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Numerical and experimental investigation of suction anchor design aspects

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ABSTRACT: For the design of suction anchors for offshore foundations API standards are applicable. In order to investigate the exact behaviour and interaction of suction anchors in the sea bottom a combined numerical / experimental research was performed at Delft University of Technology. In centrifuge tests as well as by means of three-dimensional finite element calculations the influence of various parameters, among which the height / diameter ratio (H/D), the mooring attachment height (h/H) and the attachment angle (α), was investigated for suction anchors in dry sand. The research shows a good agreement between the numerical and experimental results. It is concluded that the actual horizontal bearing capacity of the suction anchors is well beyond the maximum anchor force that is allowed according to the API standards. The research also provides clear insight in the failure mechanism that occurs in the sea bottom due to excessive anchor forces. It is concluded that the best position of the cable attachment point is at 2/5 of the anchor height.

This paper mainly concentrates on the numerical modelling aspects and the (graphical) results. Graphs of the maximum anchor force are presented in non-dimensionalised form, so that they can be easily applied to suction anchors with other dimensions.

1 INTRODUCTION

In recent years, suction anchors (or suction piles) have been applied increasingly often in offshore engineering (Wang et al., 1978; Senpere et al., 1982). These types of anchors are attractive because of the convenient installation method. An anchor with a diameter of 9 m and a height of 10 m can be installed in a few hours, by using a pump only. In related experimental research (Allersma et al., 1997) the installation process was investigated by means of a centrifuge test and a linear relationship was found between the pressure and typical installation parameters such as height, diameter and wall thickness. More recently, attention was focused on the static horizontal bearing capacity (Allersma et al., 1999).

In practice, suction anchors are used for several different loading conditions. The horizontal loading conditions may be significant when suction anchors are used for the anchoring of floating offshore systems. This contribution deals again with the static horizontal bearing capacity, but the attention is focused on numerical analysis rather than the experimental results.

Since prototype tests are very expensive and time consuming, the investigation of the bearing capacity of real scale devices under different circumstances is of limited practicality. In small scale tests it is much easier to change parameters. The soil type can be varied, as can the dimensions of the suction anchor and other installation parameters. In a small scale test, however, problems arise concerning the stress dependent behaviour of soil. Furthermore, the measured loads are so low that measurements are not accurate enough to visualise differences in design. These restrictions can be overcome by performing small scale tests in a geotechnical centrifuge or by means of numerical simulations with the finite element method. The latter method has become applicable to the engineering practice, since nowadays finite element programs with convenient user-interfaces and automated numerical processes, like PLAXIS, are available. It is the authors' opinion that the combination of both methods (FEM and centrifuge) is a strong approach to the design of suction anchors, as an alternative to the use of conservative API standards.

The aim of this study was to examine the influence of several parameters, such as the anchor height (H), the attachment point (h/H), the attachment angle (α)

...on the horizontal bearing ... in dry sand. The numeri- ... with a preliminary 3D ... version 6. The numerical results ... the results of centrifuge tests and ... of the American Petro- ... 1993).

... SUCTION ANCHORS

... is a large diameter steel cylinder ... the top either by a dome formed ... stiffened plate. The cylinder is ... Pump inlets and relief valves are ... as well as the lug to connect the ...

... can be launched from an installa- ... the aft deck of a supply boat, must ... the sea floor. The cylinder is low- ... with open valves so that the en- ... rapidly.

... has penetrated the sea floor by its ... relief valves are closed. To avoid ... are started, additional weights are ... cohesionless soils like sands to ... into the soil sufficiently.

... water out of the pile by ... mounted on the top causes a pressure ... the external hydrostatic water ... water pressure inside the pile. The ... generates the driving force for soil ... permeable soils water will flow ... to the tip of the pile during pump- ... stress around the tip and between ... plug is reduced due to local fluidi- ... reduction, the driving force is suf- ... penetration of the pile. Pumping is ... the designed penetration depth. ... is reached in about 20 min to 1 ... on the soil configuration, the pile ... pump capacity.

... pore pressures in the soil regain ... The loads are therefore resisted ... similar way to a conventional driven ... regard to friction. The pump, the ... measuring equipment mounted ... pile, can be made retrievable for ... complete installation.

