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HORIZONTAL CAPACITY OF LARGE-SCALE MODEL ANCHORS

RESISTANCE HORIZONTALE DE MODELES D'ANCRES A GRANDE ECHELLE

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SYNOPSIS: Catenary moored floating offshore structures may be tethered to suction anchors (foundations with skirts) penetrated into the seabed. The project consisted, in part, of performing five large-scale field model tests subjected to a predominantly horizontal load, and measuring the behaviour. The model testing program included static and cyclic tests, with different points of hinged attachment between tether and anchor along with the use of a mudline liner in some cases. The liner was used to inhibit the formation of a tension crack behind the model. The equipment and data acquisition system functioned successfully.

Three of the main objectives of the project were to: (1) Study the effect that the location of the point of attachment between tether and anchor has on the pull-out resistance and mechanism. (2) Study the effect of a thin flexible liner attached to the model at mudline elevation on preventing a tension crack at the back of the model, thus increasing the capacity. (3) Study the impact of load cycling on capacity.

From the measured capacities the following quantitative conclusions were found concerning the relative effect of loading point, liner and static/cyclic test type.

- Lowering the point of attachment between the tether and anchor from the mudline to midway between mudline and skirt tips was to approximately double the capacity for both the static case with no liner and the cyclic case with liner.
- Attaching a mudline liner to the model increased the capacity by about 50 per cent for the static, midway down loading case.
- Cycling the model reduced the capacity by about 10 per cent for the midway down loading with liner case.

INTRODUCTION

As the oil industry further exploits existing fields and progresses towards the exploration of deeper waters, the use of smaller production systems becomes more widespread. The conventional installation of piled moorings for subsea systems and compliant structures such as tension leg platforms (TLP) or catenary moored platforms are becoming increasingly more expensive. A structure equipped with a foundation skirt system made of concrete or steel, and installed with the use of suction, offers a cost effective alternative for such concepts. Large penetration forces may be mobilised through the development of a temporary underpressure inside a chamber (like a caisson compartment under a subsea installation or a platform mooring): the difference between the outside hydrostatic pressure and the inside underpressure, times the exposed plan area, represents the additional driving force. The applied suction is released after installation. After installation the structure, to a large extent, provides a holding capacity by suction when loaded statically or cyclically.

The project consisted of performing five large scale (1.4 m x 0.7 m x 1.4 m deep) field model tests on anchors installed by suction. The predominantly horizontal loading conditions (10° from horizontal) simulate those of a catenary moored platform anchor or one of a group of skirt cell foundations connected by a flexible frame.

Three of the project objectives were as follows:

- Study the effect that the location of the point of attachment between the tether and anchor has on the pull-out resistance and failure mechanism.
- Study the effect of a thin flexible liner attached to the model at mudline elevation on preventing a tension crack at the back of the model, thus increasing capacity.
- Study the impact of load cycling on capacity.

To accomplish these objectives the measured results of the tests were compared with each other.

PROJECT DESCRIPTION

The five model tests in this project were performed at Lysaker (Oslo), Norway. The Tjernsmyr clay at this site was saturated and undisturbed. Table 1 shows some typical soil data for Tjernsmyr clay at the test site and a site 350 m away. Note that the depth for the model tests was from 1.8 m to 3.2 m in Table 1.

Table 1 Geotechnical parameters for the two investigated sites in the Tjernsmyr area. Upper 4 m

Parameters	Snorre CFT test site, 1989	Selected test site, 1990
Thickness of organic top layer (m)	1.1	1.1
Undrained shear strength, s_u (kPa) (measured fall cone/vane values)	5-10	5-10
Sensitivity, S_t (below 2 m depth)	6-10	6-12
Natural water content (%)	60-80	60-80
Plasticity index (%)	28	25
Salt content (g/ℓ)	6-10	4-8
Unit weight of soil (kN/m^3)	16	16
Water table	0.1 m below surface	0.1 m below surface

The same model was used for all five model tests. Table 2 describes aspects of the tests. The model consisted of two cylindrical skirt compartments tangentially connected as shown in Figure 1. The location of the model tests within the test excavation is shown on Figure 2. The base area was about

Table 2 Characteristics of the model tests as tested

Model test	Test type	Loading point (load direction 10° from horizontal)	Mudline liner	Date performed
1	Static	5 cm below ground level	No	1990-09-24
2	Static	5 cm below midway between skirt tip and ground level	No	1990-10-08
3	Cyclic	5 cm below ground level	Yes	1990-10-24
4	Cyclic	5 cm below midway between skirt tip and ground level	Yes	1990-11-05
5	Static	5 cm below midway between skirt tip and ground level	Yes	1990-11-19

