



Performance of Bucket Foundation Resting on Sand Subjected To Vertical Load

A. H. Haddad*, R. Amini

Semnan University, Semnan, Iran

ABSTRACT: In comparison with the monopile foundation, bucket foundation is an economical option to reduce the construction costs of offshore wind turbines. It is similar to a suction caisson, which is driven into the soil like an upside-down bucket. Various available scientific researches have stated that how the length of skirt affects the ultimate capacity (q_{ult}) of bucket foundations that are utilized for different kinds of offshore applications. The experiments and 3D FE analyses have been performed to assess the ultimate vertical load capacity (V_{ult}) of bucket foundations. The experiments were conducted on loose sand and it shows that as the length of the skirt increases, the q_{ult} enhances. A conceptual relationship as a depth factor was suggested to estimate the V_{ult} of bucket foundations on the sand with regard to embedment ratio and soil friction angle. The FE analysis results have shown that the inner soil in the bucket foundation approximately behaves as a rigid body under the vertical loading. Therefore, it might be supposed that with similar dimension, the q_{ult} of embedded and bucket foundation is close. Moreover, it was found that due to the increase in the slip length of bucket foundation, the foundation failed in greater settlement than surface footing.

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1- Introduction

Nowadays, political and economic strategies are being pursued to make the most effective use of the power of offshore wind turbines, which besides being a rich source of renewable energy; it does not emit any emissions. Additionally, due to the immediate and increasing need for renewable energy, fewer fossil fuels are being consumed in order to put an end to the heavy reliance on fossil fuels.

The cost of the foundation of the offshore wind turbine (OWT) is a large part of the total cost of the superstructure and foundation of the wind turbine. Therefore, many researchers have been concentrated on the economic design of the foundation. Offshore wind turbines are commonly installed on either monopile foundations or gravity-based foundations (Randolph & Gourvenec 2011). The bucket foundation is a unique and innovative foundation, which is commonly denoted as a suction caisson or skirted foundation. In contrast to deep foundations, bucket foundations are easier to set up and costly and massive installation apparatus is not needed (Houlsby and Byrne 2000; Ibsen et al 2004).

Bucket foundations could be utilized instead of monopile foundations for the offshore facility, take for instance the offshore wind turbines. The bucket foundation has some skirts around the top plate which strictly confined the within soil. It leads to transfer superstructure load to the bottommost soil because the within soil behaves as a rigid body (Eid 2013). The diameter of this type of foundation

for wind turbines reaches to 30 m and the maximum value of embedment ratio of foundation, skirt length to foundation diameter (d/D), is often less than unity (Houlsby et al. 2005; Tjelta 2015). Foundation loads, soil conditions and installation methods might result in different d/D ratios. The schematic view of a bucket foundation is shown in Figure 1.

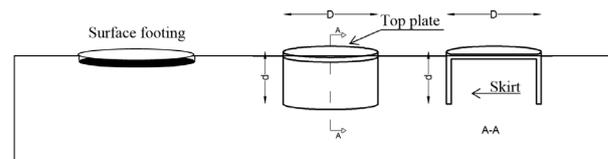


Figure 1. Schematic view of a bucket foundation and surface footing

Although many attempts have been made (Barari and Ibsen 2012; Ibsen et al. 2012) in order to study the behavior of shallow foundations, the bearing capacity (q_{ult}) of bucket foundations is a demanding and challenging subject. Owing to the internal mechanisms of inmost soil and the foundation embedment of bucket foundations, the evaluation of vertical and general bearing capacities requires to be expanded. Design guidance of offshore foundations is presented by the API (2000), DNV (1992) and ISO (2003) amongst others. The onshore design code has been established based on the classical bearing capacity theory which is applied for designing offshore shallow foundations (Barari & Ibsen 2012). Terzaghi (1943) proposed a method of finding the q_{ult} of shallow

Corresponding author, E-mail: haddad@semnan.ac.ir

foundation based on the limit-equilibrium technique by dint of an easy analytical way. Most of the conventional approaches utilized the limit-equilibrium theory to calculate the q_{ult} of foundations. As a result of sliding on a slip line, the foundation collapses and the soil weight would be fulfilled the collapse criterion. Blatantly, the longer the slip line, the greater the q_{ult} . The skirts around of bucket foundations could lead to the rise in the slip line's length and as a result, q_{ult} .

Bucket foundations are commonly subjected to combined loading. Therefore, the combined loading interaction diagrams on sands have been proposed to describe the behavior of bucket foundations (Cassidy et al. 2002; Ibsen et al. 2014; Martin 1994). The models have major components, including yield envelope in terms of three-dimensional (3D) loading space (V-H-M), hardening rule, and flow rule. The size of the three-dimensional yield envelop is controlled by the vertical load capacity of the foundation (Ibsen et al. 2014).