... MODEL

... anchors is based on the analyti- ... by the American Petroleum ... In this calculation procedure the horizontal bearing capacity P of piles in sand is formulated empirically for shallow depths (H/D<5) by

$$P_{ult:s} = (C_1 z + C_2 D)\gamma_s z \qquad (1)$$

and for large depths (more than 10 times the pile diameter) by

$$P_{ult:d} = C_3 D \gamma_s z \qquad (2)$$

where z = depth below mudline, D = pile diameter, γ_s = unit weight of soil and C1, C2, C3 are coefficients depending on the soil internal friction. The values used for C are presented in Table1.

Table 1. Used C-values in the API calculation.

φ [°]	C1	C2	C3
25	1.25	2.00	15.00
30	1.93	2.67	28.15
32	2.45	3.17	40.38

The API calculation assumes that the pile is loaded purely horizontally ($\alpha = 0°$).

4 CENTRIFUGE TESTS

In the framework of this research, more than 20 centrifuge tests were carried out to examine the influence of the different parameters on the horizontal bearing capacity of suction anchor scale models. The tests were performed on dry dune sand at an artificial gravity of 150g. For the suction anchor scale models, brass cylinders with a constant diameter (D) of 0.03m (4.5m in prototype) and different heights (H = 0.03m, 0.05m and 0.07m) were used. The load was applied by attaching a cable at the desired position and desired inclination to the anchor and by pulling the cable backwards at a speed of approximately 2mm per minute, while the displacement and the reaction force were measured. For more details on the centrifuge modelling reference is made to Allersma et.al., 1998.

5 FINITE ELEMENT MODEL

Together with the experimental work, 3D finite element calculations were made to check the results of the centrifuge tests and to evaluate to what extend both methods can be used for the design of suction anchors. The FEM analyses were made with a preliminary 3D module for laterally loaded piles of PLAXIS Version 6. With this version it is possible to analyse axisymmetric structures with non-axisymmetric loads using a full 3D formulation. Based on a 2D input of the geometry and element distribution, the model is extended into a full 3D model, using 20-node (quadratic) brick elements with 2x2x2 points Gaussian integration. These elements were used for the modelling of the soil as well as for the anchor and the interaction between the anchor and the soil. It was not aimed to model the thickness of the anchor plate and the interaction zone precisely, so arbitrary small rows of elements were used for to model these items in combination with proper model parameters.

The displacement boundary conditions were such that the nodes at the bottom were fully fixed and the nodes at the outer vertical boundary could only move in vertical direction, whereas the other boundary nodes were fully free to move. An example of a three-dimensional mesh with 196 20-node elements as used for the analysis of a suction anchor is shown in Fig.1. For the modelling of soil behaviour in the preliminary 3D module only the Mohr-Coulomb model was available. The soil behaviour was assumed to be drained. The effective parameters as used in most of the analyses are listed in Table 2. For the interface layer between the anchor and the soil the same model parameters were used, except for the friction angle, which was taken 22 degrees, i.e. a reduction of 0.63 compared to $\tan\varphi_{soil}$. The anchor wall was modelled by means of Hooke's law for isotropic elasticity, using an arbitrary high Young's modulus of more than 10^4 times the modulus of the surrounding soil.

The initial vertical stresses were generated from the weight of the soil column. The initial horizontal stresses were a factor K_0 times the initial vertical stresses, where K_0 was based on Jaky's formula $1\text{-}\sin\varphi$. Water pressures were not considered at all.

