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AN EXPERIMENTAL STUDY OF THE DRAINED CAPACITY OF BUCKET FOUNDATIONS FOR OFFSHORE APPLICATIONS

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ABSTRACT

Today, wind energy offers the most competitive production prices for renewable energy. Therefore there are strong political and industrial forces, especially in northern Europe, which support the development of the offshore wind industry.
The present paper presents the results of drained tests on offshore bucket foundations for wind turbines in saturated dense sand. The bearing capacity of bucket foundations subject to combined loadings which are of interest particularly to the offshore geotechnical engineers, were calculated and found to be largely dependent on embedment ratios and load paths. Based on the results of the analyses, new failure criteria are calibrated for bucket foundations, in contrast to previous studies using the failure envelope approach which have suggested that yield surface is constant in shape.

INTRODUCTION

A shallow foundation known as a load carrying structure transfers the loads directly to the underlying soil. The ratio less than or equal to four for depth to width is simply called a shallow foundation (Das, 1999). The bearing capacity of soil can be defined as the foundations resistance when maximum pressure is applied from the foundation to the soil without arising shear failure in the soil.
Many approaches are generally used to predict the bearing capacity of foundations including the laboratory and in situ studies. Prandtl (1921), Reissner (1924), Terzaghi (1943), Meyerhof (1963) and Vesic (1973) were among the first authors who presented plastic equilibrium theories to determine the ultimate bearing capacity. A bucket foundation is a circular surface foundation with thin skirts around the circumference. Bucket foundations have been used extensively in offshore facilities, such as platforms, wind turbines, or jacket structures (Tjelta and Haaland, 1993; Bransby and Randolph, 1997; Luke et al., 2005; Barari and Ibsen, 2012; Ibsen et al., 2012).
In practice, the shape of the yield surface for different foundation types have been investigated either experimentally or numerically, especially within the last decade. The purpose here is to study the interaction between the bucket foundation and surrounding soil which is certainly important for the wind turbine applications. The challenge is to provide a realistic modelling of the foundation, under all probable applied loads, so that it can be incorporated in a structural analysis. The proposed models in the literature assume a hardening of the yield surface that is controlled by the vertical plastic settlement of the foundation.
The shape of the yield surfaces presented in the following can be expressed by the following general empirically equation.

$$f=\left(\frac{H}{h_0V}\right)^2+\left(\frac{M}{m_0DV}\right)^2-2a\left(\frac{H}{h_0V}\right)\left(\frac{M}{m_0DV}\right)-F(V,V_t,V)=0 \quad (1)$$

where f describes a yield surface corresponding to the shape of the failure surface, D is the diameter of the foundation and V_t is the tension capacity of the bucket foundation. The general shape of the surface is determined by the three parameters h_0, m_0 and a in the radial-planes. The parameters h_0 and m_0 determines the size of the yield surface at the widest section of the surface along the V-axis by $H_{M=0}/V$ and $M_{H=0}/DV$ respectively. Where $H_{M=0}$ is the value of H at

intersection with the M=0 axis and $M_{H=0}$ is the corresponding value for M.
The eccentricity parameter, a determines the rotation of the ellipse in the radial planes. An example of the complete three dimensional shape of a rotated yield surface based on the Eq. 1 is shown in Fig. 1 for a circular surface footing.

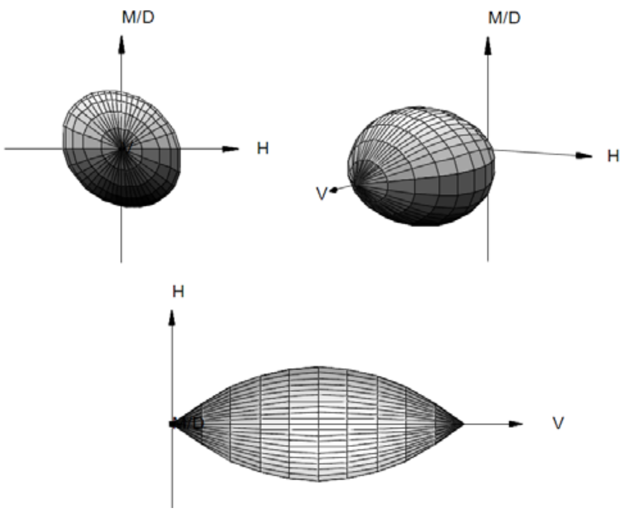


Fig. 1. Illustration of yield surface for a surface footing shaped as a parabola and rotated ellipse, according to the expression of f from Byrne and Houlsby (1999).