Quite a lot of experiments have been conducted to evaluate the qult of bucket foundations subjected to the vertical and general loading. 1-g physical experiments proved that the increase in the q_{ult} and the reduction in the settlement of foundations are the direct results of the inclusion of skirts (Ibsen et al. 2012; Al-Aghbari and Dutta 2008; Villalobos 2006). Due to the utilization of bucket foundations in European regions, most previous experimental studies have been conducted in medium dense to dense sand. Therefore, limited studies have been done on the q_{ult} of bucket foundations in loose sand. Villalobos (2006) reported that bucket foundations fail in the general failure mode in dense sand. Moreover, based on the work hardening plastic theory, an expression for yield surface was proposed to evaluate the behavior of bucket foundations. However, the case is different from loose sand and the bucket foundation penetrates into the sand and as the load increases, the foundation settlement increases.

Numerical investigations have been performed on the skirted foundation to study how the depth of embedment has affected the shape and size of yield locus. Moreover, in order to define the bucket foundation's behavior subjected to the general and vertical loading, several equations and charts were suggested (Bransby & Randolph 1999; Gourvenec 2008; Eid 2013; Barari et al. 2017). Collectively, these studies outline a critical role for the vertical load capacity on the size and shape of yield envelop of bucket foundations. The relationship between the V_{ult} of foundation and embedment ratio (d/D) has been widely investigated and it was demonstrated that it is dependent on the embedment ratio and soil relative density (Barari et al. 2017; Byrne and Houlsby 1999; Ibsen et al. 2012).

Depth Factor

Byrne and Houlsby (1999) performed some experiments to evaluate how the suction caisson foundation behaves in dense sand. They recommended a relationship to predict the V_{ult} of the suction caisson foundation. This formula which is also called depth factor has been devised on the basis of the Bolton and Lau's q_{ult} factors (1993) so as to estimate the bucket foundation's V_{ult} , as the Equation 1 (Byrne & Houlsby 1999):

$$\frac{V_{Bucket}}{V_{Surf}} = 1 + 0.89 \frac{d}{D} \quad (1)$$

where, $V_{surface}$ and V_{Bucket} stand for the vertical load capacity of surface footing and bucket foundation respectively, and the skirt length and the diameter of foundation are symbolized by d and D . The Equation 1 was proposed to predict V_{Bucket} with regard to d/D . The V_{ult} of foundation on cohesionless soil is commonly calculated on the basis of the Terzaghi's theory, the Equation 2:

$$V_{ult} = \left(\frac{1}{2} \gamma' DN_{\gamma}^* + qN_q^* \right) \left(\frac{\pi D^2}{4} \right) \quad (2)$$

in which, γ' and q stand for the effective unit weight of soil and the surcharge load at the footing base respectively. N_{γ}^* and N_q^* represent the V_{ult} factor for the circular foundation. In a study into the behavior of bucket foundations, Byrne and Houlsby (1999) stated that the V_{ult} of bucket foundation (V_{Bucket}) could be calculated from the sum of the V_{ult} of foundation and the frictional resistance between the skirt and the soil. Therefore, the V_{Bucket} can be presented by the Equation 3:

$$V_{Bucket} = \left(\frac{1}{2} \gamma' DN_{\gamma}^* + qN_q^* \right) \left(\frac{\pi D^2}{4} \right) + \left(\frac{\gamma' d}{2} K \tan \delta \right) (\pi D) \quad (3)$$

where δ is the angle of the friction wall and K is the coefficient of the earth pressure. In order to express the depth factor for the bucket foundation, the normalized form of V_{Bucket} is presented in Equation 4:

$$\frac{V_{Bucket}}{V_{Surface}} = 1 + \frac{2d}{DN_{\gamma}^*} \left(N_q^* + \frac{2d}{D} K \tan \delta \right) \quad (4)$$

In contrast with the value of N_q^* , $K \tan \delta$ has a small value for a typical soil which is less than 0.3. Therefore, the $K \tan \delta$ term in Equation 4 can be ignored and the Equation 4 can be rewritten by the following equation:

$$\frac{V_{Bucket}}{V_{Surface}} = 1 + \left(\frac{2N_q^*}{N_{\gamma}^*} \right) \cdot \frac{d}{D} = 1 + (n) \cdot \frac{d}{D} \quad (5)$$

According to Equation 5, the growth in the embedment ratio (d/D) results in an increase in the capacity of the bucket foundation. Moreover, it is obvious from Equation 5 the fitting parameter "n" ($n = N_q^*/N_{\gamma}^*$) depends on the friction angle of soil.

