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An Alternative Probabilistic Seismic Hazard Assessment Method in Areas of Low-to-Moderate Seismicity

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ABSTRACT

Probabilistic seismic hazard assessment (PSHA) has been widely used as a rational approach of determining seismic design loads but there are limitations with the use of the conventional PSHA procedure in areas with a paucity of local seismicity data. In this study a generic model for setting minimum level of seismic hazard was developed by analysing seismicity data that had been surveyed around the globe on land. Elastic response spectral acceleration values corresponding to a range of return periods have been calculated by the use of a number of well-known ground motion prediction equations based on the estimated level of seismicity. Results can be presented in the form of design charts which show the sensitivity of the predictions to changes in various modelling parameters. This modelling approach is designed to make the PSHA procedure more transparent.

1 INTRODUCTION

Probabilistic seismic hazard assessment (PSHA) which was first introduced by Cornell-McGuire (Cornell 1968; McGuire 1976) has become universally accepted practice for quantifying the level of seismic hazard. As introduced in almost every textbook on earthquake risk assessments (e.g., Dowrick 2009), Cornell-McGuire PSHA procedure is resolved into four key steps namely: (i) identification of potential seismic sources; (ii) characterisation of each source by magnitude recurrence modelling; (iii) ground motion predictions for all considered earthquake scenarios; and (iv) integration of contributions from multiple sources with the considerations of both aleatory and epistemic uncertainties. The spatial distribution of hazard levels so obtained from the assessment is usually presented in the form of contour map which becomes an integral part of a seismic design standard.

Alternative PSHA procedures have been proposed by various researchers over the last two decades with an aim of enhancing the robustness of hazard estimates (e.g. McGuire 1993; Frankel 1995; Kijko and Graham 1999; Tsang and Chandler 2006;

Tsang et al. 2011). However, all PSHA procedures are based on the premise that past events should be indicative of potential hazards for the future. This has been found to be true to a certain extent in some evaluation studies (Kafka 2007; Camelbeeck et al. 2007) but is very dependent on the sample of data that is sufficiently large to capture the underlying long term seismic processes and trends. Whilst the philosophy of PSHA is straightforward and the procedure as a whole is well known, important discretionary judgement needs to be exercised in every step of the modelling (and step (i) in particular) in lower seismic regions where few data points are available. It can be shown that when the method is applied to model local hazards in countries where local seismicity data is scarce, the predicted level of hazard can vary by more than 100% based on different assumptions of the source zonation. Importantly, earthquake motions recorded from all around the world exceed those indicated in seismic hazard maps more frequently than expected (Tsang 2011) and the huge residual risk is highlighted in the discrepancies between the actual and expected numbers of fatalities (Wyss *et al*. 2012).

In regions of low-to-moderate seismicity historical earthquake events which have magnitude (M>4) exceeding the threshold of causing structural damage is typically very sparse. 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 only a few millimetres per year. The rate of occurrence of intraplate earthquakes is not uniform in space and time. Activity rates have been found to vary significantly from land and sea, and between plates (Bergman and Solomon 1980; Okal and Sweet 1981). Seismicity within a region can also be subject to both spatial and episodic variations (Leonard *et al*. 2007). In the absence of a definitive emerging seismicity pattern there is a great deal of uncertainties over the size and location of the earthquake generating sources.

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 (> 2500 years) design return period considerations than to normal design considerations for building structures. Furthermore, a very long lead time is required to deliver results that are considered useful for drafting structural design code provisions.

A finely divided source zones model (for PSHA) would predict a high level of hazard in the vicinity of areas where earthquakes have occurred in recorded history but the main concern with this type of model is the inherent underestimation of seismic hazard in areas where the historical database does not show any significant local seismic activity. 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. There is no general consensus over the minimum threshold (baseline) hazard to account for intraplate seismicity.

In contrast, a broad source zone modelling approach predicts a uniform level of hazard and fails to identify "hot spots" of relatively high seismic activities within an intraplate region. Both modelling approaches, when used on their own, would run the risks of understating seismic hazard in certain areas. The authors support continuing the practice of using conventional PSHA for predicting spatial variation of seismic hazard surrounding areas where activities are expected to be higher. At the same time, and importantly, a broad source zone modelling approach should be adopted to establish the minimum hazard level which is the subject matter of this paper.

The assumed seismicity level in the broad source zone model must not be lower than that inferred from the average global rate of recurrences of intraplate earthquakes (Section 2). The PSHA methodology as applied to an area of uniform seismicity is then introduced (Section 3). Predicted ground motion hazards expressed in the form of a design response spectrum as derived from PSHA based on global rate of recurrences is then presented (Section 4). Results of sensitivity analyses are aimed at informing engineers, and other end users, of the cause and effects of changes in values of the assumed rate of recurrences (Section 5).

2 GLOBAL RATE OF RECURRENCES OF INTRAPLATE EARTHQUAKES

The global seismic activity modelling approach introduced in this section draws upon the vast landmass of a number of stable continental (intraplate) areas around the globe to compensate for their lower rates of seismic activity. This is expected to provide a much more robust representation of seismic activity in stable continental areas compared with locally developed models.

In this method, the rate of intraplate seismic activity is estimated from the *Global Strain Rate Model* of Bird *et al*. (2010) recognising that tectonic movements can be classified into four deformation regimes namely: (i) *Subduction*; (ii) *Diffuse Oceanic*; (iii) *Ridge-Transform*; and (iv) *Continental*. The rate of recurrence of earthquake events in the four deformation regimes was modelled using the *Seismic Hazard Inferred From Tectonics* (SHIFT) approach which involves monitoring tectonic activities through analysis of data from *Global Position System* (GPS) geodetic velocity measurements. Earthquakes generated from (all land and sea) areas that are not part of any of these deformation regimes are classified as intraplate earthquakes. The rate of intraplate activities around the globe which represents only 2.7% of shallow seismicity was modelled by taking an empirical-averaging method. An average activity rate based on the number of events (of magnitude equal to and exceeding 5.66) per *square meter* and per *second* was estimated at 4.27×10^{-22} which is translated into 0.67 (or $10^{-0.17}$) number of events in an area of 1,000,000 km^2 over a 50-year period. This occurrence rate estimate is for all intraplate earthquakes occurring on either land or sea around the globe.

