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Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Vaitkunaite, E., Molina, S. D., & Ibsen, L. B. (2012). *Comparison of Calculation Models for Bucket Foundation in Sand*. Department of Civil Engineering, Aalborg University. DCE Technical Memorandum No. 17

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ISSN 1901-7278
DCE Technical Memorandum No. 17

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by

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June 2012

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Published 2012 by
Aalborg University
Department of Civil Engineering
Sohngaardsholmsvej 57,
DK-9000 Aalborg, Denmark

Printed in Aalborg at Aalborg University

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Comparison of Calculation Models for Bucket Foundation in Sand

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Abstract: The possibility of fast and rather precise preliminary offshore foundation design is desirable. The ultimate limit state of bucket foundation is investigated using three different geotechnical calculation tools: [Ibsen 2001] an analytical method, LimitState:GEO and Plaxis 3D. The study has focused on resultant bearing capacity of variously embedded foundation in sand. The 2D models, [Ibsen 2001] and LimitState:GEO can be used for the preliminary design because they are fast and result in a rather similar bearing capacity calculation compared with the finite element models of Plaxis 3D. The 2D models and their results are compared to the finite element model in Plaxis 3D in this article.

1. INTRODUCTION

The typical offshore projects are covering large areas and contain up to 100 foundations. Usually the geotechnical soil conditions vary from one place to another. During the preliminary design it is desirable to make fast and as much as possible precise estimations of foundation dimensions and realistic price estimation.

Three calculation methods are investigated in this paper. The 2D models, an analytical method [Ibsen 2001] and a numerical method LimitState:GEO are compared to the finite element program Plaxis 3D. The first two methods require considerably less time than the 3D model and therefore are preferred in the preliminary design phase.

This paper presents results and compares the different calculation methods. It also provides investigation about the friction angle estimation in 2D models. This knowledge is applicable not only for the wind turbine foundation, but for bucket foundation dimensioning in general. As a good example for bucket foundation use are Wave Energy Converters. Loading on the foundation is taken similar to the one coming from the last mentioned structure.

1.1 Soil Parameters

Dense Aalborg University Sand No. 1 is chosen for the study, because its properties are well known and tested in Aalborg University Soil Mechanics laboratory. The sand consists mainly of quarts. Characteristic sand properties are given in Table 1.

Table 1. Characteristic properties for Aalborg University Sand No. 1.

Parameter	Marking	Units	Value
Triaxial friction angle	φ'_{triax}	^{0}	38.8
Plane friction angle	φ'_{pl}	^{0}	42.7
Dilation angle	ψ	^{0}	9
Void ratio	e_{insitu}	-	0.6
Unit weight	γ	kN/m^3	20.25
Young's modulus	E'_{50}	kPa	39290
Reference Young's modulus	E_{50}^{ref}	kPa	47890
Parameter	m	-	0.58
Density index	I_D	%	80

The friction on the wall is calculated using the properties listed in Table 2.3 [DNV 1992]. Since circular bucket and monopile are similar in shape and materials, the interface friction, δ, is assumed the same. The interface friction depending on density index is listed in Table 2 and visualized in Figure 1.

Table 2. Density Index and interface friction on steel skirt.

Definition	Density Index [%]	Average [%]	Friction, δ $[^0]$
Very loose	0-15	7.5	15
Loose	15-35	25	20
Medium	35-65	50	25
Dense	65-85	70	30
Very dense	85-100	92.5	35
SELECTED	80	80	32.2

