Effect of Embedment on the Vertical Bearing Capacity of Bucket Foundations in Clay

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ABSTRACT
To evaluate the undrained behaviour of bucket foundations installed on Yoldia clay, 100 tests on bucket foundations subject to vertical and moment loadings were conducted at Aalborg university geotechnical centre. Bucket foundations are tubular steel foundations that are installed by sealing the top and applying suction inside the bucket. The hydrostatic pressure difference and the deadweight cause the bucket to penetrate the soil. In the present study, results of an experimental study addressing the effect of embedment (skirt length to the diameter) on the undrained bearing capacity of bucket foundations under vertical loading are reported. The field tests have been accompanied by the finite element numerical simulations in order to provide better understanding of influential parameters on the behavior of bucket foundations.

RÉSUMÉ
Pour évaluer le comportement non drainé des fondations seau installé sur terre battue Yoldia, 100 tests sur des bases seau sujet à des charges verticales et le moment ont été menées au centre de l'Université d'Aalborg géotechnique. Seau fondations sont des fondations en acier tubulaire qui sont installés par sceller le dessus et d'appliquer le vide à l'intérieur du seau. La différence de pression hydrostatique et le port en lourd cause le seau à pénétrer dans le sol. Dans la présente étude, les résultats d'une étude expérimentale portant sur l'effet d'encastrement (longueur de la jupe au diamètre) sur la capacité portante des fondations non drainées seau sous chargement vertical sont signalés. Les essais au champ ont été accompagnés par les simulations numériques par éléments finis afin d'assurer une meilleure compréhension des paramètres influents sur le comportement des fondations seau.

1 INTRODUCTION

Skirted foundations are shallow foundations in which the footing is reinforced by the addition of vertical plates, or skirts. Traditionally, bearing capacity studies have focused on vertical loading (Prandtl 1921; Hill 1950).The proposed relationship presented by Terzaghi (1943) is modified by the addition of several correction factors (e.g. depth, shape and inclination factors) (Meyerhof 1951, 1953; Brinch Hansen 1970).

Tani and Craig (1995) have given a detailed summary of the bearing capacity studies on offshore foundations, although most of them were limited to the surface foundations. They presented a few findings related to the skirted foundations on non-homogeneous soil, using stress characteristics approach. Al-Aghbari and Mohamedzein (2004) developed a modified bearing capacity equation for skirted strip foundations on dense sand. A series of tests on foundation models were carried out to study the factors affecting the bearing capacity of foundations with skirts. However, their work lead to presenting several factors including foundation base friction, skirt depth, skirt side roughness, skirt stiffness and soil compressibility incorporated in the general equation for bearing capacity. It is also studied the circular skirted offshore foundations on non-homogeneous soil through several works. Hu et al. (1999) studied the bearing capacity of the skirted foundations with degree of non-homogeneity (kD / s_u) of soil up to 30 as well as the skirt roughness and embedment ratio up to 5 times the foundation diameter. Additionally, Yun and Bransby (2007) reported the numerical work specifically for investigating the effects of the embedment ratio on the horizontal-moment foundation capacity under no vertical load in both uniform strength and normally consolidated undrained soil.

Due to foundation cost in connection with offshore wind turbines as high as up to 30% of the total costs, the foundation design is presently undergoing large attention with the increased interest in offshore wind turbines (Kelly et al. (2003)). Large cylindrical structures constructed by steel that is open at the base and closed at the top are called bucket foundations which are recently being used in offshore wind turbines, see Figure 1. The cylindrical part is denoted “bucket skirt” and upper plate that closes the bucket is denoted “bucket lid” or “top plate”. In the present study, the ultimate limit states under vertical loading are presented in terms of loads non-dimensionalised by the foundation geometry and soil undrained shear strength.

Figure 1. Sectional view of bucket foundation

2. PROTOTYPE OF BUCKET FOUNDATIONS

The bucket foundation is a welded steel structure consisting of a tubular centre column connected to a steel bucket through flange-reinforced stiffeners (intermediate part, see Figure 2). The stiffeners distribute the loads from the tubular centre column to the edge of the bucket. The wind turbine tower is connected to the tubular centre column with a flange connection. The lower part of this flange connection is welded on the tubular centre column during the production of the bucket. No transition piece is therefore needed. The wind turbine tower is connected to the flange above mean sea level.

