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DEVELOPMENT OF SEISMIC HAZARD MAPS FOR SRI LANKA

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ABSTRACT: Hazard maps characterizing seismic risk in the intraplate island region Sri Lanka, were produced using a probabilistic approach. Identification of seismogenic source zones located in and around the country was carried out based on both the seismotectonics and historical seismicity of the region. A catalogue of recorded independent event data was prepared using many local and international archival sources, based on which a reliable and sufficiently complete data set was obtained. Temporal recurrence rates of seismic activities of identified seismic source zones were established for pre-estimated periods of completeness determined using the Stepp's method. Attenuation models derived based on region-specific seismological parameters of the subject region were applied in the hazard computation. Hazard values in terms of peak ground acceleration and elastic spectral acceleration of 5% damping ratio for 475, 975 and 2475 year return periods were interpreted in raster maps. Hazard values showed that the area around the capital city - Colombo possesses the maximum expected PGA (in rock sites) which is about 0.043*g* for a 475 year return period. Most of other areas in the country indicated relatively low ground motion levels leaving a clear conclusion that the country lies in a low seismic region.

1. Introduction

Expressing ground motion parameters as of an exceeding probability in a given period of time is a widely accepted technique in risk analysis in the engineering seismology. The methodology has proven to be advantageous in accounting for uncertainties associated with seismological properties (identified as seismic sources and earthquake properties – magnitude and location, earthquake recurrence) and with attenuation models applied in the ground motion estimation, in comparison to other conventional methods such as deterministic analysis.

The study presented in the paper is an application of the above introduced "probabilistic seismic risk analysis" for Sri Lanka, an island whose seismotectonic location is often claimed to be in a stable continental region. Tectonic location of Sri Lanka guarantees that the country is hardly subject to interplate or plate-margin earthquakes, as the major plate boundaries are located at least 1000-1500 km away from the country (Fig. 1). Intraplate or mid-plate earthquakes, on the other hand, are relatively in abundance in the region and can pose direct threats of striking at the country's close vicinity. Seismicity and seismogenic features in and around Sri Lanka have rarely been drawn the attention of local researchers. Only a few published studies are yet available in literature (Abayakoon, 1996; Fernando and Kulasinghe, 1986; Gamage and Venkatesan, 2012; Gamage et al., 2013; Peiris, 2007; Uduweriya et al., 2013; Vitanage, 1994; 1995). However, these studies are important in the sense of providing certain essential insights in nourishing the discourse on seismicity and seismic risk of the country. A complete assessment of risk due to any hazard may require various collaborative works by professionals such as technical experts in the field (for earthquake hazard – seismologists, geologists, engineers), risk analysts, economists, social scientists, etc., yet the role of "technical experts" among others can be decisive since future forecasts solely rely upon their works.

The seismic hazard analysis method applied in the study basically followed that described in Cornell (1968). Seismic source zonation, earthquake catalog preparation, recurrence rates estimation, attenuation relationships application and hazard values in terms of ground motion parameters computation, are separately described in the paper. Computed ground motions in terms of Peak Ground Acceleration (PGA) and Spectral Accelerations (SAs) at 0.1, 0.5 and 1.0 s natural periods for 5% critical damping ratio, are represented by maps in the results and discussion section.

