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Comparison of the behaviour of a drag embedment anchor using 1-g and centrifuge scale model testing

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ABSTRACT: Offshore wind power cable failure currently accounts for the majority of the cost associated with insurance claims for offshore wind projects. Faults that occur typically take 100+ days to repair during which time energy is not being transmitted to the electricity grid. The most effective method for protecting the export cables from fishing and anchor related damage is to bury them in the seabed, but current guidance on how deep they should be buried is ambiguous. There are a number of variables that influence the penetration of anchors, such as the anchor size (typically considered as a mass of the anchor), the fluke length, fluke angle (or opening angle) and the soil type into which the anchor is being deployed. The fluke length and the angle vary depending on the anchor size, the anchor type (fixed or flipper style) and the manufacturer of the anchor (the same anchor from different manufacturers can have slightly varying dimensions). Current industrial guidance suggests that an anchor's penetration behaviour can be predicted based upon its fluke length, the vessel displacement and the soil type but this does not consider the physical properties of the soil or the overall geometry of the anchor. In this paper a comparison of the penetration behaviour of a Class F (AC-14) anchor has been investigated in loose soil using centrifuge and 1-g model scale testing. The results indicate that the 1-g testing is able to match the behaviour of the anchor testing in the centrifuge in terms of both the position of the anchor and its orientation during the dragging event.

1 INTRODUCTION

In order to transmit electrical power and data across the world's oceans and seas from offshore assets such as wind turbines to land, large lengths of submarine cables are required. Damage to these cables can cause disruption to global connectivity and power grids, as the damage can take considerable time to repair, with some faults requiring 100+ days before being brought back online (Moore et al., 2021). As the UK transitions from fossil fuels to renewable energy alternatives over the coming 30 years, there is expected to be a drastic increase in the number of installed offshore wind farms surrounding the UK, which will require a large network of submarine cables to be installed. Many of these cables will need to span over shipping lanes and fishing grounds which make them susceptible to damage from objects that are being dragged across the seabed, mainly drag embedment anchors and fishing gear.

1.1 Protection of submarine cables from snagging

In order to protect the cables from anchor snagging in emergency anchoring events, submarine cables are typically buried below the seabed. Current burial equipment can bury a cable up to a depth of 3.0 m beneath the seabed, through the use of techniques such as ploughing, jetting and trenching. Although these methods of protection are considered to be relatively cheap, there is a substantial increase in cost associated with increasing burial depths across the entirety of a cable run. The increase in cost is a result of the increase in time required to install the cable to greater depths as lower towing velocities may be required to maintain the stability of the plough, which results in longer vessel hire times and additional fuel costs. (Robinson et al., 2019; Robinson et al., 2017)

To determine the appropriate burial depth of the cable along a specified route a cable burial risk assessment (CBRA) (Carbon Trust, 2015) is undertaken. This process consists of segmenting the route into sections based on available site investigation data and assessing the required burial depth in each given section independently based upon a variety of known factors. These factors are the level of activity (frequency of vessel movements and likelihood of emergency anchor deployment), the size and type of vessels which as likely to be using that section of the route and the soil conditions.

In an ideal scenario, the cable would be buried below the penetration depth of all anchors that are likely to cross the path of the cable, but it is not financially viable to do so, therefore a statistical analysis is undertaken to determine the probabilistic risk to a cable being snagged by an anchor and a compromise between the cost and risk is achieved.

1.2 Existing studies on the penetration behaviour of anchors in sand

Very few studies on the penetration behaviour of anchors are currently available, which has led to uncertainty around the actual behaviour of anchors in different soil conditions. Most of the available data consists of full-scale field trials of a limited number of anchor geometries and soil conditions. The penetration depth in the studies are not directly measured, but inferred using other sensing technology such as water pressure sensors attached to an anchor and seabed sonar scans.

