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Insight into the post-liquefaction behaviour of skirted foundations

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ABSTRACT: With rapid growth of energy production from offshore wind farms, the construction of wind turbines has developed very fast around the world. An important phenomenon in seismic areas is liquefaction in saturated sandy soils that can be resulted in a wide range of structural damages from excessive settlement of foundations to general failure. New generation wind farms are planned to be built at regions that may be vulnerable to the seismic hazard. In this study, a series of experimental studies was conducted to study the behavior of bucket foundations and surface footings in response to the upward seepage-induced liquefaction. The experimental results show degradation of bearing capacity of bucket foundation and surface footing as result of excess pore water pressure development in sand. The inclusion of skirts can confine the soil around foundation and consequently reduce the settlement of bucket foundation more than that of the surface footing. Moreover, it was observed that the bearing capacity of foundation in liquefiable soils would be enhanced with increasing of skirt length and foundation width.

1 INTRODUCTION

Energy crisis is increasingly recognized as a serious, worldwide public concern owing to the growing demand and the finite fusil resources, which has heightened the need for renewable energy resources such as wind, radiation and geothermal. Wind energy resources are unlimited and considered as clean energies. Nowadays, modern wind turbines can generate economic, renewable, safe and no-pollutant energies. In order to supply the wind energy with high efficiency, wind turbines are installed in windy coastal and offshore regions (Houlsby *et al.*, 2005).

The construction cost of the foundation of offshore wind turbines is about 30% of the total cost of the superstructure and the foundation. Therefore, the economic design of the foundation is critically important and many researchers have focused on it. Offshore wind turbines structures are commonly constructed on either gravity based foundations or monopiles (Randolph and Gourvenec, 2011). Figure 1 shows the foundation types of offshore wind turbines. The two past decades have seen the rapid development of using of the bucket foundation, especially for offshore wind turbines.

Bucket foundation is a type of caisson foundations which is commonly called "suction caisson" due to the use of suction in its installation process. The main difference between the bucket foundation and the surface footing is the existence of some skirts around it which improve its performance and bearing capacity compared to the surface footings (Eid, 2013; Barari *et al.*, 2017). Bucket foundations are usually made of steel which are installed in the shape of an inverted bucket. The behavior of bucket foundations subjected to the vertical loading and the general loading has been investigated and complete plasticity models have

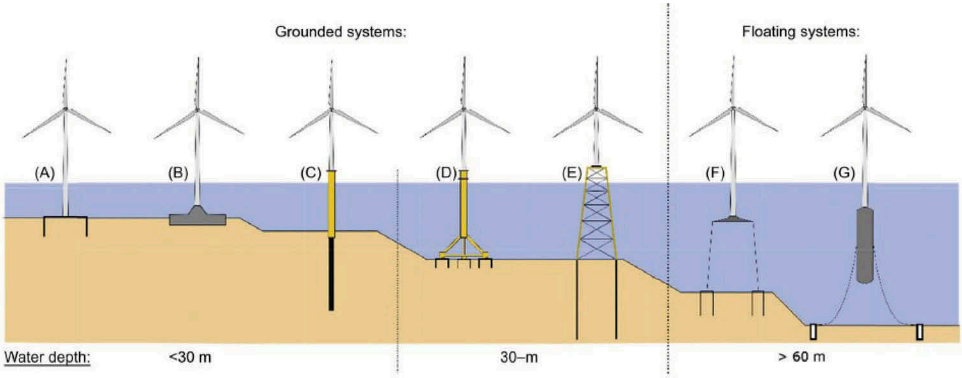

Figure 1. Different types of the foundations of offshore wind turbine, from left to right: A) bucket foundation; B) gravity foundation; C) monopile foundation; D) tripod caisson, E) jacket foundation, F and G) floating structures (Barari and Ibsen, 2014)

been provided to describe the behavior of bucket foundation subjected to the general loading (Achmus *et al.*, 2013; Ibsen *et al.*, 2014; Park *et al.*, 2016).

