Concept Study of Foundation Systems for Wave Energy Converters

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Concept Study of Foundation Systems for Wave Energy Converters

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Abstract: Analysis of possible foundation solution for Wave Energy Converters (WEC) is presented by investigating and optimizing novel foundation systems recently developed for offshore wind turbines. Gravity based, pile and bucket foundations are innovative foundation systems that are analyzed. Concept studies for all three foundation systems, geotehcnical design methods of foundations and discussion about the differences in the means of structural design, installation and cost are presented in the paper.

1. INTRODUCTION

Wavestar C6 is a wave energy converter (WEC) designed to deliver 600 kW of electrical power to the grid. The purpose of this paper is to compare and evaluate three foundation concepts for WEC. The proposed systems are based on bucket, pile and gravity based foundation. These types are widely used in offshore structures and therefore may be well applicable.

There are two different ways to transfer the load into foundation. WEC can be supported by two or four legs, which makes the difference in load transfer from the structure through the foundation to the soil, see section 1.2. The loading is explained in details in section 1.3. Six possible foundation solutions are presented and analyzed using three geotechnical tools. The programs used are analytical [Ibsen 2001], numerical 2D program LimitState:GEO and finite element program Plaxis 3D.

1.1 Dimensioning scheme

Foundation dimensioning scheme is shown in Figure 1, it describes the full concept study modeling process of the foundation solutions. First three parts shown in the scheme are presented in this paper. Primary dimensioning is done with an analytical program, which differs depending on foundation types. Afterwards a numerical 2D program LimitState:GEO is employed for secondary dimensioning and optimization. Thirdly, Plaxis 3D is employed for last optimization and verification in ULS and SLS conditions. A completed geotechnical design is followed by structural design, where steel design of buckets and piles is done in ULS conditions. Finally the price estimation can be carried out for the foundation and installation costs. The last two are analyzed in [Vaitkunaite and Devant Molina 2012].

It is chosen to investigate possibility of installing one wave energy converter in Horn's Reef II. The location and soil properties are described in section 1.4.

1.2 Structural solutions

Several foundation concepts are potential of fulfilling the aim of WEC, successful installation and performance. The structures are visualized in Figure 2 to Figure 4.

Wavestar has at present a grid-connected prototype installed in Hanstholm (Denmark). The prototype has been

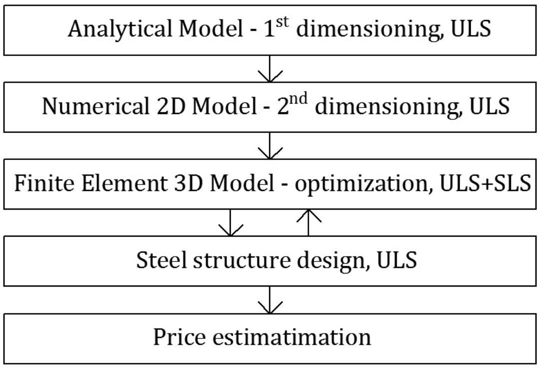

***Fig.* 1**. Modeling process

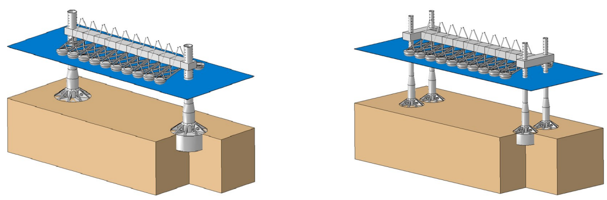

***Fig.* 2**. Bucket foundation. After [Wavestar 2011]

installed on four concrete foundations in soil predominated by chalk. Due to the overturning moment foundations are working in tension and compression, also they have to resist the horizontal wind and wave loads. The four-leg WEC C6 superstructure is supported on foundation in distances of 80 and 17 meters. When the overturning moment is large, it might be desirable to increase distance for the four-leg structure achieving smaller pull-out and compression forces. That is why a 30 meters distance is also investigated. Additionally a solution with two foundations is considered in this paper as it is expected to be more cost effective. In such solution dominant are horizontal wind and wave loads as well as self-weight of the structure. More information about load cases is given in section 1.3.

