Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

A hybrid probabilistic seismic hazard analysis of a low and moderate seismic region: Sri Lanka – a case study

S.Venkatesan

School of Civil, Chemical and Environmental Engineering, RMIT University.

J.P. Wepitiya Gamage

College of Engineering and Science, Victoria University.

N.T.K. Lam & E. Lumantarna

Department of Infrastructure Engineering, University of Melbourne.

ABSTRACT: Probabilistic seismic hazard assessment (PSHA) is a well-known approach adopted by researchers towards estimating seismic design loads. However the application of such approaches to regions with paucity of data is fraught with difficulties and uncertainties. Regions like Sri Lanka pose further challenges due to the nature of seismic activities and the distribution of seismic sources. Colombo the capital city has been subjected to a few earthquakes historically (Mw >5) but the rest of inland region have been subjected to mild seismicity within the continental crust. In recent times there are reports of seismic effects experienced from long distant earthquakes that originated from the oceanic crust outside the landmass. The first and second authors have presented attenuation models for the region in earlier publications. In this paper, the authors have presented hazard estimates from conventional PSHA approach from earlier works and compared some salient results with seismic hazard averaged from global seismicity data. Results show that seismic hazard of Sri Lanka is less than world average. Using notional PGA values and Colombo as a hot spot region, a design response spectrum that can be easily adopted by practising engineers is recommended as a guide for estimating seismic loads.

1 INTRODUCTION

The well-known Probabilistic Seismic Hazard Approach (PSHA) introduced by Cornell (1968) and McGuire (1976) can be summarised using the following key steps: (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 necessary allowances for uncertainties. Results obtained from such analyses are usually presented in the form of contour maps or raster maps for further applications.

The above methodology has been applied at a global level in most seismic hazard estimations. However most PSHA approaches (e.g. McGuire 1993) are based on the assumption that past events are indicative of future events. While this assumption is acceptable from a normal standpoint, it has been shown that the estimations can vary as much as 100% depending upon the level of zonation considered in step (i) noted above. This problem is even more compounded for regions that lack sufficient data. For example, the occurrence of earthquakes with magnitude >4 is very sparse in typical low-moderate seismic regions governed by intraplate seismic activity. This non-uniform rate and occurrence of seismic activity in both space and time leads to the absence of a regular seismic pattern which can ensue great deal of uncertainties in modelling the source, zones, recurrence and attenuation in the PSHA approach. Thus it is important to exercise careful judgements to avoid unreliable results. Low seismic regions like Sri Lanka may provide similar modelling challenges as explained below.

Sri Lanka is situated well away from major tectonic plate boundaries such as the Sunda trench and transform ridges of the Southern Indian Ocean as shown in Figure 1. The mild intraplate activity in these oceanic crusts can generally be categorised as uniform seismicity for modelling using PSHA approach. Although there is a fair distribution of M>5 events in the region outside Sri Lanka, the land mass is typically subjected to M<4 earthquakes. Of importance to note is the evidence of a few historical earthquakes. Out of these a magnitude 5 event that caused significant destruction around Colombo in 1600's is well recognised (although the magnitude, distance and intensity are fairly questioned by researchers). These select occurrences of historical events might warrant a "hot spot" type approach. In PSHA a well-defined hot spot zone may estimate a higher level of hazard around that region and may underestimate the hazard in other areas of the country. In contrast broad source zone models may lead to uniform hazard estimation without the identification of hot spots in the regions. Both these approaches on their own run the risk of underestimating the hazard in some parts of the region (Lam et al 2015). Thus the choice lies in the judicious selection of the zones and the application of the method. Therefore, the authors have resorted to a hybrid modelling approach by maintaining Colombo as a hot spot region and treating the rest of the country for uniform seismic hazard.

Given the scant research on seismic hazard surrounding Sri Lanka (Udeuweriya et al 2013; Gamage and Venkatesan 2014) it would be logical to compare our estimations with analogous regions and comparisons based on world average. This benchmarking exercise may provide additional credibility to our earlier works. We have used the "world average on intraplate seismic activity approach" specified in Lam et al (2015) for benchmarking. This hybrid approach shows that Sri Lanka's seismicity is less than world average. The next section of the paper presents the PSHA approach and the third section evaluates and compares with the world average. The fourth section presents the results of response spectrum followed by concluding remarks.

