Evaluation of Liquefaction Potential of Western and Eastern Coastal Areas in Sri Lanka

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***ABSTRACT*:** There has been an increasing concern on earthquake related disasters in Sri Lanka after 2004 tsunami. It is partly due to the fact that that most of the important structures in Sri Lanka are founded on loose sandy soils along the coastal areas. During a strong earthquake, there is a huge possibility that these loose sand deposits may liquefy causing significant damage to the structures founded on them. In addition, some of the coastal areas suffer frequent floods, which may magnify the damage due to liquefaction. Standard Penetration Test (SPT) and Cone Penetration Test (CPT) are widely used for the site specific evaluation of liquefaction potential of sandy soils. In this paper, results of the analysis of liquefaction potential based on SPT resistance values are presented. Here, 46 bore holes from Colombo and east- coast were analyzed, and the liquefaction potential was evaluated by means of a factor of safety against different earthquake magnitudes and different ground water levels. From the analysis results, liquefiable areas and the depths of liquefiable areas were identified. It was observed from the analysis of 24 boreholes in Colombo area that, 3-13 m depths from ground surface are liquefiable during a 6.5 magnitude earthquake, while on average 4-10 m depths are liquefiable in Batticaloa, Mutur, and Ampara areas in the east coast under normal ground water conditions.

KEYWORDS: Standard Penetration Test, Cyclic stress ratio

1. INTRODUCTION

Liquefaction is a phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking or other rapid loading. Liquefaction denotes a condition where a soil will undergo continued deformation at a constant low residual stress or with low residual resistance, due to the build-up and maintenance of high pore water pressure, which reduce the effective confining pressure to a very low value [3]. Steven [6] suggested that liquefaction occurs in saturated cohesionless soils under undrained conditions. Liquefaction has been responsible for tremendous amount of damage in historical earthquake around the world.

Damage caused by liquefaction is so vast that repairing of structures on liquefied ground is very difficult and costly. Earlier experimental attempts to study the liquefaction behavior of soils are dated back to 1966 where Seed and Lee (1966) conducted a series of undrained cyclic tri-axial tests on saturated sand and reported that the onset of liquefaction was primarily governed by the relative density of sand, the confining pressure, stress or strain amplitude and the number of cycles. Since then, extensive studies on liquefaction has been carried out throughout the world.

In Sri Lanka, there is high risk of earthquakes in near future, as a result of the formation of new fault line. Therefore, it's worthwhile to investigate the liquefaction potential of sand deposits in Sri Lanka and identify the nature of the threat. In this paper, liquefaction potential of sand deposits in different part of Sri Lanka has been evaluated by means of a factor of safety against liquefaction for different earthquake magnitudes and different ground water levels based on corrected SPT $(N1)_{60}$-values. Finally, the liquefiable areas and critical liquefiable depths have been identified for earthquake magnitude of 6.5, under different ground water levels.

2. METHODOLOGY

The "Simplified procedure" originally developed by Seed and Idriss (1971, 1982) with subsequent refinement by Seed. et. Al. (1985) was used for the assessment of liquefaction potential of sand deposits in Sri Lanka. This procedure essentially compares the cyclic resistance ratio (CRR) at a given depth with the earthquake-induced cyclic stress ratio (CSR) at that depth from specified design earthquake [7].

2.1 Evaluation of cyclic stress ratio (CSR)

Seed and Idriss (1971) formulated the following equation for calculation of the Cyclic Stress Ratio (CSR) induced in the soil by the design earthquake [7]:

$$(\tau_{cyc}/\sigma'_{vo}) = 0.65(a_{max}/g)\,(\sigma_{vo}/\sigma'_{vo})\,r_d \qquad (1)$$

where, a_{max}= peak horizontal ground acceleration generated by the earthquake, g = acceleration of gravity, σ_{vo}=initial vertical total stress, σ'_{vo}=initial vertical effective stress, r_d=stress reduction factor.

Seed and Idriss (1971) introduced the stress reduction coefficient rd as a parameter describing the ratio of cyclic stresses for a flexible soil column to the cyclic stresses for a rigid soil column. They obtained values of rd for a range of earthquake ground motions and soil profiles having sand in the upper 15m and suggested an average curve for use as a function of depth. The average curve, which was extended only to a depth of about 12 m, was intended for all earthquake magnitudes and for all profiles [4]. The r_d versus depth curve developed by Seed and Idriss (1971) with added mean value lines (after Youd and Idriss, 1997) is shown in Figure 1 [7].

