An experimental method to study the behavior of piled raft foundations under vertical and horizontal loading

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Abstract

In recent years the idea of using piled raft foundations to reduce the settlement of the raft instead of group pile is proposed by various researchers through experimental and numerical studies. Because of interaction effects between raft-pile-soil under different loading conditions, understanding the behavior of a piled raft foundation is so complicated. The aim of this research is to investigate the behavior of piled raft foundations and unpiled rafts under vertical and vertical-horizontal loading in small-scale. Besides, present loading systems for imposing vertical, horizontal, and combined have some disadvantages. High price, complicated structure, heavyweight, and risk of dealing with high-pressure oil to maintain the needed force are the most important defects of the mentioned systems. So In the present study, an innovative system to impose vertical and horizontal loading is presented. The density of the soil, length, and the number of piles were changed to conduct 20 tests on the unpiled raft and piled raft foundation. According to the results, increasing the number and length of piles reduce the settlement and increase the bearing capacity of the raft under vertical-horizontal loading.

Keywords: Raft, Pile, Vertical and horizontal loading, Laboratory modeling

1. INTRODUCTION

The foundation of a structure due to various loading conditions such as wind, earthquake, etc., in addition to the vertical load of the structure, can be loaded under different loading conditions such as inclined, lateral, or a combination of them. In the process of designing a suitable foundation, if the subsoil has sufficient bearing capacity and acceptable settlement, the first option is a shallow foundation. If the settlement of the shallow foundation exceeds the acceptable range, the idea of using piles is suggested. Using piles can enhance the bearing capacity of the subsoil and decrease the settlement of the foundation [1, 2]. The system of piles and foundation can be analyzed as a pile group or piled raft foundation. In a piled raft foundation, the bearing capacity of the raft is considered and the bearing capacity of the system is much more than the pile group with the same number of piles [3, 4]. Because of various interactions in the load distribution mechanism between piles and raft the behavior of the piled fat foundations has been studied by different researchers and confirmed the efficiency of this system [5-12].

Wu et al. by conducting experimental tests on piled raft foundation, single pile, and unpiled raft, investigated the load-settlement behavior and concluded that the bearing capacity of the piled raft is more than the combination of the pile group and the unpiled raft [13]. Lee and Chung performed tests on piled raft and pile group on the sand and expressed that the bearing capacity of the piled raft is (20-30)% more than the unpiled raft, also when the distance between piles is less than 5 times the pile diameter, the bearing capacity of the piled raft reduces [14]. El-Garhy et al. by changing the number and length of piles and the raft thickness studied the behavior of piled raft foundations. Based on the results, increasing the number or length of piles increased the load sharing ratio of piles and reduced the stress under the raft [15]. Patil et al. investigated the behavior of piled raft foundations under vertical loading and expressed that at the initial loading stages the piles carry more portion of the imposed load and by increasing the settlement the portion of the raft from the total load increases [16]. In addition to the vertical loading, the raft can be influenced by the combination of vertical and horizontal loading. In this condition, using piles under the raft, can enhance the overall stability of the structure and reduce the settlement of the raft [17]. Generally, because of the interaction effects between raft-soil-pile, a pile group or a piled raft should be designed for the combination of vertical or horizontal loading [18]. Regarding the previous studies, the behavior of a piled raft foundation under the combined vertical and horizontal loading is so complicated and ambiguous and a few experimental researches have been conducted in this field. Therefore, this study aims to introduce a new combined loading system and investigating the behavior of piled raft foundation under vertical-horizontal loading.

2. THE LOADING SYSTEM AND COMPONENTS

The current loading systems to impose horizontal and vertical loading have a few shortages like complexity, high cost of loading components and steel frame, and using high-pressure oil which would change the rate of loading [19-22]. Therefore, in the present study, a novel loading system is designed and constructed and the most important abilities of this system are:

- The ability to impose vertical and horizontal loading simultaneously with a steady rate
- Using simple construction and inexpensive components
- Adjustable loading rate with high accuracy in vertical and horizontal directions
- High safety in comparison to the loading systems using high-pressure oil

In this system, as shown in Fig.1, water with a steady rate instead of high-pressure oil is used to impose the vertical and horizontal load. The maximum rate of loading is about 200 $^{N/min}$ which can be considered as static loading condition [23].