Special attention was paid to the of modelling the attachment point of inclined loads. In reality, the load acts at one side of the anchor, resulting in an additional overturning moment. This situation can exactly be modelled in the centrifuge tests, but in the numerical model the load acts in horizontal direction all around the anchor. As a result, the attachment point is effectively located in the centre of the model and does not introduce the additional overturning moment. In order to match the conditions and results of the centrifuge tests, a vertical correction, Δv, had to be made to the attachment point, which is given by:

$$\Delta v = -\,0.5\ D \tan\alpha \qquad (3)$$

According to Eq. (3), the corrections for different attachment angles for an anchor diameter of 4.5 m are:

α [°]	0	10	15	20	25	30
-Δv [m]	0.0	0.397	0.603	0.819	1.05	1.30

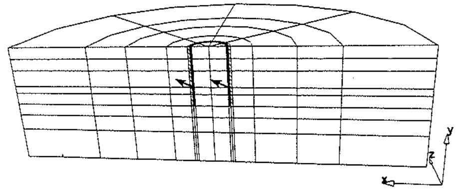


Figure 1. 3D FE mesh for analysis of suction anchor

Table 2. Model parameters used for dune sand

Parameter	Symbol	Value	Unit
Unit weight	γ	17.0	kN/m^3
Young's modulus	E'	15000	kN/m^2
Poisson's ratio	ν'	0.35	-
Cohesion	c'	1.0	kN/m^2
Friction angle	φ'	33.0	°
Dilatancy angle	ψ	3.0	°

6 CALCULATIONS AND RESULTS

Starting from the initial stress state, a first elasto-plastic calculation was performed on a standard configuration in which the load was stepwise increased until failure. The standard configuration involves the following set of parameters:

Anchor height, H:	7.5 m	
Diameter, D:	4.5 m	(H/D = 1.33)
Attachment height, h:	3.0 m	(h/H = 0.4)
Attachment angle, α:	15°	
Model parameters:	according to Table 2	

Fig. 2 shows the development of the load as a function of the displacement at the top of the anchor for the standard configuration. From the plot the maximum anchor force, P, can be evaluated, which is around 14800 kN. This value serves as a reference value for other situations.

Fig. 3 shows a 3D plot of the deformed mesh at the moment when the maximum anchor force is reached.

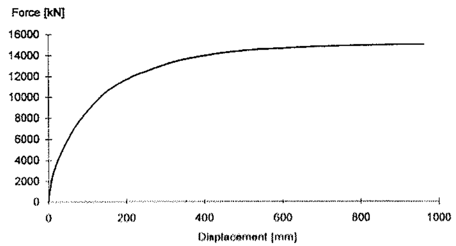
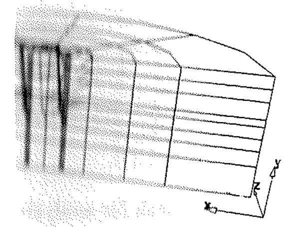


Figure 2. Load-displacement curve for standard configuration



...ed 3D mesh when reaching the ...m anchor force.

...the first analysis for the standard ...calculations were performed in ...the parameters influencing the ...were varied (one at a time). The ...were in accordance with the stan... Underneath an overview is ...important numerical results:

...variation:

7.5	10.5
1.67	2.33
14800	24200

...ight variation:

0.33	0.40	0.60	0.80	0.95
16300	14800	10500	9470	7350

...gle variation:

10	15	20	25	30
16300	14800	13400	12200	10900

...on variation:

20	22	25	33
0.56	0.62	0.72	1.00
14000	14800	15200	16400

...from the above results, the at... ...nd attachment angle have a major ...esults. The influence of the inter... ...the roughness of the anchor, is ...s of fact, the anchor height has an ...e as well, but this is obvious.

...OF RESULTS

...able to compare the results of the ...API, centrifuge, FEM) and to pres... ...spective dimensionless form, the re... ...anchor force was divided by the ...sand inside the anchor, i.e. the unit ...s the inner anchor volume.

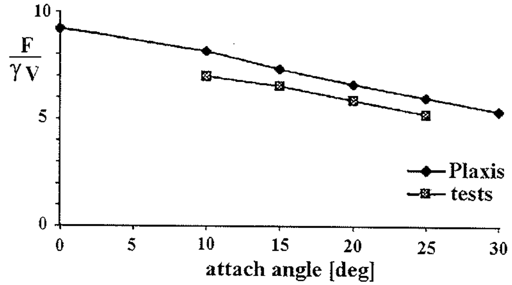


Figure 4. Comparison of non-dimensionalised forces (attachment angle variation).

