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Response Analysis of a Suction Pile Under the Influence of Mooring Tension

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Abstract— *The thesis focuses on the numerical prediction of the ultimate capacity of suction piles in normally consolidated clay in the Gulf of Guinea. Suction piles can be subjected to horizontal, vertical or inclined load. Each load scenario affects the response of the pile and thus, the ultimate holding capacity of the suction pile. Soil with low permeability was simulated using Plaxis-3D and applied as pressure and friction on the pile. Suction pile aspect ratio is 4.5. The suction pile is modelled using Abaqus . The suction pile plate is 40mm thick. An 8 node quadratic shell element with a geometric seed size of 100mm is used. The suction pile was subjected to certain specified load until soil collapse occurs; the value of tension load on mooring line was recorded. The angle between the mooring line and the horizontal was varied for the simulation to determine the worst angle to cause soil collapse around the pile. The maximum horizontal force and maximum vertical force were deduced for each load case. The angle between the mooring line and the horizontal was 33.3o when a force of 15290kN caused the local soil collapse, for lateral load, the load that causes soil collapse was much larger ; 25261kN. The pullout capacity of the pile was tested by a purely vertical force and a much lesser force caused collapse. Hence, the point of load application has a great effect on the ultimate local soil resistance and pile capacity. The above result is enough to conclude that the point of application of load along the entire length of the suction caisson together with the angle at which it is applied plays a key role in determining the mode of failure of the soil body around the suction pile.*

Keywords— *Abaqus, Loads, Suction, Failure, Resistance, Ultimate, Collapse.*

I. Introduction

1.1 Background of the Study

As the demand for oil and gas increases, there has also been a considerable increase in the size and complexity of offshore structures to be able to cater for this demand. Over the last few decades, exploration and exploitation of oil and gas have moved from shallow waters to deep waters. These changes have created the need for foundation systems with large capacity to carry these structures and also to withstand the more adverse environmental loads imposed on such structures by the activities of wind, waves and water current. Suction piles (also called suction caisson, suction anchors or suction buckets) are widely used all over the world for supporting offshore structures in water depths were the use of driven piles, mostly used for fixed structures, will prove difficult, uneconomical and practically unsafe. Thus, offshore construction and installation entails the various process and stages put in place to fabricate offshore equipment and install them safely in order to achieve a specific purpose. Bai & Bai (2010) stated that suction pile anchors resist vertical uplift loads by various mechanisms depending on the load type. The following are the various types of loading:

- *Storm loading*:
  - External skin friction;
  - Reverse end bearing (REB) at the tip of the piles;
  - Submerged weight of the anchor.
- *Long-term loop current loading*:
  - External skin friction appropriately reduced for creep and cyclic
    effects due to long-term duration of the current;
  - Reduced value of reverse end bearing;
  - Submerged weight of the anchor.
- *Pretension loading*:
  - External skin friction;
  - Smaller of internal skin friction or soil plug weight;
  - Submerged weight of anchor.
- *Suction piles resist horizontal loads by the following mechanisms*:
  - Passive and active resistance of the soil;
  - External skin friction on the pile wall sides (as appropriate);
  - Pile tip shear.

The pullout capacity of the caisson is one of the main concerns. The caissons are usually connected to the floating structures by a mooring line which is attached to a pad eye on one side of the caisson. The pullout behaviour of suction caissons installed in both sand and clay is of great interest of many oil and gas development projects. Numerical modelling of suction caisson in sand is complex and thus, is very limited. Deng and Carter (2000) conducted FE analyses of suction caisson in sand assuming axisymmetric loading conditions using the AFENA FE software package and Mohr-Coulomb soil model. Iftekharuzzaman and Hawlader (2012) also conducted three-dimensional FE analysis using Abaqus/Standard FE software, where they encountered some mesh distortion issues at large displacement. Limited number of research is available in the literature to estimate the pullout capacity of suction caissons in sand. The mechanisms involved in the installation of a caisson in sand are different from those of in clay. In sand, the seepage due to applied suction plays a significant role (Ahmed, 2014). This study focuses on analysis of suction pile in clay. The suction anchor considered is 27m long and 6m in diameter (Aspect Ratio; L/D = 4.5), the plate thickness for the pile material is 40mm. The finite element (ABAQUS & PLAXIS 3D), which is used

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consists of solid elements for the soil, shell elements for the pile (caisson) structure, and the interface elements to stimulate the soil-structure contact. The contact simulation includes the effects from friction and potential separation of the soil from the structure.

