Experimental study on seismic response of structure with Piled raft foundation

Alireza Saeedi Azizkandi
School of Civil Engineering, Iran University of Science and Technology, Iran, asaeedia@iust.ac.ir
Mohammad Hassan Baziar
School of Civil Engineering, Iran University of Science and Technology, Iran, Baziar AT iust.ac.ir
Boshra Razmi
School of Civil Engineering, Iran University of Science and Technology, Iran, b_razmi@civileng.iust.ac.ir

ABSTRACT: Pile foundations are widely used when shallow foundations cannot sustain large and heavy structures in both static and dynamic conditions. Due to increased interest towards the piled foundations, their behavior has been of crucial concern for researchers and engineers. Many large structures and important buildings rely on piled foundations in order to have better performance regarding these foundations pivotal role in diminishing the overall settlement and raising damping and bearing capacity. Observations from past earthquakes have shown that piles in soils generally perform not well and those installed in sandy soils are more susceptible to problems like excessive soil movements or bending moment in the pile. No doubt, the behavior of pile foundations under earthquake loading could be determinant of structural performance and safety too and that is the reason why further investigation on the soil-foundation-structure effects could be beneficial. In this paper, shaking table tests were performed on piled raft foundation with and without structure to assess the validity of the used method. Piles are hollow steel ones embedded in homogenous dry sand. Varying characteristics have been considered for structure including: slenderness, stiffness, weights, frequencies and then the pile foundation performance under seismic loading has been investigated. The results from different analyses are presented. Moments in piles and the influence of structure's stiffness, slenderness and frequency are of issues evaluated in detail and further discussed.

RÉSUMÉ: Les fondations sur pieux sont largement utilisées lorsque les fondations superficielles ne peuvent pas supporter de grandes et lourdes structures dans des conditions statiques et dynamiques. En raison de l'intérêt accru pour les fondations sur pieux, l'étude de leur comportement a été d'une importance cruciale pour les chercheurs et les ingénieurs. Beaucoup de grandes structures et bâtiments importants s'appuient sur des fondations profondes afin d'avoir une meilleure stabilité. Les observations des séismes antérieurs ont montré que les pieux dans les sols ne se comportent généralement pas bien et ceux mis en place dans les sols sableux sont plus sensibles aux problèmes tels que les mouvements excessifs du sol ou le moment fléchissant dans les pieux. Sans doute, le comportement des fondations sur pieux en cas de tremblement de terre pourrait aussi être déterminant pour le comportement de la structure et la sécurité, et c'est pourquoi une étude plus approfondie des effets de la structure sol-fondation pourrait être bénéfique. Dans cet article, des tests sur table vibrante ont été réalisés sur des fondations sur pieux avec et sans super structure pour évaluer la validité de la méthode utilisée. Les pieux sont en acier creux, noyés dans du sable sec homogène. Des caractéristiques variables ont été envisagées pour la structure, y compris: l'élancement, la rigidité, les poids, les fréquences et ensuite la performance des fondations de pieux sous charge sismique a été étudiée. Les résultats des différentes analyses sont présentés. Les moments en pieux et l'influence de la rigidité, de la finesse et de la fréquence de la structure sont des questions évaluées en détail et discutées plus en détail.

KEYWORDS: piled raft, shaking table test , structure's stiffness ,pile moment

1. INTRODUCTION

The raft foundation is a common system in construction. In the cases that there is high-rise building (external loading is very much) or settlements is more than allowed limits, placing some piles under the raft is a good method. According to soil resistance, in condition that raft and piles have bearing role, designed foundation is piled raft. Applying this system is due to decrease differential settlements and it is the main advantages of this system. Poulos and Davis presented the pile raft concept for the first time. Then some researchers like Burland et al (1977), Cooke (1986), Chow (1987), Ta and Small (1996), Kim et al (2001) and Poulos (2001), studied on system behavior in different loading conditions.

Piled raft system has complicated behavior under seismic loading, because of kinematic interactions between piles, raft and soil. Furthermore, the soil behavior is not linear in high acceleration and separation at contact surfaces (pile and soil, raft and soil) is possible. Thus, there is no comprehensive studies on analysis, designing and exact behavior of piled raft under dynamic loading.