The influence from the eccentricity parameter on the shape of the yield surface in the radial plane is illustrated in Figs. 2 and 3. From the figures it can be seen that the parameter not only rotates the ellipse but also stretches the surface in the second and fourth quadrant.

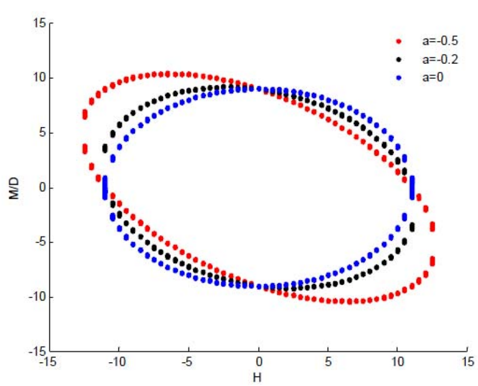


Fig. 2. Influence of a on the yield surface in the radial plane. h_0 *=0.11* m_0 *=0.09,* $V = 0.5V_{pre}$ *and* V_{pre} *=100.*

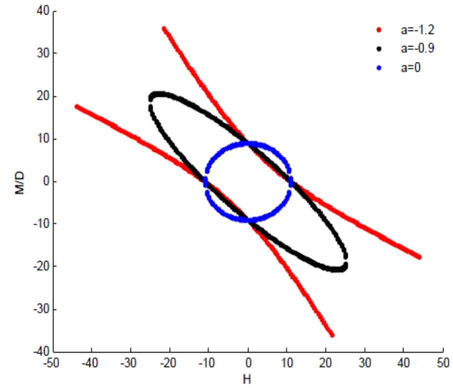


Fig.3. Illustration of the limitation on the value of a. h_0 *=0.11* m_0 *=0.09,* $V = 0.5V_{pre}$ *and* V_{pre} *=100.*

The yield surface functions presented clearly have one drawback, relative to the behavior of bucket foundations. The yield surface of a bucket foundation will not intersect the V-axis at zero vertical load, but at a negative value due to the tension capacity. This is also noticed by Villalobos et al. (2004, 2005). They suggested a modified yield function by introducing a dimensionless constant, t_0. They finally proposed $F(V,V_t,V_{pre})$ as

$$\left(\frac{\beta_{12}}{(t_0+1)^{(\beta_1+\beta_2)}}\right)\left(\frac{V}{V_{pre}}+t_0\right)^{2\beta_1}\left(1-\frac{V}{V_{pre}}\right)^{2\beta_2}.$$

The constant t_0 is proposed to be a function of the skirt thickness, t relative to the diameter of the bucket.
The apex of the yield surface at low vertical load is specially of great importance for wind turbine foundations, due to the small self-weight of the structure. The yield surface expression by Villalobos et al. (2005) are based on experiments on bucket foundations with a single embedment ratio equal 0.5 on saturated medium dense sand.

YIELD SURFACE PARAMETERS

The curvature factors, β_1 (low stresses) and β_2 (high stresses) mentioned above allow adjustments to the parabolic shape of the yield surface along the V axis in order to fit the experimental data. The choice of β_1 and β_2 determines the value of $v = \beta_1/(\beta_1+\beta_2)$, i.e. the location of the peak of the parabola along the v-axis as well as the slope of the ends of the parabola, see Fig. 4. β_{12} are merely defined so that h_0 and m_0 retain their original meanings. The value of β_1 and β_2 is generally found to be close to but less than 1. Values of β_1 and β_2 less than unity reduce the sharp angles of the yield surface at the intersections with the V-axis, see Fig. 4.