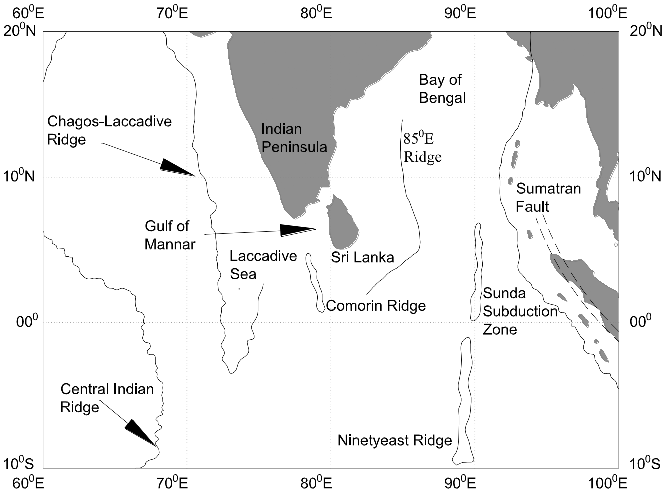


Fig. 1 - Tectonic location of Sri Lanka in the northern Indian Ocean region

2. Methodology

2.1. Seismic source zones

Sri Lanka owns a very little information particularly on seismic sources within the country, therefore in the study, seismic zonation in the local context (Zones 5 and 6) was performed primarily based on historical seismic activities of the country. However, the regional zonation was carried out, to a certain extent, based on identified tectonic structures in the surrounding oceanic crust. All the identified regional zones (Zones 1, 2, 3 and 4) were characterized as broad area zones, and this is because their mild activity rates which allowed a uniform seismicity to be safely assumed through the whole area. Final source zones defined in the study are shown in Fig. 2.

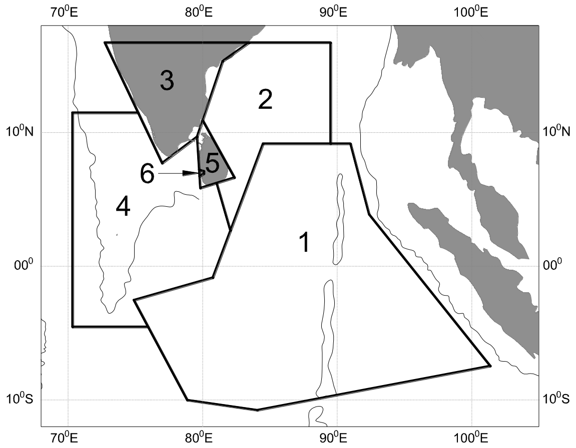


Fig. 2 - Source zones defined in the study. Source zones 1, 2, 3 and 4 characterize regional intraplate seismic activities outside Sri Lanka, while 5 and 6 are based on sparse local seismicity within the country.

2.2. Catalog data

Data were obtained from several sources; online archival data bases such as 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 used. When the same event appeared in several data bases (mostly in newer events), priority was given to ANSS information and then to others. Records were compiled over a long period of duration, starting since as early as 1507 and spanning till 2014.