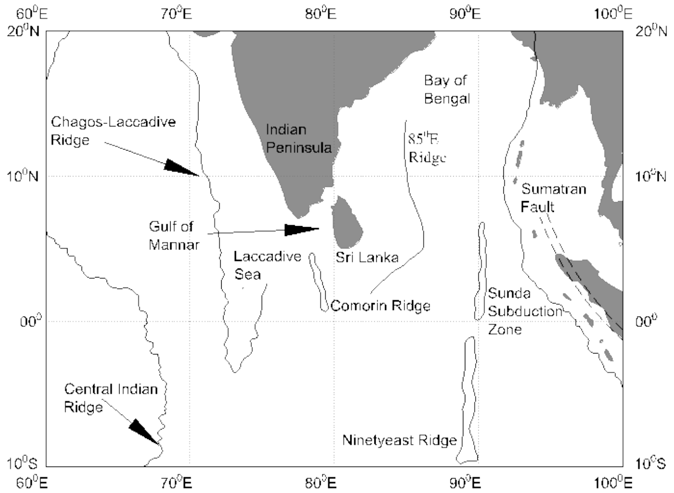

Figure 1. Location of Sri Lanka and surrounding tectonic plates

2 SEISMIC HAZARD ESTIMATION PROCEDURE BASED ON PSHA

2.1 Seismic source zones

Based on the previous discussions, six seismic zones were identified for Sri Lanka. Zones 1, 2, 3 and 4) were characterized as broad area zones based on mild activity rates that allowed the assumption of uniform seismicity in these zones. Colombo was maintained as a hotspot region 6 while the rest of inland was maintained as region 5 as shown in Fig. 2.

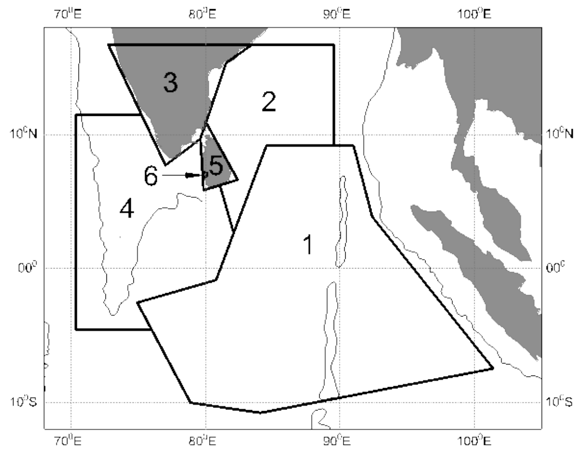

Figure 2. Source zones defined in the study. Source zones 1, 2, 3 and 4 characterize regional intraplate seismic activities outside Sri Lanka, while 5 and 6 are based on sparse local seismicity within the country.

2.2 Catalogue data

Data were obtained from several sources; ISC (International Seismological Centre), ANSS (Advanced National Seismic System), NEIC (National Earthquake Information Centre) and GFZ-GEOFON (German Research Centre for Geosciences), GCMT (Global Centroid Moment Tensor catalog), and some previously published data (Abayakoon, 1996; Fernando and Kulasinghe 1986; Uduweriya et al 2013) were also used. Events repeated in several data bases were carefully avoided with priority given to ANSS database based on the quality of information available. Records were compiled over a long period of duration, starting as early as 1507 and until 2014.