Ibsen and Barari (2012) re-examined the depth factor proposed in Equation 1 and it was reported that Equation 1 was inaccurate for foundations in sand. Therefore, on the basis of a recommended expression of N_{γ} and the soil friction angle of dense sand, they modified the Equation 1 as the following equation:

$$\frac{V_{Bucket}}{V_{Surf}} = 1 + 2.1 \frac{d}{D} \quad (6)$$

The V_{Bucket} was reported to increase linearly with the embedment depth by Barari et al. (2017) who proposed a suite of depth factors and the following equations for dense, medium dense and loose sands, which are based on

FE analyses:

$$\begin{aligned} (V_{Bucket} / V_{Surf})_{Dense\ sand} &= 1 + 2.5(d / D) \\ (V_{Bucket} / V_{Surf})_{Medium-Dense\ sand} &= 1 + 2.2(d / D) \\ (V_{Bucket} / V_{Surf})_{Loose\ sand} &= 1 + 2(d / D) \end{aligned} \quad (7)$$

In order to determine the V_{Bucket} , Barari et al. (2017) utilized the limited settlement criterion, which defined the V_{ult} as the load at a certain settlement, 0.1D. In an investigation into the scale effect on bearing capacity factors, Cerato and Lutengger (2007) utilized this criterion to determine the V_{ult} of surface footing. They stated that the limited settlement criterion is a completely arbitrary method to define V_{ult} and it would lead to reasonable results. Whereas Vesic (1975) demonstrated many foundations fail in the settlement ratio of less than 10 %, but in the case of the loose to medium one, the ultimate V_{ult} might reach a bigger ratio up to 30%. It was reported that the limited settlement criterion might produce an unrealistic result. Vesic (1975) proposed the minimum slope failure load criteria to find the V_{ult} . This criterion defines the failure load at the point where the slope of the load-displacement curve reaches zero or constant. Paikowsky et al. (2010) based on extensive investigations suggested the minimum slope criterion as the failure criterion for all foundations, including those with the general loading.

The fitting parameter value (n) proposed in Equation 7 for medium to dense sand corresponds reasonably to the previous experimental results and the theoretical relationship which was proposed in Equation 5. However, it's likely to have the inaccurate "n" value for loose sand in Equation 7 which may lead to irrelevant results.

It has been reported that with the equivalent depth, the V_{Bucket} is a little less than an embedded foundation by Eid (2013) and Barari et al. (2017). Therefore, a graph (Figure 2) has been drawn through various derived "n" values versus the soil friction angles. Moreover, the fitting parameters "n" were derived for a range of relative densities (Table 1). It is obvious from Table 1 and Equation 5, the fitting parameter n grows with the decreasing of soil friction angle and no precise value of fitting parameter n could be extracted for the related friction angles. The greater values of n indicate the better performance of the bucket foundation in loose sand in comparison with dense sand. Equation 5 was derived for an embedded foundation (Eid 2013; Barari et al. 2017). Therefore, duo to the behavior of within soil under vertical load, it might be corrected for a bucket foundation.

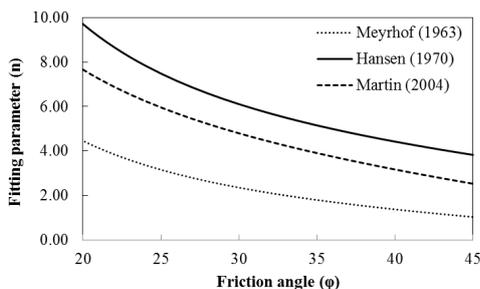


Figure 2. Fitting parameter (n) was derived from the soil friction angle

Table 1. Fitting parameter (n) of depth factor for the foundation in sand

	Method of Modeling	Relative density (%)	n
Meyerhof (1963)	Therotical	80	1.37
		55	1.79
		35	2.10
Hansen (1970)	Therotical	80	4.42
		55	5.15
		35	5.69
Martin (2005)	Therotical	85	3.02
		55	4.31
		35	4.91
Byrne and Houlsby (1999)	Physical	> 80	0.89
Villalobos (2006)	Physical	83	2.14
		47	3.00
		40	4.00
Eid et al. (2009)	Physical	71	1.15
		57	1.70
		44	2.55
Ibsen et al. (2012)	Physical	> 80	2.10
Barari et al. (2016)	Numeical-Physical	80	2.50
		55	2.20
		40	2.00

The Aim of the Study

Most studies have only focused on the q_{ult} of shallow foundations; which is a topic that has been extensively studied and approached by researchers. The V_{Bucket} in sands, especially in the loose-saturated sand is not widely investigated and the majority of the previous studies have been carried out on the medium to dense sands (Villalobos (2006); Eid (2009)). The failure mode of foundations in the compressible soil almost is punch-shear mode and finding a unique failure load is difficult. Furthermore, owing to the greater depth of bucket foundations, those foundations in the sand with low relative density often fail in punch-shear mode.

Therefore, the V_{Bucket} is more challenging to find than that of shallow foundations.

The difficulties in finding the V_{Bucket} are investigated in this research using a series of experimental tests and FE analyses. Our work aims to propose a general expression as a depth factor to predict the V_{Bucket} on the basis of the friction angle and the embedment ratio (d/D).