The rate of seismic activity rate is conventionally defined using the *Gutenberg-Richter* magnitude recurrence relationship of the form:

$$\log_{10} \mathrm{N(M)} = a - b\mathrm{M} \tag{1a}$$

where N(M) may be defined as the expected number of earthquakes $\geq$ M occurring within an area of 1,000,000 km^2 over a 50-year period, and a and b are defined as the seismic constants. Alternatively, Eq. (1a) may be re-written as follows:

$$\log_{10} \mathrm{N(M)} = a_5 - b(\mathrm{M} - 5) \quad (1b)$$

where a_5 is the logarithm of the total number of earthquakes with M ≥ 5, within the same area and period.

The global intraplate seismic activity rate can be translated into a value of a_5 = 0.42 (being -0.17 +0.9 × 0.66), or a value of a = 4.9 (being -0.17 +0.9 × 5.66), based on assuming b = 0.9.

It is noted that b – values are typically in the range of 0.8 – 1.1 and have been found to vary from region to region across the globe as well as the style of faulting (Heety 2011). The b – value was estimated to be around 0.93 on average for earthquakes featuring a thrust-faulting mechanism which is typical of earthquakes in intraplate regions (GA 2012, citing the work of Schorlemmer *et al.* 2005). Independent regional specific studies identified b – values of 0.88 for Australia (Allen et al. 2004), 0.92 for the Indian sub-continent (Jaiswal and Sinha 2006; 2007), 0.91 for New Madrid, Eastern North America (Stein and Newman 2004) and 0.9 for Africa (Heety 2011). All these regions are predominantly intraplate in tectonic terms and a b – value of 0.9 is considered to be a reasonable assumption for the purpose of developing a generalised global seismicity model for intraplate regions.

The average activity rate value of a_5 = 0.42 is translated to approximately **2 − 3** events exceeding M5 for an area of 1,000,000 km^2 and exposure period of 50 years (asterisk is used in the notation where the rate of occurrence is normalised with respect to this standard area and exposure period). This averaged activity rate (which covers both land and sea) is one order of magnitude lower than that identified for activities in *Diffuse Oceanic* (ii) regimes; two orders of magnitude lower than *Continental* (iv) regimes; and three orders of magnitude lower than the *Subduction* (i) and *Ridge Transform* (iii) regimes. Thus, the activity rate inferred from the global catalogue dataset for intraplate regions is shown in the *Rate Map* of Bird et al. (2010) to be well aligned with those inferred from GPS geodetic velocity measurements for high seismic regions.

Interestingly, studies of intraplate seismicity in oceanic regions over the period 1963 − 1980 revealed much lower number of counts of events (Bergman and Solomon 1980). There have been as few as **1 − 2** intraplate events occuring in oceans (based on the full catalogue) when normalised to an area of 1,000,000 km^2 and exposure period of 50 years. Oceanic areas adjacent to India have the highest count (3 − 4) whereas areas adjacent to Africa have the lowest count (< 1). These normalised figures show that seismicity in oceanic areas is overall lower than the average seismicity of land and oceanic areas combined as is represented by the global seismicity model of Bird *et al*. (2010). Thus, the normalised counts of event on land (continents) alone should be higher than 2 – 3 as inferred from the model of Bird *et al*. (2010).

Attention is next turned to intraplate events occurring on land in stable continental areas. The event number count of M ≥ 5 earthquake events over a period of 50 years on land is listed in Table 1 for individual countries (or regions) that are wholly away from any tectonic plate boundary. The limited exposure period of 50 years was chosen to minimise issues associated with incomplete datasets from historical earthquake events to obtain estimates of the rate of earthquake recurrence. The on land event number counts were then normalised to the land area of 1,000,000 km^2 consistent with the conventions adopted earlier when presenting results from study by Bird *et al*. (2010) and by Bergman and Solomon (1980).

Only earthquakes occurring on land have been included in the event counts reported in Table 1 in order that when the number of events is divided by the land area of the respective country the normalised figures from each of the listed countries can be compared. All earthquake magnitudes of the historical events have been converted to the moment magnitude scale as per conversion relationship provided in McCalpin (2009). No correction for aftershocks has been applied given that the number of aftershocks of intraplate earthquakes exceeding M5 is insignificant and hence the effect of including aftershocks in the event count statistics is minor.

The important observation is that the normalised event counts as presented in Table 1 are all very consistent. In most cases the individual normalised event counts are in the range 4 – 6 (except for a couple of countries where the total counts are too small to have statistical significance). A small country (e.g., Peninsular Malaysia) may have no event recorded in the past 50 years which does not mean that the seismicity for that country is zero. In view of the figures shown, the average normalised event count for intraplate earthquakes occurring on land can be taken as **5** which is higher than the normalised event count of 2 – 3 as inferred from the global activity rate model of Bird et al. (2010) for intraplate earthquakes occurring on both land or sea but is nonetheless within an order of magnitude agreement. This rate of recurrence of intraplate earthquakes occurring on land based on results of surveys on a global scale is translated to the value of $a_5 = 0.72$ or $a = 5.2$ assuming $b = 0.9$ for an area of 1,000,000 sq km over an exposure period of 50 years.

The rate of seismic activity based on taking the global average can be used to determine a minimum level of hazard where seismicity data in a region is too sparse that the statistics of local historical earthquakes cannot be relied upon to quantify the rate of recurrence of future earthquakes. There are other situations where the rate of recurrence in an area may significantly exceed the predicted global, or regional, average. For example, the spatial distribution of earthquake activities in Central and Eastern United States (CEUS) show that some 80 – 90% of the epicentres of earthquakes exceeding M5 were located within only one-third of the area according to results of a regional seismological survey study (Kafka 2007). In other words these relatively active parts of the CEUS have 2.5 – 3 times more earthquakes per unit area than that estimated by the assumption of uniform seismicity across the entire region of CEUS. In view of the need to assume a rate of recurrence which is higher than the global average in certain areas a K_D factor is introduced herein in order that the number of times the predicted rate of recurrence exceeds the global average can be specified. Thus, the relationship between value of a_5^* and K_D is given by the following expression:

$$a_5^* = 0.72 + \log_{10}(K_D) \tag{2}$$

Deciding on the value of K_D involves judgement over the delineation of the earthquake generating sources, and well informed judgement can be made should there be good knowledge of the historical seismicity pattern and geology of the region. The methodology presented in this paper is not intended to substitute judgement. The methodology is intended to be used as a convenient means to show how ground motion predictions would change should different assumptions (judgement) be made in the source model in order that the PSHA process becomes much more transparent.

