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Parametric Study on the Settlement of Piled Raft Foundation for High-Rise Building

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Abstract: Piled raft foundation is a composite construction consisting of three elements, piles, raft and subsoil. It has been commonly used for the foundation of high rise building in recent year. The combined effect of piles and raft can reduce the maximum and differential settlement and it can lead to more economical foundation design as compare to the conventional pile foundation. This paper focus on the settlement of piled raft foundation of a high-rise building resting on sandy soil in Yangon area. The critical column load of superstructure is obtained by using ETABs software and loading consideration for superstructure is based on UBC -97. Soil type is sandy soil and the upper soil layer where the raft located is sandy silt. This study considered the type of bored pile and the allowable bearing capacity is calculated by Hansen's method, Tomlison's methods and Meyerhof's Rule of Thumb method. The simplified analysis is made by Poulos – Davis - Randolph (PDR) method to estimate the load –settlement curve and load distribution between piled and raft. The piled raft foundation is analyzed by SAFE software, in which the raft is modelled as a thin plate and the piles and soils are treated as springs. In this study, a parametric study is made on raft thickness, pile length and number of piles. The increase in raft thickness do not have much significant effect in reducing maximum and differential settlement but it is uneconomical due to increasing of moment. The maximum settlement is reduced by increasing pile length and number of piles.

Keywords: piled raft foundation; parametric study; simplified approach; load distribution; settlement.

1. INTRODUCTION

The growth of population and the scarcity of land has been needed to build many high–rise building. These building impact huge axial load to the soil through their foundations. So the foundation of high -rise building needed to design to resist the superstructure load safety and to transfer these load to the soil. Moreover, it can be effectively supported the stability of the building. In conventional design, mat and pile foundations are used to support these heavy loaded buildings [1], [2], [3]. In recent years, piled raft foundations have been commonly used as a kind of foundation for high- rise buildings. Actually, it is a combination of raft foundation and pile foundation and it is composed of three elements raft, piles and subsoil. It is mostly used where the raft foundation alone provides nearly adequate bearing capacity but it can cause settlement. In piled raft foundation, load is distributed between piles and raft, so the load from the superstructure is taken partly by raft and piles [4]. The design process of piled raft foundation is described in three stage and the load-settlement curve of piled raft has been estimated based on stiffness of members [5], [6]. There are difference techniques that have been developed for analysis of piled raft foundation. The overall settlement and differential settlement are analyzed by hybrid method in [7]. Design method and simplified analysis based on stiffness of pile group stiffness and raft stiffness have been presented by many researchers in [8], [9]. Numerical analysis is made by finite element method in which raft are modelled as a plate and piles treated as non-linear springs in [10]. Behaviour of piled raft is also analyzed with pile of different lengths subjected to horizontal and vertical loadings by using finite layer method [11]. In piled raft foundation, the performance of parameters plays an important role for the stability of foundation. Parameters of piled raft foundation are raft thickness, piles length, piles diameter, piles spacing, piles configuration and number of piles. This paper focus on the parametric study of raft thickness, piles length and number of piles and made a discussion the influence of these three parameter on the stability of foundation. In this study, firstly, parametric study is made on load distribution and found tri-linear load settlement curve by using simplified approach. Then, parametric study is made on settlement of piled raft foundation by using SAFE software and discuss the results. The rests sections are comparison of simplified analysis and software analysis and conclusion.

2. SOIL CONDITION

The type of soil in Bahan township, Yangon area is sandy soil. The groundwater table exists at 18 ft below the ground level. The underlain sand layer is covered by sandy silt layer near the surface. The layer of soil where the raft located is sandy silt. The allowable bearing capacity of subsoil below raft is 2.01 ton/ft^2 and the required bearing capacity is 2.69 ton/ft^2. Allowable capacity is nearly the required capacity but it cannot provide the satisfied bearing capacity values and can cause settlement. Piled raft foundation is suitable for this type of soil and it can improve bearing capacity and reduce the settlement. Liquefaction check must be taken for sandy soil but soil report has been proven that there is no liquefaction in the soil stratum. The allowable pile capacity is calculated by Hansen's method, Tomlison's method and Meyerhof's Rule of Thumb methods. The allowable pile bearing capacity is 500 tons at 41 m and it is about 100 tons at 12m.

