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A Macro Seismic Hazard Zonation for Sri Lanka

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Abstract: This paper describes the outcome of a comprehensive study carried out to analyse the seismic hazards affecting Sri Lanka. The main seismic threat is from oceanic earthquakes originating at failed Mannar rift zone and Comorin ridge off the west to south west coast with some secondary influence from South Indian crustal earthquakes. The analyses were performed using Deterministic Seismic Hazard Assessment, Probabilistic Seismic Hazard Assessment and seismic wave propagation using FLAC software ignoring the overburden attenuation within the landmass. The seismic scenario included 100 years earthquake catalogue with an characteristic earthquake of magnitude 6.9 at a distance 90 km from the west coast. Historical records of earthquakes in the vicinity of Sri Lanka indicate that 1615 earthquake was the most significant earthquake that affected Sri Lanka. The analyses show that South West to North West coastal areas are the most vulnerable to seismic hazards. There is also reflection of seismic waves leading to amplification of seismic waves in the central highland.

Based on the analyses described above, a seismic hazard map for Sri Lanka dividing the country into two zones of seismic intensity and response spectrum is provided accordingly. The study was constrained by the lack of recorded data of past earthquake responses within the country and a network of seismic stations are proposed in the paper for future data collection.

Keywords: Mannar rift zone, Gutenberg–Richter relationship, Response spectrum

1. Past Seismic Activities close to Sri Lanka

The earliest documentary record of an earthquake affecting Sri Lanka is based on a pamphlet published in Lisbon in 1616 describing an event which took place on 14 April 1615 near Colombo (Gunasekara, 2000) [9]. This record is described in detail bySeneviratne et al. (2019) [17]. Even though the original paper is not very scientific and contains many religious interpretations, there are many interesting facts which can be extracted.

In the period preceding the main event, there are accounts of:

"*Dead fish thrown up from the sea so poisonous that people who ate them died. The atmosphere most infected with Putrefaction and bad odour which killed people and birds. People were scared to go to the sea side let alone bathing as those who did were fallen sick*".

The above facts are consistent with gas release through the seabed, which is a possible activity in the active Mannar rift zone.

"*On the day of earthquake, the sun set half an hour earlier than on other days*".

The logical explanation for this may be a gas emission at the source of tectonic activity rising up in the atmosphere blocking the sun. If this is correct, the tectonic activity occurred approximately in the direction of west of Colombo. The distance to the activity is proportional to the height of the clouds at the time of sunset, which can be calculated using basic geodetic principles.

"*It was seven in the evening when thunder shook the air with such force and the earth quaked so violently that, unable to remain in the houses people rushed out to the streets fearing to be buried under the falling ruins of the buildings. Then bolts of thunder fell from the heavens. The thunderbolts had their effect, destroying and laying low not only the most sumptuous edifices but also the meanest cottages leveling all, and the few that the fire had not consumed were destroyed by the earthquakes*".

Thunder, lightning and fire have been commonly observed in such earthquakes in the past, according to literature. The number of casualties has been stated as 2000 with many houses destroyed and wide deep cracks visible on the ground.

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Based on the damage, the magnitude of the earthquake can be estimated as 6.5 with epicenter close to Colombo.

No other earthquake of similar magnitude has occurred since then. However, there had been a number of seismic events, particularly the events in 1938 and 1940, which were felt in many parts of the island though no casualties or significant damage had occurred. The 1938 earthquake was felt strongly in the western province and central highland, but not so much in eastern province. Within Sri Lanka, very little seismic activity (3 - 3.5 Richter scale) has been recorded (Fernando and Kulasinghe, 1986) [7]. No major seismic activity has been recorded coming from south east and north of Sri Lanka in the recent past except the Tsunami caused by 2004 earthquake (Sunda trench earthquake).