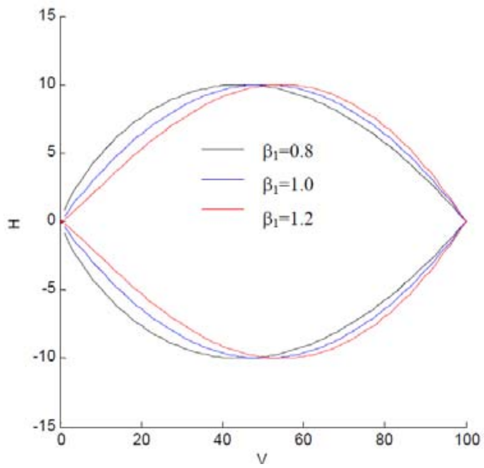


Fig.4. Influence of curvature factors on the shape of the yield surface. β_2 *=1.0 and m=0-plane.*

The values of β_i are limited by a value equal 1.0 as the failure surface for larger values becomes concave. For $\beta_1 = \beta_2$ =1 the yield surface is seen to coincide with the expression from Gottardi et al. (1999) and the widest section in the radial plane is located at *v*= 0.5. The value of *v* is in the literature generally found to be between 0.45 and 0.5 for surface footings, i.e $\beta_1 <\approx \beta_2$. This is in contrast to observations from tests, from which the slopes of the yield surface at the apex's indicate that $\beta_2 < \beta_1$, e.g. Butterfield & Ticof (1979), and Gottardi et al. (1999).

For surface footings Houlsby and Cassidy (2002) suggested that the expression from Martin (1994) is simplified by choosing a =0 and $\beta_1 = \beta_2$ =1 which will correspond to observations from by Butterfield and Ticof (1979). Also Byrne (2000) commented that the introduction of the *β*-factors is not appropriate for surface footings, as the general trend of yield surface is not significantly influenced.

In Model C the yield surface is assumed to be constant in shape (Gottardi et al. 1999). Byrne & Houlsby (1999) however found that for circular surface footings on dense sand the shape changed with the vertical preload ratio, V_{pre} / V_0 . This change was fitted to the following expressions:

$$h_0 = h_{0,peak}\left(1 - 0.36\ln\left(\frac{V_{pre}}{V_0}\right)\right) \tag{2}$$

$$m_0 = m_{0,peak}\left(1 - 0.36\ln\left(\frac{V_{pre}}{V_0}\right)\right) \tag{3}$$

where $h_{0,peak}$ =0.11 and $m_{0,peak}$ =0.08 corresponding to the yield surface at peak bearing capacity. Eqs. (2) and (3) are validated for $0.025 \langle V_{pre} / V_0 \langle 1$.

From tests on bucket foundations in dense sand, the values of h_0 and $h_{0,peak}$ are found to be enhanced significantly with an increase in the embedment ratio whereas the value of m_0 is found not to be affected from the embedment ratio (Byrne 2000).