1.3 Loads from water and wave

Loads on the foundation are provided by Wavestar A/S. This paper presents only storm load case, when the superstructure is lifted to the highest position and locked. Dur-

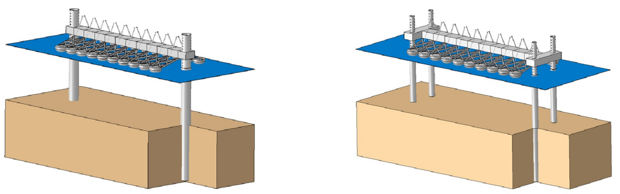

***Fig.* 3**. Pile foundation. After [Wavestar 2011]

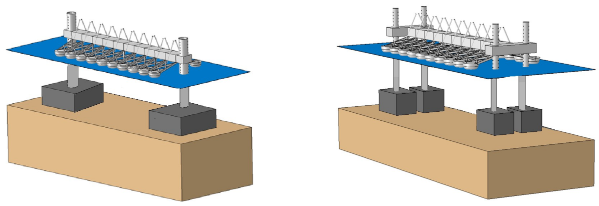

***Fig.* 4**. Gravity based foundation. After [Wavestar 2011]

ing this load case it is expected that the structure needs to resist the largest wind and wave loads. Further is assumed that this is the most unfavorable situation and therefore the governing case for design process. Calculations are performed for the ultimate limit (ULS) and serviceability limit state (SLS). Safety factors taken from [DNV 2007] are applied for the characteristic loads as well as material strength in the ULS calculations. Characteristic loads are calculated for several diameters of foundation pile and presented in Tables 1 and 2.

Water depth of 16 meters is assumed, because WEC efficiency is high in this water depth. The loads are estimated for various diameters of foundation legs; Ø2, Ø3 and Ø4 meters. Structural scheme in four legs case is shown in Figure 5.

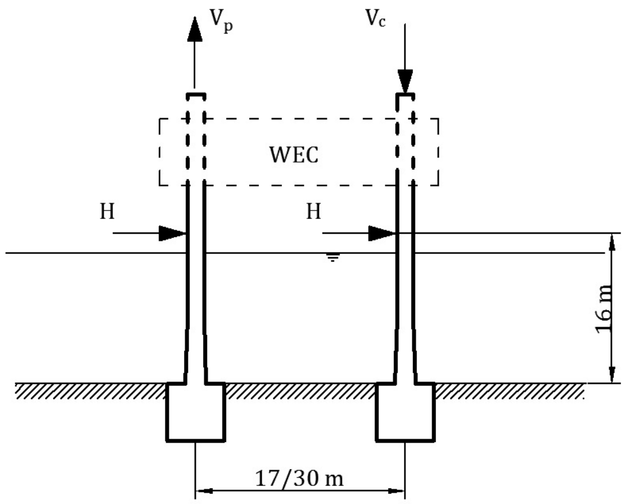

***Fig.* 5**. Structural scheme in four legs case.

1.4 Soil conditions

Soil conditions are taking from CPT data of Horn's Reef II project. Wavestar A/S has a vision to install the wave energy converter in a position around wind turbine H7.

Table 1. Characteristic loads for 1 of 2 foundation legs.

Description	Units	Ø2	Ø3	Ø4
Wind load on WEC	kN	467	467	467
Moment arm for wind load	m	29.34	29.34	29.34
Wave force on pile	kN	1007	1557	2280
Moment arm for wave load	m	15.82	16.04	16.15
Weight of superstructure	kN	7840	7840	7840

Table 2. Characteristic loads for 1 of 4 foundation legs.