The increasing tendency in use of bucket foundation in seismic and hazardous areas is brought new issues and difficulties. One of the main important seismic geotechnical risks in seismic areas is soils liquefaction. Soil liquefaction might lead to heavy damages resulting from bearing capacity degradation and the rotation of shallow foundation. Infrastructure system performance is critically affected by soil liquefaction that requires further investigation. There are limited research works on the behavior and the settlement mechanisms of skirted foundations in liquefied soils (Yu *et al.*, 2014; Yu *et al.*, 2015).

Yu *et al.*, (2015) conducted a series of centrifuge experiments on the suction caisson-supported wind turbine models in order to study the behavior of bucket foundation in liquefied soils. It was reported that increasing the foundation diameter and the skirt length of foundation have major effect on decreasing the pore pressure and settlement of foundation. Most of the previous studies have focused on evaluation and estimation of liquefaction-induced settlements of mat foundations and limited studies have been carried out on the bearing capacity degradation of shallow footings as result of the soil liquefaction, let alone those for skirted foundations.

Jafarian et al. (2016) conducted a series experimental investigation to study the behavior of small-scale foundations on liquefiable soils. It was suggested that the upward seepage could create the conditions similar to the complete soil liquefaction during the earthquake. They reported that due to the increase of the pore water pressure, the soil strength and stiffness may decrease while foundation still shows considerable amount of bearing capacity.

The major objective of this study was to investigate the behavior and the performance of bucket foundation in liquefied soils. In this study, several 1g physical model experiments were conducted at various constant levels of excess pore-water pressure by applying upward seepage to the foundation soil deposit. The tests were designed to study the bearing capacity changes and the settlement of bucket foundations in the presence of excess pore water pressure.

2 EXPERIMENTAL WORK

The post-liquefaction behavior of bucket foundation is an important issue and that might have a significant impact on the total performance of the offshore wind turbine (OWT). Use of upward seepage for representation of earthquake-induced excess pore pressure was employed by previous researchers (Calvetti *et al.*, 2004; Jafarian *et al.*, 2016). Calvetti *et al.*, (2004) investigated the performance of buried pipes in post-liquefaction phase by varying the pore water pressure.

In this study, the bearing capacity of surface and bucket foundations were evaluated in two soil conditions including the saturated soil (i.e., which is indicate of response prior to seismic shaking) and the complete liquefaction in the presence of excess pore water pressures ratios of 0 and 1, respectively. The excess pore water pressure ratio is defined by equation (1).

$$r_u = \frac{\Delta u}{\sigma'_{v0}} \tag{1}$$

Where, r_u is the excess pore pressure ratio, Δu is the excess pore pressure and σ'_{v0} is the initial vertical effective stress of the soil.

In order to investigate vertical bearing capacity of bucket foundation in saturated sand, some experiments were conducted on small-scale foundations. For this purpose, a large soil container of 1.20 m in length, 0.9 m in width, and 0.9 m in height was selected. The container was fabricated by steel and at one side of container a Plexiglas sheet was installed for visual observation of soil deformation during loading. A schematic view of the experimental setup is demonstrated in Figure 2. A hydraulic jack was used to apply vertical load, and two LVDTs and a load cell installed on foundation to measure vertical displacement versus vertical load.

A setup was also installed beneath the container to generate excess pore pressure in the soil mass. This system consisted of the input and output water flow pipes in the test container; and the water pressure increased by pumping water into the container, and subsequently the pore pressure and upward seepage increased the excess pore pressure ratio (r_u). The test was performed in different levels of the excess pore pressure ratio (r_u) in order to evaluate the impact of pore pressure on the excessive settlement of foundation and degradation of bearing capacity of foundation. Due to the upward water pressure beneath the sample, the soil might be scoured and the pressure distribution might not be uniform; hence, a layer of gravel with a thickness of at least 5cm was placed at the bottom of the container and its surface was covered by a reticular rubber with pores for water penetration in order to avoid the scour phenomenon. The gravel layer and the reticular net above allow water to pass through, inhibit the scour and contribute to the uniform pore pressure distribution.

