A STUDY OF SEISMIC STATUS OF COLOMBO, SRI LANKA

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ABSTRACT

Although Sri Lanka is situated in an area supposed to be categorized as aseismic, records show that there had been some earthquake activities in the past, with some destruction in the areas close to the capital city, Colombo. Considering the fact that disastrous earthquakes have shown up in other so-called aseismic areas in the world, it has been decided to formulate an analysis focusing on Colombo city.

A series of investigations has been carried out to evaluate local site response characteristics against different levels of seismic action. This is mainly to identify the contribution from the local site structure in characterizing the seismic damage. The study included the analysis of the geotechnical structure of the study area, determination of the dynamic parameters of the local soil profiles, designing of hypothetical earthquakes to stimulate the seismic action, surface response analysis and an approximate evaluation to assess the areas more susceptible to soil liquefaction.

The information on the local soil stratigraphy has been determined based on the borehole log data representing soil profiles distributed throughout the study area. The corresponding soil dynamic parameters have been determined using empirical correlations with Standard Penetration Test (SPT) values and the results have been justified at two locations by comparing with those obtained from spectral analysis of surface wave method.

The equivalent linear response computer program ProShake has been used to perform the surface response analysis of 123 selected locations. Fifteen modified input motions of the El-Centro Earthquake record, representing earthquakes of magnitude ranging from 5 to 7 in Richter scale and epicentral distances ranging from 10 to 180 km were used in the analysis. The possibility of difference in the peak ground acceleration up to ten times between two neighboring areas in Colombo due to a potential seismic event is demonstrated.

The locations susceptible to potential soil liquefaction have been identified using an approximate method based on the SPT value and accordingly about 70% of the locations considered are prone to soil liquefaction.

1. INTRODUCTION

Sri Lanka is situated in an a seismic zone away from major plate boundaries or any active faults (Figure 1). However, historically there had been records of many seismic events within Sri Lanka and in the neighbouring areas, which had considerable influence on the island. Even though it is likely that many of these earthquakes are very small in magnitude and also many had epicentres far away from the country, the necessity to study seismic effects on Greater Colombo area has become an important concern considering the increasing degree of urbanization with time.

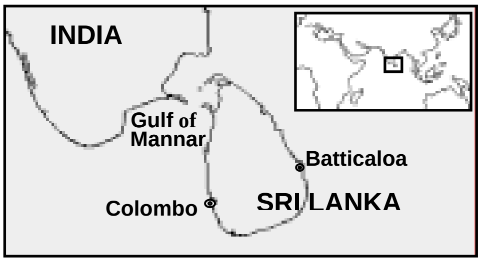

Figure 1: Geographic Position

In the past there had been many inter-plate earthquakes reported in so called Stable Continental Regions (SCR). It has been observed that the damage caused by such earthquakes tend to be very high due to lack of preparedness. Past seismic history, distance from any active fault, and the local site conditions have great influence in the magnitude and the characteristics of the damage caused by an earthquake. The first two factors deal with a remote system, which controls the seismic input at the local site. The third one depends upon the site characteristics controlling type as well as the magnitude of damage caused by an earthquake.

The current study primarily focuses on assessing the influence of local site factors in and around Colombo, Sri Lanka, on any future seismic damage. The seismicity of the region and estimation of typical strong motion parameters due to earthquakes of different magnitude epicenter distance combinations likely to occur around the area are also studied.

2. SEISMICITY OF THE REGION

From 1600 A.D. to date there are about 100 earth tremors reported in and around Sri Lanka (Abayakoon, 1988). Some of these events are described in historical records and more recent events have been identified by geological institutions such as United States Geological Survey (USGS), Geological Survey of India (GSI). Many of these events have been categorized under shallow earthquakes and the epicentral distances were closer to Colombo than other major cities of Sri Lanka.

One of the very recent earth tremors felt in Sri Lanka was due to an earthquake of magnitude 5.9 in Richter scale which occurred on 21-09-2001. The epicentre of this event was located at 52° 55′ 44″ N, 82° 30′ 30″ E, about 720 km S-SE of Colombo (USGS). Two other recent events were reported from Southern India, with magnitudes of 5.0 and 5.4, on 29-01-2001 and 26-09-2001 respectively. The second caused three deaths. On 07-

12-1993 there was a seismic event with epicentre located about 170 km from the west coast of Sri Lanka in the Gulf of Mannar. This was an earthquake of magnitude 4.7 in Richter scale and was felt in most parts of Sri Lanka including Colombo.

