An experimental study of inflatable offshore anchors in soft clay

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Introduction

Since many remotely operated vehicles (ROVs) are neutrally or positively bouyant, any activities that require any significant reaction load, e.g. *in situ* soil testing, are not possible without additional anchoring or clump weights. Whilst the majority of ROVs used by the offshore oil and gas industries have the necessary hydraulic and pneumatic control systems to employ anchors, previous attempts to develop seabed fixity have had variable success. These include standard anchor systems, such as helical screw, suction, duckbill and plate anchors. Any viable alternative must provide a cheap and reusable system that will provide sufficient pullout capacity and be able to operate in the demanding deep offshore environment.

This project had the aim of determining whether a flexible, inflatable anchor system may provide sufficient uplift capacity to fix ROVs during offshore activities. A series of physical model tests have been used to assess the performance of the proposed anchor system in terms of pullout capacity and mobilisation distance. A limited range of anchor designs and operating conditions were investigated to provide data for this assessment. This paper describes the experimental methodology, anchor system and the testing of the system using an artificial clayey soil.

Experimental methods

Physical model testing was carried out in a large cylindrical steel container of 700 mm internal diameter and 1200 mm height. A series of tests involving constant velocity pullout of a range of anchors, with varying geometries was conducted. A large computer controlled screw jack was used to extract the

Silt and siltation. Thomas Telford, London, 2001

anchors and this was fixed to the top of the container using cross beams. The anchors were pulled out of the soil using a rigid hanger.

The inflatable anchor system geometry is shown in Figure 1. The anchor consisted of a cylindrical steel tube (35 mm diameter, D) around which was fastened to a rubber membrane. Fluid or air can be pumped into the annular space between the tube and membrane to inflate it. The anchors were embedded to different depths (H) and the length of the inflatable section (L) was also varied. The fluid in the rubber membrane was pressurised by means of two screwed pistons, one of which may be driven by computer control to maintain a constant pressure. Constant volume was maintained by pressurising the system under computer control, then preventing further movement of the pistons.

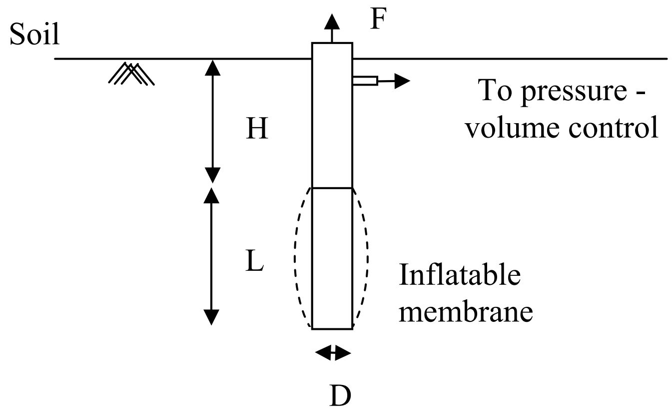

Figure 1: Geometry of inflatable anchor system

Computer control of the experiments was by means of HP-Vee programs. These monitored the inputs and took appropriate action to control the actuators. Values for load, pressure, travel etc were calculated, stored to disk and displayed on graphs as the experiment progressed. Where *constant pressure* was required any change in pressure in the system from a set value was used as feedback to drive the piston and thus bring the pressure back to the required value. Where *constant volume* testing was required a pressure was developed under computer control and then the actuator was disengaged to prevent any further change in fluid volume. The pressure-volume change relationship could also be investigated if necessary during an experiment.

The anchor tests were conducted on a blend of Speswhite kaolin and Congleton sand. Congleton is a silicate sand with a uniform grading of sub-rounded particles, D_{50} = 0.3 mm and specific gravity G_s = 2.65. The angle of repose of this soil is 32-34^o. The range of densities for this soil are found to vary between ρ_{max} = 1.78 t/m^3 and ρ_{min} = 1.51 t/m^3. Speswhite kaolin clay is a commercially produced kaolin with G_s = 2.68, liquid limit of 65% and plastic limit of 30 %. The angle of friction for this soil is 22^o.