A number of small-scale model foundations were built in order to study the vertical bearing capacity and settlement of offshore surface footings on the experimental scale. In the present study, the foundations were circular having diameters of 10 cm and 20 cm and aspect ratios (i.e., ratio of the foundation skirt height to diameter) of 0, 0.5 and 1. Figure 3 shows the foundations utilized in the campaign of experimental study.

Babolsar sand taken from the Caspian Sea in a region so called Babolsar County was used to model the soil medium. It is however classified as poorly graded sand (SP) according to the

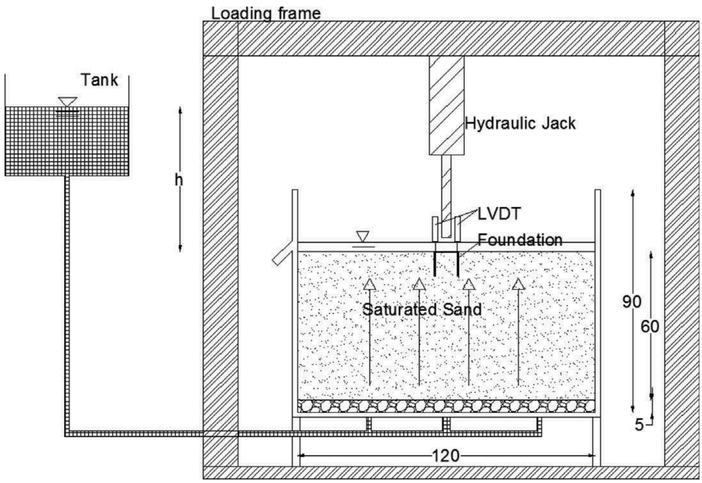

Figure 2. Schematic view of the experimental setup and upward seepage

Figure 3. Small-scale bucket foundations

Table 1. Characteristics of Babolsar sand

G_s	2.73
Dr (%)	30~35
D_{50}	0.2
D_{10}	0.16
Max void ratio, e_{max}	0.54
Min void ratio, e_{min}	0.73

Unified Soil Classification System (USCS). The characteristics of Babolsar sand are summarized in Table 1.

3 MODEL CONFIGURATION AND TEST PROCEDURES

In the 1g tests, sands should be prepared with a very low density on small-scale in order to achieve the behavior of loose sands during liquefaction. Accordingly, the present study utilized the water sedimentation method to build a uniform soil medium with a low density. In this method, the test container was first filled with de-aired water, and then the sand was poured from the height of 10cm above the water surface. Sand deposited in the water due to its own weight and a uniform soil medium was created with a relative density of 30%. This process of soil medium creation is very similar to the sedimentation of young deposits in the nature.

After leveling the sand surface, the surface footing was placed on the soil. Foundations were installed in the middle of the test container and placed in their own situation with a slight hydraulic pressure for installing the bucket foundations. The foundations were loaded at a rate of 5mm per seconds by a hydraulic jack. Two digital rulers (LVDT) with the measurement capacity of 100 mm and the accuracy of 0.01mm were used to measure the foundation settlement; and a S-shaped load cell with the maximum nominal capacity of 20KN and the accuracy of 1.5KN was used to measure the forces. Data logging was done by the eight-channel data logger (AL4-8) device.

The test schedule includes the evaluation of bearing capacity of bucket foundations in different level of excess pore pressures ratio. Table 2 presents the testing program of the bearing capacity of 10cm and 20cm diameter foundations. The first group of tests was subjected to the static loading prior to generation of excess pore pressure. In the second suite of tests, when foundation installed, excess pore-water pressure was generated and kept constant by steady-state upward seepage. Subsequently, the foundations were loaded until reaching the ultimate limit state (ULS). In other words, the second group of tests simulated the soil conditions after the onset of liquefaction and aimed to determine the bearing capacity of foundations in the liquefied soils.