Studying the data obtained from USGS and some other locally recorded events, Abayakoon (1998) found that ten earthquakes with their epicentres within the island of Sri Lanka; seven of these were close to Colombo. The first documented earthquake in Sri Lanka occurred on 14-08-1615 and had an estimated magnitude of 6.5 on Richter scale. This caused severe damage in Colombo, killing thousands of people and destroying hundreds of houses. Two more events in 1814 and 1938 the former causing severe destruction in Batticaloa have also been mentioned (Vitanage, 1995).

3. INFLUENCE OF LOCAL SITE CONDITIONS ON SEISMIC RESPONSES

Both geotechnical characteristics of soil/rock present within the site and the structural characteristics of any super structure on it are considered as the local site condition in relation to any seismic event. The two characteristics have their own systems responses to dynamic loading. The dynamic properties of soil/rock at a site play an important role in modifying the characteristics of the earthquake strong motions.

Soil liquefaction is an important consequence of earthquakes, having the potential to cause extensive damage to structures. Strength of the seismic motion and susceptibility of the soil to liquefaction will determine the extent of soil liquefaction at a site.

The potential of local site effects in alternating strong ground motions was well demonstrated in many past earthquakes and reported by many authors (Seed et al., 1969[2], Celebi et al., 1987, Seed et al., 1991, Kramer, 1996).

4. GEOTECHNICAL STRUCTURE OF THE STUDY AREA

Data from about 300 boreholes at 200 locations situated within Greater Colombo area have been used to determine the stratiagraphy of the study area. From the borehole log analysis it was found that the depth of the top soil layer is in the range of 5 m to 25 m. Based on the dominant soil type, the locations can be classified into three main groups viz. locations dominated by sand profiles, locations dominated by clay layers and locations dominated by peat deposits.

A map showing the distribution of borehole locations and some of the key areas within the study area is given in Figure 2. Sand profiles were found in most part of the Colombo Municipality areas and some other adjoining urban areas along the Galle Road, from Colombo Fort to