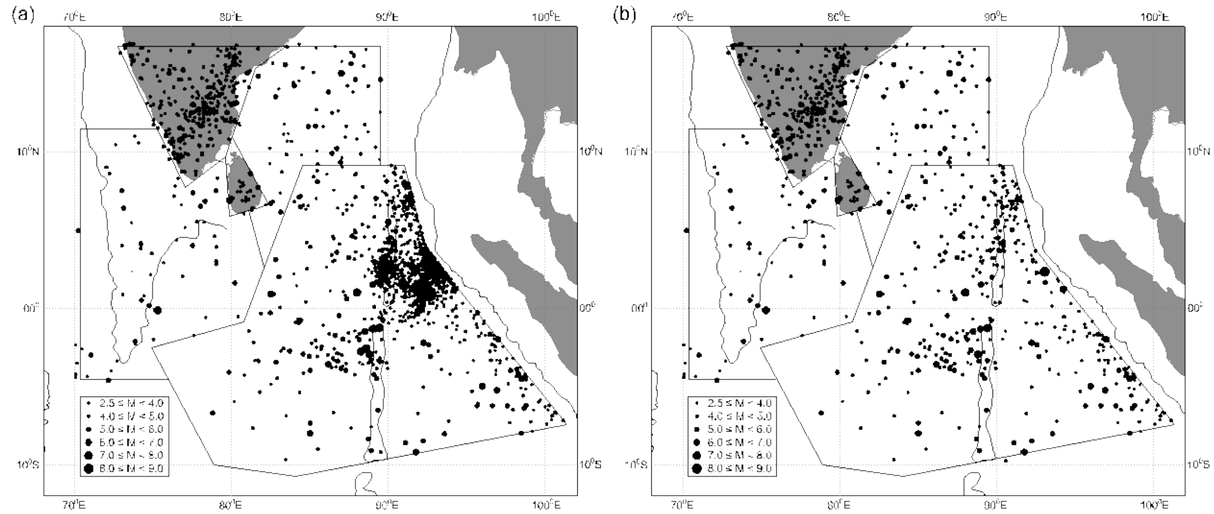

Figure 3. - Epicentral locations of earthquake catalog data used in the hazard computation in the study. (a) before declustering (2421 events) (b) after declustering (870 events).

The original catalog of all source zones contained a total of 2421 events (including dependent events) for the selected period. Variation of hypocentral depth of selected events was assumed not having any relation with recurrence rates, and therefore, effects due to "depth" and any uncertainty in depth were negated for the study. Data were originally in various magnitude types such as ML and MS for most of the older events and Mw, mB and mb for newer events reported within the instrumental period. These different magnitude types, other than Mw, were converted to a unified scale Mw, using relationships developed for mid-plate and stable continental regions based on global data (Johnston 1996; Nuttli 1983). It is noted that Mw is widely used in the ground motion attenuation models worldwide. Local events available in the form of intensity values were converted to Mw using relationships developed by Greenhalgh et al (1988). Epicentral locations of earthquake catalog data in assigned source zones are shown in Fig. 3, where Fig. 3a and 3b, respectively, show data before and after removing dependent events. It is evident that source zone 1 carries the highest number of dependent events out of all the zones for the selected time period.

2.3 Declustering approach

In the study, dependent events were eliminated by applying the time and space windows of Gardner and Knopoff (1974). However, Gardner and Knopoff's (1974) spatial windows for dependent events of a large magnitude main event appeared to be underestimating actual likelihood areas of aftershocks of some major earthquakes occurred in the region. Two such mega events are noteworthy of mention; Mw 8.6 on 11th April 2012 and Mw 9.3 on 26th December 2004. The former was an intraplate event located within source zone 1 near Ninetyeast Ridge, while the latter was identified as an interplate event at the subduction zone outside source zone 1. Dependent events of the second event were identified based on rupture areas given in Ammon et al (2005) and US Geological Survey's earthquake summary maps (2005). Such analysis helped in the elimination of other major aftershocks generated in the aftermath of the Mw 9.3 earthquake in 2004. Similarly the Mw 8.6 earthquake has so far generated hundreds of dependent events since April 2012, and probably would represent the largest known aftershock sequence in the selected data set (see Fig. 3b). Many of dependent shocks of this event were carefully removed through a manual process based on observations such as small time gaps with the main event and significant increase of the activity rate in the area post the main event.

The final catalogue after the declustering included 870 events which is about 36% of the original catalogue size. This is not a surprise, since many of small and moderate magnitude events, particularly in source zone 1, were aftershocks of major earthquakes. Temporal distribution of final "independent" earthquake data of the whole region was compared with the Poisson distribution. Events with medium and higher sizes (Mw = 4.0) generated only after 1965 were considered for the comparison, in which 1965 was kept as a cut-off in parallel with the World Wide Standard Seismograph Network (WWSSN) program launched in 1964. It was found that the declustered catalogue sufficiently complied with a Poissonian distribution. Although this compliance cannot be expected for all "independent events" worldwide we assumed a Poissonian distribution as this assumption provides a convenient basis for future estimations of hazard and comparisons.