Despite the fact that the seismic excitations might reduce the soil strength and resulting bearing capacity of foundations, the bearing strength could never reach zero (Jafarian *et al.*, 2016). According to the testing program, the skirted footings were subsequently subjected to the vertical loading, and their bearing capacity was examined in the saturated deposit as well as the upward-seepage induced liquefied strata.

4 TEST RESULTS AND ANALYSIS

In the present research, there was no observed soil bulging around the foundations. An increase in the load increased the amount of settlement in the load-settlement graphs; and there was not any obvious peak which indicated the punching behavior of foundations in the soil due to the low density of sandy soils. Vesic, (1973) determined that the shallow foundations in the low-density soils ($D_r = \frac{e_{\max}-e}{e_{\max}-e_{\min}} \times 100 \leq 35\%$) entered into the soil by increasing the load without soil swelling around the foundations and failed in the punching shear mode. Vesic (1973) described the minimum slope failure load criteria to determine the bearing capacity of shallow foundation in loose sand. According to this criterion, ultimate bearing capacity is defined as a point of load-settlement curve where its slope reaches zero or becomes steady. In all tests of this study, a peak load was never observed, and bearing capacity was defined as a point where the slope of load-settlement curve becomes constant. Figure 4 shows the results of loading tests on the skirted foundations in the saturated loose sand.

Results demonstrated that inclusion of skirts enhances bearing capacity of the bucket foundation in loose alluvium. An increase in embedment ratio (*d/D*) increases bearing capacity, and due to soil confinement, the skirts decrease the settlement of bucket foundation.

In the subsequent test series, the amount of pore-water pressures were deliberately increased and r_u reached the value of 1. The experimental results indicated that the bearing capacity of foundations decreased due to the reduction of effective stress between sand particles by increasing the pore-water pressure. Figure 5 shows the load-settlement curves of foundations with diameters of 10cm and 20cm in complete soil liquefaction (r_u=1).

Despite the significant reduction of soil strength due to the excess pore-water pressure and decreased effective stress, the sand still had a significant strength; and foundations had bearing capacity. Jafarian et al. (2016) indicated that an increase in the pore-water pressure led to the

Table 2. Details of test program

Case	Skirt length to diameter (d/D)	Foundation diameter (cm) (D)	r_u
1	0	10	**0**
2	0.5	10	**0**
3	1	10	**0**
4	0	20	**0**
5	0.5	20	**0**
6	1	20	**0**
7	0	10	**1**
8	0.5	10	**1**
9	1	10	**1**
10	0	20	**1**
11	0.5	20	**1**
12	1	20	**1**

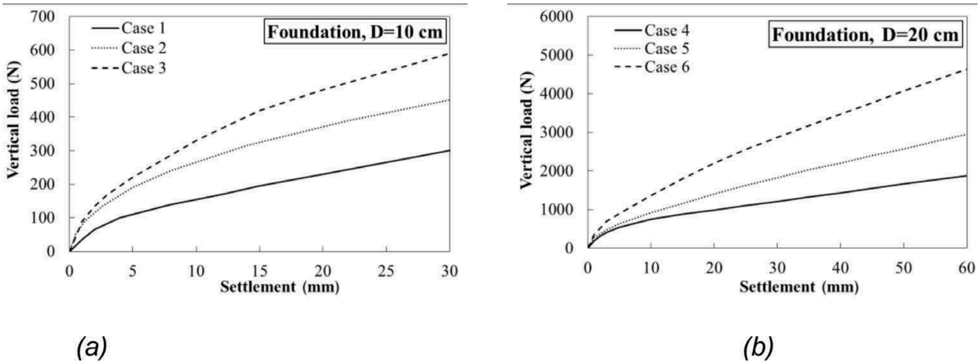

Figure 4. Load-settlement curve of foundations with diameter of: a) 10 cm and b) 20 cm