The steel bucket consists of a vertical steel skirt extending down from a horizontal base resting on the soil surface. The prototype of the bucket foundation is shown in Figure 2.The bucket is installed by means of suction. Lowering the pressure in the cavity between the bucket and the soil surface causes a water flow to be generated, which again causes the effective stresses to be reduced around the tip of the skirt and the penetration resistance is reduced. When the bucket foundation has been installed, the loads from the wind on the wind turbine will cause the foundation to be influenced by a large moment. The stability of the foundation is ensured by a combination of earth pressures on the skirt and the vertical bearing capacity of the bucket.

It is important to realize that the loading regimes on offshore turbines differ in important respects from those on structures usually encountered in the offshore oil and gas industry. Firstly the structures are likely to be founded in much shallower water: 10 *m* to 20 *m*. Typically the structures are relatively light, with a mass of around 600 *t* (vertical dead load 6 *MN*), but in proportion to the vertical load, the horizontal loads and overturning moments are large. For instance the horizontal load under extreme conditions may be about 60% of the vertical load, as discussed by Houlsby et al. (2005).

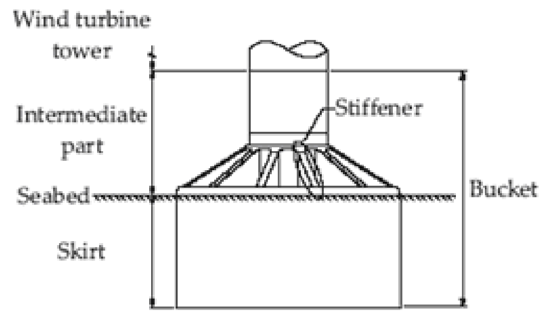

Figure 2. Definitions and illustration of the prototype of the bucket foundation in Frederikshavn

In November 2002, the first bucket foundation for a fully operational wind turbine was installed at the offshore test facility in Frederikshavn, in the northern part of Jutland, (Figure 3). The project is described in Ibsen et al. (2005). The wind turbine is a Vestas V90-3.0MW turbine and was at the time being the largest wind turbine in Denmark with a total height equal 125 *m*. The diameter and the skirt length of the bucket foundation are equal 12 *m* and 6 *m* respectively, and the total weight of the foundation is 135 tons. The bucket foundation prior to installation is shown in Figure 4. The installation of the bucket foundation was carried out by the geotechnical department at Aalborg University.