Description	Units	Ø2	Ø3	Ø4
Wind load on WEC	kN	233.5	233.5	233.5
Moment arm for wind load	m	29.34	29.34	29.34
Wave force on pile	kN	1007	1557	2280
Moment arm for wave load	m	15.82	16.04	16.15
Weight of superstructure	kN	7840	7840	7840
Pull/compression load, 17 m	kN	2680	3744	5138
Pull/compression load, 30 m	kN	1519	2122	2912

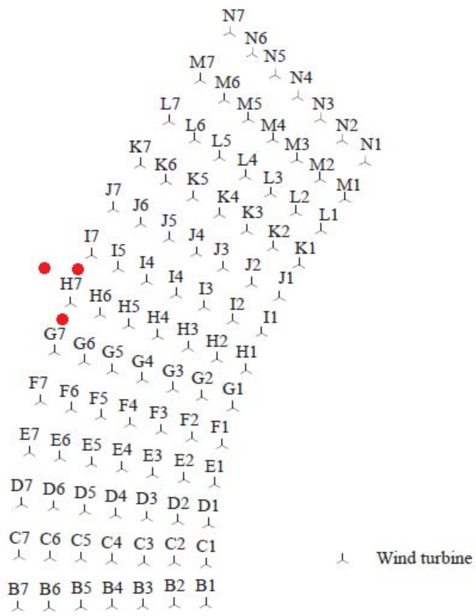

***Fig.* 6**. Possible placement for WEC in Horns Rev II

The possible positions are shown in Figure 6. According the position of WEC, CPT soil profile in H7 position is prescribed to the data.

Seven soil layers up to 33 meters depth are estimated from the CPT-data. More exact calculations and the data itself is presented in [Vaitkunaite and Devant Molina 2012]. The soil unit weight and strength parameters are presented in Table 3. It is estimated that the soil in the last two layers is overconsolidated with $OCR = 2$. The last soil layer is silt with undrained shear strain strength $s_u = 563kPa$.

Table 3. Characteristic soil properties in Horn's Reed H7.

Alt.	Description	γ $[kN/m^3]$	φ' $[^0]$	φ'_{red} $[^0]$
-6.5	Sand Medium	19.5	38	37.1
-7.9	Sand Coarse	19.5	38	37.1
-12	Sand Medium	19.5	35	34.0
-24.8	Gravely sand	20.0	38	36.2
-26.5	Sand Fine Clayey	19.5	32	30.8
-30.5	Sand to Silty Sand	18.0	32	30.5
-33	Silty sand to sandy silt	18.5	-	-

2. BUCKET FOUNDATION

Three different geothecnical programs are employed. Results for two and four leg structure are provided in tables after each section. More about bucket foundation calculation methods that are presented in this paper can be found in [Vaitkunaite et al. 2012].

2.1 Dimensioning based on analytical calculations
Analytical method [Ibsen 2001] determines ultimate limit state (ULS) of 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 are rotating around a point in each of them as visualized in Figure 7.

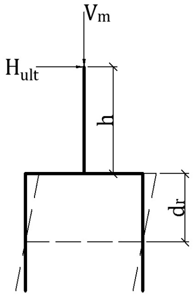

Fig. 7. The assumed rotation of the bucket. After [Ibsen 2001]

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 8) 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 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. The earth pressure, E, is calculated by 1. For the active and the passive sides the earth pressure factors, K, have different expressions, it is assumed that the walls are rough.

$$E = (\gamma z K_\gamma + p K_p + s_u K_c)\, D \tag{1}$$

where p is passive pressure in $\left[kN/m^2\right]$.

A large eccentricity is considered, $0.3b' < e < 0.5D$. Dimensionless factors (s, i, N) are employed to the bearing capacity formula (2), according Appendix G in [DNV 2007].

$$\frac{R_d}{A'} = 0.5\gamma' b' N_\gamma^e s_\gamma i_\gamma^e + c N_c s_c i_c^e \tag{2}$$

Results from the analytical program are presented in Table 4. The estimated dimensions are skirt diameter, D, skirt length, d, and load adequacy factor, AF. 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 a ration