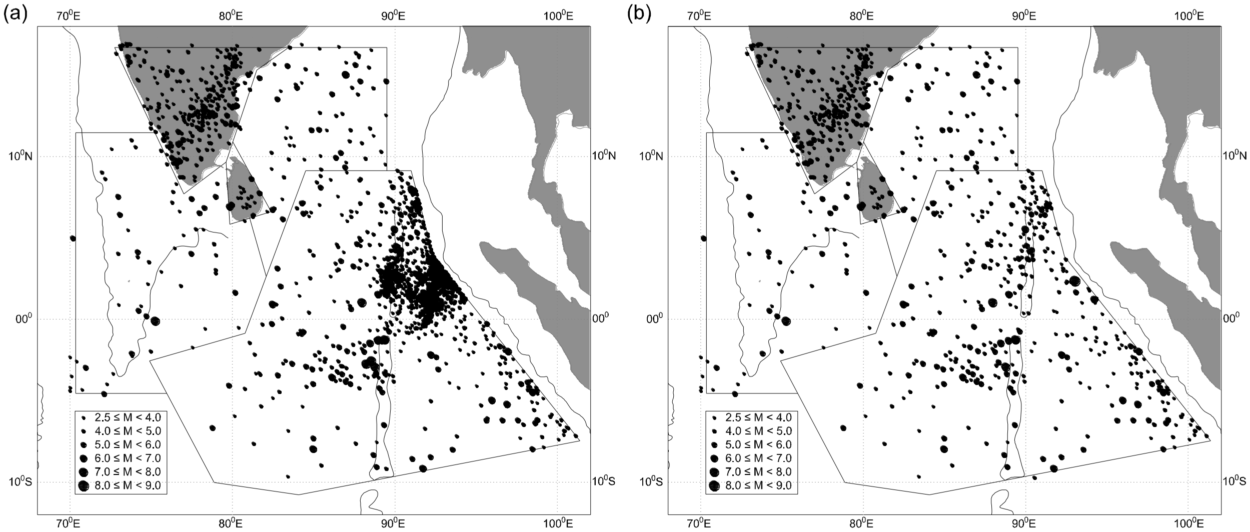


Fig. 3 - Epicentral locations of earthquake catalog data used in the hazard computation in the study. (a) before declustering (2421 events) (b) after declustering (870 events).

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). Mw was considered optimum for the final catalog as it was the same magnitude that used in the ground motion attenuation models applied in the study. Few of local events available in the form of felt reports as intensity values were converted to Mw using relationships developed by Greenhalgh et al. (1988) for the Australian continent.

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

In the study, dependent events were initially eliminated by applying the time and space windows of Gardner and Knopoff (1974). However, some dependent events, mainly aftershocks of large magnitude main events (events with magnitude greater than about Mw 8.0) showed arising at further more distances away from the main event than the respective distance windows for such a magnitude assigned in their study. In other words, 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 major earthquakes occurred in the region. Two such mega events are noteworthy in the subject region; 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 occurred 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). Classification based on these modified aftershock areas resulted in to recognize a new set of other events triggered within source zone 1 as dependent events of the main event Mw 9.3, but their epicentral locations are still far away by up to thousands of kilometers from the main event and Sunda subduction zone. 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 the event (in this case mostly aftershocks), those remained after the initial sieving by the method of Gardner and Knopoff (1974), were carefully removed through a manual process based on some intuitive observations; small time gaps with the main event, significant increase of the activity rate in the area after the main event, etc.

The final catalog after the declustering included 870 events, and was just about 36% of the original catalog 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 cutoff in parallel with the World Wide Standard Seismograph Network (WWSSN) program launched in 1964. It was found that the declustered catalogs sufficiently comply with a Poissonian event arrival, although, the actual arrivals found to be slightly waying off from chi-square goodness values. Actual form of the recurrence for so-called "independent events" may or may not be Poissonian, but be bound by other complexities which need to be addressed in separate contexts; independent data may still be contaminated by dependent events, the data set may not be "complete" enough (still missing some data), the period considered may not be lengthy enough for reflecting recurrence characteristics of much larger events; actual data may have a variation from the Poisson distribution, etc. Despite these probable uncertainties, actual independent events were assumed following a Poissonian variation in the time domain.

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 (the situation especially prevails in source zone 5). Stepp's plots for selected minimum magnitudes are shown in Fig. 4, and resulted completeness periods are given in Table 1.

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

α and β - *a* and *b* values, respectively, in natural logarithms in the standard Guttenberg-Richter law
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

