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RESPONSE OF PILED RAFT FOUNDATION ON SOFT CLAY UNDER SEISMIC LOAD

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ABSTRACT

A number of researchers has extensively investigated the vertical load bearing mechanism of piled raft foundation, by applying elasticity theory and finite element method. The study on the load bearing mechanism under horizontal loading or during earthquakes, however, is very limited. This is partially because piled raft foundations are considered as raft foundations in the current design practice. Since the behavior of a piled raft foundation during earthquakes is considered fairly complex due to dynamic interaction among a raft, piles and a soil, the design procedure should include the effect of this mechanism in an appropriate manner. In other hands, the behavior of piled raft foundations under earthquake loading is an important factor affecting the performance of structures. Observations from past earthquakes have shown that piles in firm soils generally perform well, while those installed in soft or liquefiable soils are more susceptible to problems arising from ground amplification or excessive soil movements. This research comprises three major components: (1) Numerical modeling of piled raft foundation using finite element program (ABAQUSE), (2) verification of numerical program with dynamic centrifuge tests on clay pile-raft systems, and (3) performing parametric studies. The acceleration predicted by numerical method is well matched with the measured acceleration in a centrifuge test when simulating a piled raft foundation.

INTRODUCTION

In order to build a structure, it is required to use a foundation to transfer applied load to soil. As well as load transfer function, foundations should be designed in a way that produce settlements, including uniform and non-uniform settlement, which do not exceed allowable limit .

Most of old buildings were built on a strip footing or single footing and if the ground surface layer was loose and compressible, timber pile were used because of low wages and abundant wood resources. Also charcoal was used to provide a buoyant resistant layer in slough areas. But as weight and rigidity of buildings increased in the eightieth century and also due to economic reasons, these methods, particularly timber piles, gradually lost their importance. In this condition, piles were used beneath the shallow foundation, where shallow foundations fail to resist applied load or settlements exceed the allowable limit.

Analysis of pile group behavior is conducted by making two basic assumptions, i.e. pile raft (free pile group) and free standing pile group. The first assumption leads to unreal increase of axial forces in the piles, while it is possible to design piles for fewer forces through considering the role of pile cap. If the soil below shallow foundation is loose, load-bearing share can be ignored and the total load is taken by piles. The assumption of free pile group seems to be rational in such situation, whereas if the soil bellow the foundation is resistant, pile cap cooperates with piles to transfer load and a percentage of the load is transferred by shallow foundation and the remainder by piles. Due to economy importance, this topic have been the focus of attention by various researchers and consequently different numerical programs have been developed in order to analyze the pile foundation

The performance of piled raft foundation under seismic loads is a very important subject that can be effective on stability of structure. Piled raft foundations have better performance in hard soils then in soft or liquefy soil could cause problems. The idea of using piled raft foundation is first introduced by Davis and Poulos (1972). Then many researchers described the performance of piled raft systems. In the last recent decades with increase of using piled raft foundation for tall buildings instead of pile group foundation, many various techniques for their analysis are presented. For design of pile group foundations, the piles are designed for carrying the major part of the load. Whereas in the design of piled raft foundation, the load can be distributed between mat and piles and the interaction between soil-structure must be considered. The existing methods for static analysis of piled raft foundation could be divided into three groups:

a) the simplified computational methods

The simplified computational methods are presented by Poulos and Davis (1980), Randolph (1994), Van Impe and Clerq (1995) and Burland (1995).

All of these methods include simplification in modeling of soil profile and loading in mat foundation.

b) the approximate computerized methods:

1-Strip on Springs Method in which the shallow foundation assumed to lay on springs which are representative of soil stiffness like some strip footing, Poulos (1991).

2- Plate on Springs Method in which the shallow foundation is modeled as an elastic plate and piles as springs. In some first approaches of this method, some components of interaction were neglected thus the stiffness values were very high. (Clancy and Randolph (1993) and Poulos (1994))

c) more exact computerized methods

In this method, analysis of piled raft foundation is performed using numerical software such as FLAC, ABAQUSE and etc.