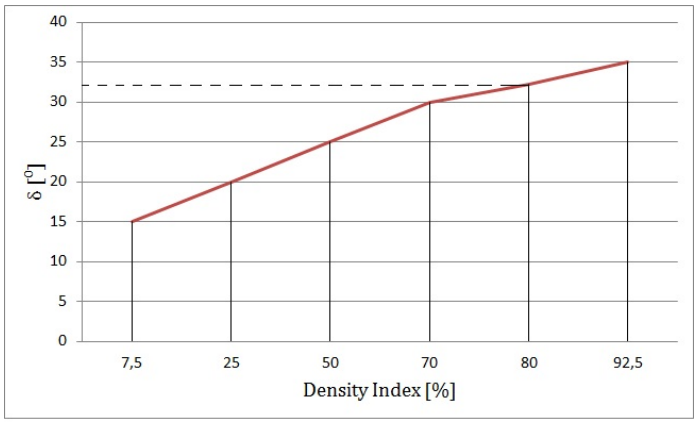

***Fig.* 1**. Density index vs. soil friction on steel skirt.

Sand with density index, $I_D = 80\%$, is chosen for further investigations. In this case interface friction angle is 32.2^0, as it is seen in Figure 1. Numerical 2D program LimitState:GEO and finite element program Plaxis 3D allow a direct input for the reduced interface strength parameters.

This input is expressed as an interface parameter, R, estimated by (1). The parameter is a ratio of triaxial friction angle and interface friction angle.

$$R = \frac{tan\delta}{tan\varphi'_{triax}}. \quad (1)$$

Having the triaxial friction angle, φ'_{triax}=38.8^0, and interface friction angle δ=32.2^0, the ratio, R, is equal to 0.8.

1.2 Geometry of Foundation
In this study the diameter, D, of the bucket is 14 meters. The skirt length is varied with 2 meters starting from 4 and finishing with 14 meters. By variation of skirt length, d, tendencies and differences between the models can be studied.

1.3 Loading
The foundation is impacted by 3 types of external loads: vertical, horizontal and moment loading. The first one is constant and independent of foundation shape. Design vertical load is 9056 kN which corresponds to weight of foundation and upper structure. Design horizontal load is 2678 kN, which is a combination of two variable wind and wave loads. It acts at 23.81 m from the seabed. The assumed water depth is 20 m.

1.4 Expressing
The output from all programs is presented in figures and expressed in terms of adequacy factor, AF, and ratio of depth and diameter, d/D. This ratio describes the foundation embedment, which influences strongly the failure mode and the bearing capacity calculations. AF parameter is depicted as factor associated to an external load. The system is in the safe regime if AF>1. On the contrary, collapse is encountered if AF<1. This factor is estimated for the horizontal load by (2). AF is the direct output from LimitState:GEO and for the other two programs it is calculated.

$$AF = \frac{H_{max}}{H_{applied}}. \quad (2)$$

2. SHORTLY ABOUT PROGRAMS/METHODS

2.1 Analytical Method
Analytical method [Ibsen 2001] determines ultimate limit state (ULS) of suction bucket foundation. It is assumed that the foundation rotates as a solid body around one point in some depth, d_r. The point of rotation can be located below the foundation level or in between of soil surface and the foundation level. In order to calculate the earth pressure it is assumed that the walls rotating around a point in each of them as visualized in Figure 2.

For the active and the passive sides the earth pressure factors have different expressions, it is assumed that the walls are rough.

When calculating bearing capacity of the bucket foundation various rotation points located on the symmetric line of the bucket are considered. The vertical, horizontal and moment equilibrium must be ensured. It is done with the use of earth pressures (Figure 3) as well as friction on the walls. It is known that earth pressure cannot work as a drag force; therefore the negative E values are set to be

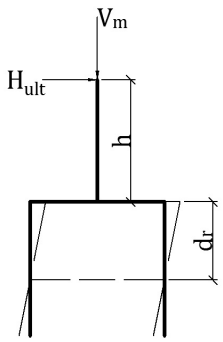

***Fig.* 2**. The assumed rotation of the bucket. After [Ibsen 2001].

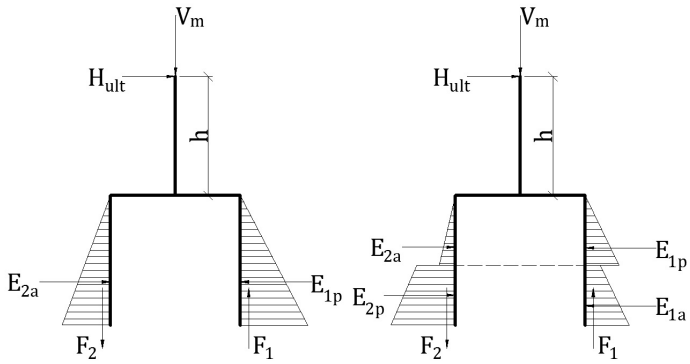

***Fig.* 3**. a. Earth pressure when rotation point below foundation line; b. earth pressure rotation above foundation level. After [Ibsen 2001].

equal to 0. The point of rotation which is the center of the line failure must also be the point of rotation used in the earth pressure calculation. The largest moment capacity is obtained if earth pressures are utilized to the full depth.