Table 1 Number of M ≥ 5 intraplate earthquake events on land in a 50 year period

Country	**Land Area (km)**	**N(M≥5) in 50 years [Recorded Number]**	**N(M≥5) in 50 years [Recorded Number Normalised to 1,000,000 km^2]**
Australia$_1$	7,692,024	45	6
Brazil$_2$	8,515,767	33	4
Eastern US$_3$	2,291,043	13	5 – 6
Eastern & Central China$_2$	1,550,974	14	9
France$_4$	674,843	4	6
Southern India$_5$	635,780	3	5
Germany$_4$	357,021	1	3
British Isles$_4$	315,134	3	9 – 10
Peninsular Malaysia	131,598	<1	<1
	Σ = 22,032,586	Σ = 116	Average = **5**

1. Data were obtained from GA (Geoscience Australia) earthquake catalogue, web reference: http://www.ga.gov.au/earthquakes/
2. Data were obtained from PAGER-CAT earthquake catalogue, reference: Allen *et al*. (2009)
3. Data were obtained from CEUS earthquake catalogue, web reference: http://www.ceus-ssc.com/
4. Data were obtained from EMEC earthquake catalogue, reference: Grünthal & Wahlström (2012)
5. Data were obtained from reference: NDMA (2011)

3 PROBABILISTIC SEISMIC HAZARD ASSESSMENT BASED ON PREDICTED RATE OF RECURRENCES

The procedure for calculation of the probability of exceedance of ground motion intensities forming part of the probabilistic seismic hazard assessment (PSHA) procedure is well established. Given that an important objective of this paper is to provide transparencies of the calculation procedure to the end users (including engineers who make use of the results for design purposes) all relevant mathematical relationships that have been employed in the computations are listed, and explained, in a logical manner in this section.

First, the conditional probability of exceedance of a response spectral acceleration (*RSa*) exceeding a targeted value (*RSa**) for a given earthquake scenario expressed in terms of magnitude-distance (M-R) combination is given by the following expression as per *log-normal* distribution:

$$\Pr\left\langle RSa \geq RSa^* \middle| \mathrm{M,R} \right\rangle = 1 - \Phi\left(Z^*\right) \tag{3a}$$

where,

$$\Phi(Z^*) = \int_{Z=-\infty}^{Z=Z^*} e^{-\frac{Z^2}{2}} dz \qquad (3b)$$

Z is the zero mean log normalized ordinate;

$$Z = \frac{RSa - \overline{RSa}}{\sigma_{\ln RSa}} \qquad (3c)$$

$\overline{RSa}$ is the estimate of the mean for the given M-R combination based on the adopted ground motion predictive expression (GMPE) and $\sigma_{\ln RSa}$ is the standard deviation of the natural logarithm of the *RSa* values.

In an area where uniform spatial distribution of seismicity is assumed, the piece of land surrounding a site can be divided into rings each of which can be treated as an individual earthquake source for the purpose of PSHA (Fig. 1a). The area of the ring is used for calculating the probability of earthquake events occurring (within the ring) and its distance from the site (the centre) is taken as the value of *R* for the purpose of Eq. (3a).

Given that the number of earthquake events exceeding magnitude (M) generated by an earthquake source in a year is given by Eqs. (1a) or (1b) the annual probability of having an even with magnitude exceeding M is

$$\lambda(M) = 10^{a-b\mathrm{M}} \qquad (4a)$$

The annual probability of having a destructive earthquake with magnitude exceeding M_{min} is

$$\lambda(\mathrm{M}_{\min}) = 10^{a-b\mathrm{M}_{\min}} \qquad (4b)$$

where M_{min} = 4 is assumed in this study.

The value of a_5* as calculated from Eq. (2) represents the number of events exceeding M5 for an area of 1,000,000 sq km in a 50-year period as discussed in the previous section. It was found that a_5* = 0.72 (for K_D =1) and that *a** = a_5* + *b*(5). Hence, *a** = 5.2 assuming *b* = 0.9.

For a circular ring:

$$a = a^* + \log_{10}\left(\frac{\frac{\text{area of ring}}{1{,}000{,}000}}{50}\right) \qquad (4c)$$

where *a* represents the number of earthquake events occurring in a circular ring.

Take an example circular ring which has area of 236 sq km and inner and outer radii of 5 km and 10 km respectively it can be shown that 50% of the area within the ring has distance from the centre exceeding the median distance of 7.91 km which is denoted as *R* (Fig. 1b). From Eq. (4c), *a* = -0.126 given that *a** = 5.2.

Consider a situation when a destructive earthquake magnitude (M) has occurred the conditional probability of the magnitude of the earthquake not exceeding *M* is denoted as *F*(M) where

$$F(\mathrm{M}) = 1 - \frac{\lambda(\mathrm{M})}{\lambda(\mathrm{M}_{\min})} = 1 - 10^{-b(\mathrm{M}-\mathrm{M}_{\min})} \qquad (4d)$$

The conditional probability of magnitude of the earthquake falling within the bin $M_i - M_{i+1}$ is $F(M_i) - F(M_{i+1})$.The total probability of the earthquake falling within the bin

$M_i – M_{i+1}$ is

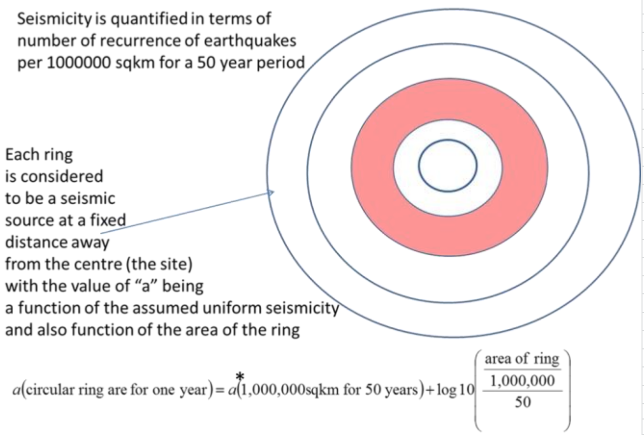
$$\Pr(\mathrm{RSa} \geq \mathrm{RSa}^*) = \lambda(\mathrm{M}_{\min}) \times [F(\mathrm{M}_i) - F(\mathrm{M}_{i+1})] \times \Pr\langle \mathrm{RSa} \geq \mathrm{RSa}^* | \mathrm{M}, \mathrm{R} \rangle \tag{4e}$$

where, M = 1/2 (M_i + M_{i+1}), R = 7.91 km.