Some of important numerical methods are mentioned at Table 1. Since the application of analysis methods among engineers depends on computer programs, the second column of Table 1 includes available computer programs to employ these methods.

Table 1. Current Analysis Methods of Pile Group

Row	Researcher	Program name	Type of soil modeling	Type of pile modeling
1	Poulos (1980)	DEFPIG	Freestanding pile group	Spring
2	Randolph (1980)	PIGLET	Freestanding pile group	Spring
3	Banerjee , Driscoll	PGROUP	Continuous medium	Continuous medium
4	H.G.Poulos, M.Makarchian (1994)	AFENA	Continuous medium	Continuous medium
5	Poulos (1995)	GARP	Continuous medium	Spring
6	poulos (1996_	API	Spring	Spring
7	Commercial programs	FLAC – ABAQUSE	Continuous medium	Continuous medium
8	Commercial programs	SAP	Spring	Spring

The researches on loading mechanism of piled raft foundation under horizontal seismic load are very limited. The importance of seismic loads on damaging on piles was proved during 1995 Kobe earthquake and 2005 Sumatra earthquake.

Kulhlemeyer (1979) investigated the performance of piles under horizontal loads using finite element method. He represented results for two loading cases of static and sinusoid loads. Angelides et al. (1981) show nonlinear response of soil by hyperbolic model. In their dynamic analysis, the piles were subjected to horizontal loads. Their result showed that the stiffness of soil-pile decreased with increasing number of dynamic cycles. The frequent shear in transient loading can decrease the cohesion between soil and pile. This could eliminate the resistance of the system.

Bhowmik and Long (1991) show that the relative stiffness of soil-pile (similar to parameters like slide and crack in contact surface of soil –pile) can be strongly affected by nonlinear response of soil, adjacent to pile.

Zhang and Small (2000) introduced a method in which the interactions between the raft and piles, raft and soil, piles and soil are completely considered and can be used for analysis of piled raft under horizontal and vertical loadings.

The performance of the structural system built on piles in clay soil under seismic loads is a subject that attracts many researchers in recent years. However, the studies on the performance of piled raft under horizontal and seismic loadings in soft clay is relatively scarce.

In this paper, first the procedure for modeling of piled raft in soft clay soil under seismic load using code ABAQUSE is represented, and then obtained results are compared with from laboratory centrifuge test results and finally the parametric studies is reported.

NUMERICAL MODELING OF PILED RAFT

The performance of piled raft under seismic load is investigated using ABAQUSE finite element code. To verify the code, the results dynamic centrifuge tests reported by Banerjee and Goh (2007), on the piled raft model are used.

The studied model include four piles with filled cross section of 1.1m in diameter and 9m in length and buried completely in clay soil.

The center to center distance of piles is chosen so that the ratio *s/d* in the direction of seismic load is 11 and in the perpendicular direction is 6.

The foundation cap dimensions are 7.5m in width, 12.5m in length and 0.5m in height. Figure 1 shows the geometry of the model and arrangement of piles and raft. In this study the Elastoplastic Mohr-Coulomb model is used (Baziar and Ghorbani (2009)) and soil parameters like internal friction angle of soil, cohesion , young modulus, and poison ratio are selected based on centrifuge test.

The interaction between soil surface and raft is considered as rough tangential behavior. The connectivity between pile tips and corresponding surface on raft is chosen as tied.