2. Geological Setting of Sri Lanka

Sri Lanka is located in the North Western region of the Indo-Australian plate. The interplate seismic activity around this plate is governed by Himalayas to the north on which it pushes against the Euroasian plate and by Sunda trench to the east on which it undergoes subduction causing earthquakes and tsunamis. The seismic activity to the far west at the mid-Indian ocean ridge and to the south are less significant in comparison to the above, as the former are zones of crustal extension compared to zones of compression in the north and east. However, some seismologists discuss the possibility of the emergence of a new plate boundary to the south of Sri Lanka (Dissanayake, 2005) [6]. The above interplate events are not considered significant as far as Sri Lanka is concerned (Thaldena et al. 2013) [20] but the tsunami hazard due to seismic activity at the Sunda trench is considerable.

In the present study, the intraplate activities spanning northwest to southwest coast of Sri Lanka in the vicinity of failed Mannarrift zone and the Comorin ridge which were not hitherto considered important are analysed in detail. This is particularly important considering the heavily populated and economically important areas near the west coast and/or within western province. The intraplate activities originating in the other regions around Sri Lanka are not considered important except to the north where intraplate seismic activity in South India may have some influence on the northern region of Sri Lanka. The intraplate seismic activity within Sri Lanka appears to be not significant (Fernando and Kulasinghe, 1986) [7].

3. Geological Significance of Failed Mannar Rift Zone and Comorin Ridge

Sri Lanka is believed to be geologically the southern continuation of peninsular Southern India although the island today is separated from the mainland India by a narrow stretch of shallow sea. This stretch of the sea is now a part of the Indian Ocean, but it opened-up as Sri Lanka drifted apart from India at the time the super continent Gondwana broke-up during the Jurassic period (Curray, 1984; Baillie et al. 2002; Kularatne et al. 2015) [5], [3], [11]. Continued rifting of continents always leads to formation of large ocean basins but it produces narrow seas or inland lakes at initial stages. Rifting produces faulted blocks of rocks with the faulting extending laterally for tens to hundreds of kilometers, and vertically downward to the mantle, providing pathways for rising magma. Zones of initial rifting therefore, are always geologically very active as they are sites of active volcanism and seismicity.

The narrow sea between Sri Lanka and South India however, is a failed rift zone; this is the underlying reason for the absence of active volcanism and seismicity today. However, the Cauvery and Mannar basins produced by the rifting process is floored by faulted blocks of continent and sedimentary successions which are about 10 kilometers thick, laid down on the faulted sea floor since the Cretaceous period. During exploratory drilling for oil in the Cauvery and Mannar basins, frozen basaltic lava flows have been encountered (Rana et al. 2008) [15]. These are inter-layered with sediments indicating that the rift zone had been volcanically and seismically active in the past.

Seismic exploration of the sedimentary succession in the Cauvery and Mannar basins has indicated relative disposition of faulted blocks of rocks on the basin floor. As the sediment load increases one cannot rule-out reactivation of the fault zones and relative motion between the already faulted blocks of rocks generating some seismicity. In the Bay of Bengal to the east and northeast of Sri Lanka, there is also evidence of sea floor spreading. The settling of sedimentary successions has given rise to earthquakes with magnitude around M5 in the recent past, the latest being in

April 2009. Although highly active seismic zones are quite far away from Sri Lanka, the potential of the above sedimentary basins to the NW and NE of Sri Lanka becoming foci of future low magnitude earthquakes (up to M6) has to be borne in mind. However, the seismic status of Sri Lanka is dominated by failed Mannar rift zone and Comorin ridge (NW basin) as very few significant seismic activities have been recorded in the NE basin.

4. Seismic Monitoring in and around Sri Lanka

A Milne seismograph was installed in Colombo Observatory in 1909. This was replaced by a Milne-Shaw seismograph in 1927. The observations from this seismograph had been connected to a global network comprising 350 seismographic stations. The original records are kept at the Department of Meteorology which succeeded the Colombo Observatory in 1972. Therefore, measured earthquake data at Colombo should be available from 1909-1992. Unfortunately however, no data from seismograph at Colombo observatory are available since 1992 as the seismograph was not in a fully functional condition.