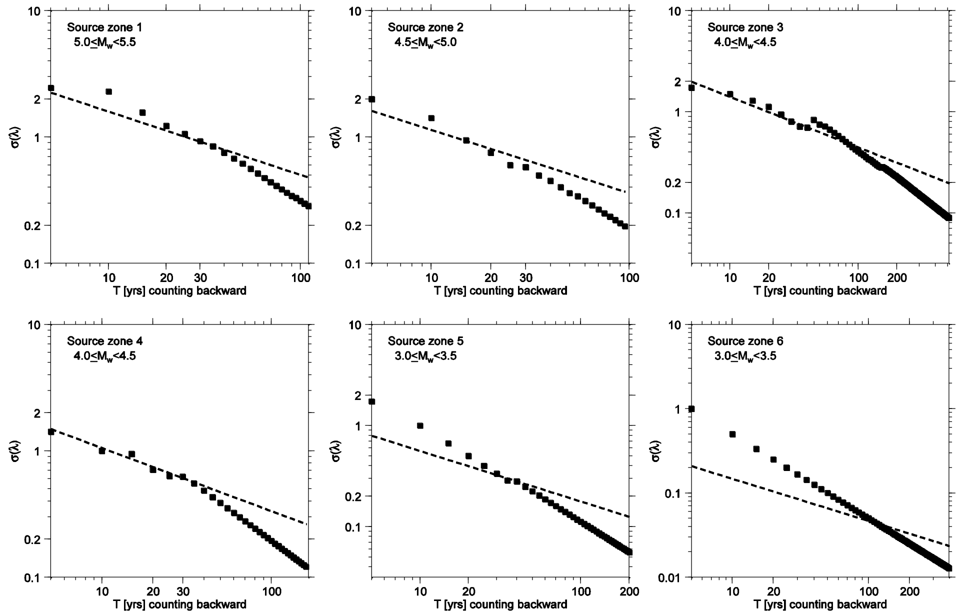


Fig. 4 - Stepp's plots of the completeness check. Selected minimum magnitude bands in each source zone are given inside the figure

The minimum magnitude applied in the Guttenberg-Richter bounded equation (see Table 1 third column) basically followed the requirement of assigning a limiting magnitude that can produce a "threshold level of risk" at the site of interest. This "threshold magnitude" ranged from a minimum of Mw 3.0 for source zones 5 and 6 to a maximum of Mw 4.5 for the distant source - source zone 1. A lower magnitude of Mw 3.0 for local source zones 5 and 6 was selected in perspective of higher "vulnerability" expected during even a small ground shaking induced at local sites in Sri Lanka, which are not yet "well-prepared" against earthquake shakings as places in other countries where design codes of practice have been properly adopted. The selection of Mw 3.5 for source zones 2 and 4 that are juxtaposed with the country, was also partly encouraged by the same reason. During the selection of minimum magnitude for hazard computation, concerns on the absence of smaller events in some magnitude classes as that done in the completeness check, were not considered, and only a magnitude which poses a minimal risk was selected for each zone. The maximum magnitude as a cut-off was generally chosen based on historical evidence of the largest event occurred in the zone. However, a bit higher magnitudes than those were sometimes selected on the basis of conservatism.

As Fig. 4 evidences, source zones 1-4 are complete at least for part of the total catalog duration for the selected minimum magnitude classes. In all these regional source zones, the variation of $\sigma(\lambda)$ for selected magnitude classes shows approximately following $1/\sqrt{T}$ slope before deviating into much steeper slopes. Source zones 5 and 6, however, are not as complete as other regional sources, since the slope of $\sigma(\lambda)$ is clearly diverting from $1/\sqrt{T}$ for the total period of catalog in both cases. Lack of event data, may be due to negligence of previous events, in local catalogs for representing the actual seismicity of the country, can be the principal reason for this incompleteness. Many of smaller and moderate magnitude events previously occurred in the country were left unreported due to inattention. Because of this reason, source zone 5, which covers most of the country's inland area, was assumed to be complete for smaller events which occurred only after the local seismic network was installed in 2000. Recurrence parameters of source zone 5 derived based on such a short period showed a little higher recurrence rate for moderate and large magnitude earthquakes than the rates given by the historical seismicity. Nevertheless, derived parameters were accepted for the hazard analysis given the additional emphasis on hazard due to moderate and large magnitude events. For source zone 6, recurrence parameters were obtained only based on the activity rates of strong magnitude events occurred in the past. Strong magnitude event occurrences in Colombo and its surroundings were noticeable in the past in comparison to other areas of the country. These strong magnitude events were assumed to be safely reported during the catalog period, in which case the catalog can be treated complete for strong events. Therefore, the recurrence relationship for source zone 6 was inferred merely based on activities of strong events reported in the zone, albeit the relationship was a little conservative for smaller events.