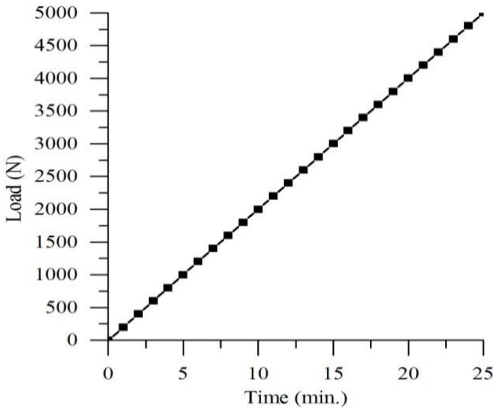

Figure 1. Maximum variation of vertical load with time

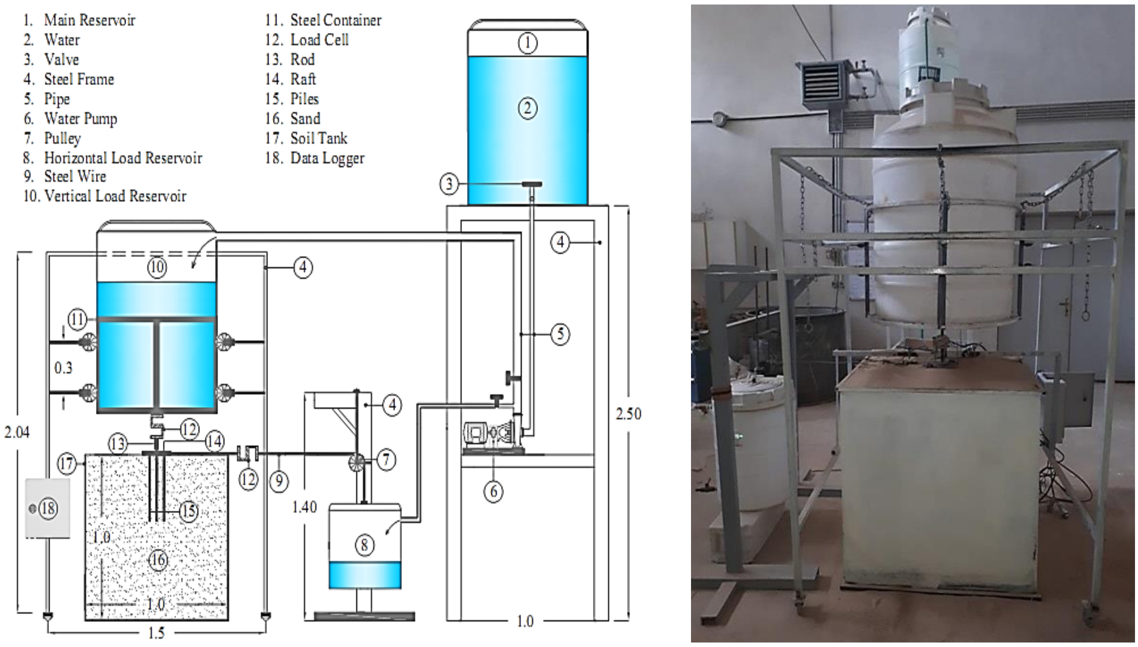

Figure 2. Schematic view and a picture of the loading system (unit:m)

In this system water as depicted in Fig.2, water discharges with a water pump from the main reservoir to the vertical and horizontal load reservoirs. Two separate valves are used to control and change the direction of loading or imposing the vertical and horizontal load simultaneously. The vertical load reservoir is put inside the steel container and surrounded from four sides by perfectly smooth and polished rails that can only move in the vertical direction. The vertical load transmits with a steel solid rod from the reservoir container to the raft surface. The horizontal loading reservoir located beside the soil tank is attached to the edge of the raft with a solid steel wire through a smooth pulley.
The measuring devices of the system consist of one vertical load cell at the top of the loading rod, one horizontal load cell at the edge of the raft, three vertical displacement transducers on the surface of the raft, and one horizontal displacement transducer attached to the side steel barrier (Fig.3). The measured values are recorded by the data logger placed on the steel frame of the loading system.

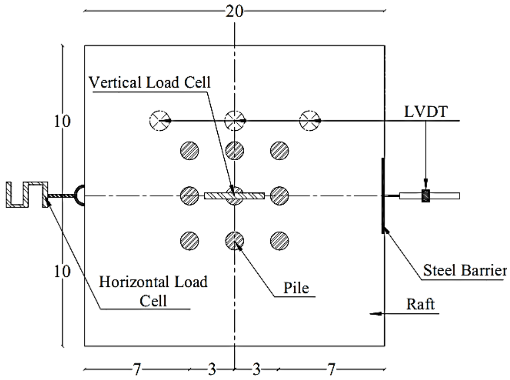

Figure 3. Schematic plan view from measuring devices, model raft, and piles (unit: cm)

3. DETAILS OF EXPERIMENTAL TESTS

3.1. TEST SAND

Firouzkouh No. 161 dry sand with the relative densities of 50% and 70% was used to fill the soil tank and model the subsoil. The new air pluviation system developed at the Ferdowsi University of Mashhad was employed to deposit the sand into the steel tank and prepare homogenous and reproducible specimens. The physical properties of the sand are presented in Table 1.