Three seismometers were installed by Geological Survey and Mines Bureau (GSMB), one in 2000 at Pallekele (PALK) connected to Global Seismographic Network (GSN), and the others in 2010 at Mahakandarawa (MALK) and Hakmana (HALK), connected to GEOFON Network. The waveform data and earthquake parameters from these seismometers are available through the internet from the GSN and GEOFON networks through GSMB.

The major problem of seismic monitoring of Sri Lanka performed in the past by government agencies is the lack of monitoring data available throughout the island. This is normally facilitated by having a series of seismometers at strategic locations. Up to date no such network has been established.

5. Earthquake Catalogue for Intraplate Seismicity in and around Sri Lanka

Early earthquake catalogues on the seismicity around Sri Lanka were prepared by Vitanage (1995) [22] and Abayakoon (1996) [1]. In addition, a number of Indian catalogues cover many earthquakes in the South Indian region (Menon et.al., 2010) [13]. In the present study to investigate the seismicity around Sri Lanka, an area bounded by Latitude 0˚N - 20˚N and Longitude 70˚E - 90˚E was selected (see Figure 1). The records from Abayakoon (1996) [1]. and Uduweriya (2014) [21] are based on the data reported by many global data bases such as IRIS data base. The data which goes back to 1063 A.D. consisting of past seismographic observations, and estimations based on damage intensity or from paleo-seismological studies, was used in preparation of the catalogue.

The epicenters of the earthquakes taken from the catalogue are illustrated in Figure 1.

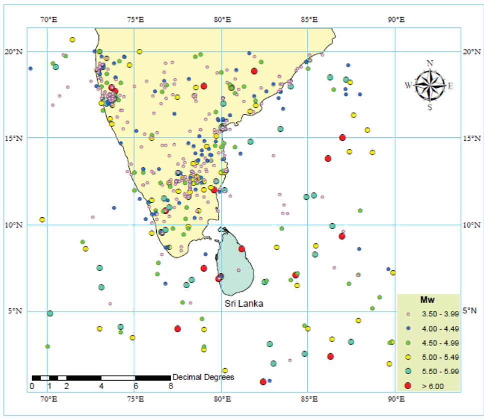

Figure 1 - Epicenters from Past Earthquakes

It is clear from Figure 1 that a high intensity earthquake zone is concentrated along the NE, SW Indian fault zone going from Ongole to Kerala. However, this fault region is far away from Sri Lanka to have any significant impact on the seismic status of Sri Lanka except in the northern region.

The seismic status close to Sri Lanka appears to be governed by the activities in the western coastal region in which failed Mannar rift zone and Comorin ridge can be easily identified as the main tectonic features. This is very clearly visible in Figure 2, which shows the filtered version of the catalogue (Catalogue B) created by narrowing down the original area to 3.5˚N-8.5˚N and 75˚E-80˚E window.

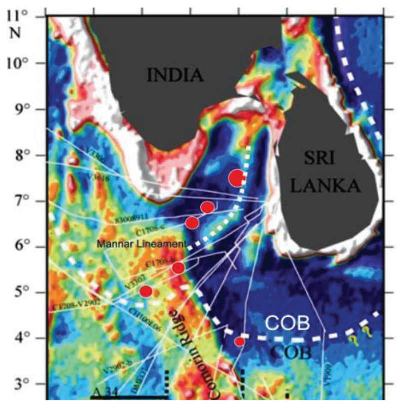

Figure 2 - Epicentres of the Earthquake Occurred on the Comorin Ridge and the Surrounding Area (Structure and Isostatic Compensation of the Comorin Ridge, North Central Indian Ocean by Sreejith et al. 2008) [18].

The seismic activities in the other coastal regions of the catalogue A appear to be insignificant in comparison according to the available data at present. The completeness of this catalogue has been tested according to the procedure described by Stepp (1973) [19]. It shows that 100 years data is sufficient for the completeness (Seneviratne et al., 2019) [17].

