VARIATION OF CARRYING CAPACITY OF PILE FOUNDATIONS DUE TO NEWLY FORMING EARTHQUAKES

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ABSTRACT

Pile foundations are used when the structure is subjected to higher loads such as high-rise building, flyovers, etc. or in a situation such that the soil condition is not supportive for heavy loads (i.e., presence of clayey soil). Pile foundation requirements depend on soil conditions as well as lithospheric characteristics of the tectonic plate that holds the construction site, among other factors. Geographical location of Sri Lanka is well away from the borders of the Indo-Australian tectonic plate; therefore, tremors and significant scale earthquakes have not been often reported in comparison to the peripheral countries locate at the plate boarders. Moreover, the most of the historically reported significant earthquakes affected Sri Lanka showed inter-plate tremor characteristics with a diluted impact on the structure. Because of these reasons seismic retrofitting techniques are not widely popular in Sri Lankan structures as well as the piling treatments as part thereof. However, in 2012 April, a series of tremors reported in the Indian Ocean closed to Sri Lanka indicating intra-plate characteristics. Furthermore, several minor tremors have been regularly reported in the South, Eastern and Central parts of the country ever since. In light of these new developments, this paper investigates the current standards and practices of piling used in for structures and construction projects in Sri Lanka and suggest possible update of piling practices reflecting the necessity of such adaptation.

***Key words*:** Pile foundation, Tremors in Sri Lanka, Intra-plate earthquake, Piling Standards, liquefaction

1. INTRODUCTION

Main function of a pile foundation is to distribute the loads in a structure to the earth. Pile foundations are used when the structure is subjected to higher loads such as high-rise building, flyovers, etc. or in a situation such that the soil condition is not supportive for heavy loads (i.e., presence of clayey soil). Moreover, the conditions of the soil are geospatially varied hence require subjective piling treatments depending on the local conditions (primarily the construction site soil) and large scale conditions (mainly the lithospheric characteristics of the tectonic plate that holds the construction site at large). Geographical location of Sri Lanka is well away from the borders of the Indo-Australian tectonic plate; therefore, tremors and significant scale earthquakes have not been often reported in comparison to the peripheral countries locate at the boarders of this tectonic plate. In effect of this sheer central location within the plate, Sri Lankan constructions and large structures have been fortunate to assume a stable and supportive ground that demand lesser pile requirements. Moreover, the most of the historically reported significant earthquakes affected Sri Lanka showed inter-plate tremor characteristics with a diluted impact on the structure. Because of these reasons seismic retrofitting techniques are not widely popular in Sri Lankan structures as well as the piling treatments as part thereof.

In April 2012, a series of tremors reported in the Indian Ocean closed to Sri Lanka indicating intra-plate characteristics. Furthermore, several minor tremors have been regularly reported in the South, Eastern and Central parts of the country ever since. Although a catastrophic tectonic plate break within the Indo-Australian plate dividing it into two can be hardly expected in the near future, intra-plate tremors linking a pathway within the plate can be an early sign of extra pressure underneath trying to release the pent up stress. These stresses can be due to various factors such as internal stress fields caused by inter-plate movements, sedimentary loading or unloading, or significant changes in fault planes within the tectonic plate. Although it may be too early to predict conclusive suggestions on Indo-Australian tectonic deformations, which require further research, it can be worthwhile to investigate the possible policy implications of the recently noted earth tremors in Sri Lanka for its construction industry.

This paper investigates the current standards and practices of piling used for structures and construction projects in Sri Lanka. It uses a positional approach by discussing the problem space in two folds: the need of new standards for piling incorporating the factors of possible frequent earth activities into the pile foundations; the possible impact of these latest developments in the country's geo-plate on the existing structures that have already been completed assuming low risk of intra-plate earthquakes. The paper initiates the much needed discussion on the topic of piling for changing conditions that Sri Lanka is subjected to as observed during the recent past. The policy implications derived in this paper would help the researchers and industrial practitioners to plan for the possible scenario of frequent earth tremors mitigating the catastrophes through adequate pile foundations.

2. BACKGROUND AND RELATED WORK

Pile foundations are used to distribute the load to the bed rock when the structure having higher loads or the existing load capacity of soil is low (when clayey soil is present). In Sri Lanka, often, low to medium rise buildings are built with less than 10 stories. If the existing soil condition is present with hard laterite then the structure can go up to 4 stories without having a pile foundation, yet the typical and advisable suggestion is to have a pile foundation if (>3) stories. Because of Sri Lanka is considered as a country subjected to intra-plate type earthquake risks, it has been a common practice in design to ignore the dynamic loading due to earthquakes. Before 1989 intra-plate regions were considered as safe zones for earthquakes. But in 1989, New Castle, Australia experienced 5.6 Richter magnitude earthquake changing the conventional thinking that the intra-plate conditions are safe for earthquakes [1].