Fig. 4 shows a comparison between numerical calculations and centrifuge test results for a variation of the attachment angle. The maximum anchor force calculated by the finite element method is generally 10% higher than the results from the centrifuge tests. This over-estimation is due to the fact that a relatively coarse 3D finite element mesh was used. Nevertheless, the tendency is the same in the sense that both methods predict a similar decrease of the horizontal bearing capacity with increasing attachment angle.

Fig. 5 shows a comparison of results for a varying attachment height ratio. The variations of the maximum anchor force are quite strong, especially in the h/H-range between 0.4 and 0.6. Although the numerical results are again some 10% higher than the experimental results, they both show the same tendency in the sense that the horizontal bearing capacity is decreasing with increasing attachment height. On extrapolating these results it may be concluded that the best position to attach the cable is at the bottom of the anchor. In practice, this may be undesirable since it may lead to installation problems, so it is questionable whether this is indeed the best situation.

Fig. 6 shows the different mechanisms and movements of the anchor when the maximum force is reached. In the standard configuration (h/H = 0.4), the anchor hardly rotates and is just translated through the soil (see Fig. 6B). In the case of a very low attachment point (h/H ≤ 0.2), the anchor is rotating backwards, i.e. with its bottom in the pulling direction and with its top in the opposite direction (Fig. 6A). This leads to the largest soil volume that is mobilised, which explains the largest bearing capacity for the lowest h/H ratio. In the situations with a high attachment point (h/H ≥ 0.6), the anchor is rotating forward (Fig. 6C).

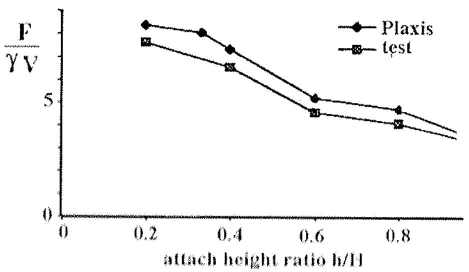


Figure 5. Comparison of non-dimensionalised forces (attachment height variation).

In Fig. 8 the influence of the relative anchor height on the non-dimensionalised maximum anchor force is visualised. Again, apart from the higher values from the FEM, both methods show the same tendency in the sense that the horizontal bearing capacity increases with an increasing relative anchor height. This is not obvious, because the anchor height also determines the soil volume, which is used to non-dimensionalise the bearing capacity. As a result, the increase of the non-dimensionalised bearing capacity as a function of the H/D ratio is less than the increase of the absolute value of the bearing capacity, as listed in the first table in Chapter 6.

In Fig. 8 a comparison is made between the measured data from the centrifuge tests and the values obtained by the API calculation. In these graphs the bearing capacities are given in prototype values. In these calculations the attachment point h/H = 0.4 is assumed. In Fig.11a the H/D ratio is considered. As can be seen there is fairly good agreement between test results and the API calculations. However, in contrast to the FEM calculations, the difference between tests and API result appeared to be dependent on the H/D ratio. The best fit was found at H/D=1.66. In Fig.11b the influence of the density is visualised at H/D=1.66. It appeared that there was a good agreement in tendency between the calculations and the tests. It appeared that for the chosen H/D ratio the calculated horizontal bearing capacity was approximately 20% lower than the values measured in the experiments. For other H/D ratios, however, larger deviations between calculations and tests were observed. It appeared that the calculations according to the API are rather conservative.

8 DISCUSSION AND CONCLUSION

The 3D Finite Element Method for deformation analysis has proven to be a good method for analysing the horizontal bearing capacity of suction anchors. In these situations it is the load that requires a three-dimensional analysis, since the geometry itself is axisymmetric. This enables a rather quick geometry input and an easy 3D mesh extension based on an axisymmetric (2D) finite element model, as available in PLAXIS. This has major advantages over a general 3D finite element model.

With the preliminary 3D PLAXIS module for laterally loaded piles it was possible to make a realistic comparison between FEM calculations and centrifuge tests for suction anchors. It is promising that there is a fairly good agreement between the results of the calculations and the tests. In particular the influence tendencies of the various parameters match very well. In general the maximum anchor forces calculated by the FEM were approximately 10% higher than the results from the centrifuge tests. It must therefore be recognized that the FEM tends to over-estimate the bearing capacity, since the FEM gives an upper bound solution, but the amount of over-estimation depends on the coarseness of the finite element mesh, which can be influenced by the user. Nevertheless, the combination of centrifuge tests and FEM calculations seems to provide a good basis for the design of suction anchors. These methods give much more inside in the deformation behaviour and the failure mechanisms than analytical calculations.