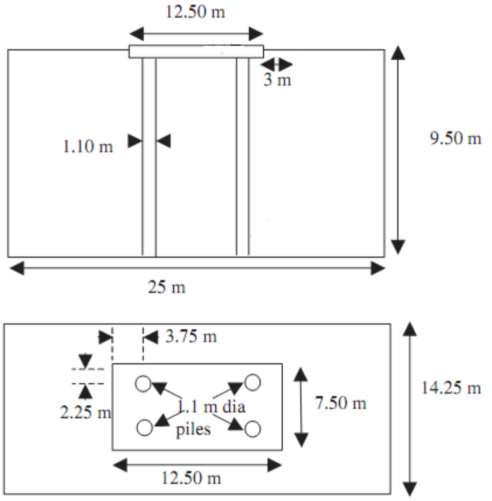

Figure1. Geometry of the model

Table2. Soil, Pile and Raft Properties

	Bulk unit weight (kN/m^3)	**young modulus (kN/m^2)**	**poison ratio**	**friction angle**	**Dilation angle**	**Cohesion (kPa)**
Kaolin clay	1.6	10^4	0.3	25	0.1	25
Steel	8	$1.8\ 10^8$	0.2	-	-	-

For these conditions, finite elements and infinite elements are used for studied region and boundary region thus there is no need for determining boundary condition in vertical boundaries. The model poles lie on center with respect to infinite elements and often coincide with center of model or center of loading.

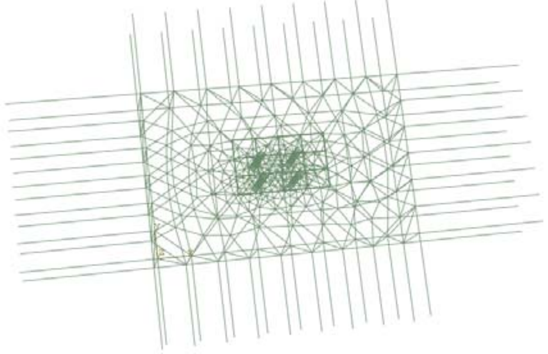

Figure2. Three dimensional soil- pile-raft models with infinite elements in boundaries of model by finite element code ABAQUSE

Then the sweep technic is used for meshing and numbering infinite elements.

After modeling and exerting uniform loading of 20 KN/m^2 on raft and earthquake acceleration on base of the model, the execution of the analysis has been started.

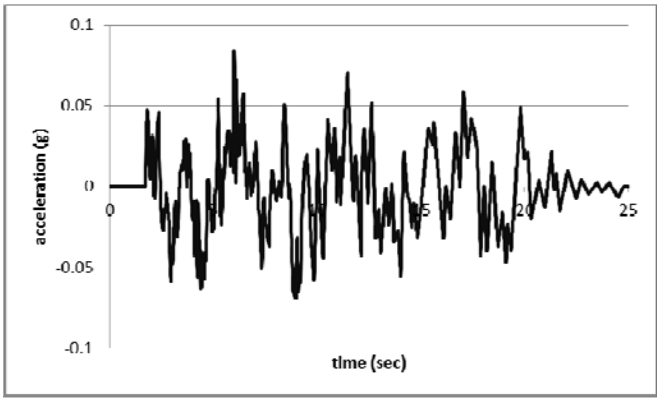

Figure3. History of Sumatra earthquake spectrum

It is noteworthy that using infinite element significantly decreases the time of analysis.

The surface acceleration results obtained from analysis and centrifuge test are presented in fig. 4. According to fig. 4, the numerical model has a good degree of precision.

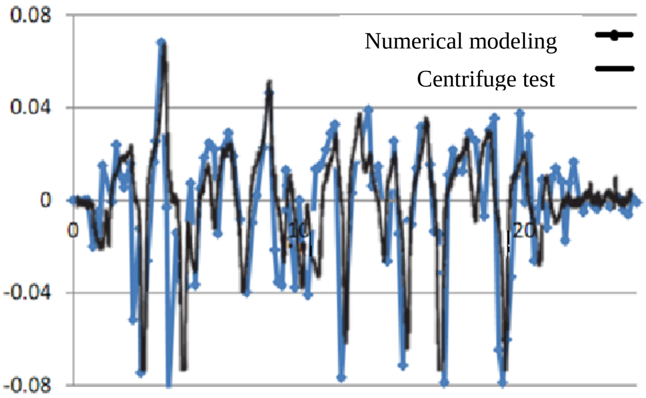

Figure4. Comparing between acceleration histogram in soil surface obtained from centrifuge test and numerical modeling

PARAMETRIC STUDIES

Studied parameters for this part are included pile length, s/d ratio and seismic acceleration.