A large eccentricity is considered, $0.3b' < e < 0.5D$. Bearing capacity is estimated according Appendix G in [DNV 2007].

2.2 LimitState:GEO
This software is capable to estimate the ultimate limit state (ULS) prior to failure of various geotechnical structures as well as retaining wall problems. The program allows 2D calculations. With several assumptions it is used for estimation of circular suction bucket ultimate limit state.

LimitState:GEO can compute numerical analysis utilizing a new technique called Discontinuity Layout Optimization (DLO). DLO discretizes the soil body in a number of nodes. Then the potential slip-lines discontinuities - sliding blocks - that configure the failure mechanism are assessed by means of node connections. The view of slip-lines is shown in Figure 4. [LimitState 2010]

The direct output is presented in terms of adequacy factor. Basically this multiplier is correlated to the load that is suspected may cause collapse. Finally the product between external load and adequacy factor determines the maximal permissible load.

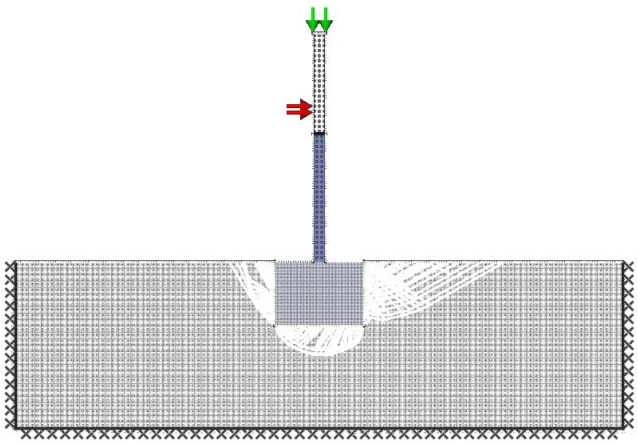

***Fig.* 4**. Discontinuity Layout Optimization (DLO) in LimitState:GEO done for bucket foundation in homogeneous soil layer. Nodal density is very fine.

2.3 Plaxis 3D

Plaxis 3D is a geotechnical program that uses finite element method (FEM) for calculations. This numerical technique enables the user to set up a model in 3 dimensions with the desired geometry and boundary conditions, see Figure 5. Subsequently a number of soil constitutive models are available and may well approximate the soil response. It is expected that this program provides the most realistic estimation of bearing capacity as well as serviceability conditions.

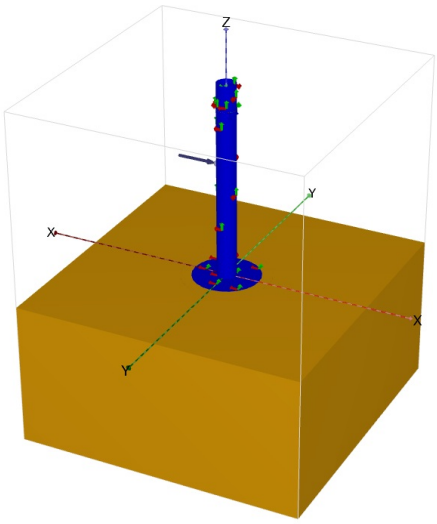

***Fig.* 5**. Plaxis 3D view of suction bucket foundation model in Aalborg University sand No.1.

The Hardening Soil model is a "second-order" model that is used for advanced analysis of soil behaviour and is selected for the suction bucket modeling. As opposed to the Mohr-Coulomb model this directly describes the non-linearity in stress-strain curve as well as stress level dependency. In the Hardening Soil model three different elasticity modules are required to describe the stiffness. These are the triaxial loading stiffness, E_{50}^{ref}, the triaxial unloading stiffness, E_{ur}^{ref}, and the oedometer stiffness, E_{oed}^{ref}, [Schanz et al. 1999]. The Hardening Soil model estimates the stiffness of the soil more accurately than the Mohr-Coulomb model. All of the mentioned stiffnesses for the Hardening Soil model are available from laboratory experimental data on Aalborg University sand No.1.