2.5. Ground motion prediction equations

The attenuation models derived by Gamage and Venkatesan (2014), and Gamage (2015) were primarily applied for the study. The local attenuation model, developed in these studies, 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 where the surrounding oceanic crust is present. Source zone 3 which virtually covers the whole continent of southern peninsular India, is assigned with a regional model already developed for the region (Raghu Kanth and Iyengar, 2007), and the model is applied with the assumption that seismological properties characterized by this model, are similar in nature with that found in the adjacent northern most continental and continental-oceanic boundary area in Sri Lanka (hopefully, the only area of Sri Lanka possible for major shakings due to seismic activities in Indian peninsula). The assumption leaves the permission for considering expected wave path modifications to be the same through the whole propagating path from the southern India to northern Sri Lanka.

2.6. Hazard computation

Hazard computation is a process that combines; (1) mean rate of recurrence of a selected magnitude (which is bound by a minimum and maximum limits) of a defined source, (2) with probability of occurrence of an event with the same magnitude at a point within the source, (3) and with probability of exceeding a certain ground motion level at the selected site due to the event. Since the computation involves estimating “probability” that the action/incident is taking place, the process naturally accounts for possible uncertainties expected in each action. The probability which a selected ground motion parameter (Y) exceeds a certain value (y) due to a M magnitude event occurred at an independent R distance from the targeting site is given by;

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

f(*M*) and *f*(*R*) are probability density functions for magnitude and distance parameters, respectively. In the study, hazard computations were done by using an open-source package called CRISIS2007.

3. Results and discussion

Computed hazard 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 of time, are mapped in separate raster layouts (Fig. 5). Results show that the area around Colombo is by far the most vulnerable place in the country for seismic activities. Colombo possesses nearly 0.043*g* (*g* is gravitational acceleration) of a maximum expected PGA to exceed 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 ground motions dispersing in a uniform nature through the whole area, and this ultimately warrants the region to be easily classified under the low seismicity category. Estimated values may be sometimes suggesting for a comparison of the seismicity in Sri Lanka with that in Tasmania in Australia, since some of major cities in Tasmania are also provided similar hazard factors (e.g. Hobart-0.03*g*, Launceston-0.04*g*, Devonport-0.05*g* from AS 1170.4-2007). By referring to the pattern of variation of estimated ground motions across the country, it is clear that the maximum ground motion values are associated with source zone 6 that defines the local seismicity in the area around Colombo. Although, the seismicity characterized by source zone 6 is not as much intense as that in regional sources surrounding the country such as source zones 1, 2, 3 and 4, expected ground motions due to an event in source zone 6 appear to be still dominant in the country. The key reasons for the apparent dominancy of source zone 6 over others are; 1) lower site-source distance for respective sites from Colombo than from other zones (particularly, when compared with regional zones) 2) a bit higher recurrence rates for moderate and strong events than that in the other local source - source zone 5 3) any difference in the attenuation models applied.

(a)