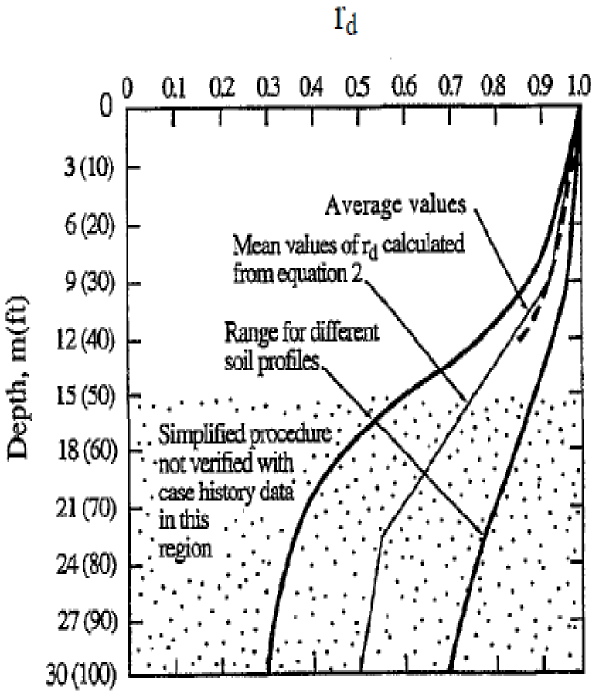

Figure 1: r_d versus depth curve (after Youd and Idriss, 1997)

2.2 Evaluation of cyclic resistance ratio (CRR)/ cyclic stress ratio (CSR) to cause liquefaction

Values of Cyclic Resistance Ratio (CRR) were originally established from empirical correlations using extensive databases for sites that did or did not liquefy during past earthquakes where values of $(N_1)_{60}$ could be correlated with liquefied strata [5]. Baseline chart defining values of CRR as a function of $(N_1)_{60}$ for earthquake magnitude of 7.5 (after Seed. et. al. 1985) is shown in Figure 2[1].

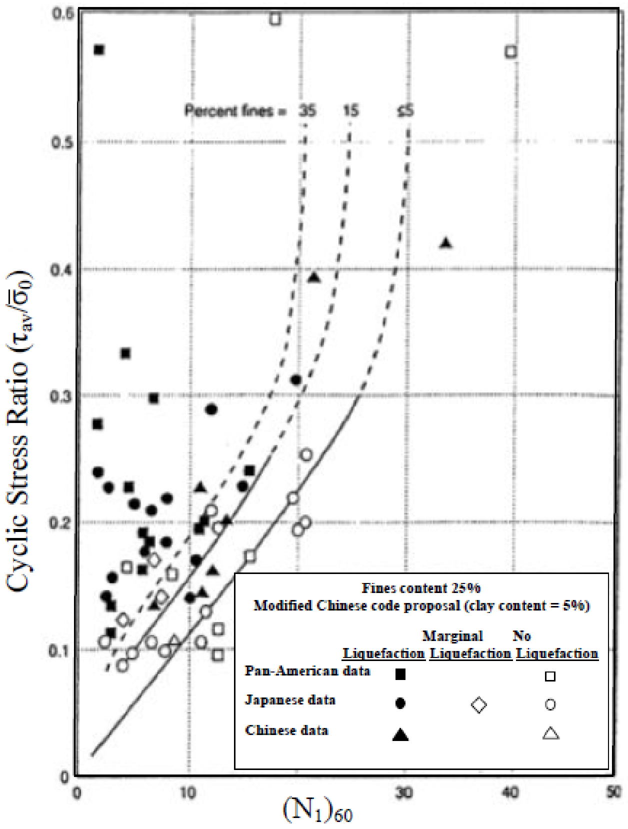

Figure 2: Relationship between CSR causing liquefaction (CRR) and $(N1)_{60}$ values for granular soils for M =7.5 (after Seed. et. al. 1985)

In Figure 2, $(N_1)_{60}$ is the SPT blow count normalized to an over burden pressure of approximately 100kPa and a hammer energy ratio or a hammer efficiency of 60% [7]. Here the curves were developed for granular soils with the fines content of 5% or less, 15%, and 35% as shown in Figure 2[1].

