Optimisation of the Geometry and Performance of a Drag Embedment Anchor

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Abstract

Drag embedment anchors generally provide a good solution for anchoring problems due to their excellent weight efficiency. In the marketing of commercial anchors it is necessary to quote the maximum holding capacity of the anchor. The simplifying assumption that the soil provides a uniformly distributed pressure on the anchor is made in the calculation of a drag anchor's anticipated holding capacity. Centrifuge testing can be conducted with the use of scale model anchors due to the stress similitude that exists between model and prototype under increased g levels. Scale model anchors were used in centrifuge testing to determine the pressure distribution acting on the anchor fluke at three distinct points situated at the centroid of three areas, defined by the shank connections to the fluke. The aim of this project is to provide suggestions for improvement of the design of the Superay anchor series through the analysis of the pressure distribution and through the determination of the reason for high unexpected holding capacities in field tests by conducting centrifuge tests of scale model anchors.

1.0 Introduction

1.1 Drag Anchor Background

Drag embedment anchors are an economical anchoring system which are often used in moorings for Floating Production, Storage and Offloading (FPSO) facilities. The Superay series of anchors are used in moorings in pearl farms and as part of cyclone moorings. Drag anchors require minimal installation effort, can be easily retrieved and then re-installed in another location, and are extremely weight efficient. The efficiency of a drag embedment anchor is determined by its holding power-to-weight ratio.

A labelled diagram of a Superay anchor is shown in Figure 1, referring to the relevant terms discussed throughout this paper. When the maximum force, or holding power, an anchor can withstand is reached the anchor is said to have reached its ultimate holding capacity (UHC). The UHC of an anchor is dependent on the anchor geometry, soil properties and drag parameters. The holding power-to-anchor weight ratio, or anchor efficiency, η_w, is the most relevant anchor statistic in comparing and assessing the performance of commercial anchors. Other commercial anchors advertise efficiencies of up to 75 (Vryhof Anchors, 2005) where field tests conducted by Superay have produced an average anchor efficiency of approximately 150.

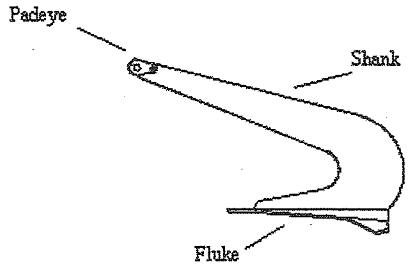


Figure 1 Anchor terms.

1.2 Objectives

The primary aim of this project was to find the pressure distribution acting across the anchor fluke and to compare the measured pressures with the total load applied to the anchor. Based on the assumption of uniformly distributed pressure across the fluke, holding power results obtained from field testing indicated that the steel fluke plate should have buckled, though it did not. Secondary objectives included the development of a spreadsheet model that is able to predict the efficiency of an anchor using the theoretical limit equilibrium analysis technique in a theory postulated by Neubecker and Randolph (1996a, 1996b), and the analysis of core samples collected from field testing sites of prototype anchors in order to classify the field test results for a particular soil type. It is proposed that suggestions for improvements to the anchor design will be made based on the results of investigations into these issues.

2.0 Drag Embedment Anchor Theory

Geotechnical problems are commonly analysed using a limit equilibrium method. An approach specific to drag embedment anchors was initially developed by LeLievre and Tabatabaee and has subsequently been modified by Neubecker and Randolph.

LeLievre and Tabatabaee's (1979) limit equilibrium method defines the failure of the soil mass as a rupture along a number of assumed surfaces, termed failure surfaces. The collapse load is calculated as the force required to initiate the sliding of the soil mass along the failure surface. The limit equilibrium method involves determining the lowest of these collapse loads over many failure surfaces.