3. PROPOSED SUPERSTRUCTURE

The superstructure is twenty-storeyed residential building and it is firstly analyzed by ETABs software. The overall height of the building is 63m, basement height is 3.5m, ground floor level height is 4m and typical floor height is 3m. The building is rectangular shape and its length is 43m and 23m width. Loading consideration is based on UBC-97 and the load combinations are considered as per CQHP guideline. 3D model of superstructure which is analyzed in ETABs software is shown in Figure 1.

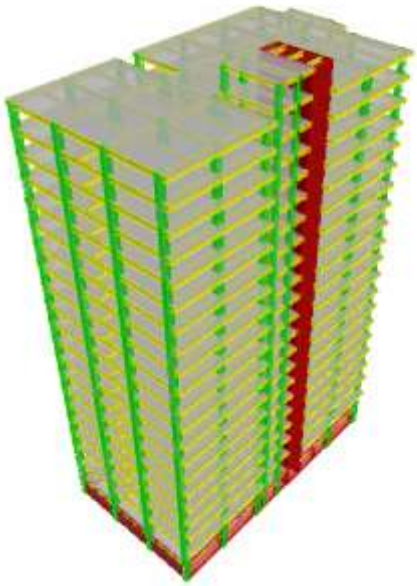

Figure 1. 3-D model of 20 storyed building

The total load of superstructure is 337.32 MN and maximum column point load is 14.508 MN.

4. MODELLING OF PILED RAFT

The philosophy of modelling of piled raft has been explained by using combined structural - geotechnical approach. To investigate the piled raft behavior, raft is modelled as a slab and piles are treated as springs. In this study, SAFE software is used for analysis of piled raft foundation. The layout of piled raft foundation in SAFE is shown in Figure 2.

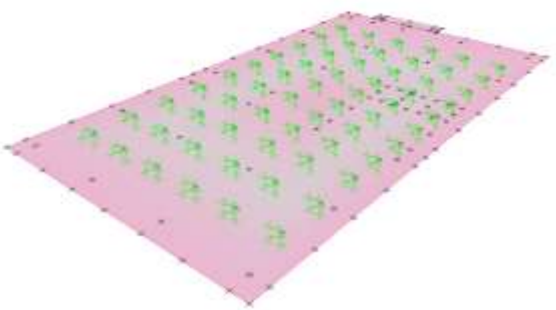

Figure 2 . Layout of piled raft foundation

5. PARAMETRIC STUDIES

Parametric studies are planned to investigate the settlement of piled raft foundation under the changes of the parameter values such as raft thickness, pile length and number of piles. In this study, three cases study were taken into consideration to analyze the piled raft behavior. The raft was modelled as a concrete element and area of piled raft is 46m x 26m. The details of three cases are as follows;

Case 1: The effect of raft thickness was analyzed in Case 1 with constant other parameters. The constant pile diameter is 1m, 67 numbers, pile spacing is 3d and constant pile length is 41m. In this case, pile raft with various raft thickness as 1.8m, 2m, 2.3m and 2.5m were analyzed to find the maximum moment and maximum and differential settlement on each thickness.

Case 2: The effect of various pile length was focus in Case 2 without changing other parameters. The constant raft thickness is 1.8m, constant 1m diameter, 67 numbers and the constant pile spacing is 3d. In Case 2, the maximum and differential settlement of piled raft foundation is observed by varying pile length such as 41m, 30m, 24m and 18m.

Case 3: Case 3 is mainly focus on the effect of number of piles by considering constant of other parameter. The constant raft thickness is 1.8m, 1m diameter and constant pile length is 41 m. In this case, the effect of maximum and differential settlement were observed with various number of piles such as 40, 60, 72 and 84. The configurations of various number of piles were shown in Figure 3.