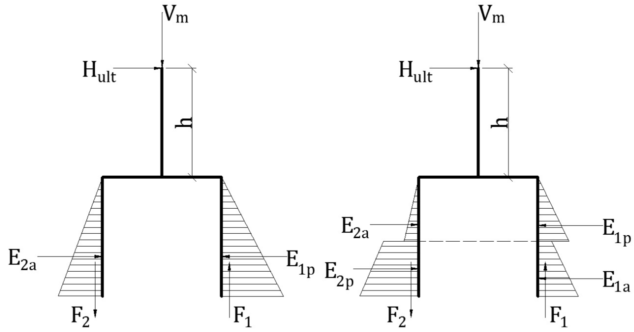

Fig. 8. a. Earth pressure when rotation point below foundation line; b. earth pressure rotation above foundation level. After [Ibsen 2001]

of the maximum allowable horizontal load, H_{max}, and the actual horizontal load, $H_{applied}$, by (3).

$$AF = \frac{H_{max}}{H_{applied}}. \tag{3}$$

Table 4. Analytical program: Bucket foundation, ULS.

Distance $[m]$	$D[m]$	$d[m]$	AF
Two-leg support			
-	8	7	0.949
Four-leg support, compressed			
17	7	7	1.057
30	8	7	1.195
Four-leg support, pulled			
17	8	8	1.149
30	8	8	1.256

2.2 Dimensioning based on numerical 2D calculations
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 bucket foundation in 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 9. [LimitState 2010]

The output is presented in terms of adequacy factor (AF). 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.

Results are presented in Table 5. LimitState:GEO allows to design various shape and position in 2D. Therefore it is possible to design pulled and compressed foundation at once for the four-leg supported structure. In such case one AF is estimated for the system.

2.3 Dimensioning based on finite element calculation
Plaxis 3D is a geotechnical software 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,

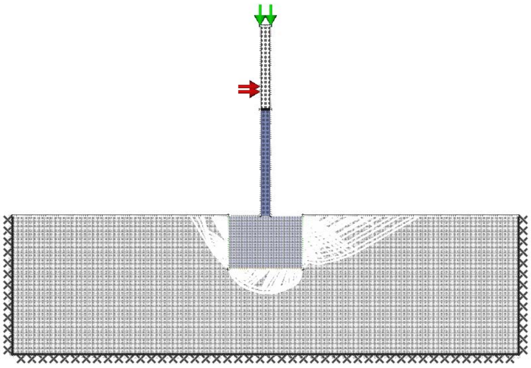

***Fig.* 9**. Discontinuity Layout Optimization (DLO) in LimitState:GEO done for bucket foundation in homogeneous soil layer. Nodal density is very fine.

Table 5. LimitState:GEO: Bucket foundation, ULS.

Distance $[m]$	$D[m]$	$d[m]$	AF
Two-leg support			
-	8	7	1.204
Four-leg support			
17	8	8	0.991
30	8	8	1.197

see Figure 10. 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.

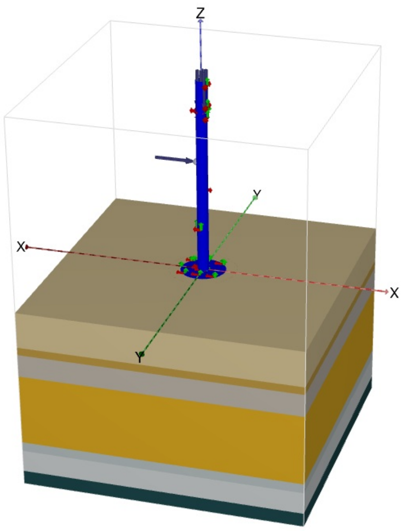

***Fig.* 10**. Plaxis 3D view of Bucket foundation model.

The Hardening Soil model is a "second-order" model that is used for advanced analysis of soil behavior and is selected for the bucket foundation 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 presented in Table 6. More details about estimation of these parameters are provided in [Vaitkunaite and Devant Molina 2012].

Table 6. Soil stiffness properties for Hardening soil model.