3. PLASTICITY THEORY

One of the factors that might explain the divergence between results is the criterion hold to determine the volumetric plastic deformations induced while shearing. Two criterion are available; those ones are associated and non-associated plastic flow rule. The difference between is introduced by the angle of dilation.

3.1 Calculations in Associated Plasticity

The theory employed in analytical calculation and LimitState:GEO obeys the associated plasticity flow rule. The principal feature of such models remain in derive the plastic potential function from the yield function. Plastic potential function is taken equal to yield function. The parameters that govern these two functions are the effective friction angle at failure, φ', and the dilation angle, ψ, respectively. Then the assumption is (3).

$$tan\psi = tan\varphi'. \tag{3}$$

To understand the model response is essential to interpret the previous assumption. Equalizing the plastic potential function to the magnitude of the yield function results that all plastic volume changes are caused by dilation behavior. Therefore in associated plasticity the soil only undergoes plastic dilation. This plasticity theory is largely supported by steel structures. Several tests have confirmed the validity of this theory for metal behavior. Although the application of associated plastic flow in soils and rocks has been disputed and documented by experimental tests. The assumption of imposing all plastic volume changes to dilation property do not hold with the real behavior of soil and rocks. It is well-known in geotechnical engineering that depending on factors likewise relative density, void ratio, overconsolidation and confining pressure soils may undergo dilation or compression while shearing. Instead a combination of friction and dilation closely agree with real behavior for such materials. The consequence of using associated plasticity for soils and rocks is in general an overestimation of the real bearing capacity of the problem. However two approaches are available when associated plasticity is utilized; upper bound solution and lower bound solution. These two theories satisfy the associated plasticity theory. The upper bound solution overestimates the real solution whereas the lower bond underestimates. Additionally the true failure load is found if bounds solutions agree in the same result.

As introduced in (3), in associated plasticity flow, the governing parameters, effective friction angle at failure, φ', and the dilation angle, ψ, are assumed to be equal. However for the estimation of the bearing capacity, two different approaches might be followed;

(a) $\psi = \varphi'$; gives good agreement. In such case dilation angle for Aalborg University sand No.1 is taken equal to the plane friction angle and takes a characteristic value of 42.7^0. Although the resultant value can be on the unsafe side, it is used in standard calculations.

(b) $\varphi' = \psi$; the solution becomes on the safe side. In the

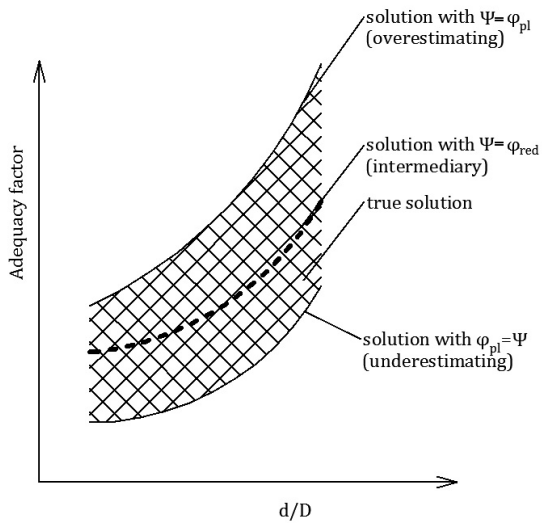

***Fig.* 6**. Inputs for models based on associated plasticity.

case of Aalborg University sand No.1 the plane friction angle becomes 9^0, which is impossibly small. Therefore this last option is discarded. Figure 6 shows the inputs and expected soil response for both methods. An intermediary solution with a reduced friction angle is utilized in this paper.