In high seismicity areas, piles must experience unexpected load and it will be more if it imposed to a big inertia force, like a tall building. In this case, that there is high stress in rigid connections between piles and raft, it is necessary to consider special requirements.

In recent years, studies show that dynamic response of this system depends on, some parameters from input motion, super structure and foundation.

Banerjee et al (2010), evaluated effect of maximum input acceleration and bending stiffness of piles. The results showed that these parameters affected pile moment and system displacement.

Han (2002), considered 20-story building and studied variables like: foundation type and relations between soil and pile. In this research, was presented that fundamental frequency of structure is impacted by type of foundation so prediction dynamic response of structure is not exact without considering foundation type. Also, non-linear behavior of soil and pile is better verified with full-scale dynamic experiment.

Giannakou et al (2010) experimented some centrifuge tests on vertical and batter piles. For structure height assessment on piled raft response, a short and a tall (1DOF) structure were considered that had similar natural period (T =0.44S). The results showed that Pile degree and height of structure are effective on pile moment and system displacement.

Hokmabadi et al (2015) evaluated response of 15-story building on 3 types of foundation by shaking table test. The foundations which were considered: shallow foundation, pile group and pilled raft system. The test results and numerical modeling were presented that drift on pile foundation is less than shallow foundation and differential lateral displacement of stories on piled raft system is the most in compare with other types of foundation.

Badry et al (2016) investigated effect of structure shape and characteristics input wave on piled raft behavior. In this research the building was asymmetry and plan geometry was considered C, L, T shapes. Finally one plan shape was reported as critical shape that created maximum displacement thus plan geometry affected response of foundation system. In this research, critical operation was observed in input motion that has maximum acceleration and it doesn't necessarily have maximum magnitude. Seismic response of piled raft foundation is mainly influenced by structure characteristics thus considering effective parameters, is necessary in piled raft designing.

In this study, the main focus is on 1DOF structure frequency and its effect on displacement and pile moments by shaking table tests.

2. FACILITIES AND TEST CONDITIONS

The shaking table model test was performed, using shaking table facility at physical modeling and centrifuge laboratory of civil engineering, Tehran University. Frequency range of this system is 0.01-15 HZ, and it produces accelerations more than 1-g. The box is made of plexiglass. The length, width and height of mentioned box are 180cm, 80cm and 120cm respectively. (Fig. 1)

Figure 1. View from the shaking table

In this study scaling factors as suggested by Iai et al [] for 1-g shaking test were employed. Geometrical scaling factor of λ=10 and the factors λ_ρ=1 and, $\lambda_\varepsilon=\lambda^{0.5}$ were employed having in mind the properties of prototype soil and dimensions of the box and the model. The table (1) summarizes the scaling factors adopted in this study.

Parameter	prototype/model	Adopted scaling factor
length(l)	λ	10
density(p)	λ_p	1
Strain	$\lambda_\varepsilon=\lambda^{0.5}$	3.16
Time	$(\lambda_\varepsilon\lambda)^{0.5}$	3.16
Frequency	$\lambda^{-0.75}$	0.1778
Acceleration	1	1
Displacement	$\lambda^{1.5}$	31.62
Stress	λ	10
EI of Piles	$\lambda^{4.5}$	31622.7

Table 1. The scaling factors

2 .1 *soil property*

Dry Firoozkuh siliceous sand no.161 having a relative density of about 60% was used as a model ground. A summary of the properties of Firoozkuh sand is available in table (2).

Gs	e_{max}	e_{min}	D_{50}(mm)	F%	C_u	Cc
2.658	0.943	0.603	0.3	0	2.58	0.97

Table 2. Soil physical characteristics

Taking into account the maximum and minimum amounts of void ration for the sand (e_{max} and e_{min} of the sand) and the dimensions of the box, in order to reach a 60% relative density of Firoozkuh sand in the box, it was necessary to pour 209 kg of it from 15cm constant height by air pluviation using a single hole hopper to finally reach 10 cm height of the model ground in the box. Also the model foundation was set in cast-in-place form by the help of the clamps and the filling of the box was then continued layer by layer until to box was completely filled. The final soil model was 90 cm in height, 80cm in width and 170 cm length with two rubber membranes which were already installed on the sides of the inner walls' of the box.