2.3 Magnitude scaling factor, MSF

The magnitude scaling factor, MSF, has been used to adjust the induced CSR during an earthquake of magnitude M by using the CSR for an earthquake magnitude, M = 7.5 The MSF is thus defined as [4]:

$$MSF = CSR_M / CSR_{M=7.5} \qquad (2)$$

Thus, MSF provides an approximate representation of the effects of shaking duration or equivalent number of stress cycles. Values of magnitude scaling factors were derived by combining: (1) correlations of the number of equivalent uniform cycles versus earthquake magnitude, and (2) laboratory-based relations between the cyclic stress ratios required to cause liquefaction and the number of uniform stress cycles [4]. Magnitude scaling factor, MSF, values proposed by various investigators (reproduced from Youd and Noble 1997a) is shown in Figure 3 [7].

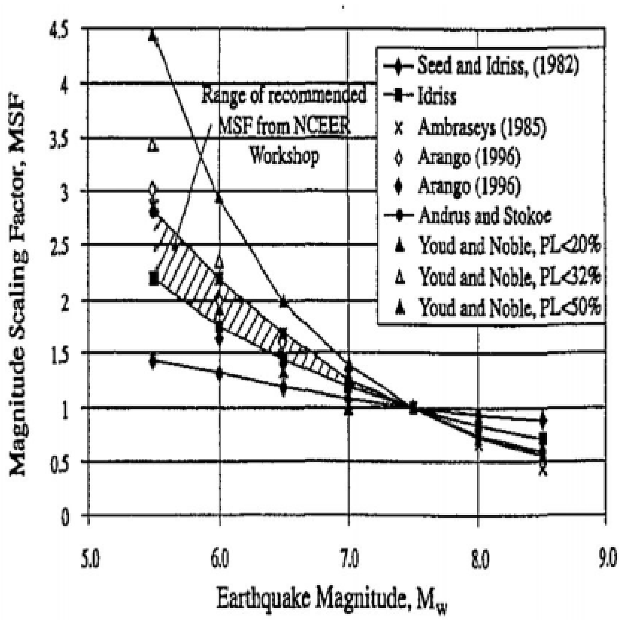

Figure 3: Magnitude Scaling Factors, derived by various investigators (reproduced from Youd and Noble 1997a) [7].

In this paper magnitude scaling factor, MSF, values proposed by Arango (1996) was used to evaluate the liquefaction potential. According to Arango (1996), the magnitude scaling factor of 1.7 was used for an earthquake of magnitude 6.5 [4].

2.4 Evaluating Factor of Safety

When the values of CRR and CSR once established for a stratum at a given depth, factor of safety against liquefaction should be calculated. The factor of safety against liquefaction is defined as [1]:

$$FOS = CRR/CSR \qquad (3)$$

3. RESULTS AND DISCUSSION

In this research, 46 numbers of boreholes from eastern and western coastal areas of Sri Lanka were analyzed. The number of boreholes from different part of Sri Lanka is given in Table 1.

Table 1: No of boreholes from different locations

Location	No of boreholes
Batticaloa	10
Mutur	09
Ampara	03
Colombo	24

All the above borehole investigations were done by National Building Research Organization (NBRO) of Sri Lanka. Boreholes with loose sand layers were considered in the analysis. In addition sand layers with SPT values greater than 50 weren't considered as liquefiable layers. So they were not included in the analysis. From these borehole investigations, well graded sand (SW), poorly graded sand (SP), silty sand (SM), and clayey sand (SC) were observed in Batticaloa, Mutur, Ampara, and Colombo. The percentage of fine contents of SP and SW was taken as 5% and that of SM and SC was taken as 35%.

According to the analysis results; sand deposits from eastern part of Srilanka are more liquefiable than other areas with respect to the average factor of safety of 1.2. Comparatively, the probability of liquefaction is higher at Batticaloa, Mutur, and Ampara for an earthquake of magnitude 6.5. Also some places in Colombo metropolitan area are liquefiable at an earthquake magnitude of 6.5. The liquefiable depths for an earthquake magnitude of 6.5 under different ground water level at selected locations are given in Table 2 and

Table **3**.

When comparing the liquefaction potential of sand deposits, it is clear that the factor of safety decreases with increase in ground water level. Also the probability of liquefaction increases with increase in flood level. Some of the most critical analysis results are given in Figure 4 through 7. Here the factor of safety verses depth graph is plotted for different ground water levels. The average liquefiable depths under earthquake magnitude of 6.5 at Batticaloa, Mutur, Ampara, and Colombo, have marked in Figure 8.