2.4 Completeness analysis and recurrence rates

Stepp's method (1972) was adopted to estimate completeness periods in the study. The method assumes that earthquake occurrence in a particular magnitude class as a point process in time, following a Poisson event arrival. In the study, we concentrated on completeness periods of "smaller magnitude events" that are still capable of producing sufficient ground shakings at the selected sites. This minimum magnitude varied from Mw 3.0 to 5.0 for identified source zones depending on availability of smaller magnitude events in each source zone, and site-source distance which "calibrates" the size of magnitude needed for a lower bound shaking level. For instance, for source zone 1, Mw 5.0 was considered as the minimum magnitude for the completeness check, given the reasons that scantiness of smaller event data (Mw < 5.0) in the zone and large site-source distance between the country and source. For source zones 5 and 6, however, fairly a small magnitude Mw 3.0 was chosen mainly because of the inadequacy or sometimes the complete absence of other moderate and strong events (Mw > 4.0) reported within the country (this situation is true in source zone 5). Recurrence of earthquakes in the region are presented in Figure 4; minimum and magnitude values for the zones and `a' and `b' parameters according Gutenberg-Richter law are presented in Table 1.

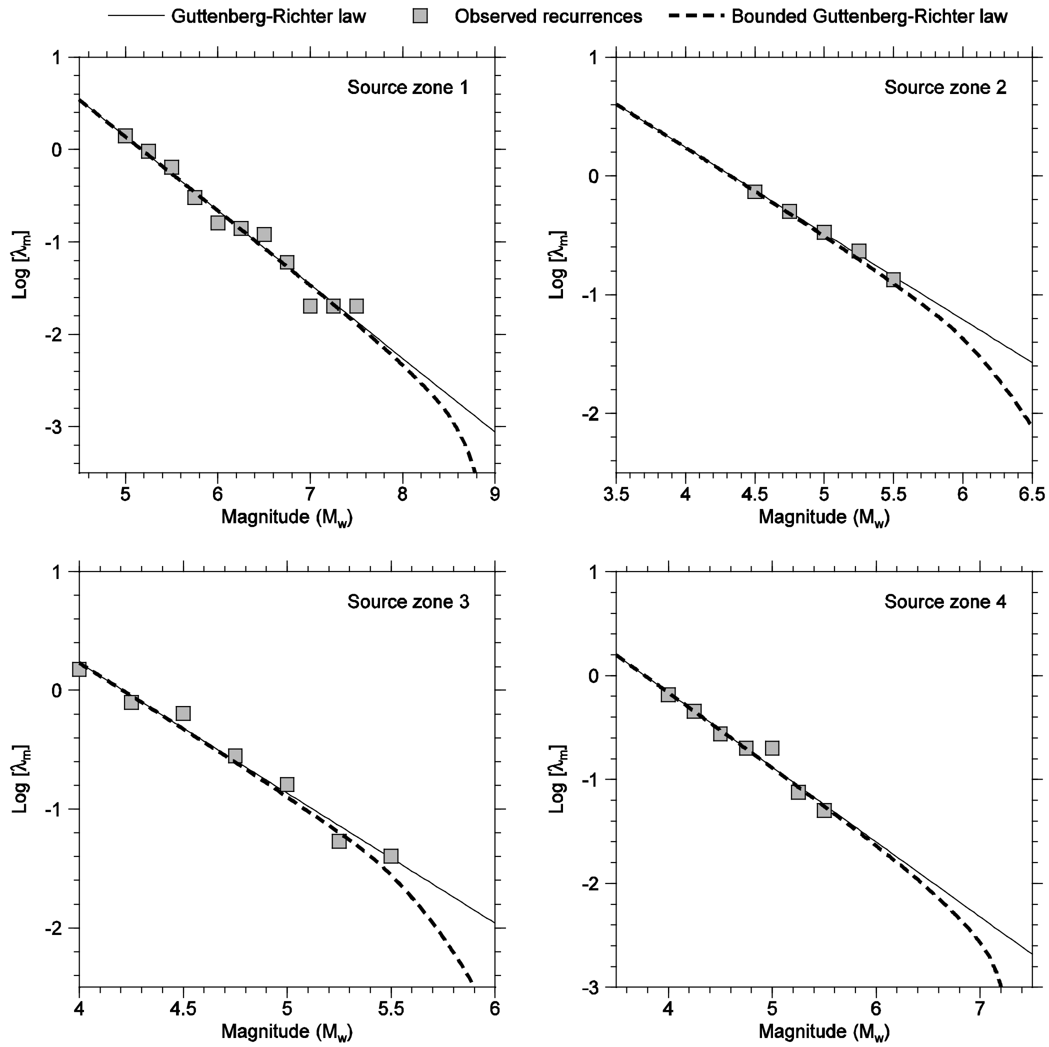

Figure 4. Earthquake recurrences for main source zones. (Note: values for region 5 and 6 are negligible and hence not shown; method of least squares used in the calculations).