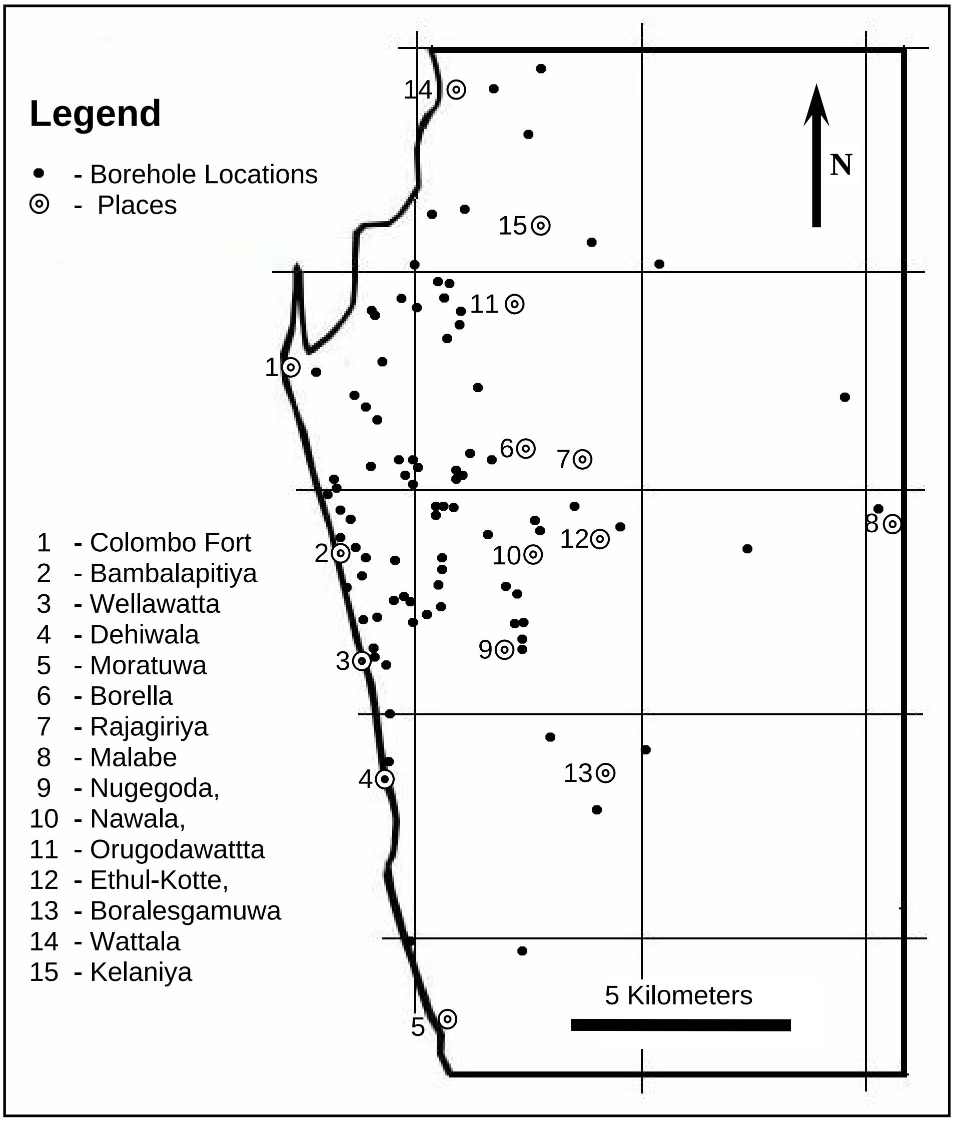

Figure 2 : Study area and the distribution of locations considered

Moratuwa (route 1-2-3-4-5 in Figure 2). Clay deposits were found as isolated pockets within Colombo Municipality area except near Borella where sand as well as clay layers have been encountered. Rajagiriya, Malabe, Nugegoda, Nawala, Orugodawatta, Etul-kotte, Boralesgamuwa, Wattala, Kelaniya are also some other locations given in Figure 2, where sand and clay profiles were observed. The peat deposits were generally found in the low-lying areas of Greater Colombo (Senenayake, 1996).

Based on the SPT values, the areas dominated by sand deposits can be identified as loose and dense profiles, and the areas dominated by clay deposits as soft, stiff and hard profiles (Das, 1990). In addition gravel was also observed at few locations within the study area. In most of the locations the soil profiles end up with the weathered rock at a depth ranging from 20 m to 25 m.

Out of the 200 locations, 123 locations have been selected to carry out the surface response analysis based on the spatial distribution of the locations and the availability of sufficient data to characterize the stratigraphy up to bedrock. Some of the soil properties determined from the borehole log information are given in Table 1. Table 2 presents parameters used to characterize the bedrock (Morochik et al., 1998, Barnes, 1995, Jayawardena, 2001).

Tabel 1: Soil data determined from the borehole log information

Parameter	Sandy soil		Gravel		Clayey soil		
	Min	Max	Min	Max	Min	Max	Avg
Unit weight / kNm^{-3}	16	22	16	22	16	22	-
Void ratio	-	-	-	-	0.3	2.0	-
Plasticity Index	-	-	-	-	-	-	30

Table 2: Parameters used for characterization the bed rock

Strata	Weathered/ Soft Rock	Rock
Average thickness (m)	15m	-
Shear wave velocity (ms^{-1})	700	2500
Unit weight (kNm^{-3})	22	28

The type of soil, SPT value, thickness of the strata and level of the ground water table are the only borehole information available in most of the area considered. After verifying the correlation of the SPT value with the soil parameters given in the literature (Das, 1990, Beck, et al. 1974) it was decided to use the SPT for sandy soils as well as clayey soils to determine the soil parameters and the results were justified for two locations with the shear wave velocity measurements made using surface wave techniques.

Empirical relationships proposed by Seed et al. (1986) have been used to determine the maximum shear modulus values for sand and gravel. An empirical relationship proposed by Hardin et al. (1972) has been used for clayey soils assuming that the clay profiles are normally consolidated. For peaty soil at low strain ($<10^{-4}$) G/Su (shear modulus/un-drained shear strength) values have been extrapolated from the relationship proposed by Seed et al. (1970[1]). Su varies from 6 to 12 kNm^{-2}, with a SPT range of 2 to 5 (Aziz, 1986) and the unit weight was averaged from the data given by Ray et al. (1986). The average modulus reduction and damping curves reported by Seed et al. (1970[1]), Seed et al. (1986), Bounglar et al. (1998) are used to characterize the dynamic behavior of the soil strata.