6. Analysis of Seismicity of Sri Lanka

Three types of analyses, namely DSHA (Deterministic SeismicHazard Analysis), PSHA (Probabilistic Seismic Hazard Analysis) and numerical analysis using finite difference FLAC software, were performed. Considering the geology of Comorin Ridge and Failed Mannar rift zone, a characteristic earthquake of 6.9 moment magnitude occurring at a distance of 90 km from NW-SW coastal line was chosen for the DSHA and the finite difference analysis. PSHA was performed using the complete earthquake catalogue.

6.1 Deterministic Seismic Hazard Analysis (DSHA)

DSHA predicts the seismic response (defined by peak ground acceleration (PGA) at a point, distance D away from the seismic source, based on an attenuation relationship available in the literature derived using observed data from seismic sources elsewhere (Reiter (1990) [16]. For the seismic scenario given above, two attenuation relationships available in the literature (Gitterman et al. 1993) [8] , and Kun-Sung and Yi-Ben, 2005) are calibrated against the monitoring data from GMSB for an earthquake of magnitude of 4.7 at a distance of 270 km from the western coastal line. The comparison showed that Gitterman et al. (1993) [8] gives the most suitable relationship for calibration data. The prediction for the given seismic scenario (6.9 magnitude at 90 km) given by Gitterman et al. (1993) [8] for selected locations within Sri Lanka are given in Table 1.

6.2 Probabilistic Seismic Hazard Analysis

PSHA was performed by considering eleven seismic zones in and around Sri Lanka. The complete earthquake catalogue from 1900 to present were used in the analysis. Three attenuation relationships: Abrahamson and Silva (1997) [2], Cambell and Bozorgnia (2008) [4] and Raghukanth and Iyenger (2007) [14] suitable for the whole region under consideration were used in the analysis. The prediction of PGA and Spectral Acceleration (SA) at point of interest within Sri Lanka were performed considering all zones. In each zone, the magnitude *M* of 475 year return period earthquake was calculated considering all past earthquakes within that zone. This earthquake was placed on the boundary of the zone closest to the point of interest and the PGA and SA at the point was calculated for magnitudes of M and M+0.3 using three attenuation relationships.

Table 1 - PGA Values at Selected Cities in Sri Lanka

City	PGA (g)	
	M=6 at 15 km	M=6.9 at 90 km
Ampara	0.004	0.006
Anuradhapura	0.007	0.009
Badulla	0.01	0.013
Batticaloa	0.004	0.005
Colombo	0.132	0.067
Dambulla	0.009	0.012
Gampaha	0.108	0.062
Galle	0.016	0.019
Hambantota	0.007	0.009
Horana	0.08	0.054
Jaffna	0.002	0.002
Kalutara	0.061	0.047
Kandy	0.018	0.021
Kurunegala	0.023	0.025
Mannar	0.003	0.005
Matara	0.011	0.013
Negombo	0.083	0.055
Nuwara Eliya	0.016	0.019
Polonnaruwa	0.007	0.009
Puttalam	0.012	0.015
Rathnapura	0.034	0.033
Trincomalee	0.003	0.004
Vavuniya	0.004	0.006

The epistemic uncertainties were dealt with by logic tree approach. The results of PSHA thus obtained for the selected locations in Sri Lanka are shown in Table 2.

6.3 Finite Difference Analysis using FLAC Software

FLAC is a general purpose finite difference software which can solve wave propagation equations in linear elastic media. A typical two dimensional cross section used for analysis is illustrated in Figure 3.