3.2 Reduced Friction Angle

Bent Hansen has proposed to use a reduced friction angle, φ'_{red}, in the calculations as an intermediate strength value and avoid then the overestimation capacity for the problem. According his observations φ'_{red} is smaller than the plane friction angle, φ'. Equation (4) presents how to calculate it.

$$tan\varphi'_{red} = \frac{sin\varphi' cos\psi}{1 - sin\varphi' sin\psi}. \tag{4}$$

Figure 7 shows the influence of plane and reduced friction angles for bearing capacity of the foundation. The reduced friction angle is used in analytical program as well as LimitState:GEO inputs. The proposed reduced friction angle is found from the calculations of the plane friction angle and dilation angle. It is approximately equal to the triaxial friction angle. Finally it is expected that using the reduced friction angle would provide a soil response in between the overestimated and underestimated calculation methods, see Figure 6. Therefore is anticipated that results from 2D models should be closer to results in Plaxis 3D.

3.3 Calculations in Non-associated Plasticity

Conversely the models in Plaxis 3D use non-associated plasticity theory. For such case, the magnitude of the plastic potential function is not taken equal to the yield function. The assumption then is (5).

$$tan\psi \neq tan\varphi'. \tag{5}$$

To assess the magnitude of the plastic potential function, the value for dilation angle is determined through laboratory tests. A rule of thumb based on engineering experience is also available to assess the dilation value for different soils. Non-associated plasticity is adopted in Plaxis 3D and

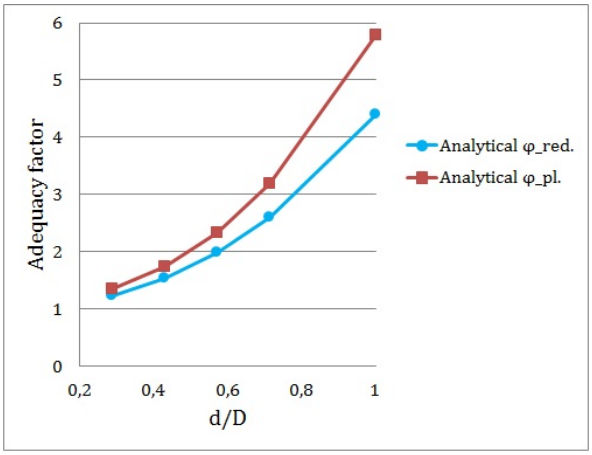

***Fig.* 7**. Analytical method: difference of φ'_{pl} and φ'_{red} used in calculations.

it is assumed that when Aalborg University sand No.1 is sheared, it eventually reaches a critical state, which can be expressed by (6). In this state critical void ratio and effective stresses are reached.

$$\frac{\tau}{\sigma'} = tan\varphi'_{crit}. \tag{6}$$

Because of dilation, the dense sand mobilizes a greater angle of internal friction, φ', than the critical, φ'_{crit} . Relation is expressed in formula (7).

$$\varphi' = \varphi'_{crit} + \psi. \tag{7}$$

When the maximum positive dilation is reached the peak of stress-deformation is achieved. Amount of it depends on shape, roughness and size of sand grains.

If shearing is prolonged, the dilation angle decreases and internal friction angle becomes more similar to the critical, as we can see from (7). Finally, when dilation is zero and the two friction angles equalizes, the fully softened critical strength state is reached. [Holtz et al. 2011]

Coming back to Plaxis 3D program it can be assumed that when triaxial friction angle and the dilation angle are used as inputs, the maximal peak stress must be reached in the calculations. This strength evaluation is expected to be the true solution.

4. RESULTS

6.1 Design in LimitState:GEO

There are two possible ways to model a bucket foundation in LimitState:GEO. Firstly skirt walls are modeled as thin sheet pile walls. Soil strength is reduced with factor 0.8 in the interfaces due to soil-structure interaction. Another model is done as a solid structure with very big shear strength and the weight of sand (20.25 kN/m^3) below the seabed line.