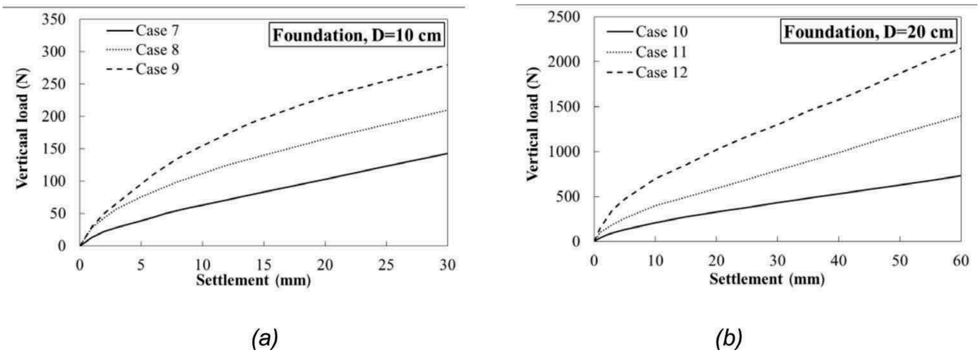

Figure 5. Load-settlement curve of foundations with diameter of: a) 10 cm and b) 20 cm, after pore-pressure generation

reduction of more than 50% in the bearing capacity of squared and striped shallow foundations compared to the conditions without the excess pore-water pressure.

In both groups of tests, the enhancement of surface footing performance is clearly evident by adding skirts around the foundations. Table 3 presents the bearing capacity of each foundation in the saturated sandy soil. Results of the first group of tests without the excess pore-water pressure indicate that the skirts increase the bearing capacity of surface footing with coefficients of more than three times for d/D=0.5 and 5.5 times for d/D=1 whereas they are independent of the foundation widths. This behavior may be attributed to the mechanism of soil confinement by foundation skirts.

It could be assumed that the foundation and soil plug together act as a unit system under vertical loading and the foundation behavior to some extent would be similar to the embedded foundations.

In the second group of tests, the bearing capacity significantly decreases due to the increase in the pore-water pressure. When the pore-water pressure is sufficiently high (r_u=1), the bearing capacity of skirted foundations decrease to less than 50 percent of that in the saturated soil having excess pore pressure ratio equal to zero (r_u=0). This reduction of bearing capacity in the foundation is due to the reduction of effective stress and the friction between soil particles leading to the significant degradation of the bearing capacity in the foundations and excessive deformations. Because of soil confinement induced by skirts around and within the foundation, the bucket foundation avoids from the significant reduction of bearing capacity and enhances the foundation integrity in harsh environmental condition. One would expect that the performance of bucket foundations in the presence of upward seepage could be than

Table 3. Measured bearing capacity for foundations with diameters of 10cm and 20cm

Diameter, D, (cm)	Skirt length, d, (cm)	Bearing capacity (N) $r_u=1$	Bearing capacity (N) $r_u=0$
10	0	35	95
10	5	150	360
10	10	260	535
20	0	305	820
20	10	1240	2794
20	20	1950	4103