However, this method was found to have limitations and weaknesses. The method is only valid when an anchor is at its ultimate holding capacity (Neubecker and Randolph 1994); considers an unrealistic two-dimensional failure wedge; and neglects bearing capacity considerations in determining the force acting on the shank. The modifications made by Neubecker and Randolph (1996a) include the bearing capacity consideration in the calculation of the shank force by means of a shank bearing capacity factor, N_{qs}, and the addition of a force on the back of the fluke during embedment. Neubecker and Randolph (1996a, 1996b) determined that the analysis of drag anchors can be divided into static and kinematic analyses. The static analysis is applied to determine the forces acting on the anchor at a known orientation and depth within the soil. The determination of these forces then allows the application of kinematic analysis in which the minimum work principle is utilised at assumed incremental displacements, which are defined in terms of rotation and penetration. The result of this analysis is an estimation of the path and behaviour of the anchor during embedment and estimation of the anchor's UHC once it reaches its final embedment and orientation.

2.1 Static Analysis

The method of static analysis determined by Neubecker and Randolph (1996a) is based on the determination of the forces acting on the anchor-soil system. Figure 2 shows the components that are present in the soil anchor system and must be determined in the calculation of anchor efficiency. For a failure wedge angle λ, soil unit weight γ'_s, soil friction angle ϕ', dilation angle ψ, soil-anchor interface friction angle δ, and fluke-shank angle β, the forces can be calculated from LeLievre and Tabatabaee's method and Neubecker and Randolph's modifications using the following equations.

Cross sectional area of failure wedge $$A = \frac{H^2 - h^2}{2\tan\beta} + \frac{H^2 \tan\lambda}{2} \quad (1)$$

Lateral extent of failure wedge $$X = \frac{H\tan\psi}{\cos(\lambda - \psi)} \quad (2)$$

Weight mobilised soil mass $$W = \gamma'_s A\left(B + \tfrac{2X}{3}\right) \quad (3)$$

Side friction: $$SF = \frac{\gamma'_s L(H+h)^2(\sin\phi' - \sin\psi)}{4\cos\psi(1 - \sin\phi'\sin\psi)} \quad (4)$$

Shank force, calculated by bearing capacity considerations F_s

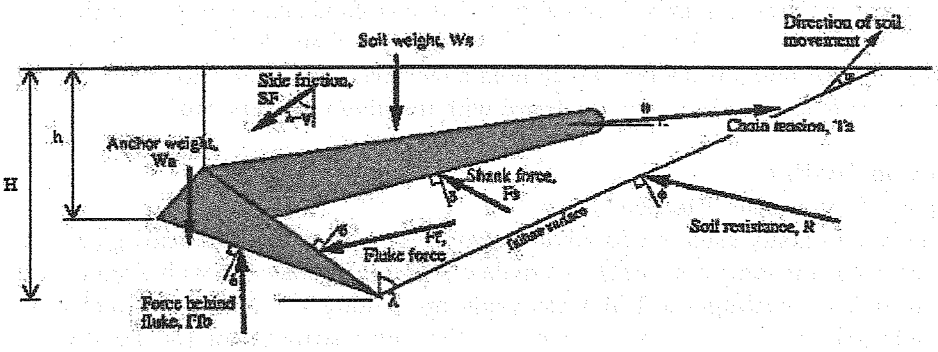
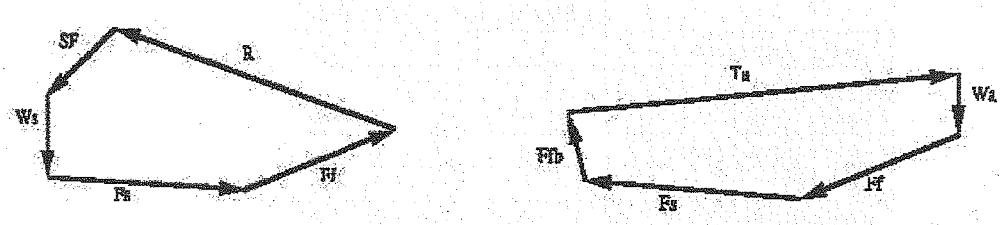
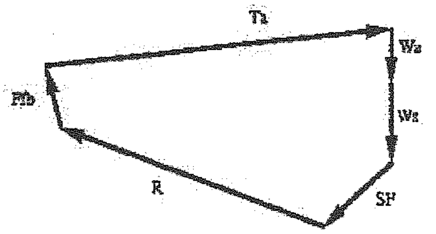


Figure 2 Soil and anchor force interaction.