Testing program

To understand the V_{Bucket} in loose sand and propose a depth factor of bucket foundation, a loading setup and soil container (0.9×0.9×1.2 m³) at Semnan University was used to model the soil-foundation model (Figure 3). To avoid boundary effects on the experimental results, the dimensions of the container were selected based on the size of the foundation models. Therefore, the width and height of the container were selected four times bigger than the foundation diameter in order to neutralize any possible impacts of the rigid-bottom of container. Based

on the results, the height does not affect the V_{Bucket} . The schematic view of the loading system is illustrated in Figure 4.



Figure 3. Experimental setup

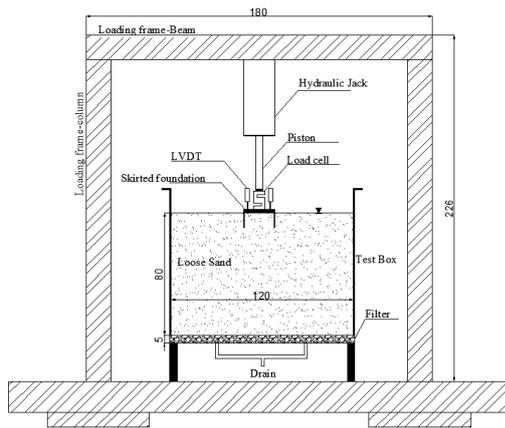


Figure 4. Model test (dimensions in cm)

The foundation models were made as a rigid body through using some open-ended steel cylinders 10 and 20 cm in diameters (D) and 2 mm thick with a top plate whose thicknesses is 5 mm. The foundations were too stiff to let the plates deflect; hence, the V_{Bucket} would not be affected by the foundation deformation. Based on the range of bucket foundations encountered in the field, the maximum value of embedment ratio (d/D) was chosen 1.

Babolsar sand with low relative density was utilized for the experiments. The soil was obtained from Babolsar shores in the northern areas of Iran. Table 2 shows the characteristics of the sand which is categorized as a poorly graded sand (SP) in the Unified Soil Classification System. Figure 5 demonstrates the grain size distribution of Babolsar sand.

In order to make the model sand deposits with a low relative density about 35% inside the container, the water

pluviation method was utilized (Lagioia et al. 2006; Wood et al. 2008). The water level in the soil container was at the ground level.

Table 3 presents the testing program that has been conducted on the foundation's models with different skirt lengths and diameters. The foundation models were mounted on the center of the soil container. A vertical load was applied by a hydraulic jack, which has connected on the top plate of foundation. Then, a load-cell was placed on the top of the foundation to measure the load. Moreover, two LVDTs were positioned on two sides of the foundation model to measure the foundation displacement. The settlement was obtained from the average readings of the LVDTs. The load of each foundation was performed to the maximum load at a constant rate of penetration of about 0.05 mm/s. An 8-channels data logger recorded the displacements and load-carrying of foundation model.

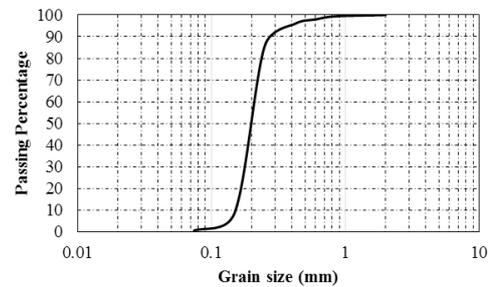


Figure 5. Particle size distribution curve of Babolsar sand

Table 2. Characteristics of Babolsar sand

Case	Diameter, D (cm)
Minimum void ratio, e_{min}	0.54
Maximum void ratio, e_{max}	0.73
coefficient of uniformity, C_u	1.68
coefficient of curvature, C_c	0.87
Specific gravity, G_s	2.73

Table 3. Testing program

Case	Diameter, D (cm)	Skirt length, d (cm)	d/D	Relative density, %
1	10	0	0	35-40
2	10	5	0.5	35-40
3	10	10	1	35-40
4	20	0	0	35-40
5	20	10	0.5	35-40
6	20	20	1	35-40

Experimental Results

The variations of load versus settlement for bucket foundations and surface footings, with the foundations 10 and 20 cm in diameter, are shown in Figure 6. These curves reveal that by growing the embedment ratio (d/D), the V_{ult} rises. Besides, the skirts through confining the within soil make a reduction in the settlement. Foundation models in all tests failed in punching shear and no failure patterns were observed during the loading test. Therefore, there is no peak point to be considered as the V_{ult} in the load-settlement curve.