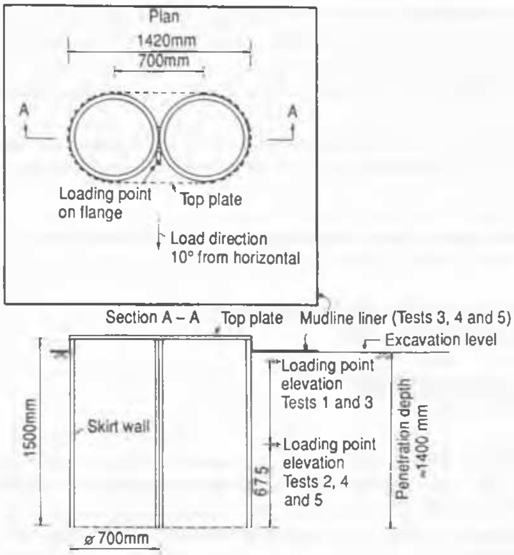

Fig. 1 Skirt configuration and geometry in plan and section

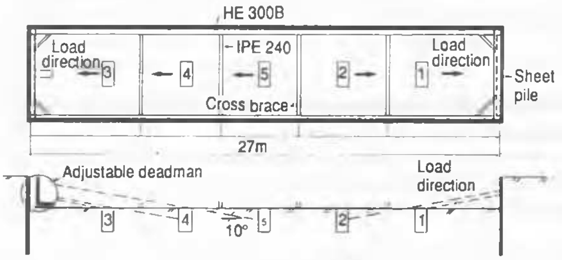

Fig. 2 Test excavation and locations

0.8 m^2, the penetraton depth was about 1.4 m and the submerged weight of the model was about 10 kN. The actuator used to bring the models to failure was inclined 10° from the horizontal.

The static model tests were brought to failure monotonically in displacement control in about 2 hours. The cyclic model tests were all performed in load control with a cyclic period of 10 seconds. The cyclic load programmes (planned and as tested) for Tests 3 and 4 are given in Tables 3 and 4, respectively. The ratio of average pretension to maximum cyclic load was approximately 1:1 for both tests so that the impact of cycling would be comparable for both tests. Load Parcels 1 through 6 are a simplified version of the peak part of a 100 year storm scaled approximately to the conditions of these tests.

Table 3 Cyclic load history for Test No. 3. Comparison of planned and actual load programmes

Planned programme				Actual programme*		
Parcel No.	No. of cycles	Average load (kN)	Cyclic load	No. of cycles	Average load (kN)	Cyclic load
1	50	12.5	2.5			
2	50	12.5	3.3			
3	30	12.5	3.8			
4	10	12.5	4.2			
5	3	12.5	4.6			
6	1	12.5	5.0		12.7	5.2
7	5	12.5	2.5			
8	50	12.5	5.0			
9	5	12.5	2.5			
10	50	12.5	5.8			
11	5	12.5	2.5			
12	50	12.5	6.6			
13	5	12.5	2.5			
14	125	12.5	7.6			8.0
15	5	12.5	2.5			
16	125	12.5	8.7			9.3
17	5	12.5	2.5			
18	125	12.5	10.1			
19	5	12.5	2.5			
20	125	12.5	11.6	20	12.8	11.3

* Values given only if different from planned

Table 4 Cyclic load history for Test No. 4. Comparison between planned and actual load programmes

Planned programme				Actual programme*		
Parcel No.	No. of cycles	Average load (kN)	Cyclic load	No. of cycles	Average load (kN)	Cyclic load
1	50	30	6.6			
2	50	30	8.8		29.9	
3	30	30	9.9			9.8
4	10	30	11.0		29.9	
5	3	30	12.1			12.3
6	1	30	13.2			
7	5	30	6.6			
8	50	30	13.2		29.9	
9	5	30	6.6			
10	50	30	15.2			
11	5	30	6.6			
12	50	30	17.5		29.5	
13	5	30	6.6			
14	125	30	20.1	110		21.0
15	5	30	6.6			
16	125	30	23.1	13		
17	5	30	6.6	0	0	0
18	125	30	26.5	0	0	0

Six displacement transducers were used to measure the movement of the model. The transducers were arranged with one end of each transducer attached to the model and the other end attached to an independent reference frame. None of the transducers were placed such that they would give a component of displacement directly and exactly. This is because they were placed around the periphery of the model and also that the geometry of the measurement system changed as the model moved.