Alt.	Description	$E_{50}^{ref}[kPa]$	$E_{oed}^{ref}[kPa]$	$E_{ur}^{ref}[kPa]$
-6.5	Sand Medium	88427	70083	265281
-7.9	Sand Coarse	128559	101890	385678
-12	Sand Medium	72548	63774	217644
-24.8	Gravely sand	130291	103262	390872
-26.5	Sand Fine Cl.	77169	75712	231508
-30.5	Silty Sand	138459	135844	415376
-33	Silt	66766	96435	200297

Results are presented in Tables 7 and 8. Pulled and compressed foundations are modelled at once for the four-leg supported structure. Serviceability limit state is also designed with the program. The requirements for the offshore foundation are divided into two contributions. One from installation and one from the loads causing permanent deformation. In this case the requirement is set to a total deformation of 0.5^0, so that 0.25^0 originates from the installation and 0.25^0 is from permanent deformations, [DNV 2007]. According to Wavestar A/S, WEC is able to perform with the recommended inclination and it is chosen to be a limit for the SLS.

Table 7. Plaxis 3D: Bucket foundation, ULS.

Distance $[m]$	$D[m]$	$d[m]$
Two-leg support		
-	8	7
Four-leg support		
17	7	7
30	7	7

Table 8. Plaxis 3D: Bucket foundation, SLS.

Distance $[m]$	$D[m]$	$d[m]$	rotation $[^0]$
Four-leg support, compressed			
-	8	7	0.22
Four-leg support, compressed			
17	7	7	0.18
30	7	7	0.20
Four-leg support, pulled			
17	7	7	0.22
30	7	7	0.21

3. PILE FOUNDATION

The same strategy as for bucket foundation is employed here. Results for two and four legs foundation approaches are provided in tables at the end of the section. More about pile foundation calculation methods that are presented in this paper can be found in [Vaitkunaite and Devant Molina 2012].

3.1 Dimensioning based on analytical calculations

Analytical method for assess the required pile dimensions is based on [DNV 2007]. The ultimate resistance of the pile is determined from the theory of plasticity where lateral and moment loadings are supported by the unit earth pressures developed along the pile wall. The unit earth pressures estimation is divided into two separate regions, depending on whether the pile is installed on moderate or great depth. The transition point between both calculations is called the transition depth, d_t, presumably in this point the unit earth pressure calculated for moderate depth presents the same results as the unit earth pressure calculated for great depth. Additionally the unit earth pressures are assessed along the pile for different soil layers. This assessment distinguishes between friction materials where unit earth pressures are calculated by (4) for range $0<d<d_t$ and by (5) for $d>d_t$. In case of cohesive materials, the unit earth pressure is calculated by (6) for $0<d<d_t$ and by (7) for $d>d_t$.

$$p = (c_1 \frac{d}{D} + c_2)\,\gamma'\,d \quad (4)$$

$$p = c_3\,\gamma'\,d \quad (5)$$

$$p = 3\,s_u + \gamma'\,d + J\,\frac{d}{D}\,s_u \quad (6)$$

$$p = 9\,s_u \quad (7)$$

The axial resistance is obtained by the skin friction combined with the end resistance. When the pile is axially loaded after the installation, the total resistance against axial loading, Q, is calculated differently either for pile acting unplugged (8) or plugged (9) manner.

$$Q = 0.9Q_{m,i} + Q_{p,j} + Q_{m,y} \quad (8)$$

$$Q = Q_p + Q_{p,j} + Q_{m,y} \quad (9)$$

In (8)and(9) mentioned parameters are illustrated in Figure 11. Term plugged specifies that the unit skin friction developed is larger than the end resistance $Q_{m,i} > Q_p$. The consequence is that the soil volume enclosed is held making a plug and preventing additional soil from entering in the pile during static loading. The term unplugged specifies that the soil volume immersed in the pile moves upwards permitting new soil moving into the pile. The term $Q_{m,y}$ cannot be utilized when the soil outside the pile is used for lateral loading, therefore $Q_{m,y}$ should be set to zero unless additional length is added, which is unwanted as additional length means additional cost. The unit skin friction, q_m,