II. METHODOLOGY

This analysis was carried out using Abaqus Finite Element Modelling (FEM) tool. The calculations are performed by numerical method using Abaqus CAE version 6.10 computer program and plaxis 3D was used to model the soil and results compared with those gotten from hand calculations. Abaqus CAE is a multipurpose software well suited for finite element analysis. It has a complete structural package with Pre and Post Processor capabilities. It is well suited for modelling various geometries and including non-linear effects. The local analysis does not consider the effect and impact of the soil (drained and undrained effect due to shear strength of surrounding soil is neglected). The global analysis, on the other hand, factors in the effect of the soil strength which is modelled as a pressure for conservativeness. Global analysis is adopted for this simulation.

Global and Local Analysis Design and Load Considerations

The structural strength and integrity of the suction pile is usually checked under the following design considerations:

- Intact Condition
- One mooring line broken condition
- Two mooring line broken condition

This analysis is carried out by adopting a 100-year wave return period.

TABLE 1.1. Environmental data.

Parameter	Value
Seawater Density	1025 kg/m^3
Water Depth	1500m
Scouring Depth	3m

Suction Pile Geometry

The dimension of the suction pile to be modelled is given as shown in Table 1.2

TABLE 1.2. Suction pile geometry.

Parameter	Value (mm)
Outer diameter	6000mm
Suction Pile Length	27000mm
Penetration Length	26000mm
Pile Plate thickness	40mm
Total Submerged Weight for holding capacity analysis	1734 kN

III. GLOBAL AND LOCAL ELEMENT MODEL

The element type used for the global and local is an eight (8) node quadratic shell element S8R with a geometric seed size of 100mm. The seed size is used to seed the part instance. It determines the meshing configuration of the suction pile model. A certain minimum mesh size is required in order to obtain an acceptable result. Seed size helps to control and guide the meshing process which will greatly affect the path of the analysis and the final result obtained. A mesh sensitivity study shows the relationship between the maximum stress and the number of elements (higher for finer meshing). S8R is a shell element with six degrees of freedom per node and it is has both bending and membrane capabilities thus making it suitable for linear and non-linear applications. It is also suitable for modelling thick shell structures because of its specific feature which allows for shear deformation.

Vertical Shear Stress on the Pilein the y-axis

Combined Loads

The basic active and passive loads are all combined and applied on the mooring pile under a given load step. For the equilibrium of the suction pile structure under the in-place condition, the various basic soil reaction load cases must balance the active forces and moments resulting from the tension load of the FPSO on the pile as given by the following expressions below;

$$\sum F_x : (C_1 \times RF_{LFX}) + (C_7 \times RF_{L1S}) = 0 \quad (3.1)$$

$$\sum F_Y : (C_2 \times RF_{LFY}) + (C_8 \times RF_{L2S}) = 0 \quad (3.2)$$

$$\sum F_Z : (C_3 \times RF_{LFZ}) + (C_{10} \times RF_{L4S}) + (C_6 \times RF_{Lg}) = 0 \quad (3.3)$$

$$\sum M_X : (C_2 \times RM_{LFY}) + (C_8 \times RM_{L2S}) + (C_{11} \times RM_{L5S}) + (C_4 \times RM_{LMx}) = 0 \quad (3.4)$$

$$\sum M_y : (C_6 \times RM_{Lg}) + (C_1 \times RM_{LFx}) + (C_3 \times RM_{LFz}) + (C_7 \times RM_{LM1s}) + (C_{12} \times RM_{L6s}) = 0 \quad (3.5)$$

$$\sum M_z : (C_2 \times RM_{LFy}) + (C_9 \times RM_{L3s}) + (C_5 \times RM_{LMz}) = 0 \quad (3.6)$$

The factors C1-C12 are load coefficients which are multiplied with the basic load cases to get the combined equilibrium load used for the analysis.

C1-C6 are factors multiplied with the basic active load cases. Whereas C7-C12 are factors multiplied with the passive load cases and they are gotten from the resolution of the equilibrium equations given above. RF and RM are reaction forces and moments for different directions, x, y and z. L_g is the gravity load due to weight of the pile.