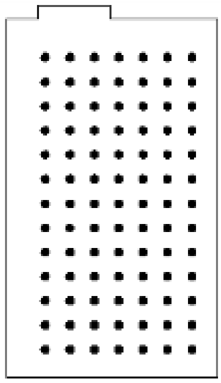

Figure 3. (a) 84 nos

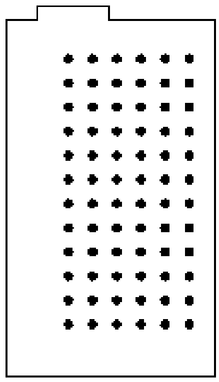

Figure 3. (b) 72 nos

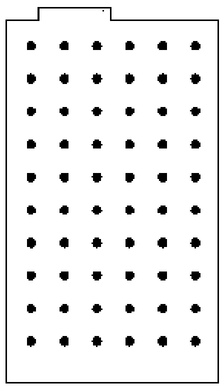

Figure 3. (c)60 nos

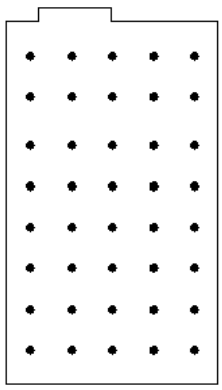

Figure 3. (d)40 nos

Figure 3. Piles location plan for Case -3

6. SIMPLIFIED ANALYSIS

Simplified approach is made by using Poulos - Davis-Randolph (PDR) method. In this method, the load – settlement relationship and load distribution between piled and raft are calculated based on the stiffness of each member. The stiffness of piled raft foundation is calculated by equation 1, where K_p is stiffness of pile group, K_r is stiffness of raft and α_{cp} is the raft-pile interaction factor.

$$K_{pr} = \frac{K_p + K_r(1 - \alpha_{cp})}{1 - \alpha_{cp}2(\frac{K_r}{K_p})} \quad (1)$$

The load sharing percent between piles and raft are calculated by equation 2, where P_r is the load carried by raft and P_t is the total applied load from the superstructure. The factor X is the the percent of load taken by raft and percentage of load carried by piles is obtained by 1- X.

$$X = \frac{P_r}{P_t} = \frac{K_r(1 - \alpha_{cp})}{K_p + K_r(1 - \alpha_{cp})} \quad (2)$$

The result of simplified analysis showed that the load distribution percent between piled and raft do not have significant changes with various raft thickness. But it was considerably effect on various pile length, the load sharing percent of piled and raft based on various pile lengths were showed in Figure 4. When increase in length, piles have been taken more percent of load because piles have more bearing capacity as increase in length.

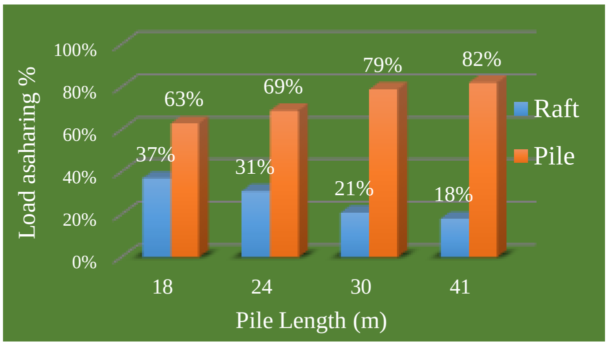

Figure 4. Load sharing (%) based on pile length

The effect of number of piles on load distribution ratio was indicated in Figure 5. It was found that the more number of piles in the group, the more percent of load can be taken by the pile group. Because the bearing capacity in the pile group is increased as increases in number in the group. But it was recognized that even the number of pile increased from 40 to 84, the load carrying percent increased about only 8 percent.