Table 1- Physical properties of Firoozkooh 161 sand

Sand	Gs	D_{50}(mm)	Cu	Cc	e_{max}	e_{min}
Firoozkooh161	2.658	0.35	2.58	0.63	0.943	0.603

3.2. MODEL OF PILES, RAFT, AND STEEL TANK

Solid steel pipes with 6 mm diameter and elastic modulus of 2.1×10^8 kPa were used to model the piles. A square steel plate with dimensions of 200 mm×200 mm×6 mm was used as the model raft. To prevent any stress interactions among the piles, the center to center distance of piles was chosen five times the pile diameter (i.e. S/D=5). To model real conditions and the friction, a thin layer of sand was glued to the bottom of the raft. To prevent any interface between piles and raft stress distribution with the sides of the soil tank The width, length, and depth of the tank should be selected at least twice the length of the longest pile and five times the raft breadth [24]. Therefore the rigid cubic steel tank with 1000 mm dimension and 5mm thickness is selected as the soil tank.

3.2. DETAILS OF EXPERIMENTAL TESTS

In this study, 20 tests are conducted on the unpiled raft and piled raft foundation under vertical and combined vertical-horizontal loading. The details of the tests are shown in Tables 2 and 3. It should be noted that the pile length to diameter and the pile spacing to pile diameter ratio are shown by L/D and S/D respectively. In the case of combined loading, first, the vertical load (V) increases up to the specific value of the ultimate vertical load (V_u), and then the horizontal load is imposed to the edge of the raft.

Table 2- Details of the experimental program under vertical loading

Studied cases	L/D	S/D	Dr (%)	Number of tests
Unpiled raft	---	---	50	1
Unpiled raft	---	---	70	1
Raft+1&5&9 piles	20	5	50	3
Raft+1&5&9 piles	40	5	50	3
Raft+1&5&9 piles	20	5	70	3

Table 3- Details of the experimental program under combined vertical-horizontal loading

Studied cases	L/D	V/Vu	S/D	Dr (%)	Number of tests
Unpiled raft	---	0.35	---	50	1
Unpiled raft	---	0.6	---	50	1
Unpiled raft	---	0.85	---	50	1
Raft+1&5&9 piles	20	0.35	5	50	2
Raft+1&5&9 piles	20	0.6	5	50	2
Raft+1&5&9 piles	20	0.85	5	50	2

4. RESULTS AND DISCUSSION

In the following section the results of the tests on the unpiled raft and piled raft foundation by changing the number and length of piles and the ratio of the imposed vertical load to the ultimate vertical load under vertical and vertical-horizontal loading are presented.

4.1. TESTS RESULTS UNDER VERTICAL LOADING

The load-settlement curves of the tests under vertical loading on the unpiled raft and piled raft foundations are shown in Figs.4-6. The tests were terminated as the settlement of the raft reached 40mm and the corresponding vertical stress is considered as the ultimate vertical stress (V_u). According to the results, by installing the piles under the raft and increasing the number or length of the piles the load-bearing capacity of the raft increases. The piles transfer the load from the raft bottom elevation to deep-seated soil through the skin friction with the subsoil around the perimeter surface area of the piles. Any increase in the number or length of the piles increases the perimeter surface area of the piles. Increasing the imposed vertical stress from the structure on the raft, produces more lateral stress and mobilizes more skin friction around the piles and as a result increases the resistance and bearing capacity of the piles under vertical loading. Regarding the results, increasing the relative density of the subsoil, increases the bearing capacity of the unpiled raft by about 10%, while increasing the number or length of the piles increases the bearing capacity of the raft more than 50%. On the other hand, by increasing the raft settlement and the vertical stress of the raft, the interactions between raft-soil-pile increases as well and reduce the efficiency of using piles as soil reinforcements and the slope of the load-settlement curves. Other researchers have reported similar results regarding the advantages of using piles to reduce the settlement and increase the bearing capacity of the raft [25-27].