Clayey soils were created by mixing 50% sand and 50% clay at 70% moisture content (approximately 2 x liquid limit) and one dimensionally consolidating a sample in the cylindrical container. This blend of sand and clay was selected to represent the typical grading and behaviour of a North Sea deposit. Pressure was applied incrementally via a rigid top cap up to the required pressure, sufficient to create a sample with an undrained shear strength of 2-5 kPa. Prior to pullout, vane tests and moisture contents were performed. For this series of tests the anchors were pushed gently into the clay and left for two hours prior to inflation and pullout to dissipate excess pore pressures. The samples of clay were double drained (i.e. from top and bottom). Although the edges of the container were unlined, since the container was large enough to provide at least 10 diameters of soil on either side of the anchor, any influence due to the rigid boundary was thought to be insignificant.

A range of model tests was conducted, with variations in geometry of the inflatable anchors and state of the soil. The variables investigated were stress history of the soil, inflation pressure (P), embedment ratio (H/L), anchor length (L), membrane thickness (t) and membrane surface roughness. A number of different forms of anchor were also tested for comparison, namely plate anchors and helical screw anchors. Only a limited range of the tests conducted will be reported herein. Further tests have been conducted on sand soils and these are reported elsewhere (Newson et al., 2003).

Experimental results

Results of pullout tests

The pullout force against anchor displacement is shown for three tests (1A to 1C) conducted on a normally consolidated clayey soil sample with undrained shear strength of 1.5 to 2 kPa in Figure 2. These tests were conducted to investigate the rate of pullout, improvements of pullout capacity with excess pore pressure dissipation and the effect of inflation of the anchor. Test 1A used a 100 mm long (L) sand roughened anchor, embedded 140 mm (H), inflated to 150 kPa (P) and left for two hours (inflated) prior to pullout at a velocity (v) of 0.018 mm/s. Test 1B used the same anchor, inflated to the same pressure, but pulled out at 3.81 mm/s immediately after inflation. Test 1C was not inflated and was again pulled out at 3.81 mm/s. For tests 1A and 1B the peak pullout loads were approximately 0.14 kN, with a mobilisation distance of the order of 20-40 mm. Test 1C shows a similar mobilisation distance and a lower peak load of 0.05 kN.

There appears to be very little difference between tests 1A and 1B, which suggests that for this clay mixture and state, there is marginal benefit in waiting a few hours prior to pullout. In fact, the coefficient of consolidation (c_h) for this type of material would be of the order of 1 to 10 m^2/year, hence 50% dissipation of the excess pore pressures may be lie in the range of 1.5 to 15 hours. Comparison of test 1C with tests 1A and 1B shows the effect of inflation of the bladder, which appeared to increase the pullout capacity threefold.

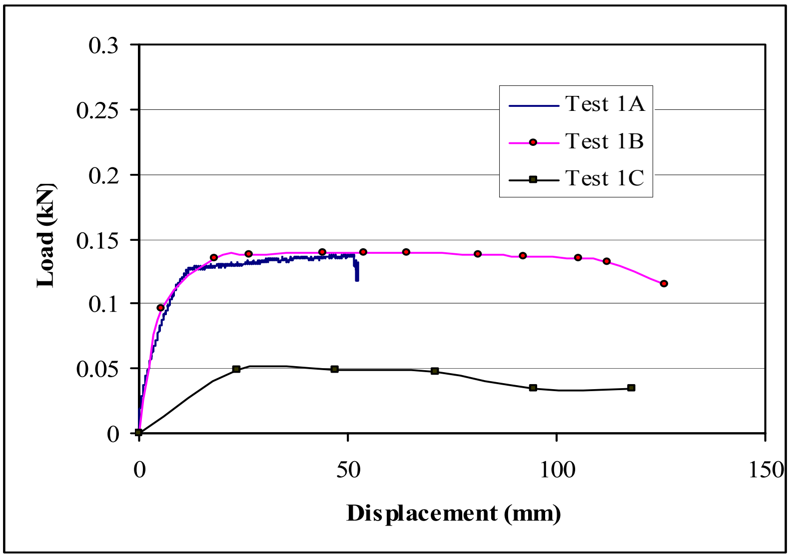

Figure 2: Force-displacement data for first series of pullout tests

A second series of tests was conducted to further investigate the increases in pullout capacity associated with dissipation of excess pore pressures developed during anchor inflation. Figure 3 shows the data from two additional pullout tests 2A and 2B. These were conducted using a 100 mm anchor, embedded to 140 mm and inflated to 150 kPa. A higher consolidation pressure was used to create the sample and led to an undrained shear strength of 3.5 to 4 kPa. Test 2A was left inflated for 16 hours prior to pullout and test 2B was pulled out immediately after inflation. The pullout velocity (v) for both tests was 3.18 mm/s. Hence tests 1B and 2B are directly comparable.