Table 2: Liquefiable depths at selected locations for existing ground water level and ground water level 0 m and 1 m above ground surface

Location	Liquefiable depths (m) below existing ground (For M=6.5)		
	Ground water level		
	Existing	Above ground surface	
		0 m	1 m
Iruthayapuram	None	1	1,2,4
Kathankudiya	3	3	3
Lagoon	3-5	2-6	2-6
Lagoon 2	1-2	1-2	1-2
Batticaloa	4-5	1-5	1-5
Batticaloa 2	3	1-4	1-4
Neelapola	4-5	4-6	1,2,4-6
Pachainoor	4-10	4-10	1-10
Pachainoor 2	8,12 -16	1,2,4-8 ,11-16	1,2,4-8 ,11-16
Pachainoor 3	5-12	1,4-12	1-12
Periyalam	1	1	1
Ganganipuram	3-8	3-8	1,3-8
Palatopur	4-8	1-8	1-8
Ampara	5	2-5	1-5
Ampara 2	2	2-4	1-4

Colombo 3- 1	10,12	10-12	10-12
Colombo 3- 2	3	3,4	3-5
Colombo 3- 3	5, 7	5, 7	5-9
Colombo 3- 4	8-9,11	3,8-12	3,8-13
Colombo 3- 5	9-11	2,8-11	1,2, 8-11

Table 3: Liquefiable depths at selected locations for existing ground water level and ground water level 2 m, 3 m, 4 m, and 5 m above ground surface

Location	Liquefiable depths (m) below existing ground (For M=6.5)			
	Ground water level above ground surface			
	2 m	3 m	4 m	5 m
Iruthayapuram	1,2,4	1-4	1-4	1-4
Kathankudiya	3	1,3	1-3	1-3
Lagoon	2-6	2-6	2-6	2-6
Lagoon 2	1-2	1-2	1-2	1-2
Batticaloa	1-5	1-5	1-5	1-5
Batticaloa 2	1-5	1-5	1-5	1-5
Neelapola	1 -6	1 -6	1 -6	1 -6
Pachainoor	1-10	1-10	1-10	1-10
Pachainoor 2	1,2, 4-8, 11-16	1,2, 4-8, 11-16	1,2, 4-8, 11-16	1,2, 4-8, 11-16
Pachainoor 3	1-12	1-12	1-12	1-12
Periyalam	1	1,4	1,4,6	1,4,6,7
Ganganipuram	1 -8	1 -8	1 -8	1 -8
Palatopur	1-8	1-8	1-8	1-8
Ampara	1-6	1-6	1-6	1-6
Ampara 2	1-4	1-4	1-4	1-4
Colombo 3- 1	10-12	10-12	10-12	10-12
Colombo 3- 2	3-5,8	3-5,8	3-6,8	3-6,8
Colombo 3- 3	5-9	5-9	5-9	4-9
Colombo 3- 4	3-4, 8-13	3-5, 8-13	3-5, 8-13	3-5 ,8-13
Colombo 3- 5	1,2, 8-11	1,2, 8-11	1-12	1,2, 8-11

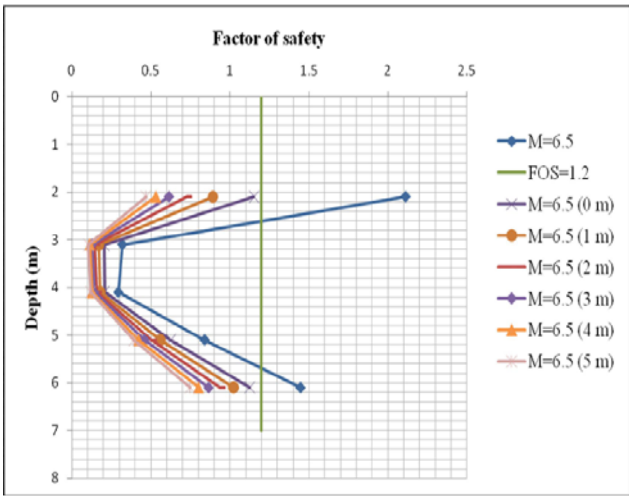

Figure 4: Factor of safety versus depth graph at Lagoon (Batticaloa)

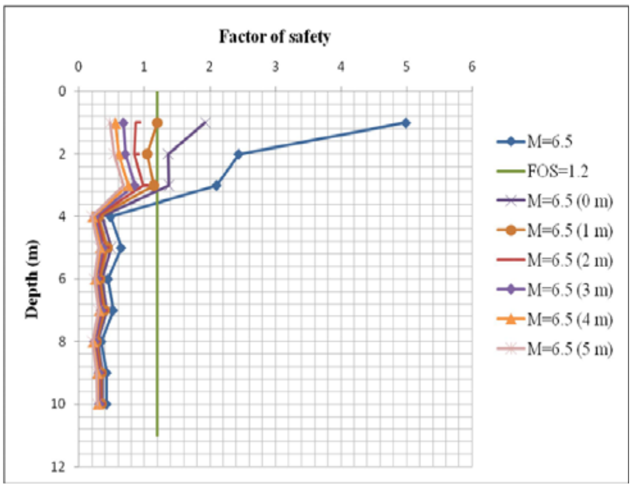

Figure 5: Factor of safety versus depth graph at Pachainoor (Mutur)