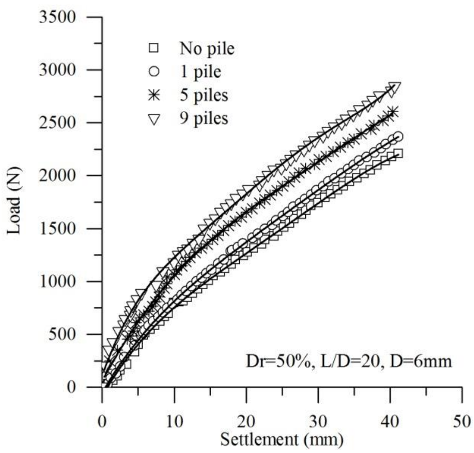

Figure 4. Load-settlement curves of the unpiled raft and piled raft foundations under vertical loading (L/D=20)

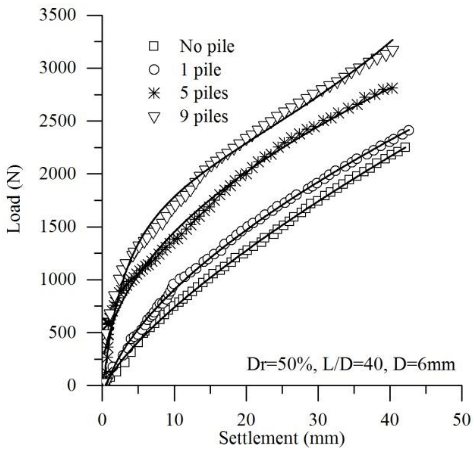

Figure 5. Load-settlement curves of the unpiled raft and piled raft foundations under vertical loading (L/D=40)

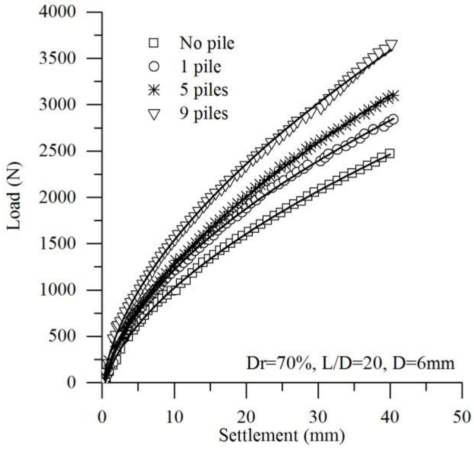

Figure 6. Load-settlement curves of the unpiled raft and piled raft foundations under vertical loading (Dr=70%)

4.2. TESTS RESULTS UNDER COMBINED VERTICAL-HORIZONTAL LOADING

The combined vertical-horizontal loading affects the behavior of the piled raft. The magnitude of the imposed vertical load is a crucial and effective issue in the load-carrying mechanism of the piled raft. In this study, initially, the predefined amount of vertical load (0.35, 0.6, and 0.85 of the ultimate vertical load) and in the following the horizontal load is imposed to the center of the raft. The horizontal loading continued until the stability of the raft was fully lost and an obvious rupture occurred in the subsoil. The details of the tests are expressed in Table 3.

4.2.1. EFFECT OF INITIAL VERTICAL LOAD AND THE NUMBER OF THE PILES

To study the effect of initial vertical load, the number of the piles were kept constant and the combined loading was imposed on the raft and the results are shown in figures 7-9. The effects of changing the number of piles on the behavior of the piled rafts for a definite vertical load are depicted in figures 10-12.

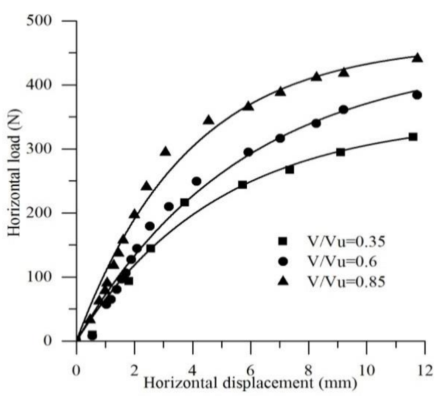

Figure 7. Effect of initial vertical load on the horizontal load-bearing capacity of the unpiled raft

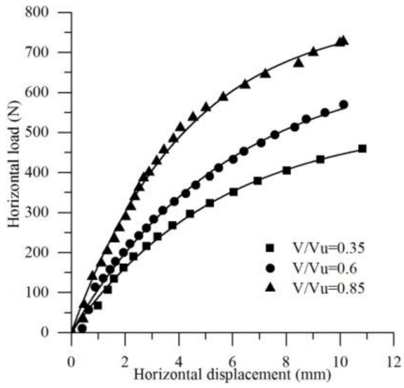

Figure 8. Effect of initial vertical load on the horizontal load-bearing capacity of the piled raft with 1 pile