The soil reaction force, R and chain tension force T_a (anchor holding power) are determined by considering the force equilibrium of the three systems shown in Figure 3.



(a) Soil force system **(b) Anchor force system**



(c) Anchor-soil system

Figure 3 Force polygons showing (a) soil only (b) anchor only and (c) anchor-soil.

2.2 Kinematic Analysis

The kinematic aspect of the anchor analysis considers the anchor embedment path as represented by the minimum energy of incremental displacements (Neubecker and Randolph 1994). The energy of the system is calculated as the sum of the dot products of the force and subsequent displacement vector for each force. Conservation of energy of the whole system is then considered, from which the UHC of the anchor can be determined.

2.3 Anchor Efficiency Prediction Spreadsheet Model

A Microsoft Excel spreadsheet model is currently being developed, incorporating sand, anchor and drag properties, to analyse the anchor behaviour and thus predict the efficiency of a Superay anchor of any given size. The program will be calibrated against field and centrifuge testing data in order to create a useful tool to determine the holding power of any Superay anchor and, if applied in reverse, to determine the anchor size to hold a required load. This model will use the limit equilibrium method as described above, coupled with iterative kinematic analysis.

3.0 Centrifuge Testing

3.1 Principles of Centrifuge Modelling

Centrifuge testing is commonly used in geotechnical problems as it allows increased g (gravity) force to be exerted on a soil sample in order to simulate prototype behaviour with a small scale model. The geotechnical centrifuges at UWA can apply up to 400g to a sample in a horizontal direction. The selected g level for testing is equal to the linear scale factor (N) between the prototype and the scale model. From the basic relationships involving the linear dimension of the scale model, the force and stress acting on the model can be determined from the prototype, in terms of N.

	Prototype	Model
Linear Dimension	L	1/N * L
Volume	V	$1/N^3$ * V
Mass	M	$1/N^3$ * M
Acceleration (gravity)	g	N * g
Force	F	$1/N^2$ * F
Area	A	$1/N^2$ * A
Stress (= F / A)	σ	σ

Table 1 Stress similitude in centrifuge modelling.

Table 1 shows that the stress acting on the prototype is equal to the stress acting on the model, and hence stress similitude exists, negating scale effects due to the small size of the model.

3.2 Geotechnical Beam Centrifuge Tests

3.3.1 Sample Preparation

A moderately dense superfine silica sand sample was prepared in a 650 x 390 x 325 mm aluminium strongbox with the use of an automatic sand hopper to produce consistent density throughout the sample. Two strongboxes were prepared: the first contained a water-saturated sand sample (Test 1) and the second sample (Test 2) was saturated with silicon oil, with a viscosity 100 times greater than water.

3.3.2 Scale Model Anchor

A 1:16 scale model anchor was constructed based on the 50 kg Superay Folding Anchor, from 0.5 mm thick, 250 grade steel plate, and tested at 16g in the centrifuge. Four strands of 1 mm fishing trace wire were plaited into a dual perpendicular sinusoidal four-way plait to resemble the links of a chain. This was attached to the anchor padeye through an idealised shackle joint. The load cell was initially connected at the anchor padeye for Test 1, but was then moved away from the padeye for Test 2 and the chain connected directly to the anchor, so that the load cell was measuring both anchor holding power and any frictional resistance along the chain.

3.3.3 Motor Driven Actuator

In both the beam and drum centrifuges, a motor driven actuator was used to drag the anchor through the sand, and to drive the cone penetrometer into the sand. The actuator has both horizontal and vertical travel directions that can be controlled by computer to travel required distances at specific speeds, between 0.1 and 3.0 mm/s.

In the beam centrifuge, the actuator was mounted on the top of the strongbox. The anchor was attached to the simulated model chain, which was threaded through two pulleys and attached to the actuator in such a way that vertical movement of the actuator caused horizontal movement of the anchor in the sand (on a horizontal to vertical scale of 2:1). For Test 1 the actuator speed was held constant at 0.1 mm/s, resulting in an anchor pulling speed of 0.2 mm/s. In the first drag in Test 2 the actuator speed was initially 3.0 mm/s (anchor speed of 6.0 mm/s) and then reduced to 0.3 mm/s (anchor speed of 0.6 mm/s) when the anchor reached its UHC. The second drag in Test 2 was conducted with the slower speed first and then increased to the higher speed after the anchor reached its UHC.