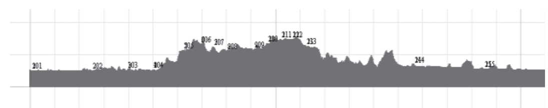

Figure 3 - Model Cross Section Developed for the Section Passing through Colombo-Batticaloa

Table 2 - PGA at Different Cities in Sri Lanka for 50, 475 and 2475 Year Return Periods

City	PGA (g)		
	T=50	T=475	T=2475
Ampara	0.002	0.011	0.027
Anuradhapura	0.007	0.034	0.074
Badulla	0.003	0.017	0.04
Batticaloa	0.002	0.011	0.028
Colombo	0.025	0.107	0.207
Dambulla	0.004	0.025	0.056
Galle	0.009	0.045	0.094
Hambantota	0.003	0.016	0.038
Horana	0.013	0.062	0.127
Jaffna	0.041	0.158	0.325
Kandy	0.005	0.025	0.057
Kurunegala	0.007	0.035	0.076
Mannar	0.033	0.134	0.28
Matara	0.005	0.028	0.061
Mullaitivu	0.008	0.04	0.101
Nuwara Eliya	0.004	0.022	0.05
Polonnaruwa	0.003	0.018	0.042
Puttalam	0.029	0.122	0.233
Rathnapura	0.006	0.033	0.073
Trincomalee	0.009	0.026	0.048

The western and eastern boundaries are the continental shelf of Sri Lanka taken along the five cross sections: Colombo-Batticaloa, Kalutara-Kalmunai, Galle-Arugambay, Chilaw-Vakarei, and Puttalum-Trincomalee. The vertical dimensions of the cross sections were taken from the 1:50000 survey map of Sri Lanka ignoring the overburden. The dynamic material properties for the analysis were taken from Jayawardene (2010) [10], which contains the results for a large number of samples. Test runs with the model indicated that all three boundaries (two sides and the base) should be wave absorbent type. The characteristic depth of all the sections was taken 10 km from the mean sea level. In the absence of any measured data, PGA and SA at the western boundary were taken as the average of seven earthquakes data taken from PEER data base having approximately similar magnitude and distance to point of interest.

The results of this analysis are also presented in Table 3. It can be observed an interesting effect that the PGA is amplified in some hilly areas.

Table 3 - PGA Values at Selected Cities in Sri Lanka

No.	City	PGA (g)
1	Galle	0.080
2	Kottawa	0.063
3	Akuressa	0.059
4	Pasgoda	0.065
5	Katuwana	0.068
6	Panamure	0.062
7	Angunakolapalassa	0.044
8	Weheragala	0.036
9	Andiawela	0.029
10	Arugam Bay	0.023
11	Kaluthara	0.082
12	EgalOya	0.060
13	Idangoda	0.053
14	Kuruwita	0.047
15	Thummodara	0.050
16	Nallathanniya	0.058
17	Maskeliya	0.060
18	Hatton	0.051
19	Lindula	0.047
20	NanuOya	0.040
21	NuwaraEliya	0.045
22	Kandapola	0.042
23	Ragala	0.044
24	Bibile	0.031
25	Kalmunai	0.024
26	Colombo	0.083
27	Ussapitiya	0.060
28	Kandy	0.048
29	Narampanawa	0.044
30	Knuckles1	0.040
31	Meemure	0.041
32	Knuckles	0.037
33	Batticaloa	0.021
34	Chilaw	0.083
35	Ella	0.068
36	Migaswewa	0.058
37	Thalpathwewa	0.057
38	Alutwegedara	0.056
39	Bulanwewa	0.048
40	Dambulla	0.045
41	Kandalama	0.043
42	Kaduruwela	0.034
43	Tambala	0.033
44	Vakarai	0.025
45	Puttalam	0.095
46	Balagollagama	0.080
47	Saliyawewa	0.074
48	Anuradhapura	0.050
48	Mihinthale	0.047
50	Tammanewa	0.044
51	Amunukola	0.038
58	Trincomalee	0.027
53	Ambagahawewa	0.038
54	Katupotana	0.034
55	Nagollewa	0.032
56	Palampoddaru	0.029
57	Ganeshapuram	0.027
58	Trincomalee	0.027

7. Seismic Hazard Map for Sri Lanka

The results of DSHA, PSHA and finite difference analyses are reasonably consistent. This may be due to the fact that the dominant seismic source for all three analyses is the same. In DSHA and finite difference analysis, the characteristic seismic source is the failed Manner rift zone while in PSHA, failed Manner rift zone contribution appears to be the dominant one.