A routine, specially developed for this type of situation, was therefore used to resolve the displacements measured by each transducer into components of displacement in the six degrees of freedom (i.e., translations along and rotations about the X, Y and Z axes). The program takes into account the initial placement of the transducers and the change in geometry as the model moves.

The coordinate system to which these displacements are resolved has its origin at the center of the model (in plan) and at the original clay surface before model penetration (in elevation). The elevation of the origin is therefore the same as the clay surface outside the model. The X coordinate direction is positive in the same direction as the horizontal tensile load component on the model (from the 10°-inclined actuator load). The Y coordinate direction is perpendicular to this and the Z coordinate direction is positive upwards (right-hand rule).

SUMMARY OF RESULTS

Static And Cyclic Bearing Capacity

The measured failure loads are summarized in Table 5.

Table 5 Measured failure loads

Model test	Liner	Test type	Load point	Measured failure load (kN)
1	No	Static	Mudline	19.7
2	No	Static	Midway	37.5
3	Yes	Cyclic	Mudline	21.8
4	Yes	Cyclic	Midway	51.0
5	Yes	Static	Midway	56.4

The first two tests developed a tension crack during loading as shown on Fig. 3. Also shown are the original and deformed locations of clay movement indicators. These water filled flexible tubes were inserted into the clay around the model prior to each test. After the test the tubes were filled with grout. After hardening they were removed. The predominant measured load-displacement (or rotation) curves for Tests 1 through 5 are shown on Figs 4 through 8, respectively.

Effect Of Load Location, Liner And Cyclic Loading

In order to accomplish the objectives stated in the introduction, a five test program was constructed such that the comparisons shown on Table 6 could be made.

From Table 6 and the measured capacities shown on Table 5, the following quantitative statements can be made about the relative effect of loading point, liner or test type if all other factors are held equal:

- Lowering the point of attachment between the tether and anchor from the mudline to midway between mudline and skirt tips was to approximately double the capacity for both the static case with no liner and the cyclic case with liner.
- Attaching a mudline liner to the model increased the capacity by about 50 per cent for the static, midway loading case.
- Cycling the model reduced the capacity by about 10 per cent for the midway loading with liner case.

These effects can best be seen by normalizing the measured capacities of each test by the lowest capacity measured (Test 1, mudline load point, no liner, static loading). The results are shown on Table 7. Figure 9 shows the load-horizontal displacement curves for Static Tests 1, 2 and 5 in order to illustrate the impacts of liner and attachment point.

Table 6 Comparisons between pairs of tests to examine load location, cycling and liner effects

Model test	Loading point	Liner	Test type	Effect examined
1 2	Mudline Midway	No No	Static Static	Loading point (static, no liner)
3 4	Mudline Midway	Yes Yes	Cyclic Cyclic	Loading point (cyclic, liner)
2 5	Midway Midway	No Yes	Static Static	Liner (static, midway)
4 5	Midway Midway	Yes Yes	Cyclic Static	Cycling (midway, liner)

Table 7 Comparison of measured capacities of various tests

Measured failure load (kN)	Model test	Load point	Liner	Test type	$\frac{\text{Measured load}}{\text{Test 1 measured load}}$
19.7	1	Mudline	No	Static	1.00
21.8	3	Mudline	Yes	Cyclic	1.11
37.5	2	Midway	No	Static	1.90
51.0	4	Midway	Yes	Cyclic	2.59
56.4	5	Midway	Yes	Static	2.86

Disregarding the small (10%) effect of cycling, the differences in capacity are mainly a function of load point and liner for predominantly horizontally loaded anchors. The largest difference between measured capacities was that of Static Tests 1 and 5 in which the Test 5 capacity was nearly three times that of Test 1 for the same anchor. This illustrates the combined benefits of lower attachment point and mudline liner.

Reasons for this capacity increase are that lowering the attachment point forces the model into more of a horizontal translation mode of failure than a rotational failure by minimizing the moments about the skirt tip. It is believed that by minimizing the moment about the skirt tip, the maximum capacity is achieved. As such, the optimal point of attachment can be calculated taking all other forces acting on the model into consideration.

With regard to the liner, its purpose is to inhibit the tension crack on the active (back) side by preventing a supply of water (and thereby loose suction) between the soil and the model. As the model tends to pull away from the soil, negative pore pressures develop. The lowest pore pressure that could develop on land in a saturated deposit is about minus one bar. Prior to this development the soil will fail in a general failure pattern. The liner appears largely to have fulfilled its purpose, even with partial leakage, by maintaining negative pore pressure during maximum pulling during static or cyclic loading. This is best seen by comparing the similar loads at the end of Test 2 and Test 5 (Fig. 9). Test 2 had no liner, whereas Test 5 did, but it was removed after the peak load was reached. All other aspects of the tests were the same.