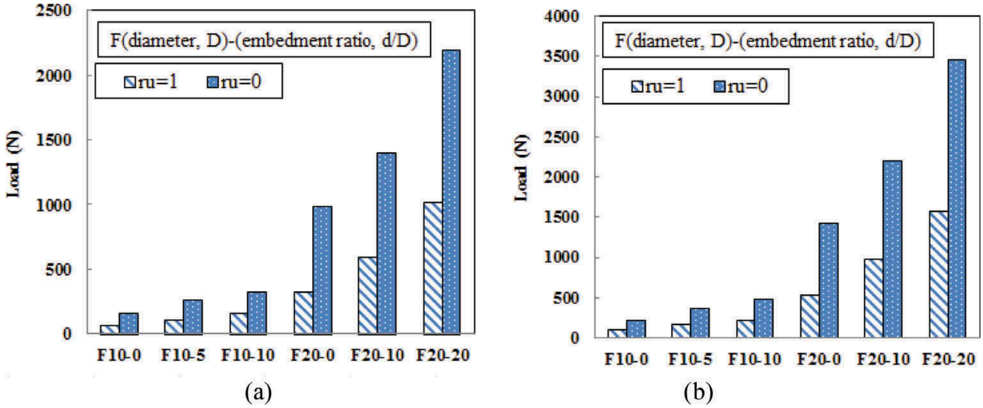

Figure 6. Comparison of the foundation loads at a certain settlement: (a) 0.1D, (b) 0.2D

the equivalent surface footing due to lateral constraints offered by skirts which prevent the migration of underlying liquefied deposit toward free-surface which may further enhance resulting sinking into the softened ground.

In general, the pore-water pressure increases due to the seismic motion and it reduces the shaft resistance of the foundations so axial loads are basically transferred to the base of the foundations; Nevertheless, the end bearing capacity is mobilized and if it is exceeded after a while, excessive settlements would be Inevitable.

Ishihara and Yoshimine, (1992) provided the graphs and equations for estimation of settlement of the free field after the initiation of liquefaction. The recent studies indicated that the foundation settlement after occurrence of liquefaction can immediately surpass the soil settlement in the free-field after one significant shear stress cycle.

Figure 6 compares the load of foundation models at a certain settlement (0.1D and 0.2D). It is apparent from this Figure that the generated pore-water pressure ratio (r_u) causes the foundations' load at a certain level of settlement decreases about 60% and the foundation models in turn experienced relatively higher settlements than the saturated soil devoid of excess pore pressure. The initiation and rate of excessive settlement of foundations in liquefied soil were roughly similar for two foundations with diameters of 10cm and 20cm.

It is interesting to note that bucket foundation increases the soil stiffness around the foundation due to its surrounding skirts; hence, it experiences less settlement than the surface foundation; and the reduction of settlement increases by enhancing the skirt height. The excess settlement of foundations could disrupt the integrity of soil-foundation systems. Therefore, in order to design foundations in the liquefied soils, it is essential to account for the post-liquefaction behavior of soil and consequent soil stiffness reduction. It can be seen from Figure 6 the bucket foundations at a higher load level about twice surface footing reached the certain settlement which was independent of the pore water pressure.

5 CONCLUSIONS

Bucket foundations are the suitable alternatives for next generation offshore wind turbines. One of the important advantages of the bucket foundation is its simple/noise free installation compared to the monopile-supported OWTs. The widespread consideration of such foundations in seismic areas has increased the importance of studying the performance of such foundations in the liquefied soils. Seismic excitations decrease the soil stiffness and bearing capacity by generating positive pore-water pressure.

The present study evaluated the behavior of surface and bucket foundations in liquefied soils. Results indicated that the generated pore-water pressure significantly reduced the bearing capacity of foundations; however the foundations showed still considerable bearing capacity even in the presence of significant shear strength degradation of foundation soil deposit. In current research, the bearing capacity exhibited a reduction of 40–50% from its initial value according to the embedment depth. In essence, authors hypothesize here that the bearing capacity of skirted foundation will experience less reduction rather than an equivalent surface footing due to the existence of skirts around the foundation. The bucket foundation had the higher bearing capacity and better performance in liquefied soils than the surface foundation due to its internal failure mechanisms and soil confinement around and inside the foundation.

Furthermore, the bucket foundation had a lower settlement than the surface foundation. This phenomenon is more evident in the liquefied soils. The bucket foundations decrease the excess settlement caused by liquefaction due to their skirts. Accordingly, the bucket foundations can be used as suitable alternatives to surface footings as they have higher bearing capacity and lower excess settlement in liquefied soils than the surface footings.

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