2 .2 *Model foundation*

The piled raft model was a square raft with four piles having rigid connections with the raft. The model raft with breadth of 50 cm and a mass of 70 kg was made of Aluminum plate with a thickness of 10cm.The piles were also made of aluminum hollow tube with outer diameter of 5 cm and thickness of 0.15 cm. The total length of the piles were 75 cm where upper 5 cm was embedded in the raft to create a rigid connection.

Center-to-center piles' spacing, s, was 20cm, 4 times the pile diameter which was 5 cm (S/D=4). For a connected case, a test was also conducted with a superstructure installed on the top of the raft to evaluate what effects the high central mass with significant moment may have on the responses. The dimension and material parameters for different elements of model foundation and superstructure are provided in table (3).

Part Name	Material	Dimensions (m)	Weight(kg)
Cap	Aluminum	0.1×0.5×0.5	70
Superstructure Beam	Steel	R=0.05,L=0.5	6.62
Superstructure Head	Steel	0.1×0.2×0.2	27.3
Pile	Aluminum	R=0.05,L=0.7	0.5

Table 3. different elements of model foundation and superstructure

2.3 Instrumention and loading system

Figure (2) illustrates the instrumentation details for the raft and piles and also the location of accelerometers are identified. Five electrical resistance type strain gages were installed on each pile to measure the fiber strains and the consequent bending moments along the piles. All data and recordings were automatically monitored and stored in a data logger.

The loading was a sinusoidal acceleration imposed to the bottom of the box through a hydraulic actuator. It is really difficult to apply the exactly same input accelerations in different tests with available shaking tables; however the input accelerations were all 7 Hz motions with the almost same peak value of 0.4g in all accelerations. Figure (3) shows a typical input acceleration measured in a shaking table test. As it is observed after 0.5 to 0.7 seconds from the start the steady state for sinusoidal accelerations were obtained.

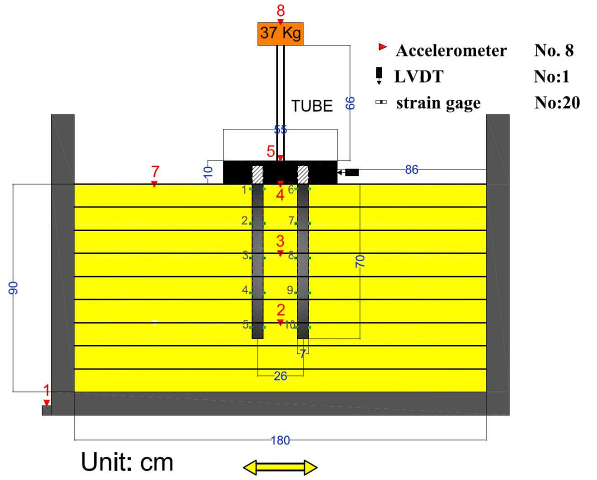

Figure 2. Model dimensions

acceleration	Without structure	With 4HZ structure	With 7HZ structure
0.2g	0.45	0.3937	0.3263
0.4g	2.380	0.799	1.306

Table4. horizontal displacement in Piled raft system

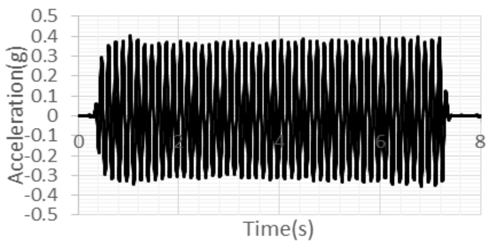

Figure 3. Input acceleration in shaking table tests

3. EXPERIMENTAL RESULTS

3 .1 *Horizontal displacement*

According to the table (4) and figure (4), when input acceleration is 0.2g, structure and its frequency don't have significant impact on horizontal displacement but at 0.4g structure frequency can decrease horizontal displacement up to 60%. The reason of this decreasing is phase difference (Fig. 5) which is created between motions of foundation and mass. The accelerometer that was fixed on foundation was in the same phase with input acceleration thus it had to show maximum displacement. Although the accelerometer was at contrast phase with structures (4 and 7 HZ) thus the lag was created with less displacement.