The analytical calculations according to the API protocol result in more conservative values for the horizontal bearing capacity. This indicates that the API rules can be used safely for the design of suction anchors in homogeneous soils.

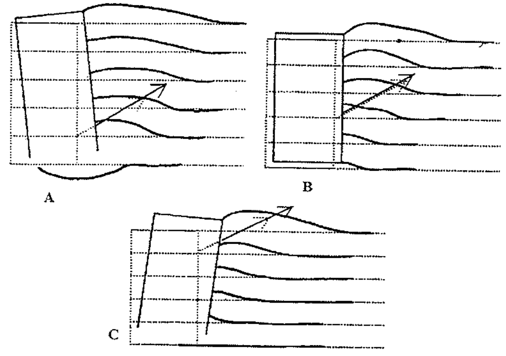


Figure 6. Comparison of different mechanisms for different attachment heights as observed both in FEM and centrifuge tests.

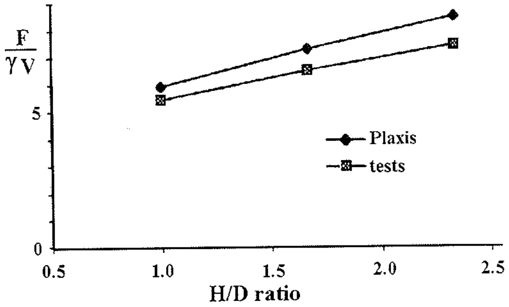
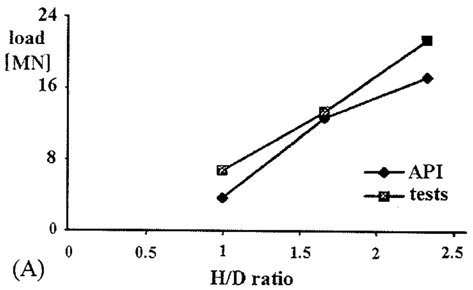


Figure 7. Comparison of non-dimensionalised forces (anchor height variation).



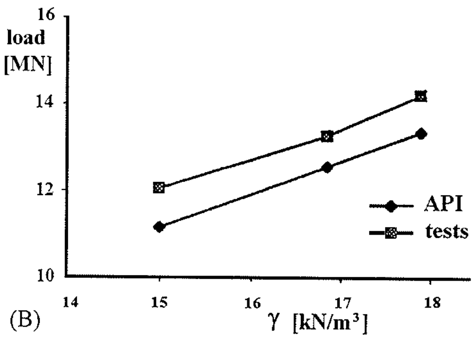


Figure 8. Comparison between the centrifuge test results and the API rules.

In the tests it has yet to be investigated how suction anchors behave in layered soils. In principle, both the centrifuge and the FEM are good tools for analysing these effects.

The variations made in the test series and the numerical analyses have led to the following conclusions:

- The attachment angle influences the bearing capacity significantly. An angle α = 10° gives a 27% higher bearing capacity than an angle α = 25°. This observation indicates that it is significant that the cable is buried in the soil after installation, so that the angle is as close to the optimum as possible.

- The bearing capacity increases at lower attachment heights. The change in bearing capacity is greatest at an attachment height between h/H = 0.4 and h/H = 0.6. However, the lower the attachment point, the more difficult it is to install the anchor. Furthermore, the location of the attachment point at the tip of the pile is practically undesireable for technical reasons. Therefore the optimum attachment height would appear to be h = 0.4 H.

- It appeared that the horizontal bearing capacity increases almost linearly with the anchor height. The API calculation for shallow depth, however, assumes a quadratic influence. This phenomenon needs to be investigated in more detail.

The results have mainly shown the behaviour of a suction anchor in sand. For other soil types, additional tests have to be carried out in order to examine whether the behaviour is similar.

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