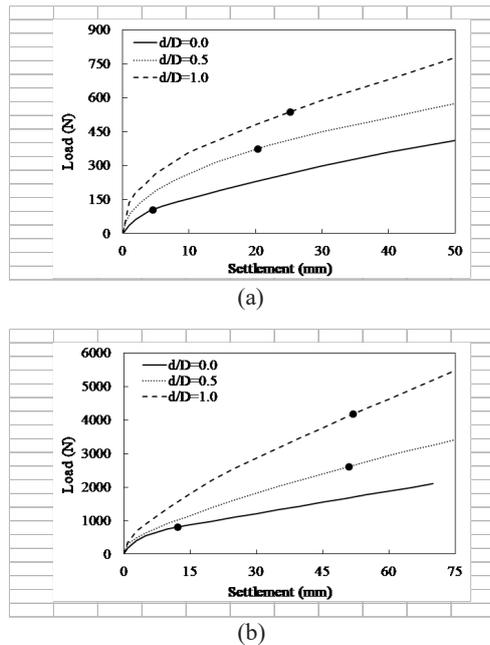


Figure 6. Load-settlement relationships for foundation models: (a) D=10 and (b) D=20 cm

The ultimate load of each test was obtained from the minimum slope failure load criteria, Vesic (1975). According to this method, Figure 7 was drawn to illustrate one example of finding the V_{ult} on the load-settlement curve. Table 4 presents the V_{ult} was obtained from the limited settlement criterion, the minimum slope failure load criteria and the corresponding settlement (S) of experimental tests at failure load. Obviously, the capacity of foundations was derived by the minimum slope failure load is bigger than those by the limited settlement method.

In comparison to the surface footing, bucket foundations failed at the higher settlement ratio (S/D), that, S stands for the settlement of the foundation. A possible explanation for this might be that due to the foundation embedment depth; the length of the slip line of the bucket foundation is higher than the surface footing. Figure 8 provides the settlement ratio vs the embedment ratio (d/D).

An experimental relationship was suggested to determine the V_{Bucket} in the loose sand based on the embedment ratio and the $V_{Surface}$ as the depth factor, Equation 8 (Haddad et al. (2018)):

$$\frac{V_{Bucket}}{V_{Surface}} = 1 + 4.49 \cdot \frac{d}{D} \quad (8)$$

Compared to the depth factor in dense sand, greater values for the fitting parameter “n” was found in loose sand.

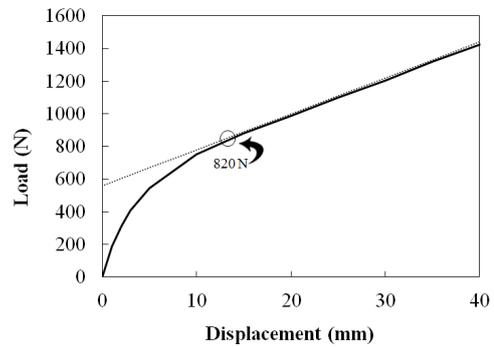


Figure 7. Utilization the minimum slope criterion for finding of bearing capacity (case 4)

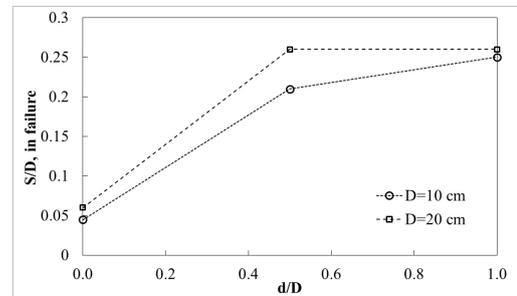


Figure 8. Settlement ratio of bucket foundation versus embedment ratio (d/D)

Numerical Modeling

FE analyses were performed using the PLAXIS 3D 2016 on a prototype foundation system to study how the bucket foundation subjected to the vertical loading behaves. The V_{ult} of a variety of surface footing, the bucket foundation and solid embedded foundation in diameter of $D=10$ m and a variety of skirt lengths was investigated. The solid embedded foundation was modeled like a bucket foundation except that its bottom is close and soil cannot penetrate into the foundation. The soil with a range of relative densities was simulated as an elastic-perfectly plastic model, Mohr-Coulomb failure criterion. The soil properties are given in Table 5 (Look 2013). The foundation model was modeled as an almost rigid element. Previous studies have said that the young modulus and Poisson’s ratio affect the load-settlement response of foundation and have no effect on the V_{ult} (Diaz-Segura (2013) and Loukidis and Salgado (2009)). In all cases, a small value (about 0.1 kPa) for soil cohesion was assigned to the soil to avoid model instability. Sensitive analysis showed that the effect of a small value of cohesion on the qult could be ignored. In numerical modeling of bucket, the modulus of elasticity and Poisson’s ratio of steel material were assigned $E=210$ GPa, $\nu=0.2$, respectively. Moreover, the thickness of the skirt (t_s) was considered 0.03 m.