The pullout data for these two tests shows increases in capacity compared to the first series of tests, with test 2A peaking at 0.34 kN and test 2B at 0.26 kN. The mobilisation distances were comparable with those of the first series. Allowing the inflation excess pore pressures to dissipate significantly shows a 30% increase in pullout capacity for this soil and state.

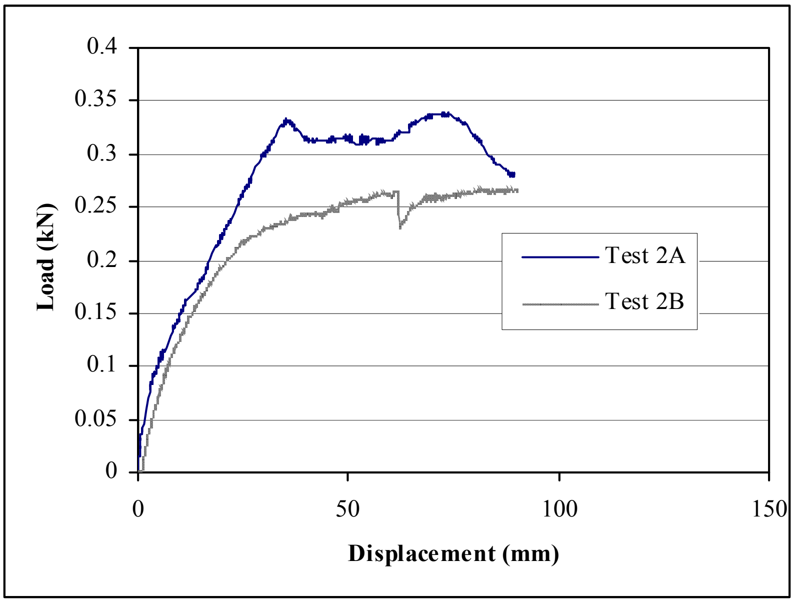

Figure 3: Force-displacement data for second series of pullout tests

Volume-pressure relationships

Since the volume-pressure relationship of the anchor can be monitored during inflation, the *in situ* stress-strain properties of the soil can be determined in a similar manner to the pressuremeter test using cavity expansion theory (e.g. Mair and Wood, 1987). This information may be used to estimate the uplift capacity of the anchor or for design and other purposes, e.g. upheaval buckling calculations. A typical volume-pressure curve (determined from the anchor system) for the clayey soil is shown in Figure 4. Analysis and interpretation of this data can provide a range of parameters, e.g. elastic (G, ν), angles of friction and dilation, lateral limit and *in situ* lateral pressures, undrained shear strength, etc..

Using this data, the shear modulus (G) can be estimated to be 650 kPa and assuming $\nu = 0.5$, this gives a value of Young's modulus, E = 1950 kPa. Due to the extremely low horizontal effective stresses (since the anchor has a very shallow embedment) the uplift or *in situ* pressure is difficult to estimate. The limit pressure (p_L) for this test is approximately 15 kPa, which agrees with cavity expansion theory (e.g. Carter et al, 1986), which suggests a value of p_L of 18 kPa:

$$p_L = \sigma'_h (1 + \sin\phi') \left[\frac{G}{\sigma'_h . \sin\phi'} \right]^{\frac{1}{2}(1 - K_a)} \tag{1}$$

where K_a is the coefficient of active earth pressure and σ'_h is the horizontal effective stress.