3.3.4 Results

The results obtained from Test 1 produced anchor efficiencies of less than 20, where Superay had field results of efficiencies of approximately 150. In comparing the methods of testing it was determined that the field test anchor pulling speed had not been modelled correctly in the centrifuge tests. The field tests were found to have been conducted under a fast pulling rate, where centrifuge testing of drag embedment anchors is usually conducted at a slow pulling rate. However the scaled pulling rate derived from the assumed, but not specifically measured nor recorded, pulling speed used in field tests produced a rate beyond the limits of the actuator.

For Test 2, it was decided to saturate the sand sample with silicon oil to increase the relative pulling speed of the anchor due to the greater viscosity of the oil. The pulling speed would effectively be increased 100-fold in the silicon oil-saturated sand sample as compared to the water-saturated sand sample, since consolidation (dissipation of any excess pore pressures within the soil) would occur 100 times slower. The anchor efficiency values derived from Test 2 were approximately 140. The only change to the sample preparation and testing procedure in Test 2 was the saturation of the sample with silicon oil rather than water, coupled with an increase in anchor pulling speed. Therefore, from the comparison of results between Tests 1 and 2 (with two anchor drags conducted within each test) it can be concluded that a rate effect exists in obtaining anchor efficiency values, through the holding power of the anchor.

3.3 Geotechnical Drum Centrifuge Tests

3.4.1 Sample Preparation

A moderately dense superfine silica sand sample was rained into the drum centrifuge channel at 20g and then scraped back to the required sample depth to produce consistent density throughout the sample. The sand sample was then saturated while in situ in the drum channel.

3.4.2 Scale Model Anchor

A 1:20 scale model anchor was constructed based on the 400 kg Superay Bolted Anchor from 1.0 mm, 250 grade steel plate, and tested at 20g in the centrifuge. The anchor was instrumented with three 500 kPa surface pressure transducers, positioned at the centroids of three separate areas on the fluke plate, as shown in Figure 4. A novel instrumented anchor loading arm, as explained by O'Neill et al (1997), was used in place of a chain in the drum centrifuge. Anchor chains cannot be used in the drum centrifuge as the chain forms a chord across the curved surface of the sand in the drum channel when tensioned, creating an upward force on the chain, which disrupts the embedment of the anchor (O'Neill and Randolph 2001). The anchor loading arm is connected to the scale model anchor at the anchor padeye through a pin connection which is fitted with two sets of strain gauges that measure the horizontal and vertical forces exerted on the anchor.

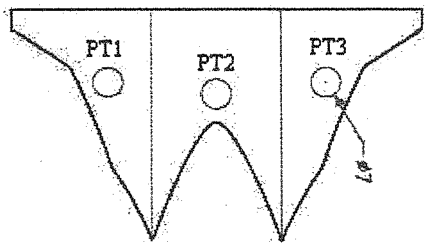


Figure 4 Pressure transducer locations.

3.4.3 Motor Driven Actuator

The motor driven actuator used in the drum centrifuge is similar to the actuator used in the beam centrifuge, where the actuator sits within the removable tool table in the centre of the drum.

3.4.4 Results

Pressure readings obtained from testing showed that the pressure distribution across the fluke area cannot be estimated by calculating an average pressure equal to the anchor holding capacity divided by the fluke area. This calculated pressure is more than 3 times larger than the pressure actually measured by the surface pressure transducers, as shown in Figure 5. It can also be seen in Figure 5 that the central pressure transducer recorded lower pressure readings than the two outer pressure transducers. Further analysis is underway to explore these results, evaluating exactly how the anchor resistance is distributed among the various components of chain, shank and fluke.