2.1. Present Practices in Sri Lanka

The British Standard is commonly used in Sri Lanka for structural constructions. BS 8004 is referred to the foundation specifications. Institute for Construction Training and Development (ICTAD) has provided some guidelines for design. ICTAD/DEV/15 and ICTAD/DEV/16 are used to get an overall idea about pile foundations. However, they lack the due consideration of dynamic loading requirements; hence, do not sufficiently incorporate with the latest development of intra-plate seismic characteristics as the country is being subjected to.
Most of other countries having codes for seismic loading are mainly concerning to resist inertia force induce by earthquakes. When the failures in pile foundations due to earthquakes are examined most of the cases were occurred due to a large inertia force. However, that does not explain the pile failures in deep positions because those have occurred when the soil gets deformed in the pile foundation. Hence, both inertia and kinematic interactions must be considered as a remedy.

2.2. Why should Sri Lanka Consider Earthquake Loading

In 2012 April, a series of tremors reported in the Indian Ocean closed to Sri Lanka indicating intra-plate characteristics. Furthermore, several minor tremors have been regularly reported in the South, Eastern and Central parts of the country ever since. On 11th April 2012, twin tremors shocked the Indian Ocean with magnitudes of 8.7 & 8.2 [2] due to the different speeds of India and Australia moving in the Indo–Australian plate (Figure. 1 & 2). With these tremors geologists are confident with their prediction of plate breaking. Although the plate breaking is a hard and slow phenomena, in the process pent up stresses can be released. If this happens the geological characteristics of Sri Lanka can change; attention to seismic activities should be high.

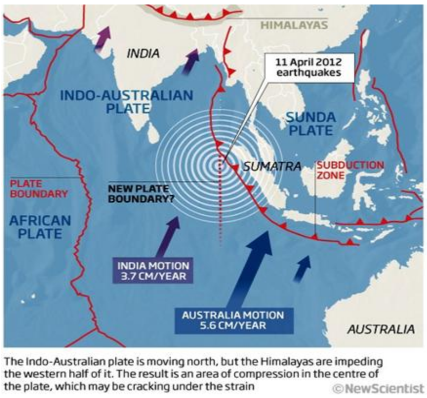

Figure 1: Tectonic movements - India and Australia with different speeds - source: New Scientist [3]

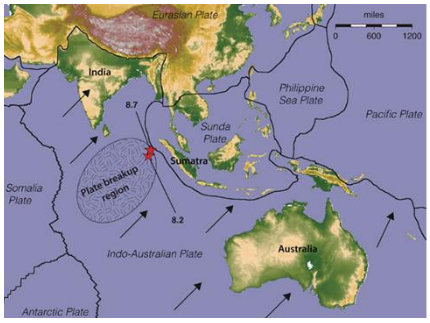

Figure 2: Plate breaking region in Indo-Australian plate - source: University of Utah [2]

If lateral loads are present, failure types will be different in a pile foundation. Soil liquefaction, lateral spreading (rotational and subsidence), flow failure, ground oscillation, loss of bearing capacity are some failure types commonly occurs in pile foundations

3. ANALYSIS MODEL

We take lateral spreading and liquefaction as the resulting affects of the potential earthquakes. Limit equilibrium analysis can be used to carry out bending moment and shear force in piles in laterally spreading soils. Figure 3 shows the schematic diagram of a single pile configuration spanning between liquefiable and dense soil layers (cross section) subject to deformation due to seismic movements (lateral spreading).

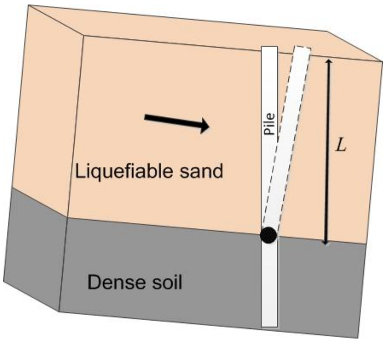

Figure 3: Analytical Model - Single pile configuration in lateral spreading soil

Figure 4 shows the free body diagram of a pile in lateral spreading soil.

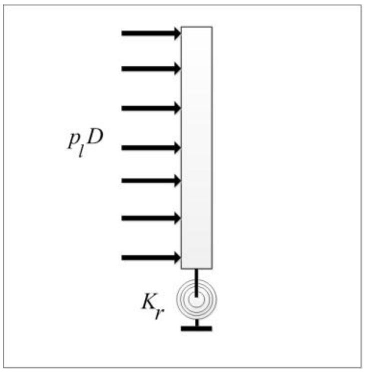

Figure 4: Free body diagram of a pile in lateral spreading soil

The force applied by the liquefied soil on the pile can be calculated by using equation (01).

$$F_p = p_l DL \qquad (01)$$

Maximum bending moment will occur at the soil interface and can be obtained using the equation (02).

$$M_{\max} = \tfrac{1}{2} p_l DL^2 \qquad (02)$$

If we consider the resisting area of the pile cap is A_C then that will increase the maximum bending moment due to laterally spreading of soil given by the equation (03).