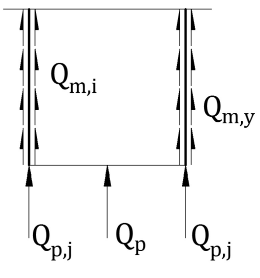

***Fig.* 11**. Axial resistance parameters on pile. After [Roesen 2011]

is calculated for the different soil layers. For drained cases (10) is utilized and for undrained cases (11). The angle of soil friction in the pile wall interface, δ, the upper limit for skin friction, f_l, the bearing factor, N_q and the limiting tip resistance, q_l, are found from [DNV 2007]

$$q_m = K\,p'_0\,\tan\delta < f_1 \quad (10)$$

$$q_m = \alpha\,s_u \quad (11)$$

The end resistance is calculated for drained conditions according to (12) where the limiting resistance, q_l, corresponds to the resistance at critical depth. The end resistance for undrained conditions is calculated by (13).

$$q_p = p'_0\,N_q \leq q_1 \quad (12)$$

$$q_p = 9\,s_u\,F_c \quad (13)$$

If $Q_{m,i}$ can fulfill (14) then vertical equilibrium can be archived without any additional length for the pile.

$$Q_{m,i} \geq F_z - Q_{p,j} \quad (14)$$

Results from the analytical program are presented in Table 9. The estimated pile dimensions are diameter, D and the required driving length, L. AF parameter is always 1, since the dimensioning process is based on statical equilibrium.

Table 9. Analytical program: Pile, ULS.

Distance $[m]$	$D[m]$	$L[m]$
Two-leg support		
-	3	16.31
Four-leg support, compressed		
17	3	15.64
30	3	15.64
Four-leg support, pulled		
17	3	15.64
30	3	15.64

3.2 Dimensioning based on numerical 2D calculations

The same strategy as it is presented in section 2.2 is followed. The view from program interface is shown in Figure 12.

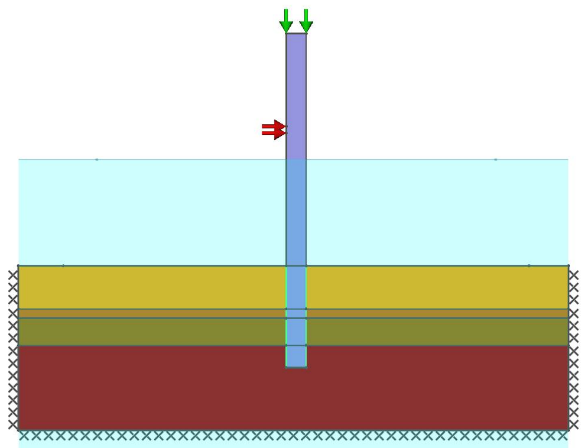

***Fig.* 12**. LimitStateGEO: 2-leg pile foundation.

Results from the numerical 2D program are presented in Table 10.

3.3 Dimensioning based on finite element calculation

Table 10. LimitState:GEO: Pile, ULS.

Distance $[m]$	$D[m]$	$L[m]$	AF
Two-leg support			
-	3	15.85	1.00
Four-leg support			
17	3	15.64	0.85
30	3	15.64	0.64

Within Plaxis 3D the final dimensions as well as verification for SLS and ULS conditions are achieved. The same strategy as in section 2.3 is followed.

Results from Plaxis 3D are presented in Tables 11 and 12.

Table 11. Plaxis 3D: Pile, ULS.

Distance $[m]$	$D[m]$	$L[m]$
Two-leg support		
-	3	15.34
Four-leg support		
17	3	14.22
30	3	14.22

Table 12. Plaxis 3D: Pile, SLS.