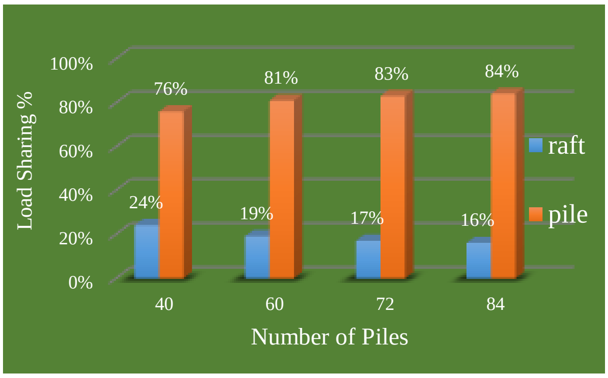

Figure 5. Load sharing (%) based on number of piles

Load – settlement curve of piled raft foundation that has been calculated by PDR method is shown in Figure 6 and Figure 7. The parameter of 1.8m raft thickness, 1m diameter ,41m pile length and 60 numbers were chosen as sampling for this load –settlement curve. By this parameter, the stiffness of raft is 580.71 MN/m and pile group stiffness is 1979.16 MN/m. The interaction factor between raft and pile group is approximated as $\alpha_{cp} = 0.2347$. This lead to the overall stiffness of the piled raft is obtained 2463.387 MN/m by equation 1. Figure 5 showed that the maximum settlement was 5.8502 mm under maximum vertical column load of 14.508 MN.

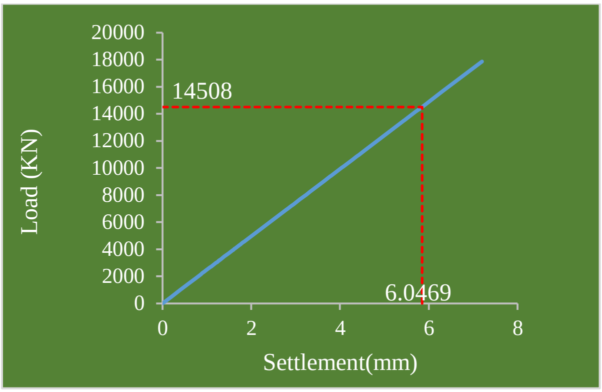

Figure 6. Load settlement curve for maximum load

The total applied load P_t at which the pile group capacity is reached its full capacity, it was calculated by equation 3, in which P_{up} is ultimate pile group capacity.

$$P_t = \frac{P_{up}}{1 - X} \quad (3)$$

The tri-linear load settlement curve calculated by PDR method is shown in Figure 7, it is showed that the total applied load of superstructure is 337.32MN and the stiffness of pile raft foundation was safety supported to this load. When total applied load further reached 928.34MN and the load – settlement curve beyond point A, the pile group capacity is fully utilized and the raft only elastic at this time.

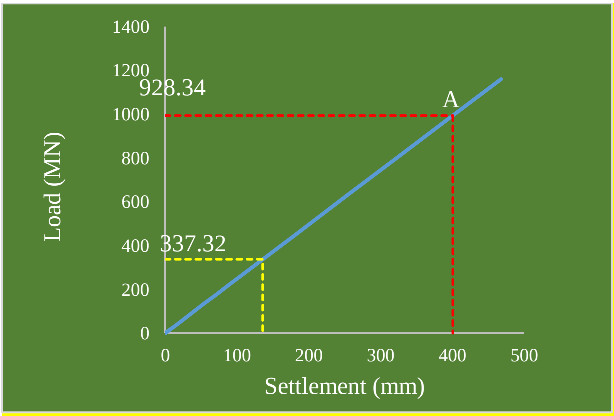

Figure 7. Tri – linear load settlement curve

The stiffness of pile raft foundation, K_{pr}, for various piles length is shown in Table 1. Where, the load Pt is the total applied load, under which the capacity of pile group reached its full capacity. Beyond this load, further applied load is supported by raft only. The value of settlement in this table is total settlement of piled raft foundation when the applied load increased to P_t and piles bearing capacity reached their ultimate limit at this time. The current applied load of superstructure in this study is 337.32 MN. Table 2 showed that the stiffness of piled raft foundation for various number of piles.