From the above figure, it is clear that source zones 1-4 do not exhibit earthquake occurrences of more than 2. Source zones 5 and 6 are dominated by historical records. Therefore the completeness of the dataset is set unreliable.

Table 1. Seismicity parameters of defined source zones

Source zone	**Stepp's test for the completeness**		**Input parameters for hazard computation**				
	Min magn. considered for the test (M_w)	**Completeness periods (yrs)**	**α***	**β****	**CV of β**	**m_o (M_w)**	**m_{max} (M_w)**
1	5.0	50	9.239	1.799	0.018	4.5	9.0
2	4.5	30	7.229	1.669	0.004	3.5	6.7
3	4.0	75	10.619	2.522	0.017	4.0	6.0
4	4.0	40	6.251	1.657	0.017	3.5	7.5
5	3.0	Incomplete	4.955	1.629	0.026	3.0	6.0
6	3.0	Incomplete	2.629	1.386	0.000	3.0	6.5

For *a* and *b* values in Gutenberg-Richter law, convert α and β values to natural logrithms
CV of β - Coefficient of variation of β
m_0 - Minimum threshold magnitude used in the hazard computation
m_{max} - Maximum expected magnitude for the source zone

2.5 Ground motion prediction equations

Gamage and Venkatesan (2014), and Gamage (2015) have developed attenuation models for local (mainland Sri Lanka) and regional (outside landmass) based on crustal classifications and seismic activities. The local attenuation model was employed in computing the seismic hazard for source zones 5 and 6. The regional attenuation model was applied in source zones 1, 2 and 4 consistent with Figure 1. For source zone 3 Raghu Kanth and Iyengar (2007) model developed for the southern India was adopted.

2.6 Hazard computation

Hazard computation based on the probability of a selected ground motion parameter (Y) exceeding a certain value (y) due to a M magnitude event at an independent R distance from the target site can be computed according to Equation (1) as established in most studies.

$$P[Y > y] = \iint P[Y > y \mid M, R].f(M).f(R).dM.dR \tag{1}$$

Where $f(M)$ and $f(R)$ are probability density functions for magnitude and distance parameters, respectively. The authors used the open-source package CRISIS2007 to derive representative values.

2.7 Salient results

Hazard computations in the form of expected ground motions (PGA and SAs at 0.1, 0.5 and 1.0 s natural periods) at rock sites in Sri Lanka having 10% (475 year return period), 5% (975 year return period) and 2% (2475 year return period) probability of exceedance in 50 years were analysed. Results show that the area around Colombo is by far the most vulnerable place in the country with a value of about 0.043*g* (*g* is gravitational acceleration) PGA expected to be exceeded in a 475 year return period. This increases to about 0.053*g* and 0.065*g* for 975 and 2475 year return periods, respectively. Rest of the country envisages relatively small PGA values and hence are not the focus of this paper.

3 COMPARISON OF HAZARD VALUES WITH WORLD AVERAGE INTRAPLATE SEISMICITY

3.1 Comparison of recurrence rates

According to Lam et al 2015, the world average intraplate seismicity, for a given period of 50 years, over a land area of 1 million sq. km, the number of events exceeding magnitude 5 is about 5. For Sri Lanka, this translates to about 2 – 3 events over a 50 year period for a given land mass of 65,600 sq.km using notional `a' and `b' values. However, the region surrounding Colombo has experienced around 5 to 10 events >M4 based on historical data. As a conservative assumption, we use 10 events of >M5 over a year period of 50 years in our analysis. Regions other than Colombo are not considered in this paper.