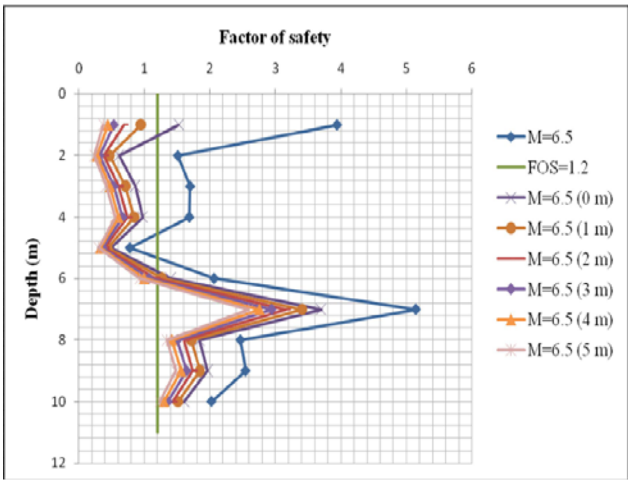

Figure 6: Factor of safety versus depth graph at Ampara

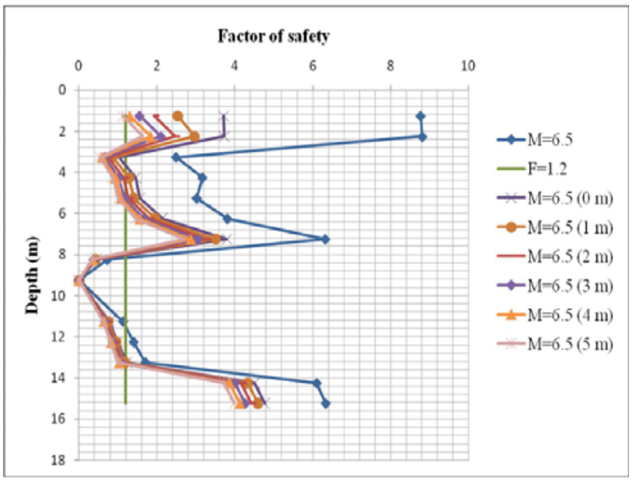

Figure 7: Factor of safety versus depth graph at Colombo metropolitan

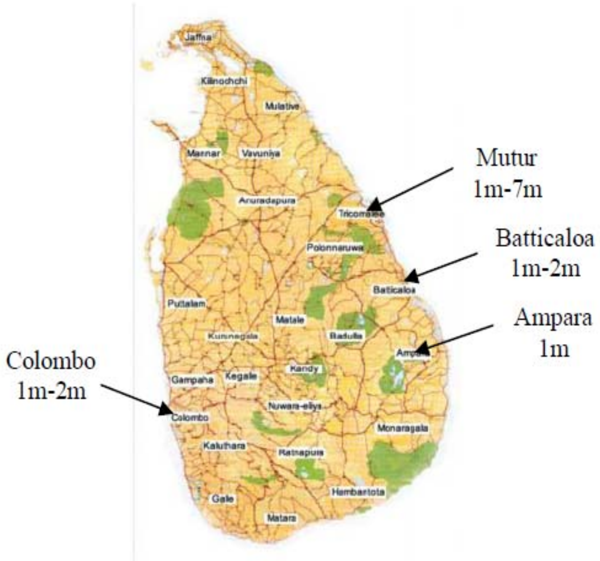

Figure 8: Average thickness of liquefiable layer around Batticaloa, Mutur, Ampara, and Colombo under existing ground water level

4. CONCLUSION

It was observed from the analysis of 46 boreholes, that, under existing ground water conditions, 3-13 m depths from ground surface are liquefiable in Colombo area during a 6.5 magnitude earthquake, while on average 4-10 m depths are liquefiable in Batticaloa, Mutur, and Ampara areas in the east coast. Also the factor of safety decreases with increase in earthquake magnitude.

When the ground water level is 2 m above the existing ground surface, it can be considered at an average flood scenario, the liquefaction potential increases on average by 75% in the Colombo area.

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