Table 4. Experimental results: Measured capacity and corresponded settlement of foundations

Case	Foundation Diameter, D (cm)	Embedment ratio (d/D)	Bearing capacity (N)	Settlement at failure, S (mm)	Settlement Ratio (S/D)
1	10	0	95	4	0.04
2	10	0.5	360	21	0.21
3	10	1	535	25	0.25
4	20	0	820	12	0.06
5	20	0.5	2794	52	0.26
6	20	1	4103	52	0.26

Table 5. Soil properties in numerical modeling

Parameter	Loose sand	Medium dense sand	Dense sand
Unit weight (kN/m ³)	19.97	20.25	20.63
Relative density (%)	30~40	50~70	80~100
Friction angle (φ)	30	35	40
Dilatancy angle	2	6	12
Young modulus (MPa)	20	45	75
Poisson's ratio (ν)	0.4	0.4	0.4

The interface elements were utilized between the foundation and soil with contact friction angle (δ) which was chosen two-thirds of the internal friction angle (Achmus et al. 2013). To evaluate the V_{ult} , at the first step, the geo-static stress field is applied in the FE model. After that, the foundation is modeled that the installation process is ignored and it is modeled to be wished in place. In the last step, a vertical prescribed settlement is applied at the top of the foundation to determine the V_{ult} , which is obtained as the sum of the reaction force across the entire foundation width.

A sensitive analysis was conducted to guarantee the capacity of the foundation, which is independent of the size of the mesh element. The mesh comprises 9,500 wedge continuum elements. Based on the sensitive analysis, the vertical and horizontal boundary conditions were selected at a distance 6 times as long as the diameter of the foundation. The prototype foundation, FE mesh and the boundary condition are demonstrated in Figure 9.

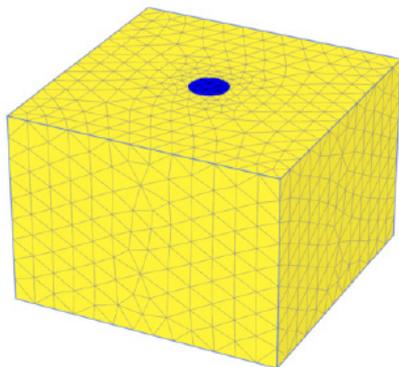


Figure 9. Mesh discretization

Back-calculations of the results of experimental tests in this study were simulated in 3D FE analysis to verify the numerical model and a reasonable agreement was found. It was preferred to utilize the results of full-scale foundations to verify the model instead of small-scale models. However, limited reports have been reported about large-scale field tests that are relevant to the bucket foundation subjected to the vertical loading.

In Figure 10a, the capacity factor ($N\gamma S\gamma$) of the surface circular foundation with $D=10$ m for the associated flow rule is compared with the resulting bearing capacity factor ($N\gamma S\gamma$) from the characteristic method. This was done using the program ABC (Martin 2005) and the results of the limit analysis by Lyamin et al. (2007) which were derived from the upper and lower bound analyses. The calculated bearing capacity factor ($N\gamma S\gamma$) is placed between the values of lower and upper bound solutions. Figure 10b compares the resulting bearing capacity factor ($N\gamma S\gamma$) for the non-associated flow rule with the values from FE analyses of Loukidis and Salgado (2009). It was found that the results of numerical modeling within this study are in good agreement with the previous studies. Due to the fact that the exact solutions of the bucket foundation are unavailable, the numerical model was verified for the shallow foundation. Therefore, it was utilized to model the bucket and shallow foundations.

Comparison of Solutions

A total of 15 FE simulations were conducted to find the vertical load capacity and the depth factor of bucket foundations. Three types of foundations including surface footing, bucket foundation and embedded solid foundation were simulated for three pairs of ϕ and ψ and three d/D ratios.