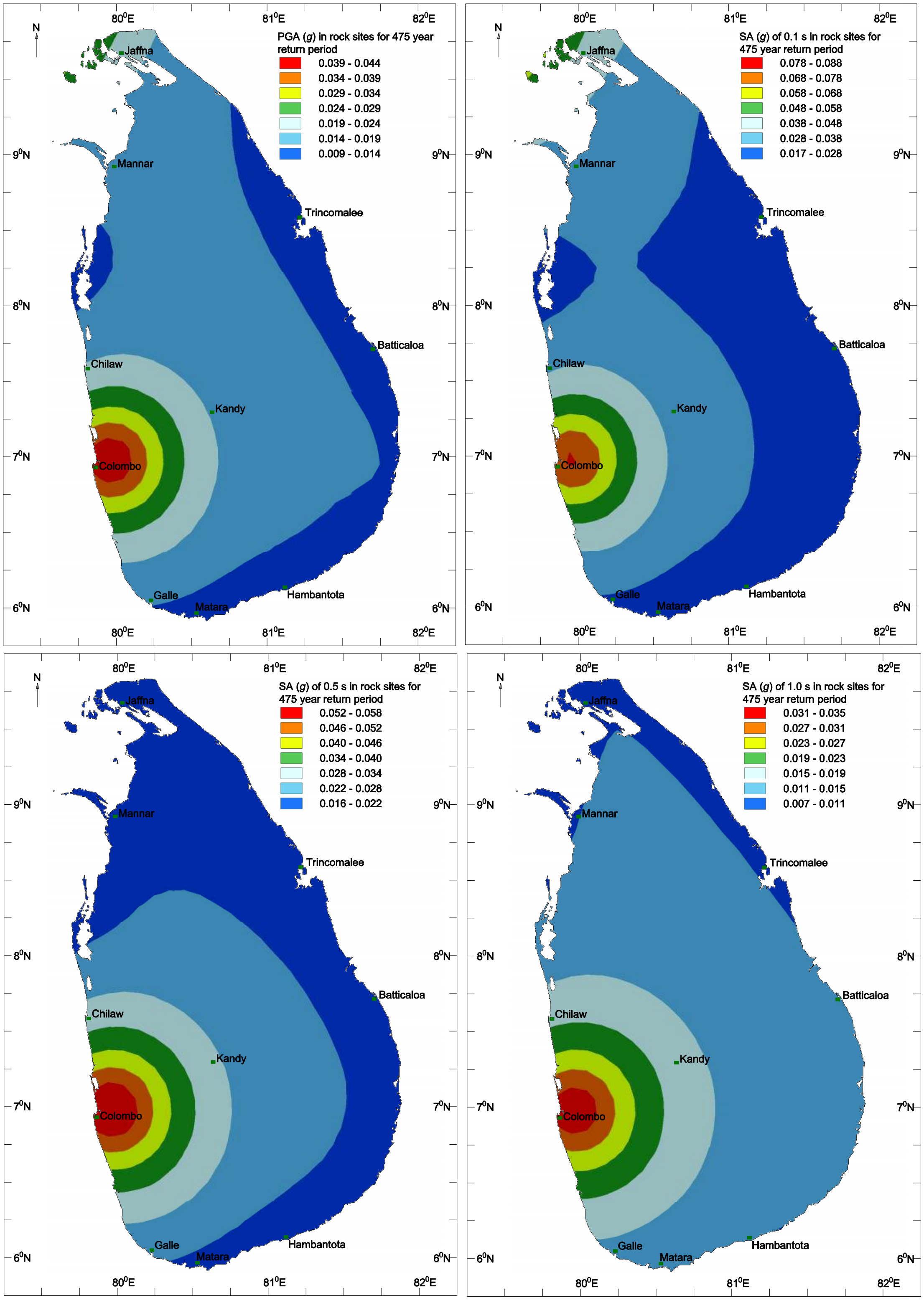
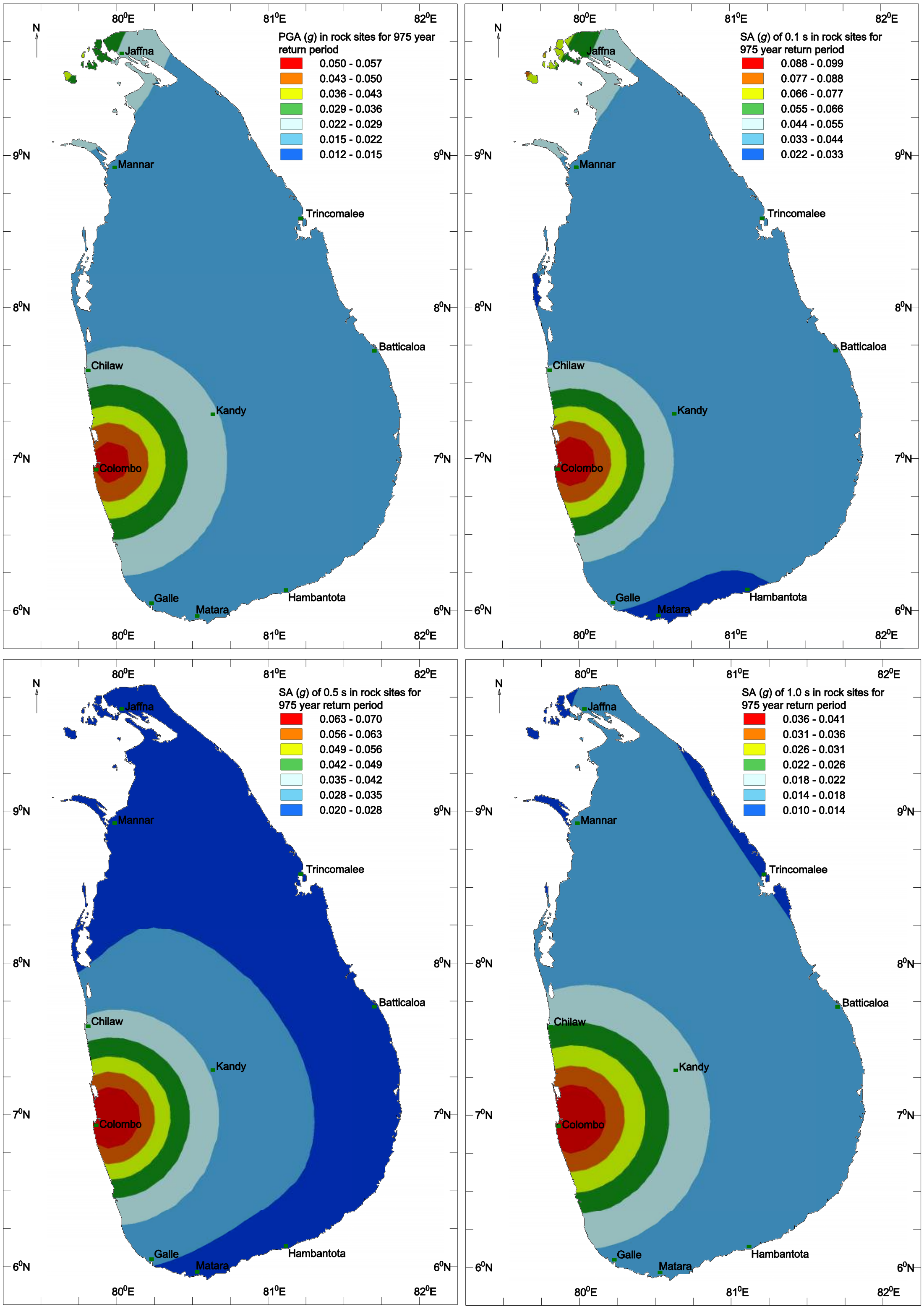