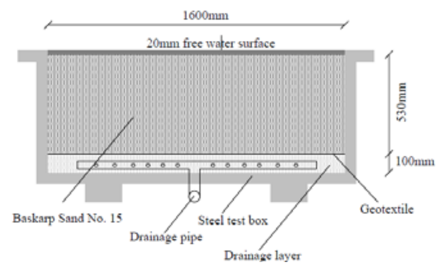


Fig.5. Geometry of the test setup

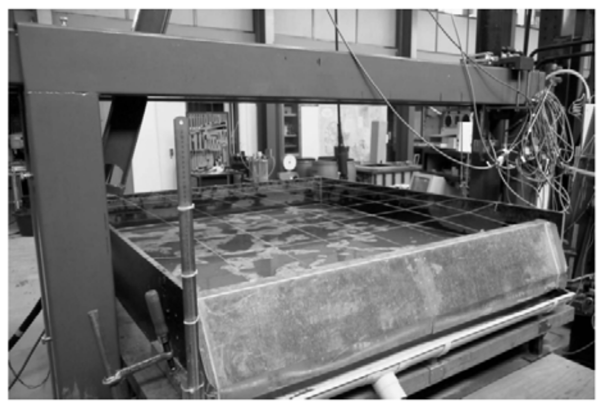


Fig. 6. The test box

TYPICAL MODEL TEST RESULTS

Normalization procedure in case of bucket foundations is clearly observed to yield different failure surfaces, depending on the embedment ratio. The combined capacity of bucket foundations is greatly affected by the lateral earth pressure on the skirt and not only the overburden pressure as the pure vertical bearing capacity. Thus different failure parameters depending on both the embedment ratio and soil strength are necessary to describe the combined capacity. This was also seen from the literature study. The data presented herein are from the tests on 200 mm buckets for vertical load corresponding to 50% of the vertical bearing capacity and saturated dense Aalborg University Sand No. 1. A schematic view of the test set-up can be found in Fig. 5 along with the text box ready for the tests in Fig. 6.

A yield surface expression that is capable of describing the combined capacity at low vertical load is presented in Eq. 4.

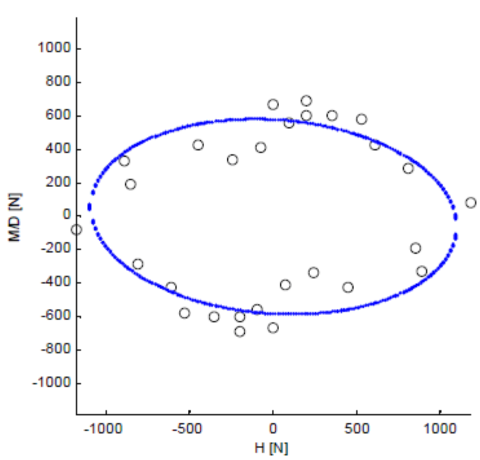
This expression is derived from a limited set of experiments with two different bucket foundations with embedment ratios of 0.5 (Villalobos et al. 2005).

$$f=\left(\frac{H}{h_0 V_{peak}}\right)^2+\left(\frac{M}{m_0 D V_{peak}}\right)^2-$$
$$2a\left(\frac{H}{h_0 V_{peak}}\right)\left(\frac{M}{m_0 D V_{peak}}\right)$$
$$-\left(\frac{\beta_{12}}{(t_0+1)^{(\beta_1+\beta_2)}}\right)\left(\frac{V}{V_{peak}}+t_0\right)^{2\beta_1}$$
$$\left(1-\frac{V}{V_{peak}}\right)^{2\beta_2}=0 \tag{4}$$

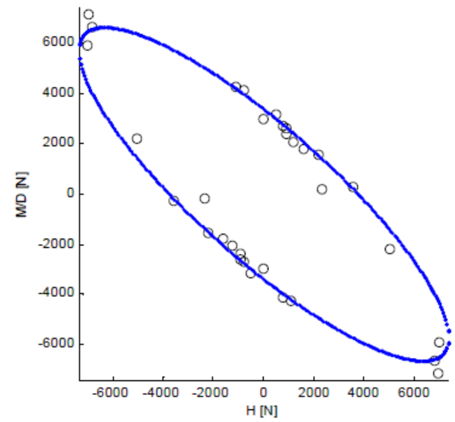
Based on the experimental results, Villalobos et al. (2005) found that the value of t_0 varies with the ratio between the diameter of the bucket foundation and the thickness of the skirt. Hence the following definition of t_0 is suggested:

$$t_0=-\frac{V_t}{V_{peak}} \tag{5}$$

V_{peak} is pure vertical capacity and given in Ibsen et al. (2012). Eq. 5 is used in the following to fit the measured capacities in the laboratory with the definition of t_0 proposed in Eq. 5. The values of the fitted yield surface parameters a, $h_{0,peak}$ and $m_{0,peak}$ at failure are given in Table 1 assuming a value of β_1, β_2 equal 1. A value of $K\tan(\delta)$ =2 is used to estimate V_t. The value of the failure parameters in Table 1 is however non-sensitive to the choice of β_1, β_2 and $K\tan(\delta)$ for V/V_{peak} =0.5.