Table 1. Stiffness of piled raft for various pile length

Pile Length	αcp	Kpr	Pt	Se
m		MN/m	MN	mm
18	0.0565	1516	472	311
24	0.0759	1892	899	470
30	0.1495	2370	1017	429
41	0.2412	2488	1021	410

Table 2. Stiffness of piled raft for various number of piles

Pile number	αcp	Kpr	Pt	Se
No		MN/m	MN	mm
40	0.1309	2116.0	658.0	311.0
60	0.2176	2399.0	928.0	386.0
72	0.2566	2549.0	1087.0	426.0
84	0.2895	2687.0	1245.0	463.0

7. RESULT OF SOFTWARE ANALYSIS

Analysis results of the effect of various parameters in piled raft foundation by using SAFEs software are described detail in the following section.

7.1 Effect of raft thickness

The result of Case 1 analysis is shown in Figure 8, which indicate that the variation of maximum settlement with respect to various raft thickness. It can be conclude that the maximum settlement decreases when increase in raft thickness. Although raft thickness increase from 1.8m to 2.5m, settlement reduce only 0.44894 mm. The influence of raft thickness on differential settlement is shown in Figure 9. The increasing raft thickness is slightly effective in reducing differential settlement.

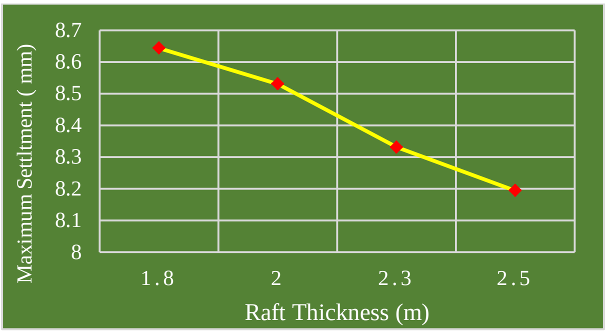

Figure 8. Effect of raft thickness on maximum settlement

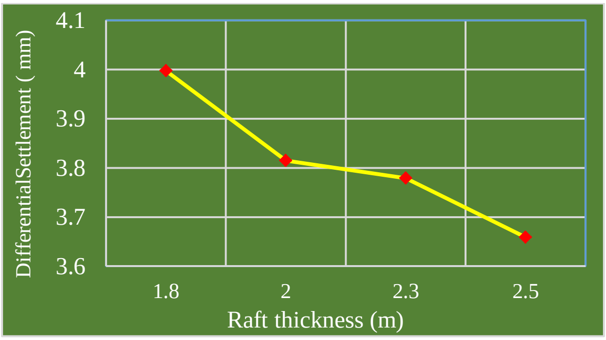

Figure 8. Effect of raft thickness on differential settlement

The influence of raft thickness on the raft moment is described in Figure 10. There was a significant increase in moment as the raft thickness increase from 1.8m to 2.5m. Increasing moment lead to more steel area and it can cause uneconomical design. From above reason, it is shown that the increase in raft thickness have a little effect on maximum and differential settlement. But it is uneconomical because there is increase in raft moment , require more steel area and increase project cost.

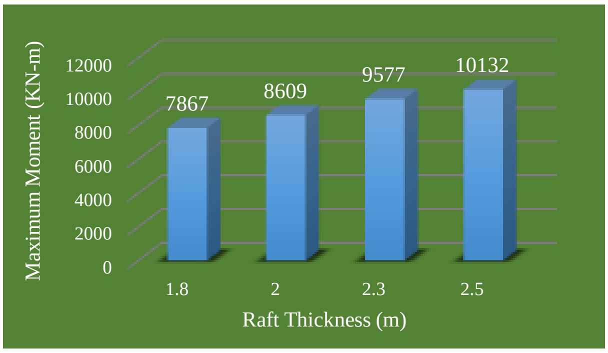

Figure 10. Effect of raft thickness on maximum moment.