Similar values for soil and steel properties are selected and the el-Centro spectrum is used for studying on pile length and s/d. Acceleration histogram of this earthquake is shown in figure 5.

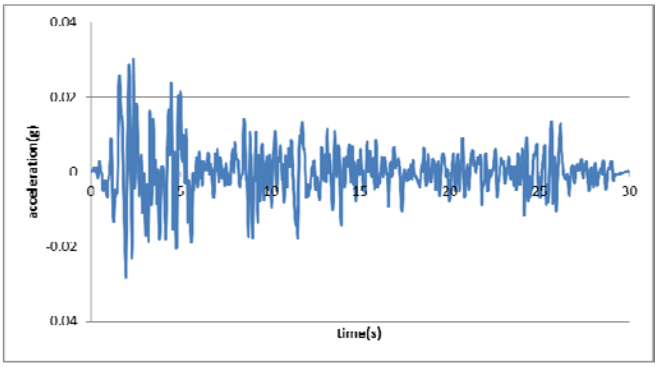

Figure5. History of El-Centro earthquake spectrum

Effect of Pile Length

The effects of pile length with 3 models of 4 piles, on the settlement of raft and bending moments of piles under seismic loads are studied.

Pile length of models is 9, 15 and 20 meter. All of piles diameter are 0.5m, the s/d ratio equals to 5 and the uniform load of 20KN/m^2 is exerted on the raft.

The settlement under uniform load applied on raft and earthquake acceleration exerted on the base for different pile lengths are shown in figure 6.

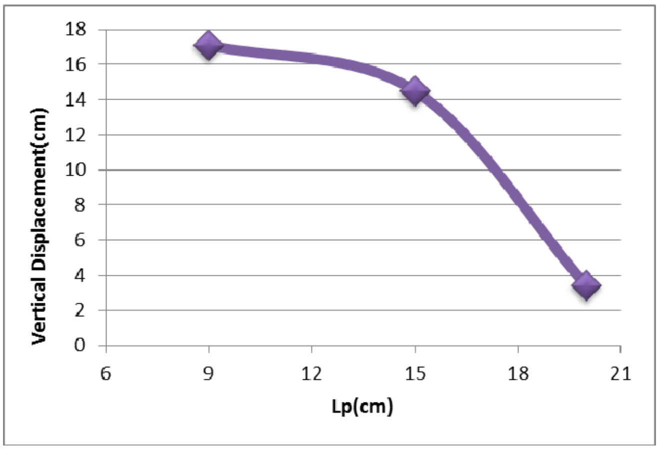

Figure 6. The effect of pile length on the settlement of raft

As shown, with increasing pile length, the settlement decreases to a significant amount.

Figures 7, 8 and 9 show the moments along pile length under mentioned loadings.