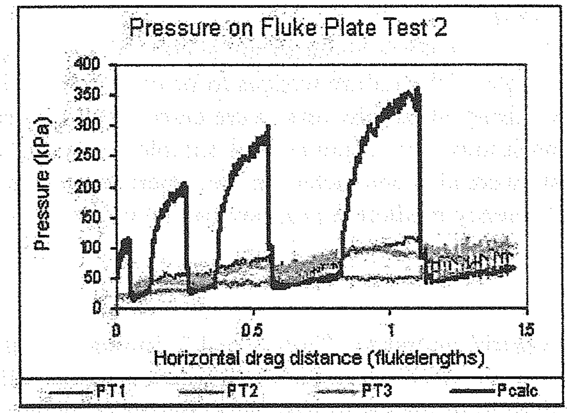


Figure 5 Comparison of measured pressure and calculated pressure.

4.0 Soil Tests

4.1 Core Soil Sample Analysis

Nine core sample tubes of soil were taken from a field test site prior to anchor field testing. These samples were taken from Cockburn Sound, near Woodmans Point, about 25 m from the water's edge across a 50 m stretch of seabed parallel to the shoreline. Each sample was taken from in front of an anchor set in position on the seabed by scuba divers. The samples were taken from the surface of the seabed to a depth of approximately 700 to 800 mm. The anchor holding capacities measured in this series of testing contained discrepancies in the results, where a smaller size anchor was holding a larger force than an anchor with twice its weight.

Analysis was conducted on representative soil samples from these core sample tubes in order to determine the required sample density for centrifuge testing. Maximum and minimum density determinations were carried out to provide the minimum and maximum void ratios, respectively, which were then used to calculate the relative density of each sample. Calcium carbonate content and water content determinations were also carried out. The specific gravity of the soil particles was also determined for use in calculations. Sieve analysis performed on the core soil samples led to the classification of the soil as a slightly silty or clayey sand, according to BS 5930: 1999. This series of soil analysis yielded results that indicated relative uniformity in the properties investigated between the samples taken at that site. This indicated that the discrepancies found in field test results at this site cannot be explained in terms of variation in the soil properties.

4.2 Cone Penetrometer Tests

In both the beam and drum centrifuge testing regimes, cone penetrometer tests were performed in the sand sample prior to, and after, the anchor drags were conducted. These tests were performed to verify that the sample had been prepared with uniform density throughout the depth of the sample. A 7 mm diameter cone was used in centrifuge tests, inserted at a rate of 1.0 mm/s.

4.3 Oedometer Tests

The increased efficiency of the anchor achieved in Test 2 of the beam centrifuge tests, in the silicon oil-saturated sand sample, may be explained in terms of the degree of consolidation within the sample, which depends on the anchor dimension and the value of the consolidation coefficient, c_v.

4.4 Direct Shear Box Tests

The friction angle of the soil is a required input in the anchor efficiency prediction spreadsheet model, as this indicates the angle of the failure wedges to be examined in determining the anchor behaviour. A series of three direct shear box tests were carried out at normal stresses of 25, 50 and 100 kPa, normally consolidated, on saturated soil samples obtained from the core sample tubes. Direct shear box tests were also conducted on the superfine silica sand used in centrifuge testing so that the anchor efficiency prediction program can be calibrated using efficiency results from the centrifuge tests.

5.0 Conclusions

The results from the beam centrifuge testing, Tests 1 and 2, indicated that a rate effect exists in relation to the pulling speed of the anchor and the consolidation in the soil. This indication still needs to be verified by results from the oedometer tests, but, if so, will provide an explanation for the larger anchor holding capacities obtained in Superay's field tests.

The simplifying assumption of a uniform pressure distribution acting on the anchor fluke was found to be very conservative, with pressure calculated under this assumption being three times larger than the measured pressure. Therefore it is inappropriate, and conservative in terms of the structural design of the anchor, to estimate the pressure by dividing the holding capacity by the fluke area. Not only is the pressure in the central region less than the pressure on the outer regions of the fluke, but the average pressure is much lower than given by this simple estimate. In light of this finding regarding the estimated pressure acting on the anchor fluke, the anchor efficiency spreadsheet model will be used to explain how the anchor holding capacity is carried through the different force components acting in the anchor-soil system. These discoveries of the pressure acting on the anchor fluke can lead to suggestions for improvement to the anchor design in terms of both material and fluke area. Lower strength material, or thinner plate, could be considered due to the lower pressures exerted on the plate, and it may be possible for refinements to be made to the shape of the fluke area due to the lower pressure in the central region.

6.0 References

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