5. SURFACE RESPONSE ANALYSIS

Fifteen different shallow earthquake cases representing a combination of three Richter magnitudes 5.0, 6.0 and 7.0 and four epicentral distances 10, 20, 40, 80 and 160 km have been selected for the analysis.

The North South Component of the earthquake motion recorded at El Centro during the 1940 Imperial Valley earthquake, USA has been used as the basic input motion for the surface response analysis. The characteristic of this motion has been analyzed and reported by many authors (Fisher, 1963, Moore et al., 1966, Seed et al., 1969[1]). The original earthquake time history has been modified to represent different magnitudes of earthquakes (Table 3) using the attenuation relationship proposed by Seed et al. (1969[1]).

Table 3: Characteristics (peak acceleration – a_{max}, predominant period - t_p) of Design Earthquakes

Magnitude (Richter Scale)	Parameter	Epicentral Distance (km)				
		10	20	40	80	160
5.0	Case No	1	4	7	10	13
	a_{max}, (gal)	40	30	25	12	3
	t_p (sec)	0.22	0.22	0.22	0.275	0.33
6.0	Case No	2	5	8	11	14
	a_{max}, (gal)	85	60	40	15	5
	t_p (sec)	0.26	0.26	0.26	0.32	0.44
7.0	Case No	3	6	9	12	15
	a_{max}, (gal)	210	160	105	37	10
	t_p (sec)	0.32	0.32	0.32	0.4	0.58

The equivalent linear response computer program ProShake (EduPro Civil systems, Inc, 1998) has been used to perform the surface response analysis.

Table 4 shows the percentage distribution of ground shaking levels (Low, Moderate and High) among the 123 locations considered for 15 design earthquake considered in the analysis.

Table 4: Distribution of shaking levels (%) corresponding to 15 design earthquake considered.

	Design Earthquake														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Low (%)	23	26	25	31	29	27	39	30	33	47	50	46	0	0	15
Moderate (%)	45	37	37	43	37	39	35	41	33	2	9	28	0	0	0
High (%)	13	28	37	5	22	31	2	9	29	0	0	7	0	0	0

The seismic amplification ratios were calculated based on the peak ground acceleration values determined at the ground surface and the peak acceleration of the input motion at the hard rock level. The amplifications values have been obtained after rounding the log (amplification ratio) to the nearest 0.2 to make the values compatible with the degree of accuracy of the estimations. An extract of these values showing the highest and lowest amplification ratio are given in Tables 5 and 6.

Table 5: An extract showing the highest values of the seismic amplification ratio obtained for the 15 levels of input motion.

Location ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
C3_8	6.3	6.3	4.0	10	6.3	4.0	10	6.3	6.3	10	10	10	15	10	6.3
C6_6	6.3	6.3	4.0	6.3	6.3	6.3	10	6.3	6.3	6.3	6.3	6.3	10	4.0	6.3
C11_1	6.3	6.3	4.0	6.3	6.3	4.0	6.3	6.3	6.3	10	10	6.3	6.3	6.3	6.3
C3_4	4.0	4.0	4.0	6.3	4.0	4.0	6.3	6.3	4.0	6.3	6.3	6.3	10	6.3	6.3
C3_2	6.3	4.0	2.5	6.3	4.0	4.0	6.3	6.3	4.0	6.3	10	6.3	6.3	6.3	4.0
C12_1	6.3	4.0	2.5	6.3	4.0	4.0	6.3	6.3	4.0	6.3	6.3	6.3	10	4.0	6.3
C8_1	6.3	4.0	2.5	6.3	4.0	2.5	6.3	6.3	2.5	6.3	6.3	4.0	6.3	6.3	2.5
C7_8	6.3	4.0	2.5	6.3	4.0	2.5	6.3	4.0	2.5	6.3	6.3	4.0	6.3	6.3	4.0
C4_2	6.3	4.0	2.5	6.3	4.0	2.5	6.3	6.3	4.0	6.3	10.0	6.3	10.0	6.3	6.3

Table 6: An extract showing the lowest values of the seismic amplification ratio obtained for the 15 levels of input motion.