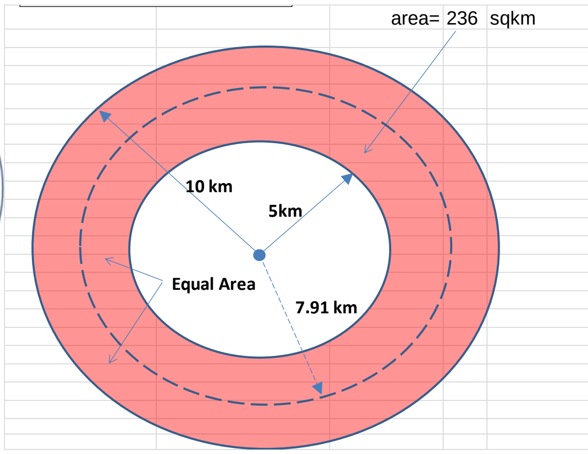
Result obtained from Eq. (4e) are to be aggregated for all magnitude bins within the range of M_{min} = 4 to M_{max} = 7 which is a reasonable assumption to make for continental regions that are remote from any tectonic plate boundaries such as Australia. An example spreadsheet implementation of the calculation is shown in Fig. 1(c). The mathematical expression for the aggregation can be written as follows:

$$\Pr(\mathrm{RSa} \geq \mathrm{RSa}^*) = \sum_j \sum_i \lambda_j(\mathrm{M}_{\min}) \times [F(\mathrm{M}_i) - F(\mathrm{M}_{i+1})] \times \Pr\langle \mathrm{RSa} \geq \mathrm{RSa}^* | \mathrm{M}, \mathrm{R}_j \rangle \tag{4f}$$

where subscript *i* and *i*+1 denote the magnitude range and *j* denotes the median distance (of a ring).



(a) Schematic diagram showing circular rings



(b) An example circular ring of 5 – 10 km radii

$$R = \sqrt{\frac{5^2 + 10^2}{2}} = 7.9$$

5	km to	10	km							
5	to	10	R=	7.91	km	h=	5.94	r=	9.89	
mi	Fm(Mi)	Fm(Mi+1)	Fm(Mi+1)-Fm(Mi)	mi	RSa mean	ln RSa mean	Z*=(ln RSa* -ln Rsa Mean)/sigma ln	F(Z*)	1-F(Z*)	λ(Mmin)[Fm(Mi+1)-Fm(Mi)][1-Φ(Z*)]
5	0.000	0.297	0.297	5.08	0.20	-1.588	0.74	0.769	0.231	0.000002
5.17	0.297	0.507	0.210	5.25	0.24	-1.415	0.40	0.657	0.343	0.000002
5.33	0.507	0.656	0.149	5.42	0.29	-1.251	0.09	0.536	0.464	0.000002
5.50	0.656	0.761	0.105	5.58	0.33	-1.096	-0.21	0.418	0.582	0.000002
5.67	0.761	0.835	0.075	5.75	0.39	-0.950	-0.49	0.313	0.687	0.000001
5.83	0.835	0.888	0.053	5.92	0.44	-0.813	-0.75	0.227	0.773	0.000001
6.00	0.888	0.926	0.037	6.08	0.50	-0.685	-0.99	0.160	0.840	0.000001
6.17	0.926	0.952	0.026	6.25	0.57	-0.566	-1.22	0.111	0.889	0.000001
6.33	0.952	0.971	0.019	6.42	0.63	-0.455	-1.43	0.076	0.924	0.000000
6.50	0.971	0.984	0.013	6.58	0.70	-0.354	-1.63	0.052	0.948	0.000000
6.67	0.984	0.993	0.009	6.75	0.77	-0.262	-1.81	0.036	0.964	0.000000
6.83	0.993	1.000	0.007	6.92	0.84	-0.178	-1.97	0.025	0.975	0.000000
7.00	1.000	1.000	0.000							
		Sum=	1.000						Combined P(RSa>RSa*)	0.000011

(c) Computation of Pr(RSa > RSa*) for the example circular ring

Figure 1 Circular Ring Model for PSHA in areas of uniform seismicity

The Return Period (RP) for any given value of RSa* is accordingly taken as the reciprocal of the calculated value of Pr(RSa ≥ RSa*) as shown by Eq. (4g).

$$RP = \frac{1}{\Pr(\mathrm{RSa} \geq \mathrm{RSa}*)} \tag{4g}$$

4 RESULTS OF PROBABILISTIC SEISMIC HAZARD ASSESSMENT EMPLOYING NEXT GENERATION ATTENUATION MODELS

In a parametric study undertaken by the authors probabilistic seismic hazard assessment were undertaken using the methodology introduced in the previous section to obtain correlations of response spectral acceleration values with return period for natural period of 0.2s, 0.3s, 0.4s, 0.5s, 0.75s and 1.0s assuming an average global rate of recurrence of intraplate earthquakes (i.e., $a_5* = 0.72$ based on $K_D = 1$) and the five *Next Generation Attenuation* (NGA) models for defining the conditional probability of occurrence of *RSa* values for given M-R combinations. The analyses have employed each of the NGA models: Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), Chiou and Youngs (2008), Idriss (2008). These attenuation models are given the abbreviations AS(08), BA(08), CB(08), CY(08) and ID(08) respectively for identification in the legend (Fig. 2). Upper and lower bound (envelope) values of *RSa* encompassing all five NGA models are also shown along with the respective median values (Fig. 3).

Design response spectra presented in different formats showing response spectral acceleration (*RSa*), response spectral velocity (*RSa*) and response spectral displacement (*RSd*) values are shown in Fig. 4 (which shows A, V and D as abbreviations to *RSa*, *RSv* and *RSd* respectively). These response spectra can be defined algebraically by the following expressions:

$$RSa = RSa_{\max} \quad \text{for } T \leq T_1 \tag{5a}$$

$$RSa = RSv_{\max} \times \frac{2\pi}{T} \quad \text{for } T_1 \leq T \leq T_2 \tag{5b}$$

$$RSa = RSv_{\max} \times \frac{T_2}{T}\left(\frac{2\pi}{T}\right) \quad \text{for } T > T_2 \tag{5c}$$

$$RSv = RSa \times \frac{T}{2\pi} \tag{5d}$$

$$RSd = RSv \times \frac{T}{2\pi} \tag{5e}$$

$$RSa = \mathrm{Min}\left(RSa_{\max}, \frac{RSv_{\max}^2}{RSd}\right) \quad \text{for } RSd < RSd_{\max} \tag{5f}$$

Results from PSHA for return period of 2500 years have been collated and translated into *RSv* values in order that a design response spectrum of the *flat-hyperbolic* form (in the acceleration format) enveloping all the *RSa* values presented in Fig. 3 can be formulated. The design response spectrum based on the predicted average rate of intraplate seismicity (i.e., $K_D = 1$) can be defined by Eqs. (6a) and (6b) and Fig. 5 for the A-V parts of the response spectrum. The second corner period (T_2) value defining the D part of the response spectrum has been treated in another publication by the authors (Lumantarna *et al.* 2012) and is beyond the scope of this paper. A T_2 value of 1.5s is recommended for earthquakes of up to M7.