Dimensions of the foundation and loading are a little different comparing it to the other two programs. LimitState:GEO calculates infinitely long structures such as strip foundation, therefore the circle bucket shape must be optimized to fit this program. After evaluation of the foundation area, the circle foundation with 14 m diameter can be transformed to a square foundation with side

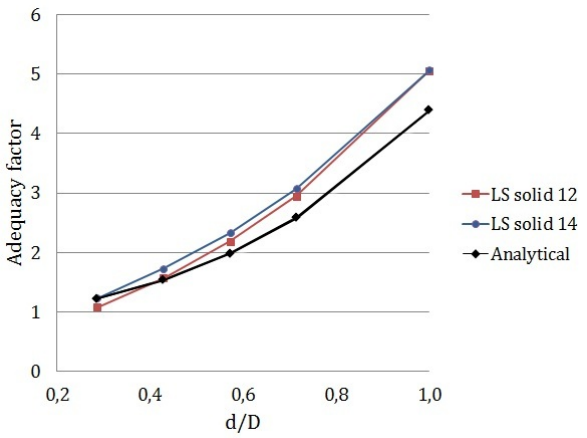

***Fig.* 8**. LimitState:GEO and analytical bucket calculation results.

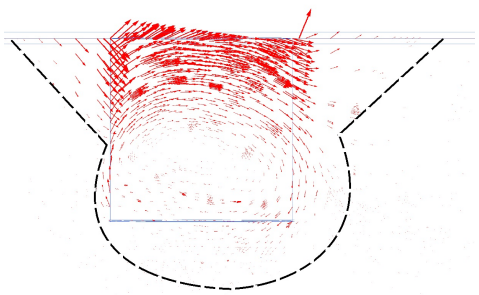

***Fig.* 9**. Plaxis 3D generated failure figure for d/D=1.

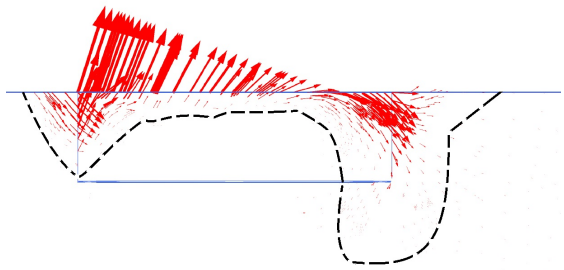

***Fig.* 10**. Plaxis 3D generated failure figure for for d/D=0.3.

length 12.41 m or a rectangular foundation of 14 m width and 11m length. This means that the width and reduced according to the length loads are used in program.

It is seen in Figure 8 that rectangle shape LimitState:GEO model gives from min. 1 to max. 19 % (average 13%) higher safety factor than in analytical bucket calculation. Square shape LimitState:GEO results into max. 11% smaller to max. 15% higher safety factor, with the average of 6%.

6.2 LimitState:GEO compared to Plaxis 3D
Another interest goes to the Plaxis 3D and LimitState:GEO comparison. First of all it should be divided into two parts; depth and diameter ration $d/D > 0.5$ and $d/D < 0.5$. The two ranges differ strongly in failure mechanism, they are visualized respectively in Figure 9 and 10. This knowledge is essential for interpretation of results from the presented 2D programs. The embedment