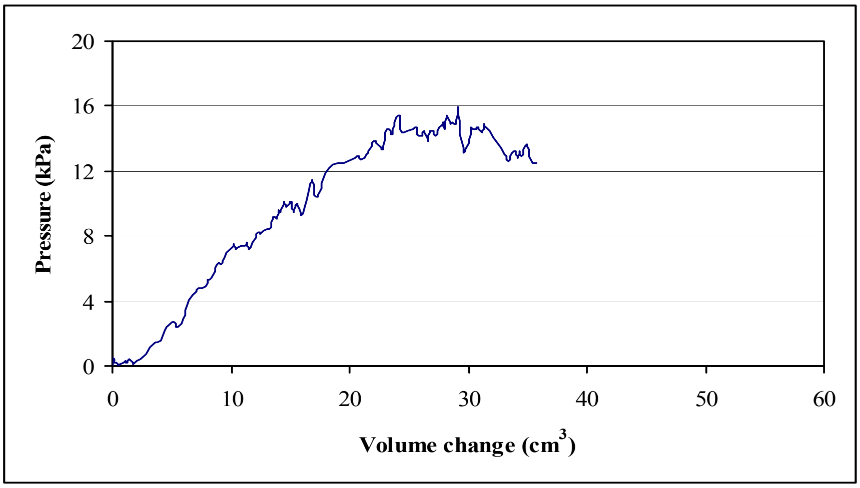

Figure 4: Volume pressure relationship for inflation phase of anchor utilisation

The undrained shear strength (c_u) can also be determined using equation (2) below (Mair and Wood, 1987). Assuming a value of N_p=6 (taking G/c_u approximately 200) then c_u is 3.2 kPa, which is comparable with the vane test measurements.

$$c_u = \frac{(p_L - \sigma_{ho})}{N_p} \tag{2}$$

where σ_{ho} is the in situ horizontal total stress and N_p is a pressuremeter constant (Marsland and Randolph, 1977).

The dissipation of excess pore pressures due to inflation of the anchor (for test 2A) is shown in Figure 5. The graph shows a 50% drop in excess pore pressure in approximately eleven hours. Using the consolidation solution of Randolph and Wroth (1979) for a cylindrical cavity, the horizontal coefficient of consolidation (c_h) was determined to be 1.32 m^2/year.

$$c_h = \frac{\left[\frac{D}{2}\right]^2 .T_{50}}{t_{50}} \tag{3}$$

where D is the cavity diameter, T_{50} is the time factor and t_{50} the time associated with 50% pore pressure dissipation.

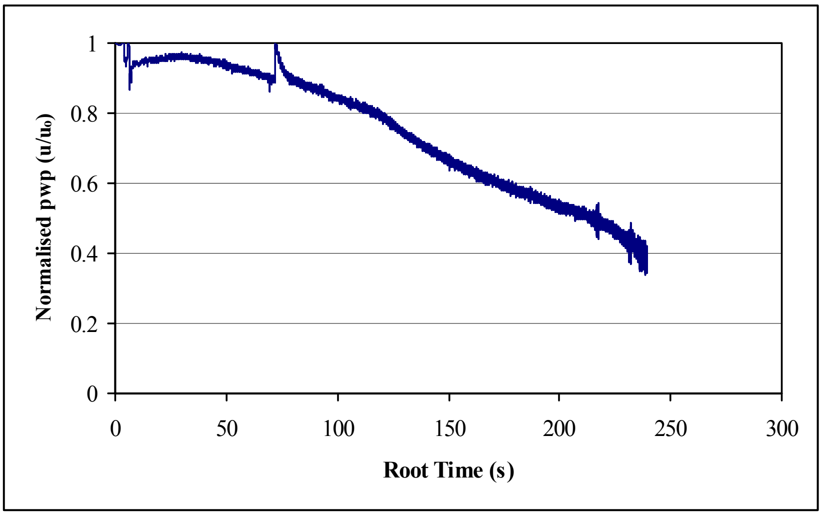

Figure 5: Excess pore pressure dissipation following membrane expansion

Discussion

The experimental data suggest that the pullout capacity of the inflatable anchor system will increase for stiffer, stronger clays and increased membrane pressures. Improvements in pullout capacity were also seen for long waiting periods after membrane inflation prior to pullout, although a shorter two-hour waiting period was found to result in the same pullout capacity. Hence the undrained shear strength and soil density (and therefore pullout capacity) may be improved by membrane loading, but for application offshore on ROVs long waiting periods are not practical. Varying the rate of pullout to determine whether a variation between drained and undrained states could be found, proved to yield the same pullout capacity. Closer inspection of the rates (limited by the gearing of the screw jack), using the dimensionless group v.L/ch suggested that both rates lay within the undrained range (Finnie, 1993). In order to achieve ‘drained’ pullout of the anchor, a rate less than 0.014 mm/hour would be required.