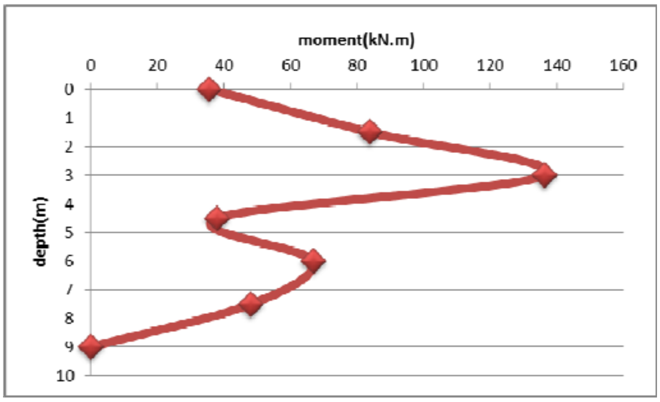

Figure 7. Bending moment graph along 9m pile

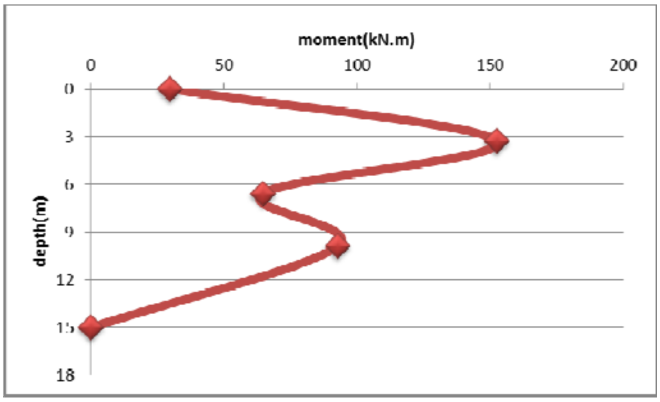

Figure 8. Bending moment graph along 15m pile

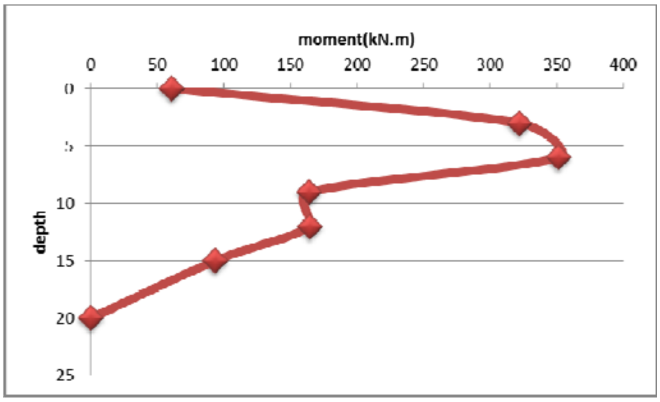

Figure 9. Bending moment graph along 20m pile

Effect of Distance to Diameter Ratio of Piles (S/D)

The effect of varying these parameters on the settlement value of raft is shown in figure 10.

As shown in figure 10, as the s/d ratio increases, the settlement value of raft at first decreases significantly and then smoothly increases. Figures 11 and 12 show the bending moments along piles length.