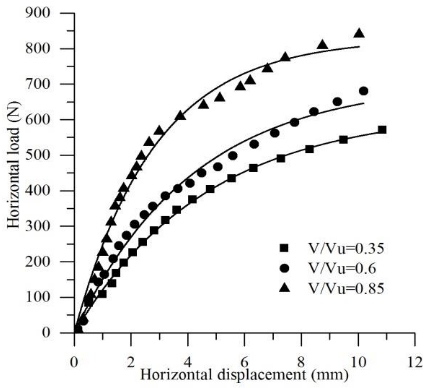

Figure 9. Effect of initial vertical load on the horizontal load-bearing capacity of the piled raft with 5 piles

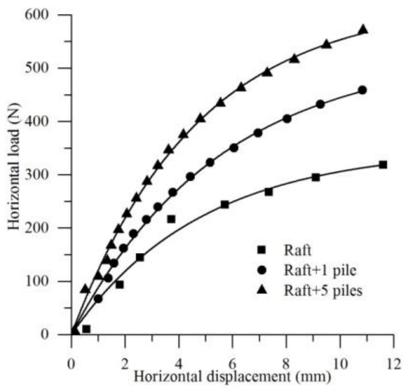

Figure 10. Effect of number of piles on horizontal load-bearing capacity (V/V_u=0.35)

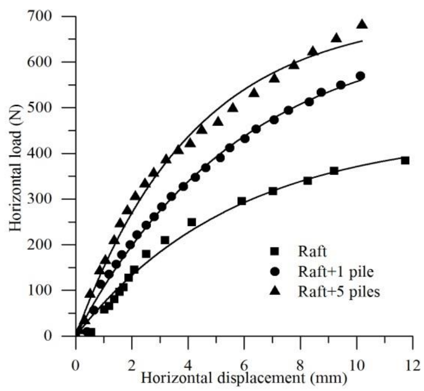

Figure 11. Effect of number of piles on horizontal load-bearing capacity (V/V_u=0.6)

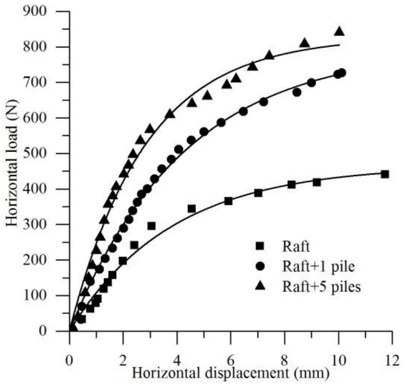

Figure 11. Effect of number of piles on horizontal load-bearing capacity (V/V_u=0.85)

In a piled raft foundation, the contact surface of the raft with subsoil and the lateral rigidity of the piles resist the horizontal loading of the raft. Increasing the initial imposed vertical load on the raft with the same number of piles increases the interlock forces between the bottom of the raft and the subsoil. As a result the shear resistance of the raft and the horizontal bearing capacity of the raft increase (figures 6-8).
As previously explained increasing the number of the piles enhances the vertical bearing capacity of the piled raft and subsequently increases the friction forces between the raft and the subsoil and the lateral rigidity of the piled raft. On the other hand, piles have a crucial role to increase the lateral rigidity of the piled raft. The shear resistance of the pile head connection and the flexural rigidity of the pile improve the horizontal bearing capacity of the piled raft significantly. As shown in figures 9-11, for any specific imposed vertical load, increasing the number of the piles increases the horizontal bearing capacity of the raft up to more than 200 percent. The results are in agreement with the previous studies by other researchers [28, 30].

5. CONCLUSIONS

In the present study details of the designed loading system with an innovative simple structure and the ability of loading in vertical and horizontal directions is presented. Also, the behavior of the unpiled raft and the piled raft foundation under vertical and combined loading conditions are investigated experimentally by the presented loading system. According to the test results, the following conclusions can be drawn briefly:

- The presented loading system can be used to study the behavior of unpiled raft, piled raft, group pile, and other geotechnical structures under combined loading.
- Installing piles beneath the raft and using piled raft foundation enhances the bearing capacity and decreases the settlement of the unpiled raft both under vertical and combined loading.
- For a given relative density, increasing the number or length of piles increases the vertical and horizontal bearing capacity of the piled raft.
- By increasing the initial imposed vertical stress for the piled raft with a specific number of piles, the bearing capacity of the piled raft under combined loading increases.

6. ACKNOWLEDGMENT

The performed tests were financially supported by the "Vice President for Research and Technology" of the Ferdowsi University of Mashhad which is acknowledged.

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