A number of studies have been reported in the literature related to soil nails, anchors and piles subjected to uplift/tensile forces (e.g. Dickin & Leung, 1990; Merrifield & Williams, 1988). Those that have investigated pressure grouted anchors or nails, and enlarged base piles may be appropriate for interpreting and predicting the behaviour of the inflatable anchors. Ignoring the friction along the smooth steel section of the anchor we may estimate the pullout capacity (F_{uo}) of the membrane (when uninflated, e.g. test 1C) using:

$$F_{uo} = \alpha . c_u . A_1 \tag{4}$$

where A_1 is the membrane surface area ($\pi . D_o . L$), D_o is the uninflated membrane diameter, L is the membrane length and α is the adhesion factor, which can vary between 0.25 and 1.

Again, ignoring the friction along the smooth steel section of the anchor the pullout capacity (F_{ui}) of the membrane when *inflated* (e.g. test 1B) maybe better estimated using:

$$F_{ui} = N_c . c_u . A_2 \tag{5}$$

where N_c is a bearing capacity factor, A_2 is the projected cross-sectional area of the inflated membrane ($\pi . D_i^2/4$) and D_i is the inflated membrane diameter.

The ratio of the uninflated to inflated pullout capacities (ψ) is therefore found from:

$$\psi = \frac{F_{uo}}{F_{ui}} = \frac{4.\alpha.L}{D_o . n^2 . N_c} \tag{6}$$

where n is the ratio of the inflated to uninflated membrane diameter (i.e. $D_i = D_o.n$)

Assuming that the inflated section causes a flow mechanism similar to the t-bar or ball penetrometer (Randolph and Houlsby, 1984; Stewart and Randolph, 1994) then the bearing capacity factor N_c would be approximately 10.5. In the tests presented herein, L = 140 mm and D_o = 35 mm, and the volume change during inflation was approximately 35 cm^3. Hence the value of n is approximately 1.2. Assuming full adhesion $\alpha = 1.0$ and equation [6] suggests the ratio of the uninflated to inflated pullout capacity is 0.26. This compares favourably with the observed pullouts shown in Figure 3 of approximately 1/3.

Similar values of bearing capacity factor (N_c) were presented by Meyerhof and Adams (1968) for enlarged base piles in clay soils based on experimental data and mathematical analysis. Their work further suggested that below embedment ratios of H/D_o of 4, the failure mechanism changes from a deep to a shallow case and the bearing capacity factor (and pullout capacity) reduces quickly. For example, for H/D_o of 1 N_c can vary from 2 to 8 for the cases of stiff and soft clay respectively.

It should be noted that in the aforementioned discussion no account has been taken of breakaway of the soil below the anchor on pullout. The flow mechanism of Randolph and Houlsby (1984) assumes the soil will flow completely around the object closing at the back, with no detachment. This would occur if the interface at the bottom of the anchor could sustain tension due to suction (or adhesion), or if the initial stresses were large enough to ensure that the stresses behind the anchor were compressive up to the failure load.

In common with the tests completed on the sand samples (Newson et al., 2003) the mobilisation distances (δ_f) for peak load were found to be quite high for the majority of tests with δ_f / (H+L) being approximately 20 %. The relative stiffness of the membrane was found to contribute considerably to this distance in the sand tests, as was increasing the roughness of the membrane. This suggests that the same may be true of the clayey soil and these reductions in mobilisation distance may be a function of the compressibility of the flexible membrane under loading (the overall volume is constant but the shape may vary) and changes in the deformation mechanism of the soil. However, the mechanisms of failure of the anchor system are currently unknown and this aspect should be investigated further to provide more accurate design for utilisation of the anchor system and to suggest improvements of the geometry. The effects of soil disturbance due to installation of the anchor also need to be investigated.

Conclusions

Based on the preliminary data shown herein, the inflatable anchor system shows considerable promise for offshore use for soft clayey soils. The additional benefits of monitoring the pressure-volume relationship during inflation have also been demonstrated, allowing the determination of a range of soil parameters to provide information for design and for optimisation of waiting time prior to loading the anchors. Further testing needs to be conducted at full scale to verify these findings.

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