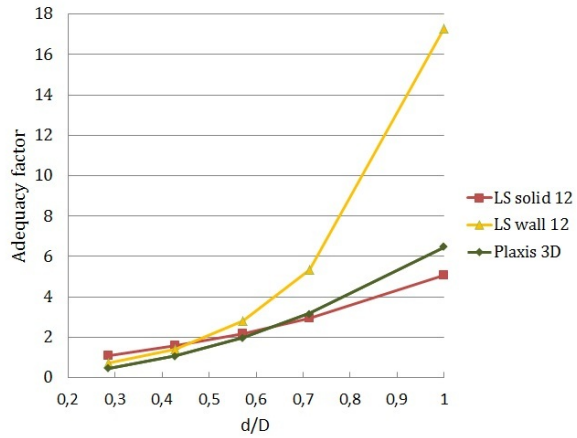

***Fig.* 11**. LimitState:GEO and Plaxis 3D results.

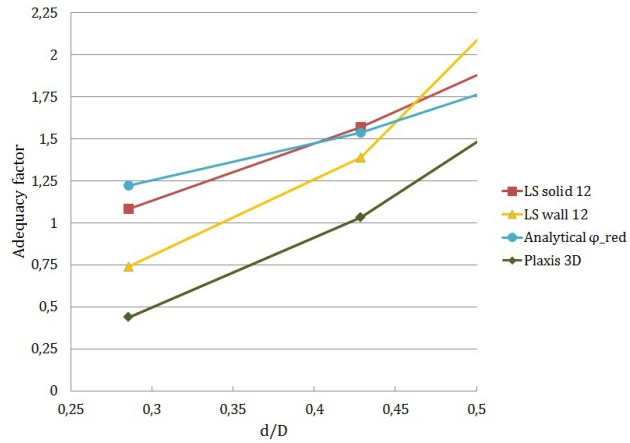

***Fig.* 12**. Analytical bucket calculation, LimitState:GEO and Plaxis 3D results in $0.1 < d/D < 0.5$.

is discussed widely in various articles. The influence of it is explained in [Holtz et al. 2011].

6.3 Comparison of three programs
As it is seen in Figure 11 when the range is $0.5 < d/D < 1$, LimitState:GEO bearing capacity is max 22% bigger than Plaxis 3D, when the structure is modelled as a solid body, similar to gravity foundation. However when the range is $0.1 < d/D < 0.5$ better results are achieved modelling skirt walls. In this case LimitState:GEO bearing capacity is overestimating the result in the average 50%, but it is still closer than the first way of modelling.

Finally the comparison of three programs is visualized in Figure 12. In the range of $0.1 < d/D < 0.5$, 2D programs are overestimating bearing capacity of the suction bucket foundation. In the range of $0.5 < d/D < 1.0$, analytical calculation method as well as LimitState:GEO solid foundation models show tendency for underestimating a little the ultimate capacity of the foundation while LimitState:GEO wall model is strongly overestimating compared to Plaxis 3D, see Figure 13.

5. CONCLUSION

After analysis of the results presented in section 4 it can be stated that LimitState:GEO as well as [Ibsen 2001]

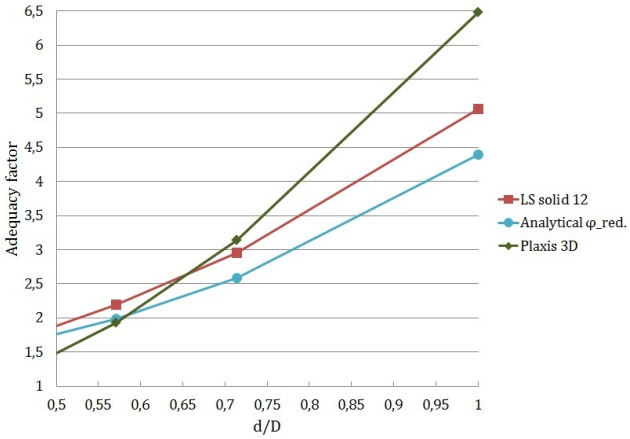

***Fig.* 13**. Analytical bucket calculation, LimitState:GEO and Plaxis 3D results in $0.5 < d/D < 1$.

can be used for preliminary design of suction bucket foundation ultimate limit state. However it is important to consider the over/underestimations according to the range of foundation embedment. It would be more reliable to model using LimitState:GEO solid "gravity" structure or analytical bucket calculation model while the embedment is in the range of $0.5 < d/D < 1.0$.

The presented results are made for the homogeneous sand soil. In reality the soil is never homogeneous, therefore each design case becomes unique and must be analyzed carefully.

Finally it can be reminded that 3D finite element programs are able to include a lot more parameters than the presented 2D programs. The plasticity flow and assumptions differ as it is explained in section 3. Therefore it is rather difficult to interpret the results directly as they come.

However a typical engineer will need the most reliable results in a short time during the preliminary design stage and the results of this paper aim for it.

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