TABLE 1.3. Soil submerged weight with depth.

Lower Range (Depth) z	Upper Range (Depth) z	Soil Submerged Unit Weight, γ' (kN/m^3)
0	8	$2.6 + 0.08 \times z$
8	18	$3.2 + 0 \times z$
18	28	$0.68 + 0.14 \times z$
28	40	$0.68 + 0.14 \times z$
40	60	$0.68 + 0.14 \times z$

TABLE 1.4. Load condition equations.

Load case	Reaction Force (N)	Moment (Nm)
Lg	Mg	
LFx	-Fx	-Fx*L
LFy	_Fy	-Fy*L -Fy*k
LFz	-Fz	Fz*k
LMx		-LMx
LMz		-LMz
L1S	$2.r\left[\int_{\frac{-\pi}{2}}^{\frac{\pi}{2}}\int_{z1}^{z2}\left(p(z).\cos^2\theta\right)dzd\theta\right]$	$2.r\left[\int_{\frac{-\pi}{2}}^{\frac{\pi}{2}}\int_{z1}^{z2}\left((z-26)p(z).\cos^2\theta\right)dzd\theta\right]$

L2S	$2.r\left[\int_{\frac{-\pi}{2}}^{\frac{\pi}{2}}\int_{z1}^{z2}\left(p(z).\cos^2\theta\right)dzd\theta\right]$	$2.r\left[\int_{\frac{-\pi}{2}}^{\frac{\pi}{2}}\int_{z1}^{z2}\left((z-26)p(z).\cos^2\theta\right)dzd\theta\right]$
L3S		$2.\pi.r^2\left(\int_{z1}^{z2}\tau(z)dz\right)$
L4S	$2.\pi.r\left(\int_{z1}^{z2}\tau(z)dz\right)$	
L5S		$2.r^2\left[\int_{\frac{-\pi}{2}}^{\frac{\pi}{2}}\int_{z1}^{z2}\left(\tau(z).\cos^2\theta\right)dzd\theta\right]$
L6S		$2.r^2\left[\int_{\frac{-\pi}{2}}^{\frac{\pi}{2}}\int_{z1}^{z2}\left(\tau(z).\cos^2\theta\right)dzd\theta\right]$

IV. RESULTS AND DISCUSSION

The reactions from active and passive load cases are summarized, and it shows that both the active and passive load cases have a direct effect on the suction pile response and should considered when performing designs. Table 1.5 below shows the reaction forces and moments obtained for the various load conditions. The reaction force for L1s is 20133.2kN for the x-direction which has the same value as L2s in the y-direction.

TABLE 1.5. Active and basic load cases from FE analysis result.

LC	Basic Loads Reactions					
	RFx (kN)	Rfy (kN)	RFz (kN)	Rmx (kNm)	Rmy (kNm)	Rmz (kNm)
Lg	0	0	1862.39	0	-282.11	0
LFx	-1	0	0	0	-8.7	0
LFy	0	-1	0	8.7	0	-3.575
LFz	0	0	-1	0	3.575	0
LMx	0	0	-1	-1	0	0
LMz	0		0	0	0	-1
L1s	20133.2	0	0	0	176339	0
L2s	0	20133.2	0	-176339	0	0
L3s	0	0	0	0	0	13743.1
L4s	0	0	4612.18	0	0	0
L5s	0	0	0	-6871.27	0	0
L6s		0	0	0	6871.27	0

TABLE 1.6. Comparison of passive load's reactions.

Load Case	Reactions		% difference
	Hand Calculation (kN)	FE Analysis (kN)	
L1s	20180	20133.2	0.23
L2s	20180	20133.2	0.23
L3s	13780	13743.1	0.27
L4s	4624	4612.18	0.26
L5s	6798	6871.27	-1.08
L6s	6798	6871.27	-1.08

The table above shows the comparison between values gotten from hand calculation and finite element analysis and the percentage difference of the results. The passive loads reactions gotten from the finite element analysis is compared with the reaction results gotten from hand calculations using the table above and it is seen that only small variations exist. So the finite element results are acceptable.

TABLE 1.7. Combined load reaction.

