GMPE of Akkar and Bommer (2007) for use in Europe and the Middle East are generally consistent with results based on employing the NGA-West2 models (Fig. 6).

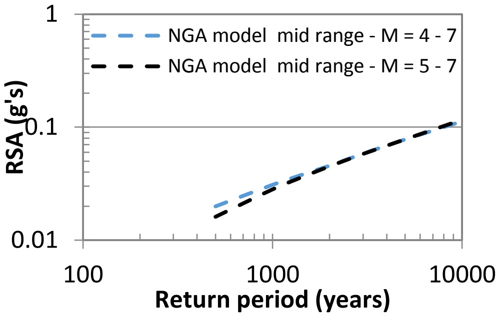
Table 4. Details of earthquakes M>5

Magnitude	Date	Time	Latitude	Longitude	Approximate Location
5.2	2015-02-16	02:57:09	-25.146	151.436	Near Eidsvold, QLD.
5.4	2012-06-19	20:53:29	-38.304	146.2	SW of Moe, Vic.
5.3	2011-04-16	15:31:18	-20.085	147.764	Near Bowen, QLD.
5.7	1989-12-28	10:26:57	-32.946	151.607	Newcastle NSW
5.5	1973-03-10	05:09:14	-34.17	150.32	Picton NSW
5	1971-07-07	07:55:00	-38.423	145.113	Westernport Basin VIC
5.3	1969-06-20	21:15:28	-38.47	146.3	Boolarra VIC



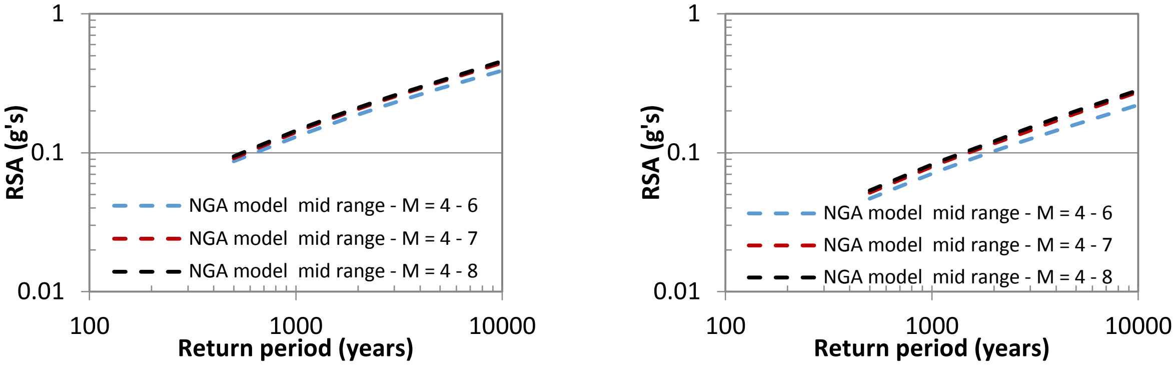
(a) 0.3s period

(b) 0.5s period



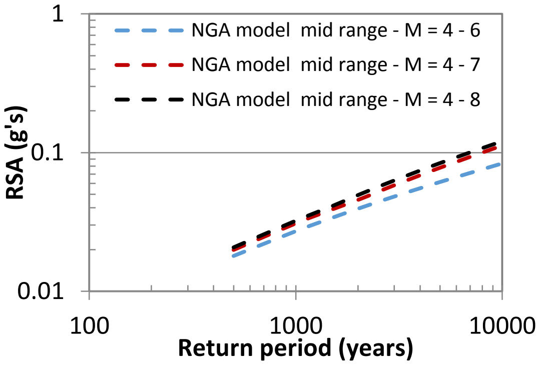
(c) 1.0s period

Figure 4. Results of PSHA on rock for different $M_{\min}$ given $K_D = 3$ and $M_{\max} = 7$



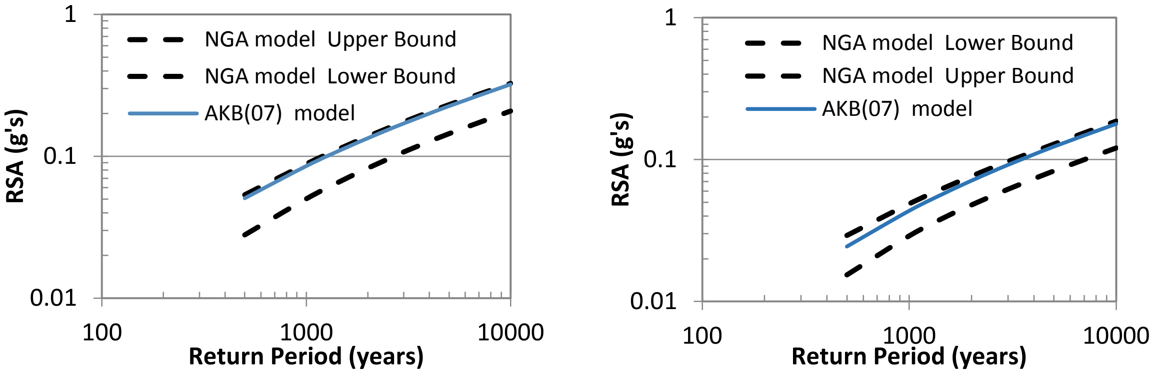
(a) 0.3s period

(b) 0.5s period



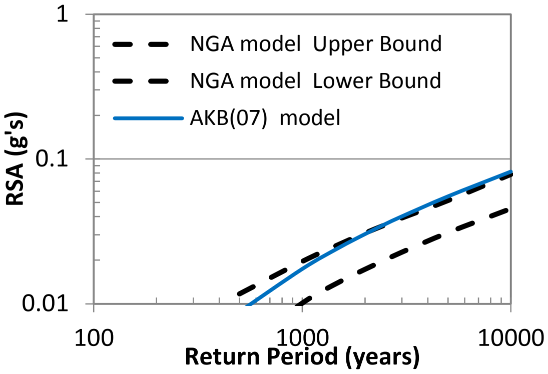
(c) 1.0s period

Figure 5. Results of PSHA on rock for different $M_{\max}$ given $K_D = 3$ and $M_{\min} = 4$



(a) 0.3s period

(b) 0.5s period



(c) 1.0s period

Figure 6. Comparison of GMPEs: Akkar & Bommer (07) vs NGA-West2 models given $K_D = 3$, $M_{\min} = 5$ and $M_{\max} = 7$

6 CLOSING REMARKS

Results of PSHA based on the assumption of uniform seismicity within a broad source zone are presented for quantifying the minimum level of seismic hazard in areas (typically areas far away from tectonic plate boundaries) where there is insufficient information to confidently delineate a spatial pattern of seismic activities. Initial predictions are based on the average rate of recurrence of M>5 events in intraplate regions which can be represented in the form: $\log_{10}N = 5.2 - 0.9M$ for a normalised area of a million sq. km for a 50 year period of exposure. K_D factors are then introduced for adjusting the seismicity level based on surveying the frequency of occurrence of events over a large area in the order of 10^6 km^2. Seismicity analysis on the eastern seaboard of Australia reveals a rate of recurrence of M>5 events which corresponds to $K_D = 3$ and a reference design *PGA* value in the range 0.06g – 0.08g for a notional return period of 500 years. Information in relation to *RSA* values for different values of K_D, return period factor, and effects of the considered range of moment magnitudes, and GMPEs have also been presented.

7 ACKNOWLEDGEMENT

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