(a)



(b)

Fig. 7. Calibrated failure criteria for bucket foundation tests with V/V_{peak} ≈0.5 and embedment ratios of (a) d/D=0, (b) d/D=1.

The value of $h_{0,peak}$ is seen as almost constant at a value of 0.16 whereas $m_{0,peak}$ is increasing with the embedment ratio towards a value of 0.135 for large embedment ratios (Fig.8). The opposite behaviour is observed from tests on bucket foundations in the literature, where a constant value of $m_{0,peak}$ was found (Byrne 2000). The value of a is seen to decrease asymptotically towards a value lower than -1 for increasing embedment ratios (Fig.9). T

Table 1. Failure parameters determined from loading tests.

d/D	a	$h_{0,peak}$	$m_{0,peak}$	$t_0(D=200mm)$
0	-0.1	0.15	0.08	0
0.25	-0.4	0.16	0.092	0.002
0.5	-0.65	0.165	0.125	0.006
0.75	-0.75	0.16	0.133	0.009
1	-0.86	0.15	0.135	0.0127

The failure criteria fitted are shown in Fig.7. The failure criteria are seen to describe the measured capacities of the tested bucket foundations well.

The experiments are carried out with identical vertical loads for each embedment ratio. Thus a small variation in the normalized load applied to the bucket during loading is present.

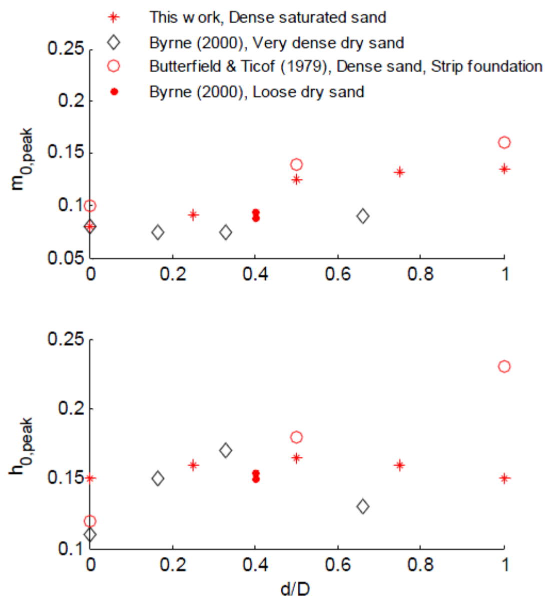


Fig. 8. Comparison of failure parameters

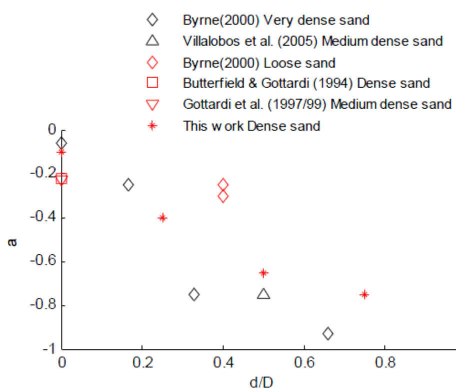


Fig. 9. Comparison of the eccentricity parameter.

CONCLUSIONS

The physical modeling is attempted at Aalborg University to determine the yield locus for bucket foundations with varying size, embedment ratio, load paths and uniform soil in vertical, moment and horizontal load space. The three-dimensional yield criterion proposed by Villalobos et al. (2005) was modified in this study in order to achieve best fit curves with the measured data from the tests. Reasonable agreement was finally obtained between both approaches as plasticity solutions and the given results by the tests.
Contrary to the behaviour displayed by Byrne (2000), where a constant value of yield surface parameter $m_{0,peak}$ is reported, an opposite behavior was observed. The bearing capacity of the bucket foundation is severely influenced by the skirt length and the load path when they are subjected to combined loading. Longer skirt length implies further mobilization of horizontal and moment capacities due to the side friction and the lateral resistance along the skirt.

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