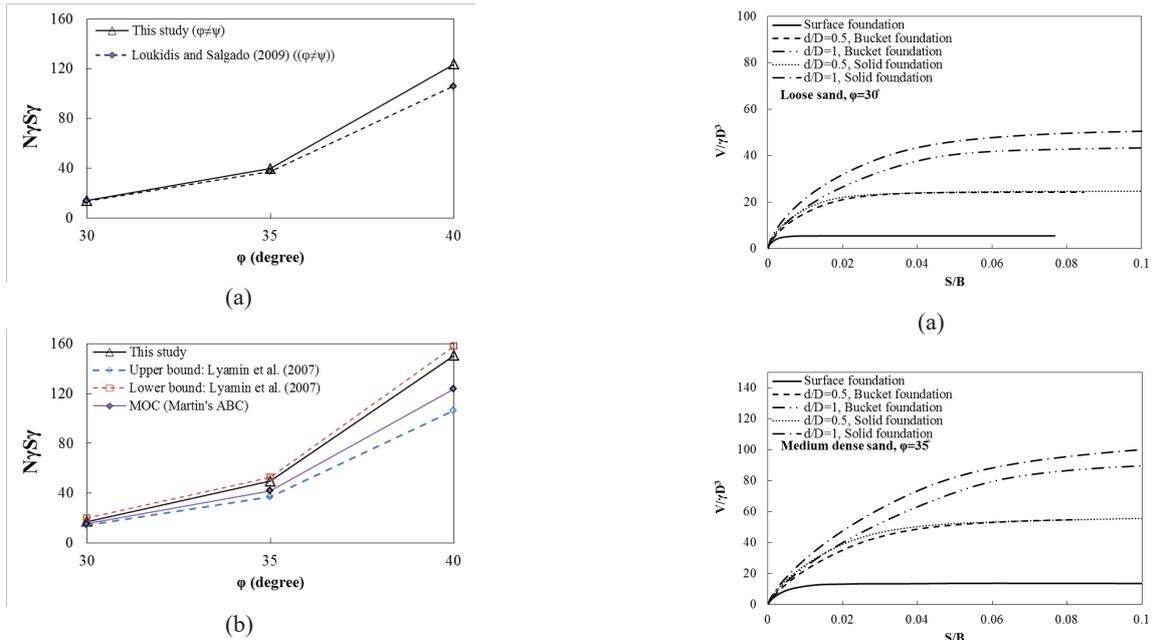


Figure 10. Verification of the numerical model with previous studies results ($d/D=0$): (a) associated flow rule, (b) non-associated flow rule

Figure 11 presents normalized load-settlement curves of the bucket foundations and the embedded solid foundations for different d/D ratios. It was illustrated in Figure 11, for all FE analysis models, the V_{Bucket} enhances with an increase in embedment ratio (d/D).

Figures 12 and 13 demonstrate the soil displacement around the surface footing, bucket foundation and embedded foundation for $d/D=1$ and $\phi = 35$. The deformation mechanism of bucket foundation is approximately similar to the embedded foundation where the failure surface was expanded into the soil zones above the level of foundation base. The only difference between the two foundations is the existence of the soil within. However, as it is illustrated, a larger portion of the surrounding soil of embedded foundation is deformed and leads to a larger wedge, which can increase the bearing capacity. The almost similar mechanisms for the embedded and bucket foundations denote that the V_{ult} of the bucket foundations is close to those of embedded foundations.

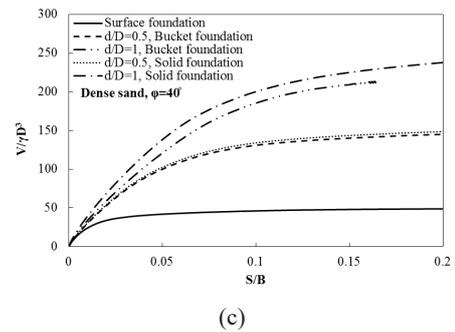


Figure 11. Normalized load-settlement of bucket and embedded solid foundation: (a) loose sand, (b) medium dense, and (c) dense