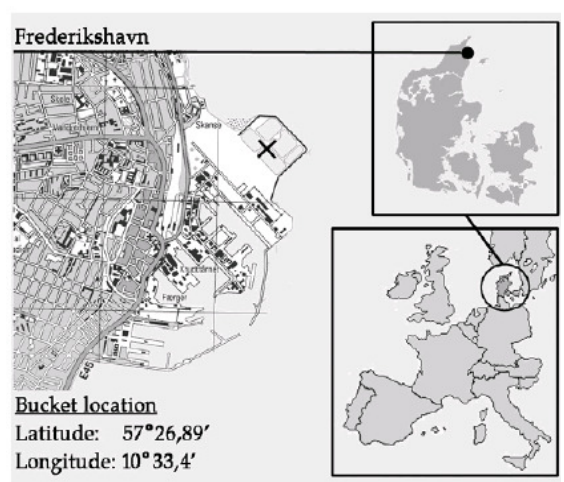

Figure 3. Location of Vestas V90-3.0MW wind turbine on bucket foundation

Figure 4. Bucket foundation for Vestas 3MW wind turbine in Frederikshavn

3 EXPERIMENTAL INVESTIGATIONS

3.1 Preparation of the Test Setup

Carrying out the vertical loading on bucket foundations is like the plate load tests presented in previous work (Ibsen and Barari, 2011a). Installation is performed by using a hydraulic cylinder until the underside of top plate reach to a direct contact with the ground. The engine associated with the loading is subsequently chosen equivalent to the plate load tests (Ibsen et al. 2011a). The bucket experiments used the same measuring equipments which were used for plate load tests including two sensors with a gauge length of 1.000 *mm* and a 5 ton load cell. The experimental data is collected via the Catman.4 program which records the signals from the instrumentation. Within the experimental arrangement, at least 10 *cm* of ground surface in the area of approximately 180×150 *cm* has been removed to reach the undisturbed clay. The experimental feature is then set and anchored with four ground anchors. The area is stretched to reach the flat surface for running the tests. To ensure full contact between the underside of the bucket foundations and the top plate, the ground surface has been filled by a tiny layer of sand (Figure 5).

Figure 5. Bucket foundation before and after installation

Installation of bucket foundation is performed with an average speed of 1.4 *mm/s*, which is relatively the same as former experiments conducted on sand at Aalborg University (Ibsen et al. 2011b, 2011c). The hydraulic cylinder is then removed and the engine is subsequently mounted to the read beams (see Figure 5).

In the vertical loading experiments, it has been necessary to modify slightly the engine setup to prevent the rotation of threaded rod. Therefore, a stiffening hanger is produced as shown in Figure 6.

Three different diameters as 20, 30 and 40 *cm* are chosen for empirical investigation of bucket foundations. The experiments conducted on plate load tests with diameter 40 *cm* resulted in failure around soil edges, which led to the setup slowly began to rise from the surface (Figure 7). Failure at soil edge is occurred at a load around 50 *KN*. Due to the aforementioned fact, the loadings are therefore conducted on bucket foundations with 20 and 30 *cm* diameters, while the experimental area is also chosen as $100 \times 150 cm$.

Figure 6. Setting up the hanger bar

Figure 7. Plate load test on 40 *cm* circular surface foundations

3.2 Experimental Results

This section presents a summary of the experiments on Yoldia clay in Grinsted. As discussed above, the bucket foundations with diameters of 20 and 30 *cm* with embedment ratios equal 0.25, 0.50, 0.75 and 1 were finally considered for the empirical investigations (Figure 8).

Figure 8. Bucket experiments with 30 *cm* foundation with 25 % embedment ratio

From the obtained four experimental load-displacement curves, it can be seen that bearing capacity is roughly the same amount along the embedment ratios of 0.25, 0.75 and 1. Only bearing capacity of foundation with 0.5 skirt length ratio does not follow this trend (Figure 9).
For the experiments with 30 *cm* diameter, it can also be observed that the bearing capacity of four different skirt lengths do not vary significantly as shown through figure 10.

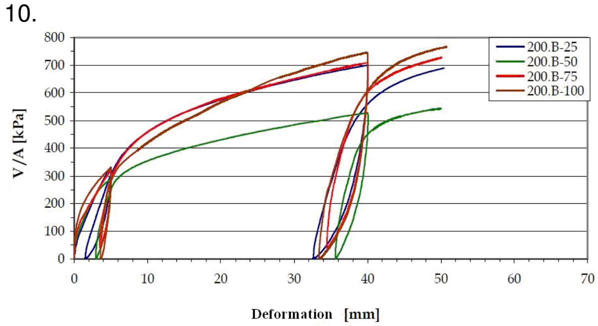

Figure 9. Vertical capacity curve for 20 *cm* bucket with four embedment ratios

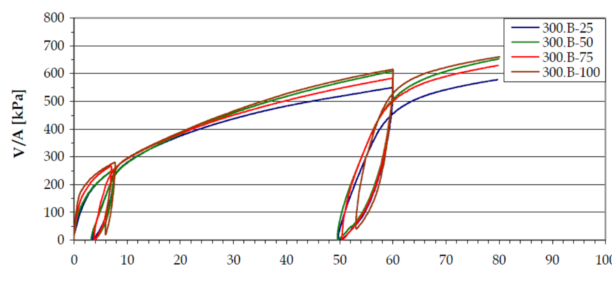

Figure 10. Vertical capacity curve for 30 *cm* bucket with four embedment ratios

4. RESULTS AND DISCUSSIONS

In order to show the effect of embedment ratio on the bearing capacity, the failure values under pure vertical loading have been analyzed numerically as well. Two dimensional finite element model of the test apparatus described in the previous sections was developed in order to study the behaviour of bucket foundations in clay more closely. In order to take advantage of symmetry, only half of the problem extent was considered in an axisymmetric model. The elastic-purely plastic Mohr-Coulomb model was selected to simulate soil behavior. The physical and mechanical properties of the clay were obtained from laboratory tests performed on samples taken from the field. These properties are E, c_u, $\nu = 0.495$ and γ=19 respectively which were discussed in details within the work presented by Barari and Ibsen (2011).