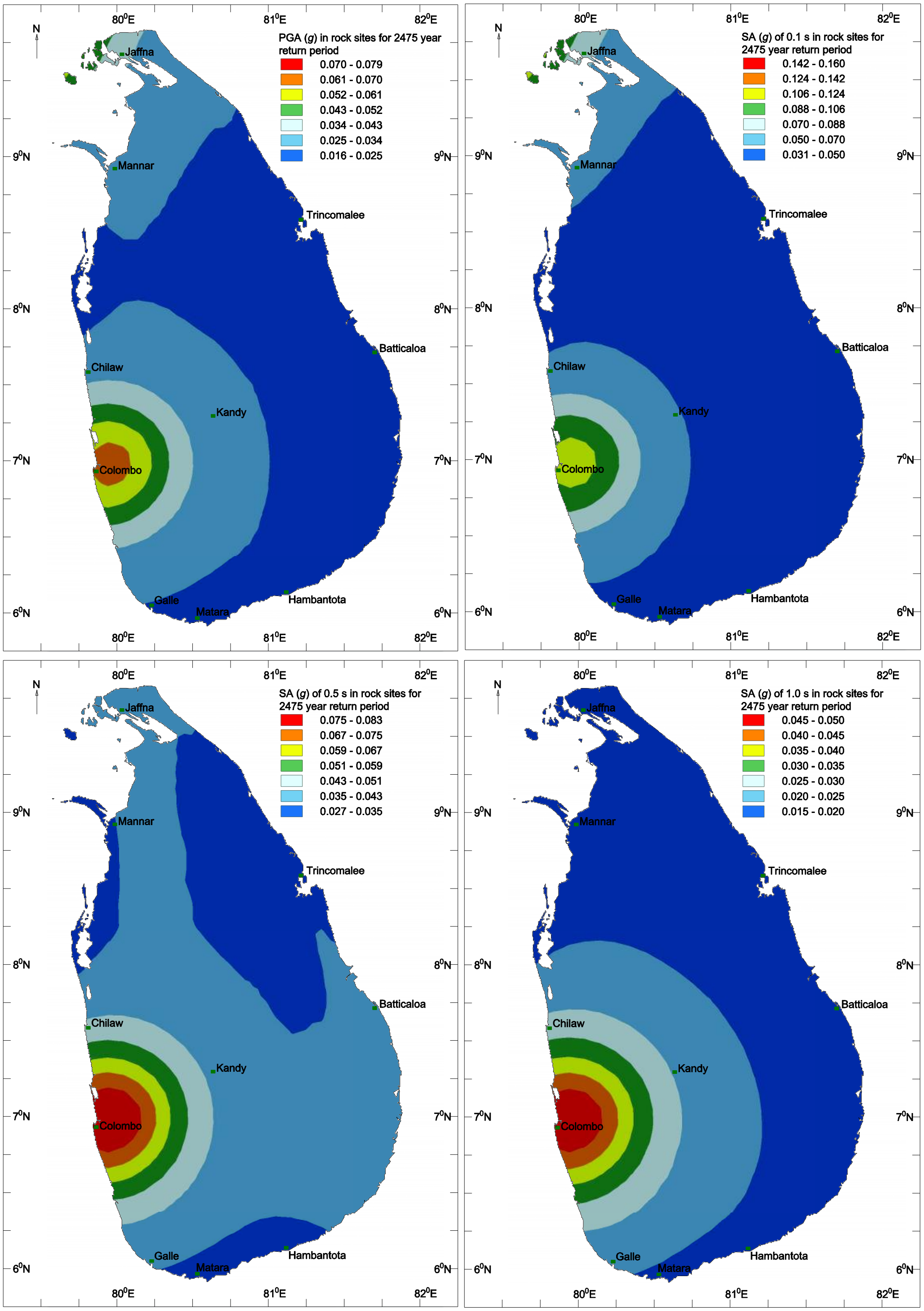