ACKNOWLEDGMENTS

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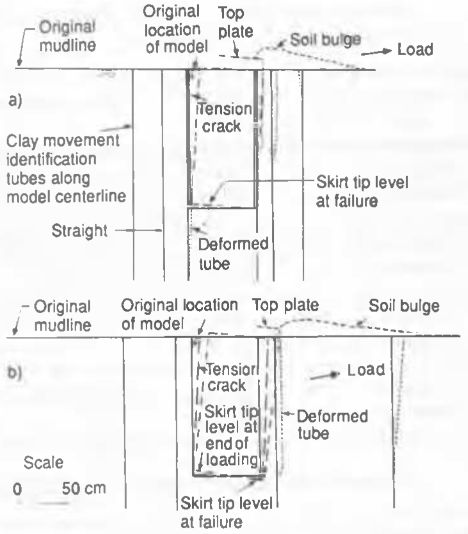

Fig. 3 Model and clay movement at large displacements a) Test 1, and b) Test 2

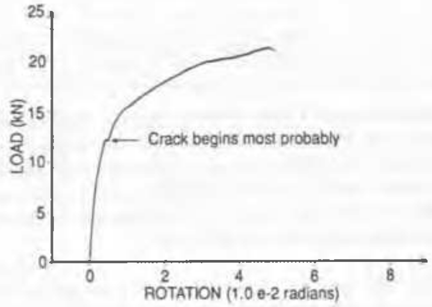

Fig. 4 Test 1 - Static load at mudline. Applied load versus rotation

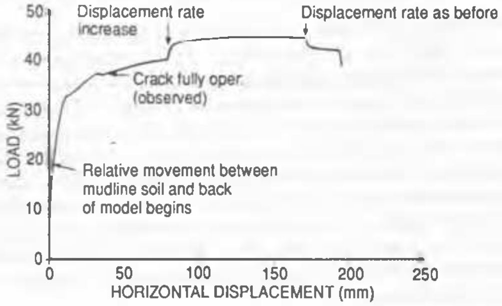

Fig. 5 Test 2 - Static load between mudline and skirt tips. Applied load versus horizontal displacement

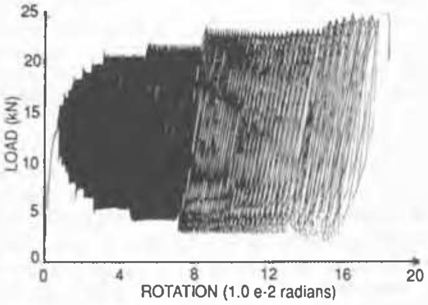

Fig. 6 Test 3 - Cyclic load at mudline. Applied load versus rotation

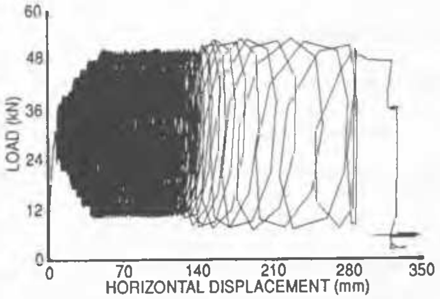

Fig. 7 Test 4 - Cyclic load between mudline and skirt tips. Applied load versus horizontal displacement

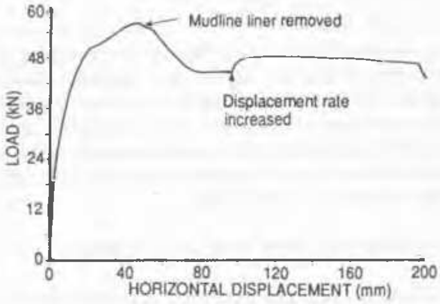

Fig. 8 Test 5 - Static load between mudline and tip - with liner. Applied load versus horizontal displacement

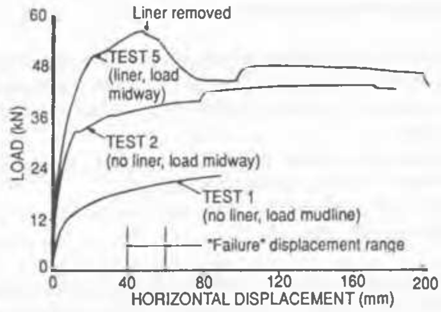

Fig. 9 Static tests - Comparisons of measured load-displacement curves