3.2 Alternative hazard computation approach

Lam et al 2015, have developed an alternative hazard modelling approach based on the assumption of uniform seismicity and considering source zones within a given land area into rings of suitable size. The area of the ring is used for calculating the probability of earthquake events occurring within that ring. It has been shown that the total conditional probability can be estimated as shown in Equation (2) with due considerations to recurrence rates.

$$\Pr(\mathrm{RSa} \geq \mathrm{RSa}^*) = \lambda(\mathrm{M}_{\min}) \times [F(\mathrm{M}_i) - F(\mathrm{M}_{i+1})] \times \Pr\langle \mathrm{RSa} \geq \mathrm{RSa}^* \mid \mathrm{M}, \mathrm{R} \rangle \tag{2}$$

where, M = 1/2 (M_i + M_{i+1}), $R = \sqrt{\dfrac{inner\ \ radii^{\ 2} + outer\ \ radii^{\ 2}}{2}}$

Result obtained from Equation 2 are to be aggregated for all magnitude within the range of M_{min} = 4 to M_{max} = 7.

We considered a radial distance of 100 km in increments of 5 km for each ring centred around Colombo. Using the attenuation equations from Gamage and Venkatesan (2014), and Gamage (2015), and using a recurrence of 10 events >M5 over a period of 50 years (this translated to K_D=2 and a_5=1 in the hybrid probabilistic approach that are also consistent with values used for analogous regions such as Malaysia), we obtained a PGA value of about 0.04 g for a 650 year return period. In view of this favourable comparison arising out of the hybrid approach, this paper recommends a notional value of 0.04g for a 500 year return period for Colombo region.

4 RECOMMENDATION AND CONCLUDING REMARKS

4.1 Design Response Spectrum

Considering the notional value of PGA = 0.04 g and the standard procedures for estimating RSA, it can be shown that RSA at 0.3s could be estimated as 0.04 x 2.5 = 0.10 g. The taper post 0.3 s can be modelled as 0.45/T. Although the spectrum may be conservative, it is to be noted that the values are consistent with international benchmarks.