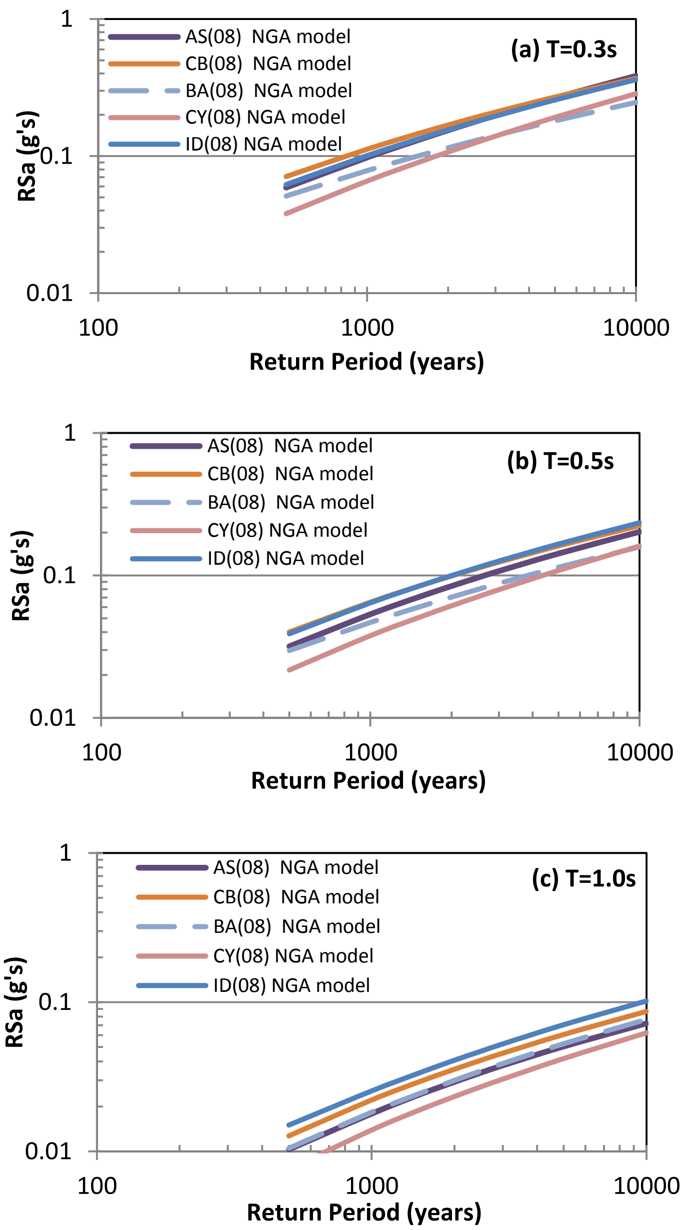


Figure 2 Results of PSHA on rock for K_D=1 for RSa at periods of (a) 0.3s (b) 0.5s and (c) 1.0s

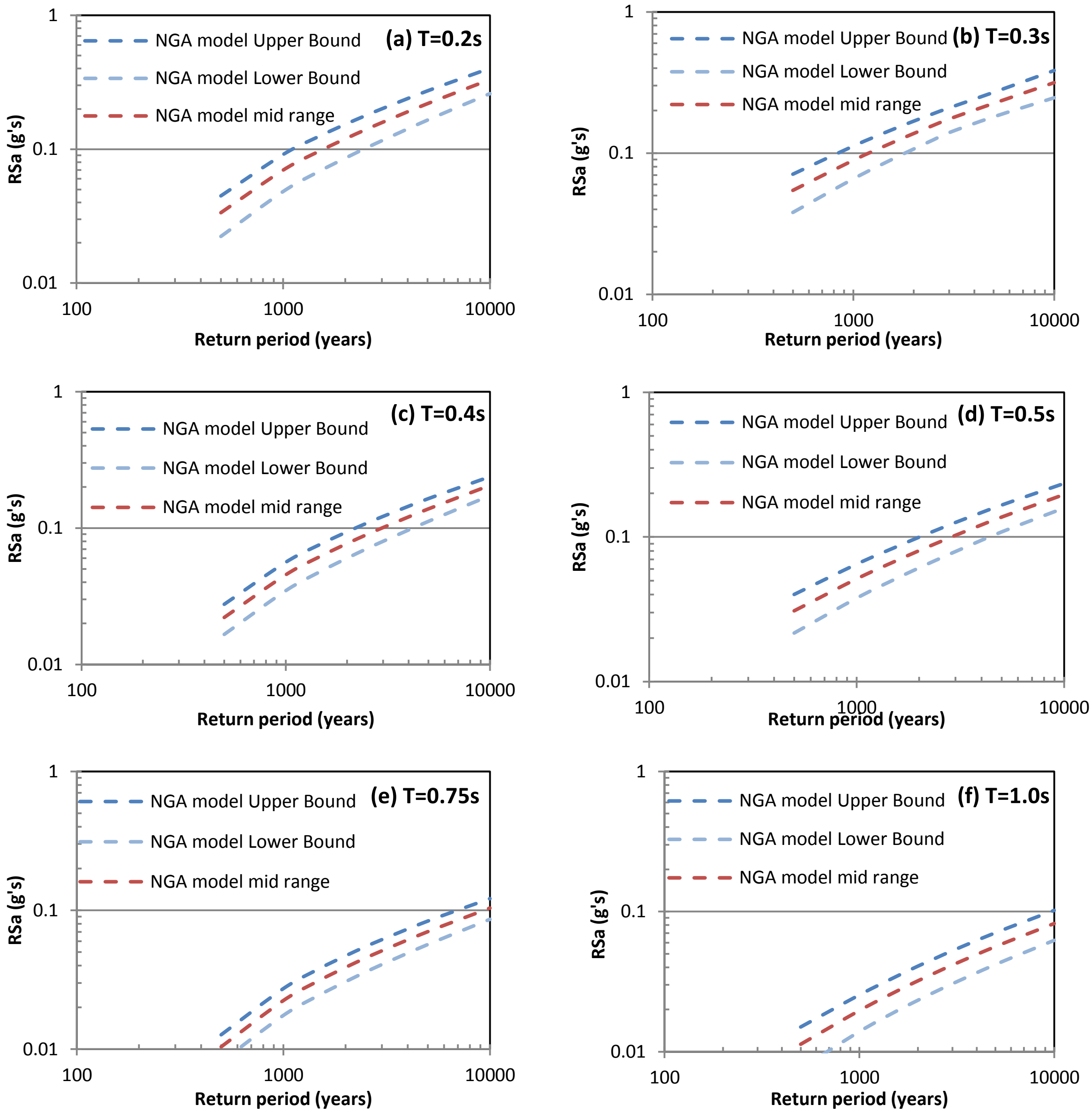


Figure 3 Envelope and median *RSa* values on rock for K_D=1 at periods of (a) 0.2s (b) 0.3s (c) 0.4s (d) 0.5s (e) 0.75s (f) 1.0s

$$RSa = 1.5 \tag{6a}$$

$$RSa = \frac{0.45}{T} \tag{6b}$$

whichever is smaller; results are expressed in units of m/s^2.