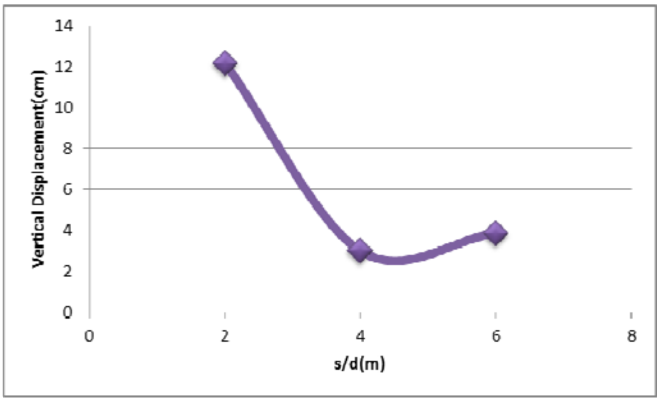

Figure 10. The effect of ratio s/d on the settlement of raft

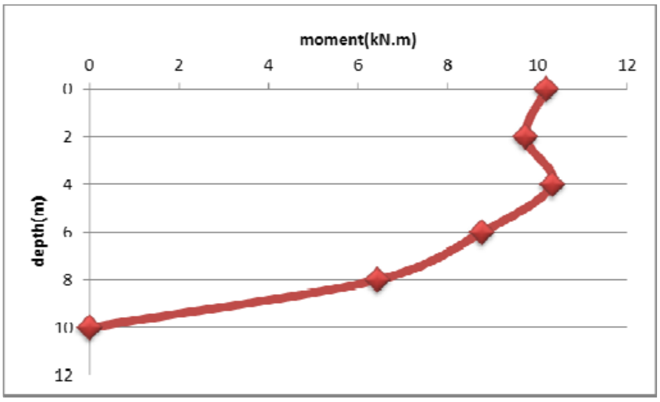

Figure 11. Bending moment graph along 10m pile with ratio s/d=2

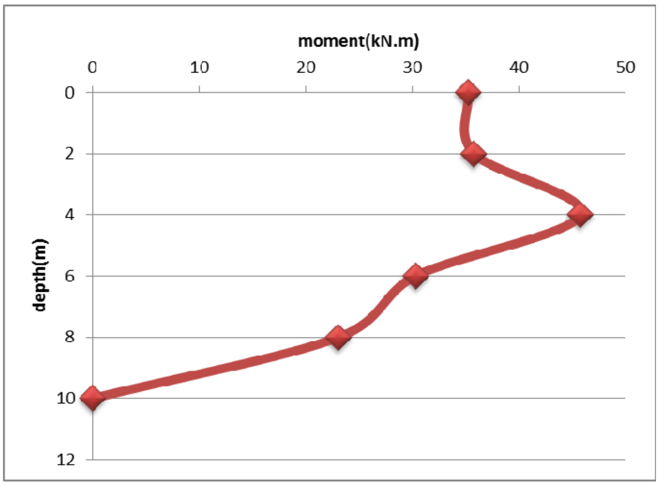

Figure 12. Bending moment graph along 10m pile with ratio s/d=4

Effect of Earthquake Spectrum

the settlement of the model with ratio s/d=4 caused on raft under acceleration spectrum for earthquakes EL-CENTRO and Sumatra (Figures 5, and 2) are compared with settlement of the raft under a sinusoid wave and showed in figure 14 some of the applied earthquake waves are shown in Table 3.

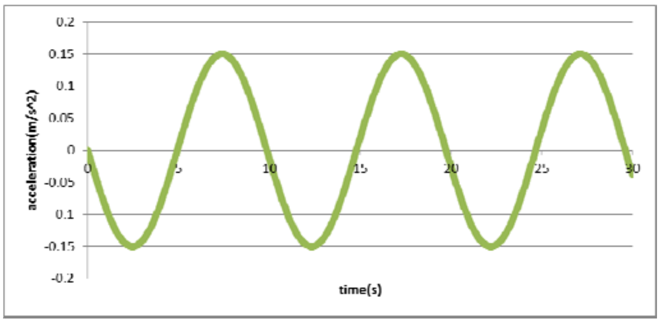

Figure 14- sinusoid wave histogram

Table 3. Current Analysis Methods of Pile Group

Earthquake	Maximum Acceleration	Time Period (s)	Settlement (cm)
El-Centro	0.028	30	2.92
Sumatra	0.0838	25	68.5
Sinusoid	0.0153	30	139

CONCLUSIONS

The obtained results show that the increase in pile length causes decrease in settlement of raft under vertical and seismic loads. However, the maximum moments in pile increases with increasing pile length. Also the study on the effect of s/d ratio also shows that with increase in this ratio, first the settlement decreases significantly and then it decreases smoothly. For lower s/d ratios, which mean the distance between piles is smaller, the interaction between piles causes the settlement to increase but with increasing this distance the interaction between piles decreases and thus causes in less settlement to occur. Therefore it can be understood that the optimum distance between piles for the design of piled raft system could cause the settlement to decrease. However, it should be note that the maximum bending moments along piles increases as the ratio of s/d increases (figures 11 and 12).

The investigations on the earthquake acceleration effects on settlement of raft show that increase in maximum acceleration and reducing the earthquake duration causes the settlement of raft to increase. However, settlement occurred under earthquake El-Centro and sinusoid wave with the same time duration showed that while the maximum acceleration in El-Centro earthquake is higher but the settlement occurred under sinusoid wave is more. In the other words, frequency of acceleration peaks is the reason for increasing the settlement.

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