The undrained shear strength and elasticity modulus values of the soil were varied in a parametric analysis in order to investigate the ultimate limit states for the bucket foundation under vertical loading. For the numerical simulation, different values of c_u have been analyzed to achieve the best fit curves with the experimental data (Figure 11). The similar procedure was followed varying the modulus of soils as 25%, 30%, 40%, and 50% and E_{25} is then chosen to reach the best agreement with the field data.

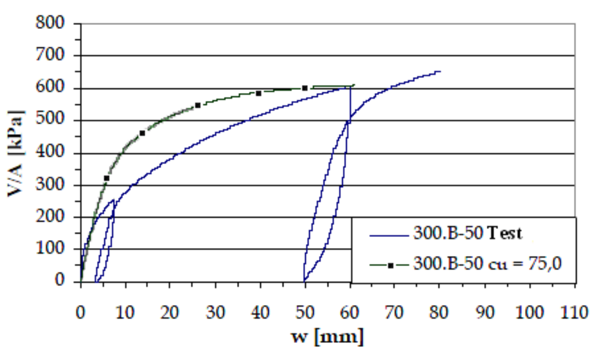

Figure 11. Load-displacement curves for bucket foundation with 30 *cm* diameter (E_{25} =9411 *kPa*)

Tables 1 and 2 depict the values of the ultimate vertical load (F_{Vult}) for surface and bucket foundations on Yoldia clay in two cases as 20 and 30 *cm* diameters evaluated by finite element analyses in comparison to the data available within the literature. The bucket foundation with skirt length ratio of 0.5 has been chosen for validation of the results. The ultimate bearing capacity under pure vertical load (F_{Vult}) for the circular surface foundation on the Yoldia Clay was calculated as 76.6 and 132.5 for the diameter lengths of 20 and 30 *cm* respectively which shows close examination with the exact solutions proposed by Shield et al. (1955) and Gourvenec and Randolph (2002).

The behaviour shown through figures and tables is due to significant sensitivity of bearing capacity to the skirt length ratios (e.g., 37 % increase in pure bearing capacity for the two cases as *D/B*=0 and *D/B*=0.5).

It is also shown that the numerical failure values obtained for the bucket foundation give an excellent agreement with the plasticity stress characteristics values presented by Houlsby and Wroth (1983) while current solutions are upper bound, unless it can be shown that lower bounds exists with the same failure values. In addition, the finite element results for bucket foundation has been validated with the plasticity ones presented by Martin (2001) for circular foundations and surprisingly, the collapse load for circular foundations obtained by plasticity solutions fall just below the numerical and experimental simulations conducted bucket foundations on.

Fig. 12 shows the variation of normalized vertical limit state ($N_{cV} = (\frac{V_{ult}}{Dc_u})$) for bucket foundation studied through current contribution by changing in embedment ratios (*d/D*), while the comparisons with the previous numerical analyses in the literature for the circular foundations (Bransby and Randolph, 1999; Gourvenec, 2008) have been illustrated. The results are normalized with respect to the area of the foundation (i.e., for plane strain area is equal to the diameter), and the undrained shear strength.

Several researchers recommended the conventional depth factors for smooth-sided circular foundations, but the applications show their capability for developing to even rough and smooth sided types.