Location ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
C7_4	2.5	1.6	0.4	4.0	1.6	0.6	4.0	2.5	1.0	4.0	2.5	1.6	6.3	4.0	2.5
C7_5	2.5	1.6	0.4	2.5	1.6	0.4	2.5	2.5	0.6	2.5	2.5	1.6	4.0	4.0	2.5
C13_3	1.0	0.6	0.4	1.6	0.6	0.4	1.6	1.0	0.6	2.5	1.6	1.0	4.0	4.0	2.5
C15_2	1.0	0.6	0.4	1.0	0.6	0.4	1.0	1.0	0.4	1.6	1.6	1.0	2.5	2.5	2.5
F4	0.6	0.4	0.4	1.0	0.4	0.4	1.0	0.6	0.4	1.6	1.6	0.6	2.5	2.5	2.5
C10_3	2.5	1.0	0.3	4.0	1.0	0.4	4.0	1.6	0.6	4.0	2.5	1.6	4.0	4.0	2.5
H8	1.0	0.6	0.3	1.0	0.6	0.4	1.6	1.0	0.4	1.0	1.0	0.6	1.6	1.0	1.6
C6_4	0.6	0.4	0.3	0.6	0.6	0.3	1.0	0.6	0.4	1.0	1.0	0.6	1.6	1.0	1.0
C4_5	1.0	0.4	0.3	1.0	0.6	0.3	1.6	1.0	0.4	1.6	1.0	0.6	2.5	1.6	1.6
E6	0.4	0.4	0.3	0.6	0.4	0.3	0.6	0.4	0.4	1.0	1.0	0.6	2.5	1.6	1.6
E9	0.3	0.2	0.2	0.4	0.3	0.2	0.4	0.3	0.3	0.4	0.6	0.4	1.6	1.0	0.6

6. SOIL LIQUEFACTION

The soil liquefaction evaluation procedure reported by Seed et al. (1970[2]) has been used to assess the potential liquefaction zones within the study area. This is an approximate method to identify the locations more susceptible to soil liquefaction. The peak horizontal shear stress i.e. the shear capacity of the soil profile against the liquefaction was determined based on the SPT values obtained from the borehole log data. Equivalent cyclic shear stresses expected to be induced due to seismic action have been determined for five levels of peak ground accelerations ranging from 0.1 g to 0.5 g at 123 locations within the study area. According to the analysis about 30% of the locations have been found to be susceptible to no liquefaction, 20% of locations were identified as having high susceptible to soil liquefaction with low level of shaking and 50% of the locations required moderate or high levels of shaking for liquefaction to occur.

7. DISCUSSION

Current analysis is intended to demonstrate the general local site aspects of a future earthquake.

Borehole log information has been used to explore the geotechnical structure of the study area. From this it was observed that loose/soft deposits as well as the dense/stiff soil profiles up to 25 m depth are present in the study area. This is an indication of considerable variation in seismic amplification ratio within the study area. The presence of loose sand deposits at many sites is an indication of locations more susceptible to soil liquefaction. However, site effects like those experienced in Mexico during the 1985 Mechoacan earthquake where the local soil profiles extended up to hundreds of meters depth, are not encountered in Colombo.

From the surface response analysis it is found that all the fifteen levels of input motions have been modified by a similar trend in all the locations. The amplification ratio ranges from 0.2 to 10. Further, for a particular level of shaking, the ratio of maximum to minimum amplification ranges from 10 to 20. However, the degree of amplification is higher in weak motions and for the case of strong shaking it becomes close to 10. This is an indication of the possibility of up to ten times variation in the level of ground shaking at two distinct locations due to a potential earthquake.

Assessment of soil liquefaction has also been covered in the current analysis. The results demonstrate the degree of liquefaction susceptibility of many locations in Greater Colombo Area.

8. CONCLUDING REMARKS

The maximum amplification ratios were observed at locations having stiff and dense soil profiles. Locations having loose and soft soil profiles tend to damp down the motion. For a given earthquake considerable variation in the distribution of the shaking in Colombo area is demonstrated. The locations which have a possibility of undergoing soil liquefaction have been identified.

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