This response spectrum infers a peak ground acceleration (*PGA*) value of 0.06g approximately based on the assumption of the value of RSa_{max} being 2.5 times that of *PGA*.

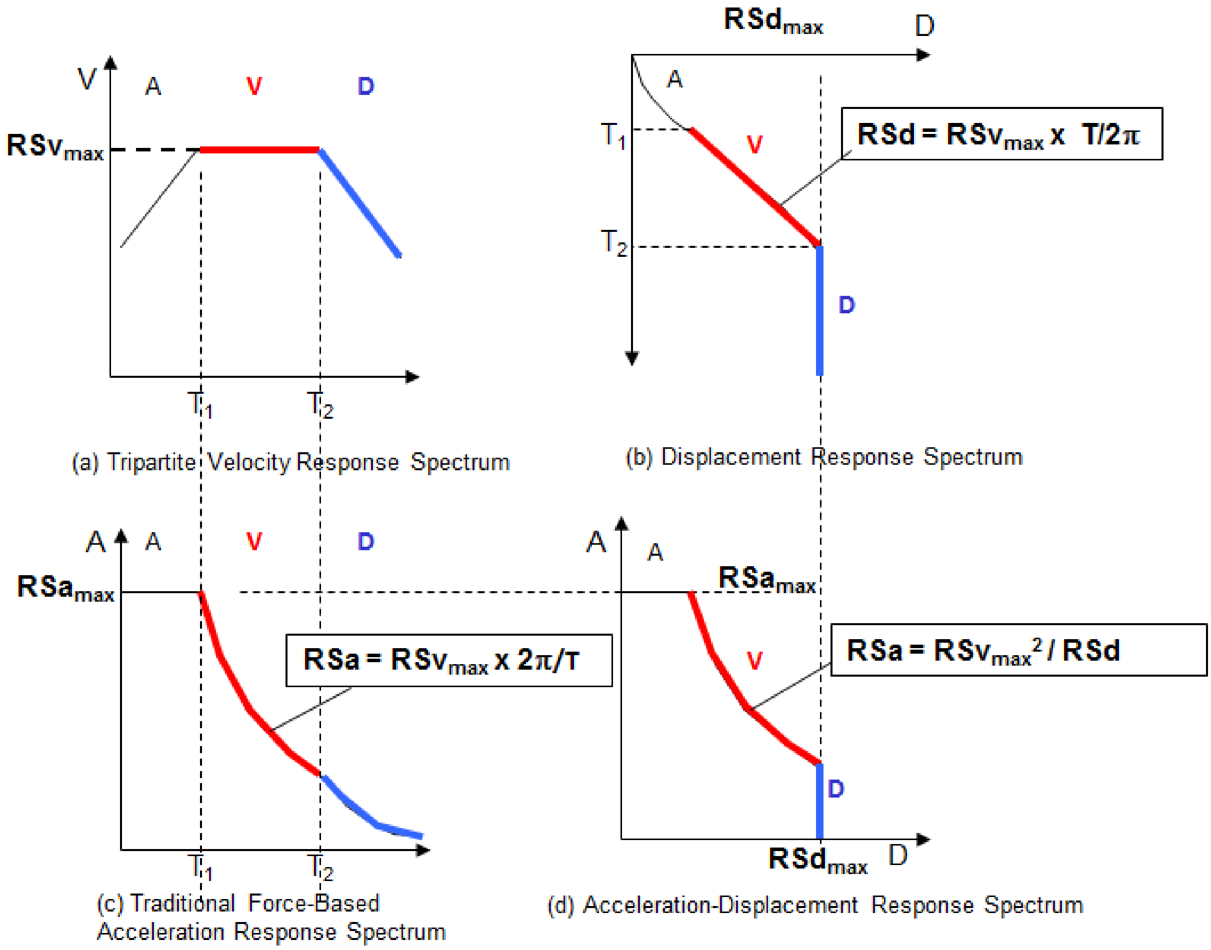


Figure 4 Design response spectra expressed in alternative formats

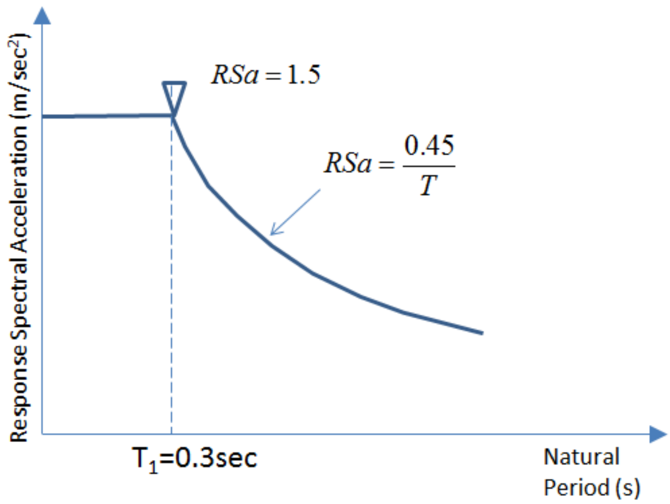


Figure 5 Design response spectrum on rock for K_D=1 and RP of 2500 years

5 RESULTS OF SENSITIVITY ANALYSIS

As discussed in Section 3 there are situations where the rate of earthquake recurrence in an area may exceed the predicted global average (i.e. $K_D > 1$). Take the Korean peninsula as example. The strongest earthquake in the 20th century happened in *Pyungbook*, North Korea in 1980 which was measured magnitude 5.3. In December 1996, a second earthquake of magnitude 4.5 struck the *Yong Wol* area which was located in the mid-east part of Korea. In June 1997, another earthquake with magnitude 4.3 struck *Kyung Ju* and was a cause of concern for many because its epicenter was located on the *Yong San Fault* which is one of the major faults that have been identified in the Korean peninsula and is about 200km long. In 2004 another strong earthquake of magnitude 5.2 occurred in *Uljiu, Kyungbook*, on the east coast of South Korea. If this latest event is also included as a "20th century event" the number of earthquakes that have occurred in the peninsula in the second part of that century would be 2. Had the M4.3 and M4.5 events been included in the event counts the inferred level of seismicity would be even