Load Condition	Combined Loads reactions					
	RF_x (kN)	RF_y (kN)	RF_z (kN)	RF_{mx} (kNm)	RF_{my} (kNm)	RF_{mz} (kNm)
Intact	0.139	0.141	0.195	0.245	0.52	0
1 line broken	0.239	0.118	0.07	0.162	0.464	0.258
2 line broken	0.173	0.316	0.130	0.345	0.475	0.168

From both Tables 1.5 and 1.6 results gotten previously, the combined load conditions for the three load conditions discussed earlier are computed as shown in Table 1.7.

Result of the Ultimate Resistances

Tilt and non-optional load attachment point will reduced the capacity compared to a perfectly vertical (non-tilted), optimally loaded anchor. To allow for the tilt installation tolerance a reduction factor was applied on the FEA Model while performing the calculation. Table 1.8 shows various mooring tension angles.

The angle the mooring line makes with the horizontal is varied from 32.5° through 35° through unequal intervals and the various results for tilt and no tilt were recorded as shown in Table 1.8 below.

TABLE 1.8. Angle at padeye and ultimate soil resistances.

Parameter	Tension (kN)	
	With no tilt and no heading	With 5° tilt tolerance and 10° tolerance heading
Ultimate horizontal resistance, H_{max}	25621	-
Ultimate vertical resistance, V_{max}	7120	-
Ultimate resistance at 32.5° relative to the horizontal	16160	13920
Ultimate resistance at 33.3° relative to the horizontal	158920	13760
Ultimate resistance at 33.8° relative to the horizontal	15720	13600
Ultimate resistance at 35.0° relative to the horizontal	15320	13320

Pile Penetration Resistance

The penetration resistance, Q_{tot}, for skirts without stiffeners is calculated as the sum of the side shear along the skirt walls, Q_{side}, and the bearing capacity at the skirt tip, Q_{tip}.

$$Q_{tot} = Q_{side} + Q_{tip}$$

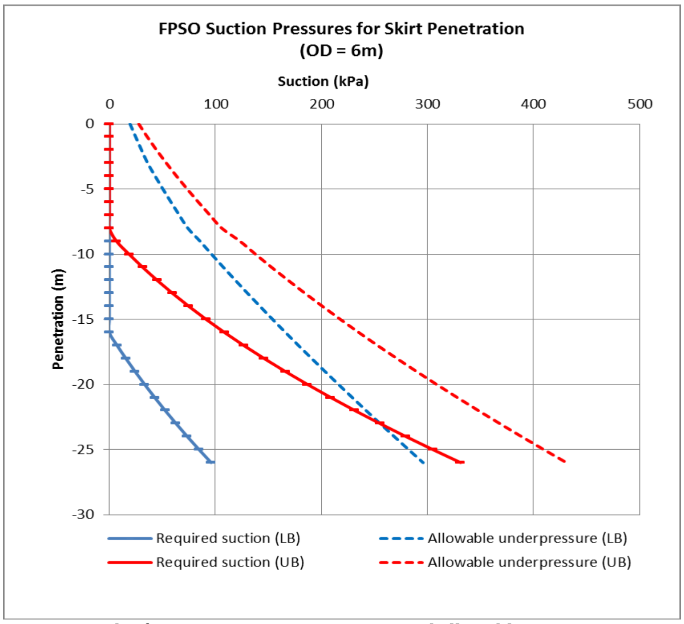
$$Q_{tot} = A_{wall} \times \alpha \times S_{u,D}^{av} + \left(N_c \times S_{u,tip}^{av} + \gamma' \times z\right) \times A_{tip}$$

The above equation shows the total soil penetration as it varies with suction pile penetration. The soil resistance to penetration is seen to increase with increasing depth.

TABLE 1.9. Shows the soil resistance to penetration as it varies with penetration depth.

Skirt length (m)	Penetration (m)	Total soil resistance to penetration, Q_{total} (kN)	
		LB	**UB**
1.00	0.00	27	37
2.00	1.00	34	175
3.00	2.00	41	331
4.00	3.00	49	504
5.00	4.00	121	695
6.00	5.00	202	903
7.00	6.00	290	1130
8.00	7.00	386	1373
9.00	8.00	490	1635
10.00	9.00	661	2048
11.00	10.00	798	2375
12.00	11.00	946	2726
13.00	12.00	1105	3102
14.00	13.00	1274	3502
15.00	14.00	1455	3926
16.00	15.00	1646	4375
17.00	16.00	1848	4848
18.50	17.50	2064	5349
19.50	18.50	2292	5878
20.00	19.00	2530	6430
21.00	20.00	2780	7008
22.00	21.00	3040	7609
23.00	22.00	3311	8236
24.00	23.00	3594	8886
25.00	24.00	3887	9561
26.00	25.00	4191	10261
27.00	26.00	4506	10984

The figure below is a plot of penetration against suction for the upper bound and lower bound condition.