Distance $[m]$	$D[m]$	$d[m]$	rotation $[^0]$
Four-leg support, compressed			
-	3	15.34	0.15
Four-leg support, compressed			
17	3	14.78	0.13
30	3	14.78	0.13
Four-leg support, pulled			
17	3	14.78	0.15
30	3	14.78	0.14

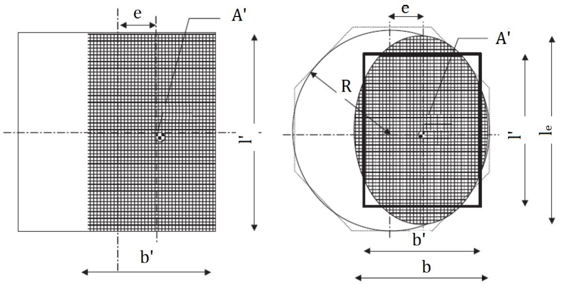

***Fig.* 13**. Effective area for square and circular foundation. After [DNV 2007]

4. GRAVITY BASED FOUNDATION

4.1 Dimensioning based on analytical calculations

Bearing capacity formulae for gravity based foundation are taken from Appendix G in [DNV 2007]. All the external loading and foundation self weight forces are transformed into design horizontal, H_d, and vertical, V_d, loads. Bottom surface of the foundation is in the direct contact to the soil in an effective area, A', calculated by (16). Size of effective area depends on the foundation shape and loading eccentricity. Several possibilities are visualized in Figure 13. Eccentricity of the foundation is estimated by (15) and it satisfies requirement for not strongly eccentrically loaded foundation, $e_{max} = 0.3b'$.

$$e = \frac{M_d}{V_d}. \qquad (15)$$

$$A' = b'l'. \qquad (16)$$

The gravity based foundation is designed of a square shape with height, H. Structure is supported on the foundation with two or four circle-section concrete piles. Bearing capacity, q_d, is estimated by (17). Formula includes bearing capacity factors, N, shape factors, s, and inclination factors, i, [DNV 2007]. Layer 3 is taken for the calculation. This layer consist on medium sand, see Table 3, and is chosen because it has a little smaller materialstrength than the two upper layers and can provide a "safer" dimensioning. Cohesionless fully drained soil is assumed, so the last term can be neglected (c_d=0).

$$q_d = \frac{1}{2}\gamma' b' N_\gamma s_\gamma i_\gamma + p_0' N_q s_q i_q + c_d N_d s_d i_d. \qquad (17)$$

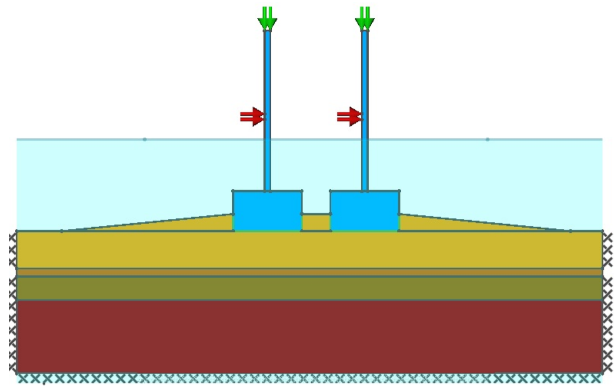

***Fig.* 14**. LimitState:GEO: 4-leg gravity based foundation

The foundation is subjected to horizontal wind and wave load, therefore the sliding capacity is also ensured by (18) and (19).

$$H < cA' + V tan\varphi \qquad (18)$$

$$\frac{H}{V} < 0.4 \qquad (19)$$

Results from the analytical program are presented in Table 13. The estimated foundation dimensions are width and length, a, and height, h. AF parameter is always 1 in this calculation model.

Table 13. Analytical program: Gravity based foundation.

Distance $[m]$	$a[m]$	$h[m]$
Two-leg support		
-	11	4.5
Four-leg support, compressed		
17	10	4
Four-leg support, pulled		
17	11	5

4.2 Dimensioning based on numerical 2D calculations

LimitState:GEO calculation is done in the same way as it is presented in section 2.2. The view from program interface is shown in Figure 14. As it is seen an assumed scour protection is also modeled, due to possible seabed eruption caused by scour.

Results from the numerical 2D calculations are provided in Table 14.

Table 14. LimitState:GEO results: Gravity based foundation.