higher. Given that the area of the *Korean* peninsula is 220,700 sq km the number of M>5 events that would be predicted in accordance with the average global rate of occurrence of intraplate earthquakes as derived in Section 2 is approximately equal to 1 (being 5 x 220700/1000000). Thus, a K_D value of 2 may be assumed (being 2 divided by 1). The same K_D value of 2 may be assumed for eastern and southern China according to results of survey listed in Table 1. In comparison, certain parts of *Central and Eastern United States* are considered to have K_D value of about 3 as per discussions presented in Section 2. In view of the event counts undertaken in various intraplate regions additional PSHA employing the circular ring model have been undertaken assuming a range of K_D values. It is shown in Fig. 6 that the T_1 value of 0.3s is fairly robust across a range of return periods and K_D values. It is also shown that the trends and bandwidth displayed by the envelopes for K_D values of 1 and 3 are similar (Fig. 7). Median RSa values based on K_D = 1, 2 and 3 are also shown to indicate sensitivity of the predicted ground motion intensities to varying modelling assumptions (Fig. 8). It is shown further (in Fig. 9) that ground motion intensities become insensitive to further increase in the value of K_D exceeding 5.

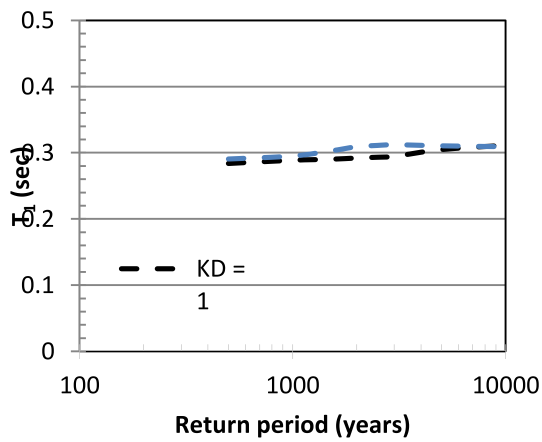


Figure 6 First corner period values

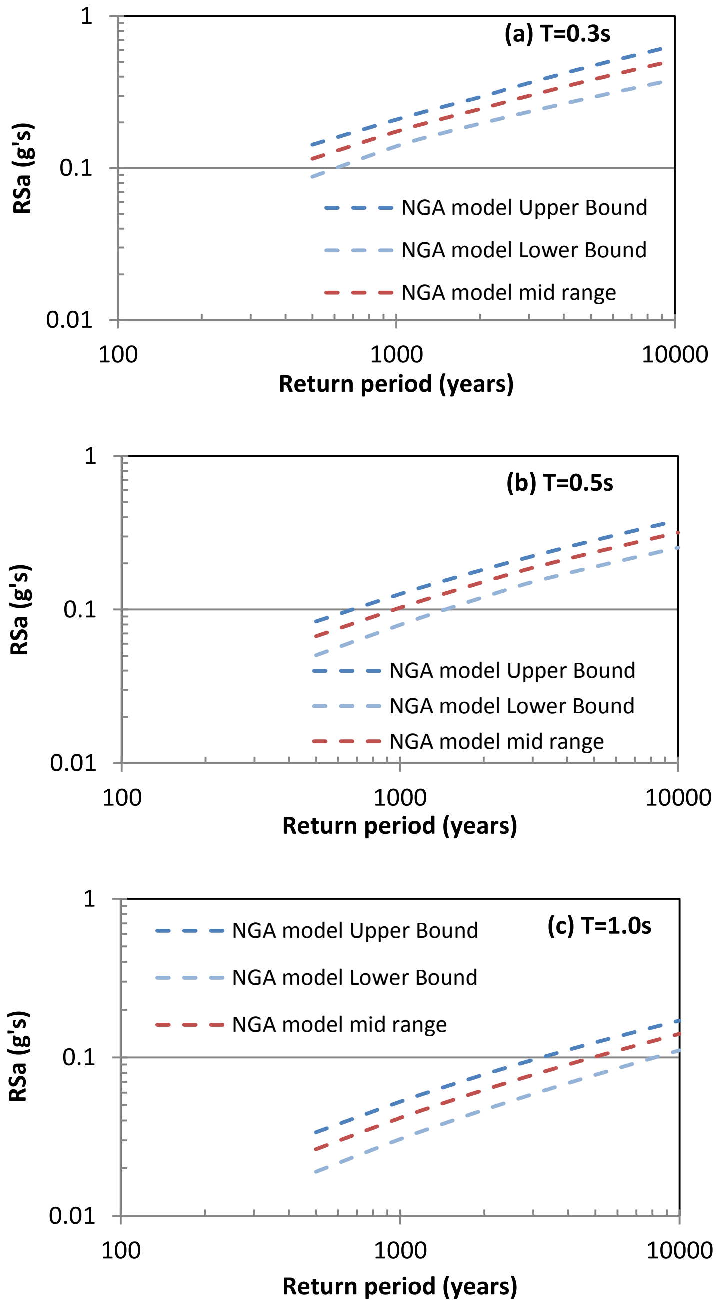


Figure 7 Envelope and median RSa values on rock for K_D=3 at periods of (a) 0.3s (b) 0.5s (c) 1.0s