A seismic hazard map for Sri Lanka is proposed considering the average PGA value at each location as given by the three analyses described above. Considering the range of average values obtained, two seismic zones were proposed as illustrated in Figure 4 as Zone 1 and Zone 2 having design PGA values of 0.1 g and 0.05 g, respectively.

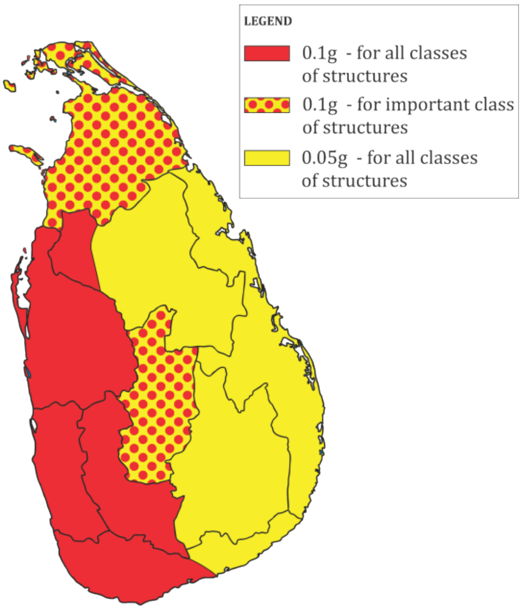

Figure 4 - Seismic Hazard Map for Sri Lanka based on Peak Ground Acceleration

The structural classes in all zones are identified as Class I (command centres, schools, hospitals, dams, public gathering places, ancient/cultural structures, highrise buildings etc.) and Class II (all the other engineered structures). In Zone 1, both Class I and Class II structures should be designed against the PGA 0.1 g. In Zone 2, Class I structures should be designed against the PGA value of 0.1 g while Class II structures should be designed against 0.05 g.

The proposed response spectra for all zones are illustrated in Figure 5 and the relationship given below.

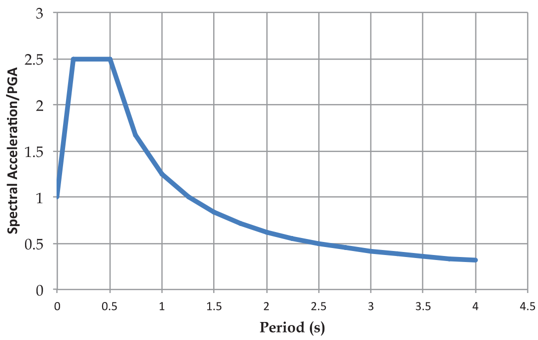

Figure 5 - Proposed Normalized Response Spectrum

$$SA = \begin{cases} (1+10T) * PGA & 0 \le T \le 0.15 \\ 2.5PGA & 0.15 \le T \le 0.5 \\ 1.25 / T * PGA & 0.5 \le T \le 4.0 \end{cases}$$

8. Seismic Monitoring Programme

In carrying out a comprehensive study on seismic status on Sri Lanka, recorded ground response at key points distributed throughout the island is required. The actual monitoring data at present are available only from three stations (Hakmana, Pallekele and Mahakanadarawa) of GSMB which are approximately aligned North-South through the centre of the island. The most vital region of western province does not have a single monitoring station. In the study described in this paper, lack of seismic monitoring data was a serious setback in trying to select appropriate attenuation relationships.

Therefore, there is an urgent need to establish a network of seismometers throughout the island so that the actual seismic response of any part of the island may be estimated to sufficient accuracy. The authors propose the seismometer configuration shown in Figure 6 for this purpose. The technical specification of seismometers should ensure that the frequency range of 0.1 Hz to 25 Hz is adequately represented.

Figure 6 – Proposed Seismometer Configuration

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