Graph of penetration, suction pressure and allowable pressure.

For a given soil profile, the required suction pressure is always lower than the allowable suction pressure. Beyond 20m penetration, as shown in Table, at first the lower bound allowable is usually adopted. When penetration does not progress any further, the lower bound allowable may be exceeded, thus the upper bound allowable profile.

TABLE 1.91. Suction anchor displacements obtained due to padeye load from mooring tension.

Configuration		Tension at padeye (kN)	Angle at padeye	Displacement at Padeye (m)	
				With no tilt tolerance ±5°, no heading	**With ±5° tilt tolerance and 10° heading**
Intact	100 years	6622	35.0	0.0345	0.0337
1-line broken	100 year	8755	33.8	0.0482	0.0477
2-line broken	100 year	13723	33.3	0.112	0.1606

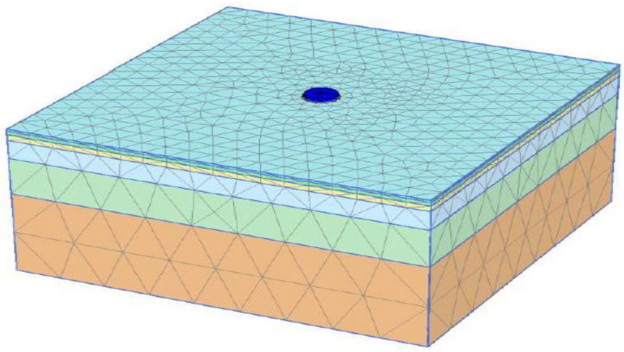


Fig. 1.92 PLAXIS 3D model of soil and pile (In-place conditions).

Discussion

From the results, tables and graph obtained during the analysis, it was shown that the undrained shear strength and resistance of the soil increase with increasing depth for both the lower and the upper bound conditions. Secondly, it is also observed that the mooring tension on each of the four mooring lines for one group of the four mooring set is least for the intact condition, more for 1-line broken condition and highest for the 2-line broken condition. Finally, the location of the padeye along the pile skirt, the angle between the mooring line and the horizontal and the mode of application of the tension affects the overall pile capacity; the vertical tension accounting more for the pullotu capacity of the pile. Also, the results gotten from the finite element analysis were compared with those gotten from the hand calculations performed using the table of equations on Table and equations 3.2 through 3.7. With no tilt, the ultimate suction pile resistance was determined and compared with the ultimate vertical suction pile resistance. The horizontal resistance was seen to be much higher than the vertical resistance. The ultimate vertical resistance which accounts for the holding capacity of the suction pile is only 27.789% of the ultimate horizontal resistance.

V. Conclusion

The research work to determine the structural integrity of a suction pile has been carried out. From the results obtained,

- it can be deduced that the angle between the mooring line and the horizontal at the padeye hole greatly affects both vertical and horizontal components of the inclined load.

- pile capacity is observed to be affected by the penetration depth.
- also, it was observed from the soil model that the allowable under-pressure increases appreciably with the depth of penetration.

A 40MN force applied at 33.3° on the padeye was used to attain soil body collapses which gave an estimated ultimate soil resistance of 15.920MN at 33.3°. However, a 60MN horizontal force applied at the padeye until the soil body collapses was used to obtain an ultimate soil resistance of 25.621MN. No submerged weight of the pile is considered at this stage. 20MN of pure vertical force applied at top centre of pile to attain soil body collapses gave an ultimate soil resistance of 6.468MN.

VI. RECOMMENDATION

Empirical models should also be developed in a suitable laboratory to verify the numerical results from modern day software. By so doing, the actual real life behaviour of the suction pile is modelled. A comparison can be made between both the numerical and empirical analysis. As suction increases, the value of the cohesion term in the bearing capacity equation, the influence of the depth factor, increases resulting in smaller factors of increase in bearing capacity when there is an increase pile size (diameter). Analysis should be carried out for sand to determine its drained and undrained shear strength.

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