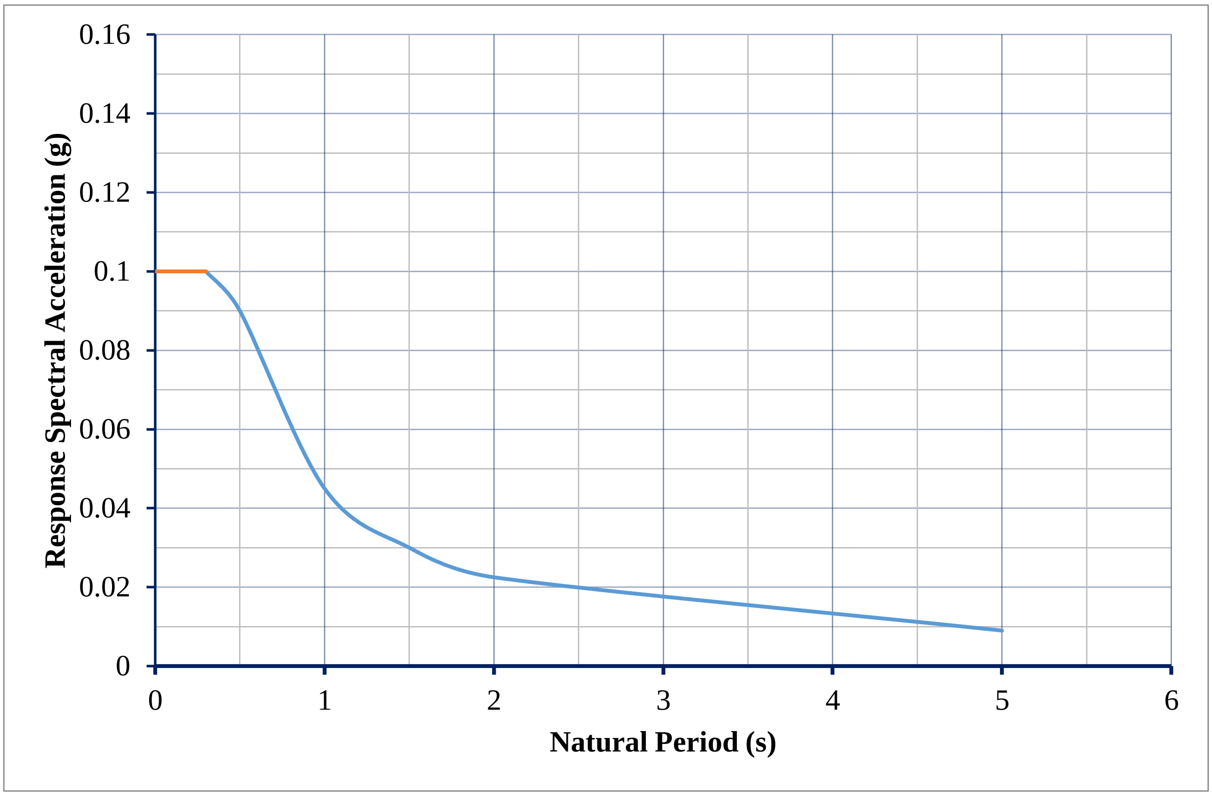

Figure 5. Design Response Spectrum on rock for regions surrounding Colombo, Sri Lanka (return period 500 years; 5% damping).

4.2 Concluding remarks

In this paper authors have investigated the possibility of developing a design response spectrum for low seismic regions like Sri Lanka using a hybrid probabilistic approach. In particular conventional PSHA approach undertaken for the whole of Sri Lanka was compared with world average seismicity rates. It was observed that Sri Lanka's seismic hazard is generally less than world average. A design response spectrum for a hot spot region has been benchmarked with other international practices. This work can potentially form the basis of a building code of practice for Sri Lanka in the near future.

REFERENCES:

Abayakoon S. B. S.1996. Seismic Risk Analysis of Sri Lanka. *Journal of the Geological Society of Sri Lanka, 6, 65-72*.

Ammon, C. J., Ji, C., Thio, H.-K., Robinson, D., Ni, S., Hjorleifsdottir, V., Kanamori, H., Lay, T., Das, S., Helmberger, D., Ichinose, G., Polget, J. & Wald, D. 2005. Rupture Process of the 2004 Sumatra-Andaman Earthquake. *SCIENCE, 308, 1133-1139*.

Cornell C.A.1968. “Engineering Seismic Risk Analysis”, *Bulletin of Seismological Society of America,58, 1583–1606.*

Fernando, M. J. & Kulasinghe, A. N. S.1986. Seismicity of Sri Lanka. *Physics of the Earth and Planetary Interiors, 44, 99-106.*

Gardener, J. K. & Knopoff, L.1974. Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian? *Bulletin of the Seismological Society of America, 64, 1363-1367*.

Grennhalgh, S. A., Denham, D., McDougall, R. & Rynn, J. M. W. 1988. Magnitude-intensity relations for Australian earthquakes. *Bulletin of the Seismological Society of America, 78, 374-379*.

Johnston, A. C. 1996. Seismic moment assessment of earthquakes in stable continental regions - Instrumental seismicity. *Geophysical Journal International, 124, 381-414.*

Nuttli, O. W.1983. Average seismic source-parameter relations for mid-plate earthquakes. *Bulletin of the Seismological Society of America, 73, 519-535.*

Gamage P. 2015. “*Earthquake ground motion models for Sri Lanka”*, PhD Thesis, Victoria University.

Gamage, P. & Venkatesan, S. 2014. “Attenuation models for expected ground motions in Sri Lanka”, In: SMITH, S. T., ed. *23rd Australasian Conference on the Mechanics of Structures and Materials ACMSM23, 2014* Byron Bay, Australia.

Lam, N.T.K, Tsang, H.H, Lumantarna, E. and Wilson, J.L.2015. An Alternative Probabilistic Seismic Hazard Assessment Method in Areas of Low-to-Moderate Seismicity, *In the Procs. the 2015 World Congress on Advances in Structural Engineering Mechanics and Materials, ES364_2212*.

McGuire, R.K. 1976. FORTRAN program for Seismic Risk Analysis, *U.S. Geological Survey Open-file Report 76–67*

McGuire, R.K.1993. Computations of seismic hazard, *Ann. Geofis., 36,181–200*.

Raghu Kanth, S. T. G. & Iyengar, R. N.2007. Estimation of seismic spectral acceleration in Peninsular India. *Journal of Earth System Science,* 116, 199-214.

Stepp, J. C.1972. Analysis of completeness of the earthquake sample in the Puget Sound area and its effect on statistical estimates of earthquake hazard. *First microzonation Conference, 1972 Seattle, WA. 897-909*.

Uduweriya, S. B., Wijesundara, K. K. & Dissanayake, P. B. R.2013. Seismic risk in Colombo – probabilistic approach. *SAITM Research Symposium on Engineering Advancements 2013.* Colombo, Sri Lanka.