7.2 Effect of pile length

The variation of settlements due to different pile length are shown in Figure 11 and Figure 12. The increase in pile length greatly reduced maximum settlement from 13.4125 mm to 8.64325 mm. As increase in length, the bearing capacity of pile is increase so it can more withsand the load over it and can reduce settlement. The value of differential settlement is slightly reduced when pile length increased from 12m to 41m. It can be summarized that maximum settlement was greatly affected by changing pile length whereas differential settlement has a little effect.

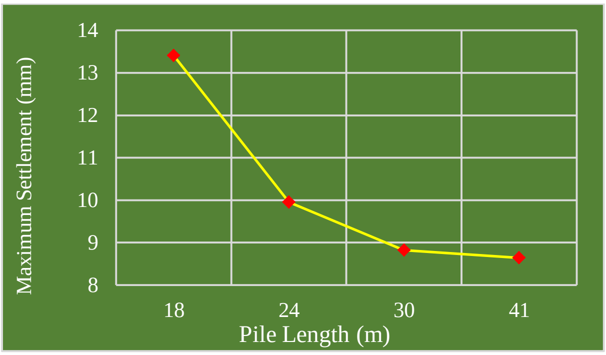

Figure 11. Effect of pile length on maximum settlement

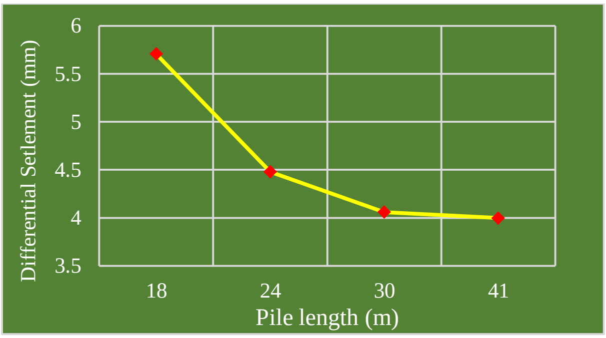

Figure 12. Effect of pile length on differential settlement

7.3 Effect of number of piles

The result of Case 3 analysis has shown in Figure 13 and Figure 14. It was showed that the increase in number of piles has a greatly effect on maximum settlement. The value of maximum settlement reduced from 11.1331mm to 7.70851 mm when the number of piles increase from 40 to 84. Bearing capacity of pile group is improved with increase in number in the group, so it can reduce maximum settlement. There was a little decrease in differential settlement with various number of piles. So, the number of piles more reduced maximum setlement than differential settlement. It was found that maximum settlement has greatly effect by increasing number of piles. But when it reached a certain limit, as 72 in this research, there was a slight effect on both settlement beyond this limit.