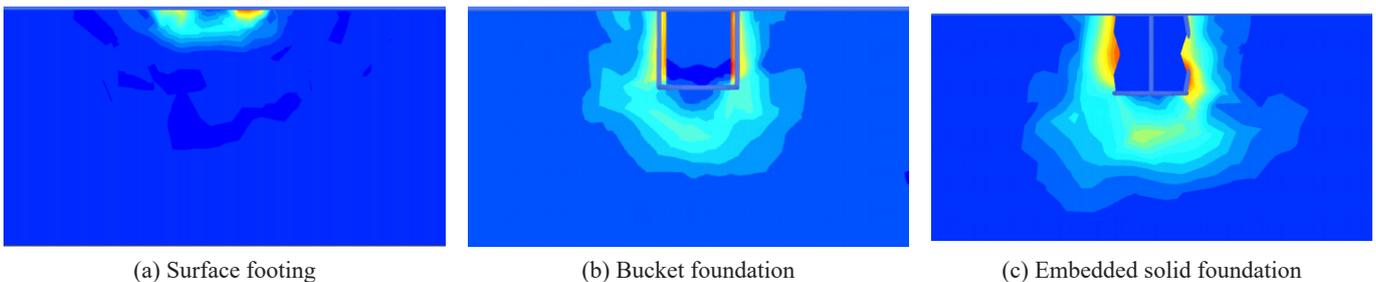


Figure 12. Failure mechanism

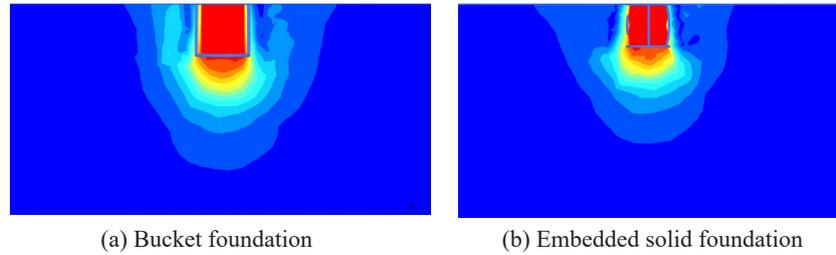


Figure 13. Displacement around of foundation

Due to the lateral confinement of the skirts of bucket foundation, it can be observed that the volumetric strain of the soil inside foundation is limited under the vertical loading and can be assumed that its behavior is like a rigid body. A similar conclusion has been reported for the bucket foundation in clay (Yun & Bransby 2007) and in sandy soils (Eid 2013; Barari et al. 2017; Park et al. 2016). A comparison of the curves reveals that the bucket foundation subjected to vertical loading behaves like the embedded foundation, which explains the negligible difference in collapse loads. It can be seen from the data in Table 6 that the V_{Bucket} with the embedment ratios (d/D) 0.5 and 1 are about 3% and 18% less than the V_{ult} of embedded foundation, respectively.

The numerical results were compared to the experimental results on the depth factor, which were presented by Byrne and Houlsby (1999); Eid et al. (2009) and Villalobos (2006). Figure 14 presents the capacity ratio ($V_{\text{Bucket}} / V_{\text{surf}}$) versus the embedment ratio (d/D). Interestingly, it was found that the capacity ratio is a linear function of the embedment ratio (d/D) and it is associated with the soil friction angle. The results indicate that the value of

depth factor is greater than one and a reverse relation exists between the depth factor and the friction angle (ϕ). Figure 15 illustrated the “n” values versus the friction angle of soil. A meaningful relation was found between the “n” parameter and the tangent of the soil friction angle. Concerning the numerical modeling results, which are presented in Figure 15, the Equation 9 for the “n” can be proposed:

$$n = -7.45 \ln(\tan(\phi)) + 2.052 \quad (9)$$

be expressed as the Equation 10 for sand with various relative densities:

$$\frac{V_{\text{Bucket}}}{V_{\text{Surface}}} = 1 + (-7.45 \ln(\tan(\phi)) + 2.052) \cdot \left(\frac{d}{D}\right) \quad (10)$$

The experimental as well as numerical results reveal the significantly greater amount of fitting parameter “n” for loose sand in comparison to those values in dense sand. In other words, for a similar foundation, the skirt has far greater impact on the V_{ult} in loose sand than dense sand.

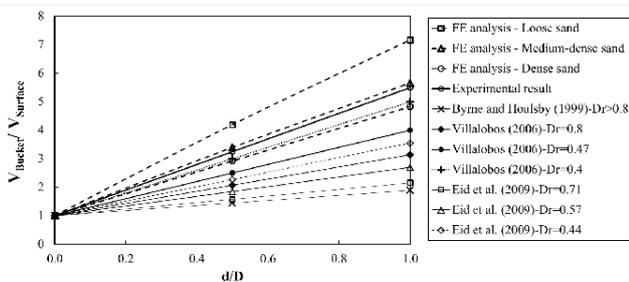


Figure 14. Normalized vertical load capacity versus embedment ratio

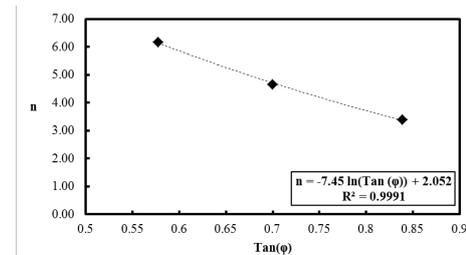


Figure 15. Fitting parameter (n) obtained from numerical modeling based on friction angle

Table 5. Soil properties in numerical modeling

Foundation	Soil density	Embedment ratio (d/D)	
		0.5	1
Bucket foundation	Loose	484	780
	Medium dense	1098	1760
	Dense	2900	4253
Embedded solid foundation	Loose	494	1020
	Medium dense	1145	2060
	Dense	2970	5100

2- Conclusion

This study aimed to realize how the embedment and failure mode affect the V_{ult} of bucket foundations. To achieve this purpose, a series of FE analyses were done on the bucket and embedded foundations to simulate how they act in sand with a range of relative densities. In addition, an experimental system was utilized to find the V_{ult} of bucket and embedded foundations in loose sand with different diameter and skirt depth. On the basis of the experimental investigations and FE simulations, the following conclusions are drawn:

- The skirts around the foundation heighten the capacity of foundation in sand since it increases the failure line length and confines the underlying soil.
- The result of the study reveals that the inner soil in the bucket foundation approximately acts as a rigid body under the vertical loading; therefore, the V_{ult} of bucket foundations is almost similar to equivalent solid embedded foundations.
- The settlement of surface footing at the failure load is equal to 6 to 12 percentage of the foundation diameter ($s/D=6\sim 12\%$). However, due to an increase in the slip length and the failure mechanism of bucket foundation, it failed in a greater settlement ($s/D=20\sim 30\%$).
- A technical term, which is called depth factor, was introduced to estimate the V_{Bucket} in sand. The depth factor depends on the embedment ratio (d/D) and the soil friction angle.

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