Fig. 5 - Computed hazard values in terms of expected ground motions (PGA and SAs at 0.1, 0.5 and 1.0 s natural periods) at rock sites in Sri Lanka for probability of exceedance (a) 10% in 50 years (475 year return period) (b) 5% in 50 years (975 year return period) (c) 2% in 50 years (2475 year return period).

(b)


PGA (g) in rock sites for 975 year return period
0.050 - 0.057
0.043 - 0.050
0.036 - 0.043
0.029 - 0.036
0.022 - 0.029
0.015 - 0.022
0.012 - 0.015
SA (g) of 0.1 s in rock sites for 975 year return period
0.088 - 0.099
0.077 - 0.088
0.066 - 0.077
0.055 - 0.066
0.044 - 0.055
0.033 - 0.044
0.022 - 0.033
SA (g) of 0.5 s in rock sites for 975 year return period
0.063 - 0.070
0.056 - 0.063
0.049 - 0.056
0.042 - 0.049
0.035 - 0.042
0.028 - 0.035
0.020 - 0.028
SA (g) of 1.0 s in rock sites for 975 year return period
0.036 - 0.041
0.031 - 0.036
0.026 - 0.031
0.022 - 0.026
0.018 - 0.022
0.014 - 0.018
0.010 - 0.014
N
80⁰E
81⁰E
82⁰E
9⁰N
8⁰N
7⁰N
6⁰N
Jaffna
Mannar
Trincomalee
Batticaloa
Chilaw
Kandy
Colombo
Galle
Matara
Hambantota

(c)



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