Distance $[m]$	$a[m]$	$h[m]$	AF
Two-leg support			
-	11	4.5	1.080
Four-leg support			
17	12	7	1.200

4.3 Dimensioning based on finite element calculation

Plaxis 3D calculation is done in the same way as it is presented in section 2.3. Dimensions from previous programs are investigated and optimized to satisfy ULS and SLS requirements.

Results are provided in Tables 15 and 16.

5. COMPARISON

5.1 Comparison of Results from Geotechnical Programs

Buckets: As it is seen from Table 8 a compressed bucket

Table 15. Plaxis 3D: Gravity based foundation, ULS.

Distance $[m]$	$a[m]$	$b[m]$	$h[m]$
Two-leg support			
-	9	9	4
Four-leg support			
17	10	10	4

Table 16. Plaxis 3D: Gravity based foundation, SLS.

Distance $[m]$	$a[m]$	$b[m]$	$h[m]$	rotation $[^0]$
Two-leg support				
-	9	9	4	0.24
Four-leg support, compressed				
17	10	10	4	0.16
Four-leg support, pulled				
17	10	10	4	0.18

requires smaller diameter and skirt dimensions compared to the pulled one in four legs case. However the pulled foundation dimensions are applied for all four supports. Analytical [Ibsen 2001] program and LimitState:GEO estimate a rather similar ultimate strength for the same foundations size. However it is not possible to optimize the dimensions in LimitState:GEO. Final dimensions are optimized in four legs case using Plaxis 3D. It can be concluded that 2D programs are underestimating a little the final dimensions of bucket foundation, but they result in a satisfying primary dimensioning.

Piles: Verifying the results from analytical model with numerical 2D model, it is seen that optimization is only possible for two legs case. For such case the results are optimized up to 3%. LimitState:GEO results in 15-36% smaller bearing capacity in four legs case. This could notify that modelling technique should probably be improved when using LimitState:GEO for four legs option. In general, analytical model results are optimized by 3-6% at the last stage which means that the model is satisfying for preliminary design.

Gravity based foundation: The employed analytical model is rather conservative. Firstly due to the assumed homogeneous soil layer with weaker soil strength parameters. However even if it is expected that LimitState:GEO can be used for optimization due to wider modeling options, it underestimates bearing capacity of gravity based foundation. Possibly the modeling technique could be improved. However the 2D models underestimate the size of foundation for up to 40% compared to Plaxis 3D models. Finally the 2D models for gravity foundation should be improved willing to get a reasonable primary design.

5.2 Two vs. Four Supporting Foundations

The comparison of two vs. four supporting foundations is done only from the geotechnical point of view. Other influences of price and structural design are presented in [Vaitkunaite and Devant Molina 2012].

Buckets: Analyzing Table 8, it can be stated that dimensions of each foundation piece do not differ significantly in two and four legs cases. However 1.68 times more material would be used for WEC supported on four foundations. The influence of distance between pulled and compressed foundation is minor too, which is seen only in small fluctuations of rotations in SLS.

Piles: Analyzing Table 12, it can be seen that in two legs case a pile is only 1.12 m longer. Yet 1.94 times more material would be used for WEC supported on four piles. The influence of distance between pulled and compressed foundation is minor too, which is seen only in small fluctuations of rotations in SLS.

Gravity based foundation: On the contrary to previous types, in Table 16 it can be seen that bigger foundations are required in four legs case. It happens due to smaller vertical load in pulled foundation. Therefore 2.5 times more material would be used in four legs case. The influence of distance between pulled and compressed foundation is not considered further.

While modeling four legs case, it was assumed that equal lateral loading is impacting both, compressed and pulled, foundations. This assumption is hard to expect in reality, because during the storm case wave length is larger than e.g. 17 m and the waves can not hit with the same force to the pile.

In the long term perspective cyclic loading influence should be considered. It is noticed that even not large but constantly repeating pull-out loads tend to impact strongly stability and serviceability of foundations. This can be another issue having a WEC supported on four foundations.

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