$$M_{\max} = \tfrac{1}{2} p_l L(DL + 2A_C) \qquad (03)$$

Various research studies have estimated the value of p_l to be between 8kPa and 20kPa based on centrifuge test. If we can find the rotational stiffness (K_r) for the denser soil layer then we can find the lateral displacement at the top of the pile due to liquefaction [4]. It is important to note that K_r is a parameter subject to soil conditions and can substantially vary from piling location to location. Lateral displacement of the pile due to liquefaction can be found by using the equation (4).

$$\delta_{top} = \left(\frac{M_{\max}}{K_r}\right)L \qquad (04)$$

4. DATA AND ANALYSIS

For this analysis to check the risk level of the pile foundation when the liquefaction occur due to the lateral load similar to an earthquake scenario, piling data from a recently completed project have been used. *Upparu Bridge* [5] was completed and opened in October, 2011. A brief analysis on the piling of this bridge is used here as a case example for the analysis. Due to the limited space, only a single pile belongs to the pier 1 of the bridge is used for this analysis.

In brief: in this pile position the first 9 m layer can be taken as fine clayey sand whereas the next 9 m layer can be taken as fine to medium clayey sand. Up to 40 m depth from the earth surface can be taken as fine to coarse clayey sand (SPT > 70). Pile diameter is 1,500 mm and pile length is 39.3 m [5].

When designing this pile foundation the project engineers have considered a lateral capacity due to certain types of loads. These include: horizontal forces due to water current, log impact, debris and wind [5]. These were considered as transverse loads. Tractive force and temperature forces were considered as longitudinal forces. Both these transverse and longitudinal forces were considered to calculate the applied horizontal force [5]. Under these considerations, the project was completed with the assumption of applied horizontal force per pile as 217.3 kN, i.e., $F_p^{\#}$; and the allowable horizontal load capacity per pile 2,86 kN [5], i.e., F_p^{*}. However, it is noteworthy that these forces do not include lateral forces due to liquefaction. Hence, we define the minimum required effective horizontal load capacity ability F_p^{*} that is required to withstand seismic impact as in the equation (5), where $0 \leq \alpha \leq 1$. For this pile analysis α=1, based on the project parameters.

$$F_p^* = \alpha F_p + F_p^\# \qquad (05)$$

For this analysis on seismic impact, four test cases of combined liquefaction scenarios were defined as in Table 1. These cases represent the minimum and maximum p_l conditions. The calculations according to the analysis models are shown in Table 2.

Table 1: Scenario definitions for pile analysis

Scenario	Description (parameters)
C_1	First soil layer liquefies, p_l = 8 kPa
C_2	First and Second layers liquefy, p_l = 8 kPa
C_3	First soil layer liquefies, p_l = 20 kPa
C_4	First and Second layers liquefy, p_l = 20 kPa

Table 2: Analysis results for the pile combinations

	C_1	C_2	C_3	C_4
p_l (kPa)	8	8	20	20
D (m)	1.5	1.5	1.5	1.5
L (m)	9	18	9	18
F_p (kN)	108	216	270	540
F_p^* (kN)	325.3	433.3	487.3	757.3
M_{max} (kNm)	486	1944	1215	4860

The minimum required applicable lateral load to withstand general earthquake impact on the pile is higher than the actual value for all four cases. Fig. 5 shows the overhead load (F_p^*-286) that could exert on the pile for each scenario, as per the present piling practices used in Sri Lanka.

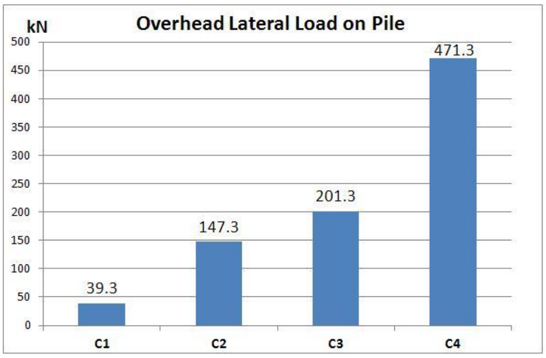

Figure 5: Additional lateral force on the pile due to liquefaction

5. CONCLUSION

This study has highlighted the significance of associating the lateral load due to soil liquefaction and spreading as a result of newly forming earthquakes in the Indo-Australian tectonic plate. With the limited space the analysis is limited to a special case of lateral spreading and liquefaction due to earthquakes, and on a single pile arrangement. For multiple pile arrangements, which distribute the load at the same time increase the total applied force subject to, a suitable vector analysis on the lateral force field should be considered. Taking everything into account it is advisable to associate soil liquefaction with the piling design for future constructions in Sri Lanka to face the challenge of emerging tremors and intra-plate earthquakes. For existing structures that have already been built with traditional piling designs, suitable rectifying arrangements preventing pile deformations due to increased bending moment is advised, although such can be challenging.

This paper has presented the latest developments in Sri Lankan seismic region, a suitable analytical model and a data analysis of a case study to show the necessity of reshaping Sri Lankan piling practices to safeguard future constructions. The paper initiates the much needed research discussion about this topic and welcomes further research to benefit the country.

6. REFERENCES

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