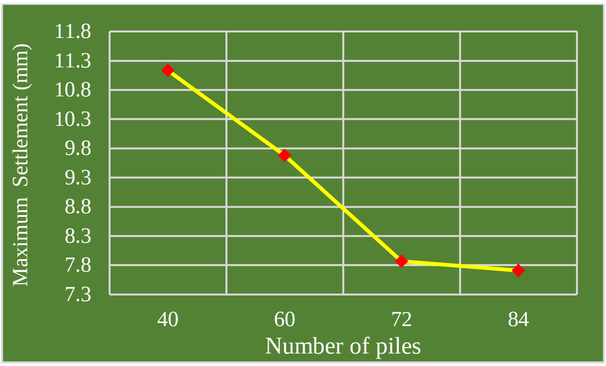

Figure 13. Effect of number of piles on maximum settlement

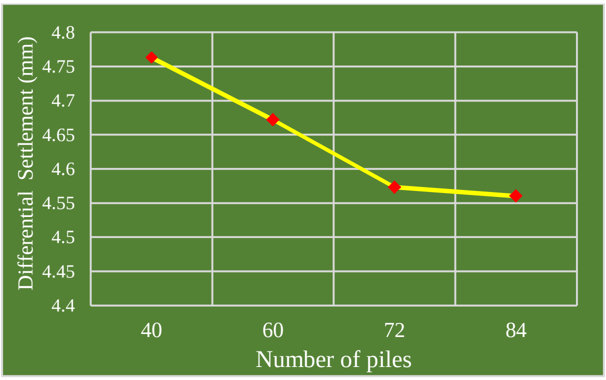

Figure 14. Effect of number of piles on differential settlement

8. COMPARISON OF SIMPLIFIED AND SOFTWARE ANALYSIS

In this study, simplified analysis is made by PDR method and this method is depended on stiffness of each member. Load distribution percent and settlement is calculated based on piles group stiffness, raft stiffness, soil stiffness and piled raft stiffness. In this method, soil stiffness is mainly depended on deformation parameter such as modulus of elasticity Es and poisson's ratio µ. Software analysis is made by using SAFE program, in which piles spring stiffness and soil subgrade modulus is based on baring capacity. Bearing capacity in these method is mainly depended on strength parameter of soil such as c and Ø. Piles spring stiffness are obtained from bearing capacity/settlement and allowable settlement is 10mm. As a results, settlement values in simplified analysis is less than as compared to software analysis. The comparison of settlement by these two methods analysis on various pile length and number of piles are shown in Figure 15 and Figure 16. So, it was recognized that the analysis based on bearing capacity gives more settlement values as compare to the analysis based on stiffness. Simplified analysis is suitable for primary analysis only and more detail analysis should be maken by software analysis.

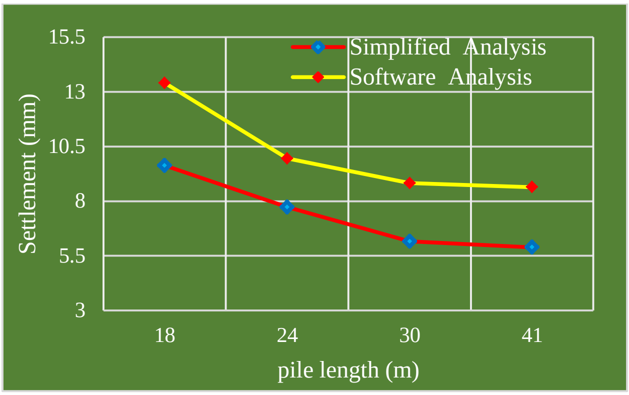

Figure 15. Comparison of settlement result from two analysis base on pile length

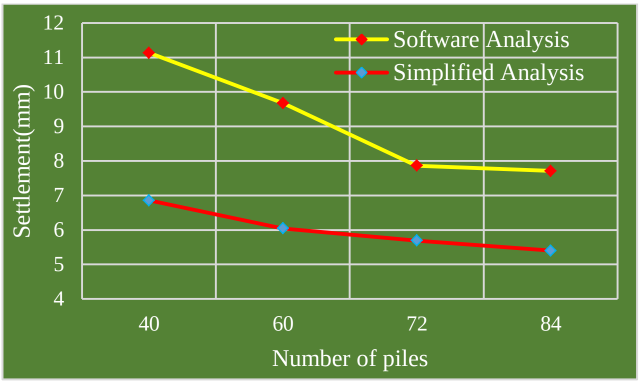

Figure 16. Comparison of settlement result from two analysis based on number of piles

9. CONCLUSION

Parametric study is made on three parameters by using finite element method and simplified analysis method. This study has found that the increase in raft thickness reduced maximum and differential settlement. But it has a slightly effect on both settlements and it is uneconomical due to increase in moment and stel area. The role of pile length is important in the piled raft foundation. Increasing pile length reduced both maximum and differential settlement. Especially, maximum settlement has a greater effect than differential settlement. The number of pile also has an important role in the performance of piled raft foundation. The increasing number of piles greatly reduced maximum settlement but it has not the great effect beyond the certain number. It was found that increase in pile length has more significant effect than increase in number of piles and increasing raft thickness, so pile length is the most important parameter in piled raft foundation. Software analysis give more settlement than simplified analysis. So, simplified analysis is suitable for primary analysis and software analysis give more satisfied result for detail analysis.

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