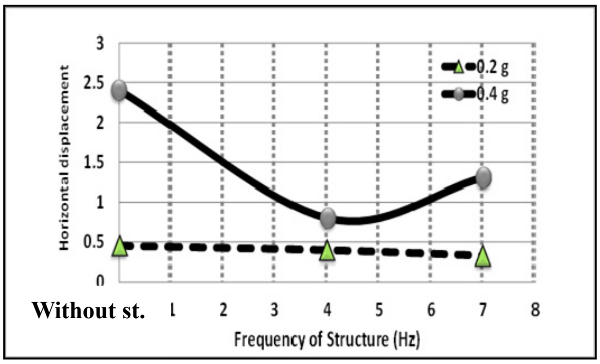

Figure 4. Effect of frequency on horizontal displacement piled raft

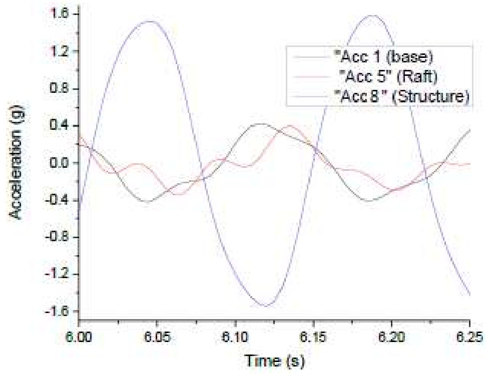

Figure5. Phase difference between cap and structure (4HZ)

3 .2 *Bending moment*

According to Fig.6, Fig.7, in the presence of structure, bending moment of piles is more than case that there is no structure because of 50cm height difference between mass and foundation. In the other hands the height structure affects pile moment.

Also, According to the Fig. 7 and8, the shaking table tests indicate that the natural frequency of structure effects on the bending moment of piles in the piled raft system. The influence of the frequency depends on the acceleration level. At high base acceleration (Fig. 7), the bending moment in length of pile is similar to in two piled raft system with 4Hz and 7 Hz frequency of structure but at the low base acceleration (Fig. 8), the piled raft-structure system of 7Hz shows the larger bending moment than of 4 Hz.

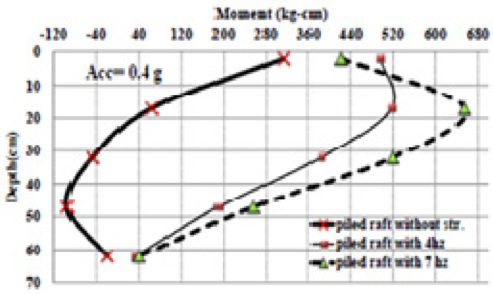

Figure6.moment along piles in 3 cases: piled raft without structure and piled raft with 4HZ and 7HZ structure, 0.4g

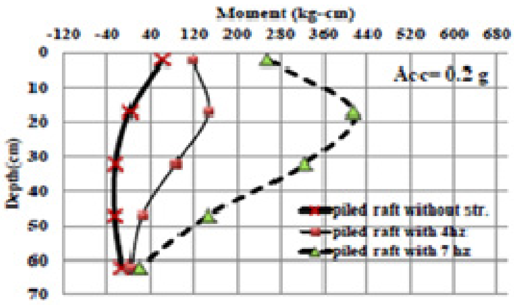

Figure7.moment along piles in 3 cases: piled raft without structure and piled raft with 4HZ and 7HZ structure, 0.2g

4. CONCLUSION

In this study, the effects of frequency on the response of the piled raft foundation and structure were experimentally studied using the shaking table tests. Two different one-degree-of freedom systems that fixed to the piled raft foundation on dry sand soil were examined. Based on the experiments conducted in this study, the following conclusions can be conisered:

(a) In the presence of structure, bending moment of pile is more than case that there is no structure, because of 50 cm height difference between mass and foundation.

(b) In models of with and without structure, location of maximum moment is different in length of pile.

(c) The nature frequency of structure is importance factor for design of the deep foundation.

(d) Considering the importance of the structure frequency is shown in table 5.

maximum displacement	maximum moment	structure frequency
b	a	Without structure
0.34 b	1.68a	4HZ
0.55b	2.13a	7HZ

Table.5. comparison between structures

(e) So, according to the results of shaking table test, foundations and structures are modeled together.

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