For pure vertical loading, they have approximated the depth factor for strip or circular foundations as a linear fraction relative to *d/D* (skirt length to width or diameter) (Meyerhof, 1953; Brinch Hansen, 1970).

$$d_{cV} = 1 + n(\frac{d}{D}) \quad (1)$$

$0.2 \subseteq n \subseteq 0.4$

The above mentioned results from experimental and finite element analyses present quadratic relationship between ultimate uniaxial vertical load and embedment ratio which can be presented as depth factor:

$$d_{cV} = 1.0036 + 0.7138\frac{d}{D} - 0.0766(\frac{d}{D})^2 \quad (2)$$

Eq.2 has been verified only for embedment ratios between 0 and 1 as well. Interestingly, the results obtained above have shown that for pure vertical bearing capacity, load-displacement curves change corresponding to the foundation type and skirt length ratio.

Tani and Craig (1995) carried out lower bound plasticity analyses and centrifuge tests to investigate the vertical capacity of skirted foundations in non-homogeneous soils. They showed that, the soil above the level of the skirt tips for strip footings does not contribute to the vertical bearing capacity, while for circular footings its contribution was small.

Given the conclusions of Tani and Craig (1995), analyses of small scale bucket foundations suggested that the vertical capacity was dependent on either the soil strength above the level of the base of the footing or embedment effects for undrained conditions.

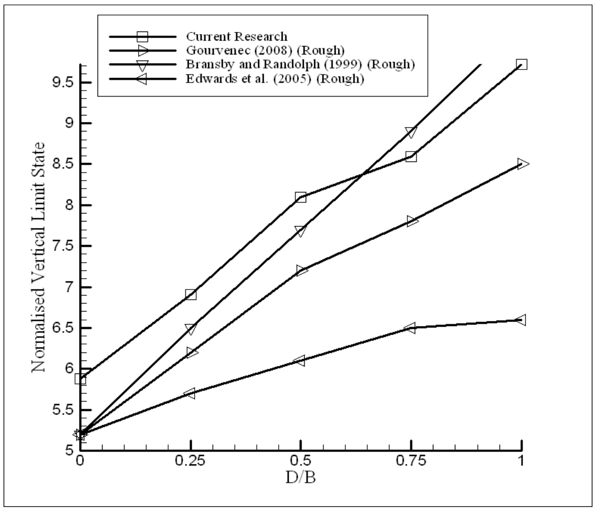

Figure 12. Ultimate vertical bearing capacity as a function of embedment ratio for Yoldia clay

Table 1. Comparison with published data

	Current Research	Gourvenec and Randolph (2002)	Shield et al (1955)	Houlsby and Wroth (1983)	Martin (2001)
Bucket Foundation (20 *cm*) D/B =0.5, c_u =65.1	105.42	97.12	-----	99.082	99.34
Circular Footing (20 *cm*) c_u =65.1	76.6	76.94	78.77	--------	

Table 2. Comparison with published data

	Current research	Gourvenec and Randolph (2002)	Shield et al (1955)	Houlsby and Wroth (1983)	Martin (2001)
Bucket Foundation (30 *cm*), D/B =0.5, c_u = 75,	182.51	167.85	-----	171.22	171.67
Circular Footing (30 *cm*) c_u =75	132.5	132.97	136.12	--------	---

5 CONCLUSIONS

One new foundation concept in relation to offshore wind turbines is bucket foundations. The concept of bucket foundations which is known from the offshore oil and gas industry is recently being used in offshore wind turbines. The loads from offshore wind turbines are characterized by vertical weight due to the slender construction combined with horizontal forces inducing a large overturning moment. A series of experimental studies on small scale buckets placed on Yoldia clay have been performed to investigate the effect of embedment on the undrained bearing capacity of bucket foundations under vertical loading. The field tests have been accompanied by finite element numerical simulations in order to provide better understanding of influential parameters on the behavior of bucket foundations.

The obtained results for circular surface and bucket foundations on Yoldia clay are compared with the plasticity solutions as well in order to verify the accuracy of the simulations. A comparison of the variation of normalized vertical limit state for circular and bucket foundations on Yoldia clay is also presented, while a quadratic relationship between ultimate vertical load and embedment ratio is proposed as discussed above in details.

Eventually, it is also shown the significant sensitivity of bearing capacity to the emebedment ratios (e.g., 37 % increase in pure bearing capacity for the two cases as *d/D*=0 and *d/D*=0.5).

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