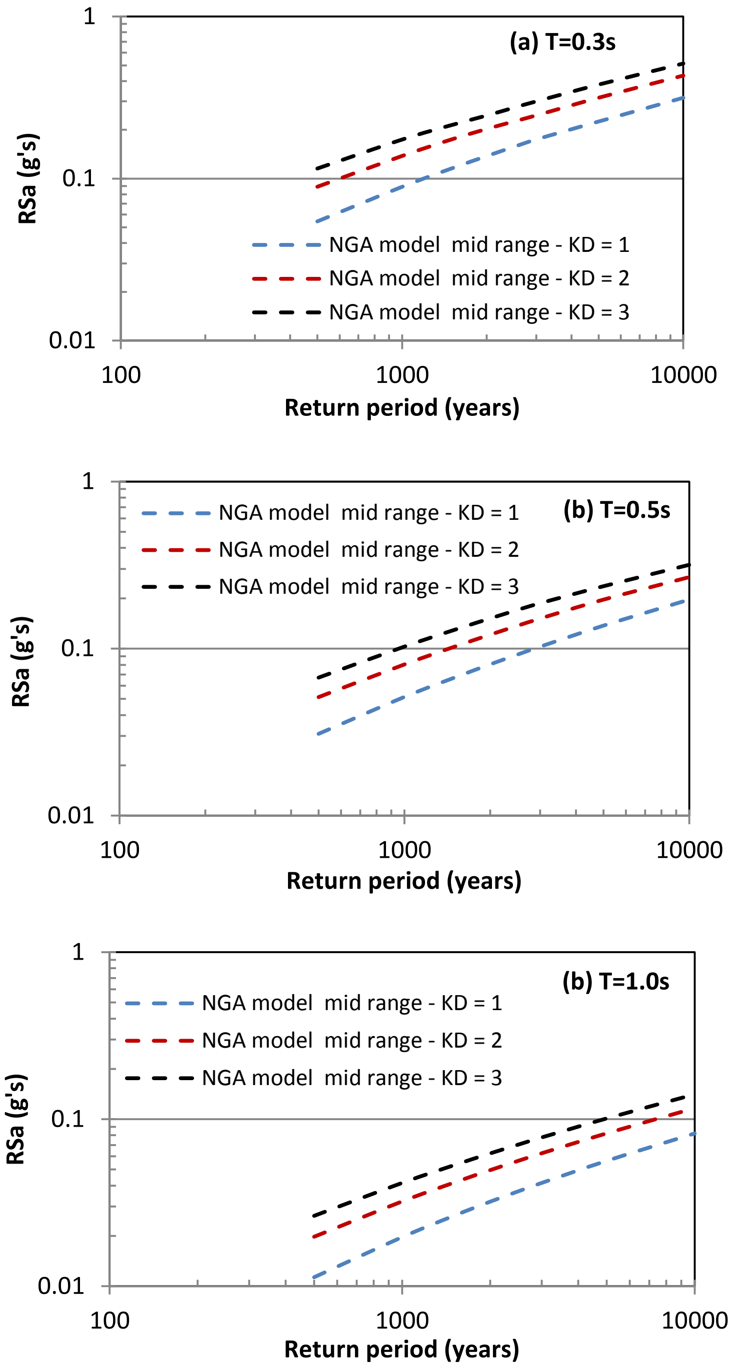


Figure 8 Median RSa values on rock for K_D= 1, 2 and 3 at periods of (a) 0.3s (b) 0.5s (c) 1.0s

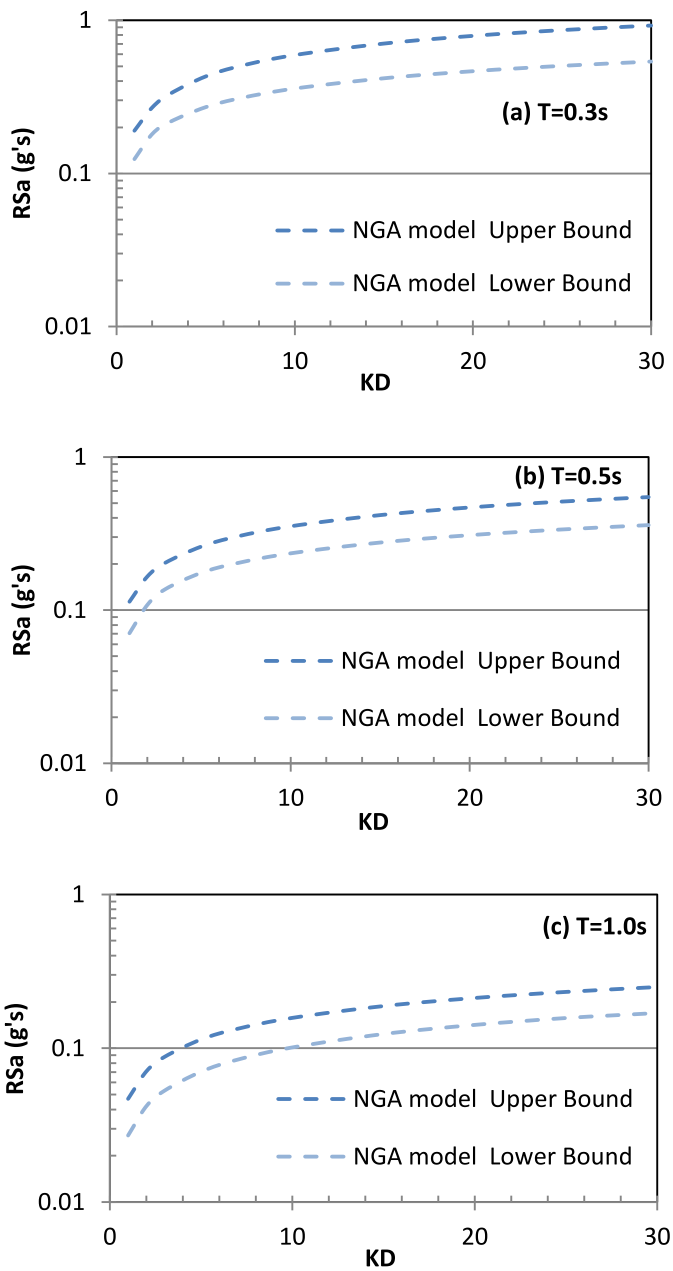


Figure 9 Envelope RSa values on rock as functions of K_D at periods of (a) 0.3s (b) 0.5s (c) 1.0s

6 SUMMARY AND CONCLUDING REMARKS

The global seismicity model presented in Bird *et al*. (2010) reports an activity rate for all intraplate earthquakes occurring on both land and sea around the globe expressed as the logarithm of the number of events ($M \geq 5.66$) on a per *square meter* and per *second* basis of: 4.27×10^{-22} which translates to 2 − 3 $M \geq 5$ events for a standard area of 1,000,000 km^2 and an exposure period of 50 years. The event number count for intraplate earthquakes of M≥5 occurring on land in individual countries as listed in Table 1 infer a higher (normalised) value of 5. A design response spectrum model corresponding to a notional peak ground acceleration (PGA) value of 0.06 approximately is recommended. Parameter K_D has been introduced to represent situations where the event counts in a region (or country) exceeds the global rate of recurrence. Further results of PSHA have been presented to show the sensitivity of the predicted ground motion intensities to changes in the value of K_D.

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