A large number of experiments on a variety of anchor geometries were conducted by the United States of America Naval Civil Engineering Laboratory (NCEL 1982,1984) to determine the holding capacity, orientation and attitude of the anchor when dragged. To measure the orientation and attitude of the anchor accelerometers were attached to the full-scale anchors and to determine the depth at the end of the pull, a pressure sensor was attached to the fluke, to estimate the final depth of the anchor. The depth and holding capacity of the anchors tested at different sites with varying soil conditions were reported and normalised by the fluke length of the anchor, in order to create a rule of thumb regarding their penetration depth. The recommendation from this study suggests that an anchor in sands typically penetrate 1 fluke length and for “looser soils” 3 fluke lengths of penetration is suggested. No indication of the physical properties of the site investigate were given and it is difficult to determine the soil conditions the anchor penetrations occurred in.

Another field scale experiment that is commonly used in industry as an indicator of anchor penetration is the German Bight study conducted in the North Sea by Luger & Harkes (2013). The aim of this study was to determine the required depth of lowering of a subsea cable in shipping lanes for a new wind farm to be installed in Germany. Two anchors were tested at three test sites in the German Bight, the chosen anchors were a 12-tonne Hall anchor and an 8-tonne AC-14 anchor. The anchors were pulled to a specified load and at a velocity to induce undrained loading conditions to simulate an emergency anchoring situation.

Similar to the tests conducted by NCEL (1982), the depth of the anchor was not directly measured. In this study a range of sensing technologies were implemented, which consisted of side scan sonar (SSS), sediment echosounder surveying (SES) and visual inspection to determine the penetration of the anchors after being dragged to a specified load. These methods were used pre and post anchor pull, and the comparison of the trench left in the wake of the anchor was use to determine its final depth.

The German Bight tests found that the AC-14 anchor had a maximum penetration depth of 0.67m (0.69 fluke lengths) which was achieved in the loosest sand and as a result of this testing guidance for depth of lowering was reduced from 3.0 m to 1.5 m, resulting in a large saving on cable burial in terms of both cost and time.

Field testing anchors is a very costly and difficult method of investigating an anchor’s penetration behaviour, due to the size of vessel required to pull the anchor to steady state behaviour (which would not necessarily be the holding capacity) and the lack of easy to use durable technology to directly measure the anchor behaviour. Therefore, as with most offshore geotechnical problems, in order to gain understanding into a specific problem model scale is the more logical solution for this type of investigation. Model scale testing allows for simplified and rapidly repeatable tests to be conducted in which the anchor can be dragged along a flat homogenous soil bed which has been constructed of materials which have been highly characterised. By simplifying the problem, a greater understanding can be achieved from the result which can then be applied to the full-scale testing models, through correlations with Cone Penetration Tests (CPTs) or other site investigation techniques.

Model scale experiments investigating the penetration depth of anchors have previously been conducted in a geotechnical centrifuge (Davidson et al., 2023; Moore et al., 2021; Sharif et al., 2023) with the penetration depth measured by excavating the model at the end of the experiment. Moore et al. (2021), conducted a series of centrifuge experiments on the AC-14 anchor in sands of different relative densities and at varying g-levels. The penetration of the anchor from these experiments was obtained by partially saturating the soil at the end of the experiment and excavating the model anchors final resting place to determine its position and attitude. Results indicated that penetration depth decreased as the relative density increased.

Sharif *et al.* (2023) used onboard sensors to measure the depth and orientation of the model anchors during the drag event. Similar to the work of Moore *et al.* (2021) the authors showed that the penetration depth is density dependent and in the loosest soil bed tested the 8.5-tonne AC-14 anchor penetrated approximately 4.0 m into the soil bed, much deeper that the 3.0 m achievable by current burial machinery. Unlike the field scale tests of Luger & Harkes (2013), the centrifuge experiments mentioned herein are conducted under drained conditions and to a maximum lateral capacity rather than to a fixed load, and as such show deeper penetration depths.

One potential problem that can occur with the centrifuge model testing is the limited drag distance that is available in the strong box, which limits the upper bound size of the model anchors, whereas the size of the instrumentation and batteries constrain the lower bound limit of the model anchor. This can result in multiple spins being required (in which the model anchor is pre-embedded into the soil) to determine the full load displacement behaviour of the anchor and its ultimate penetration depth. This increases the cost and time required to test an anchor geometry as the length of the strong box is constrained by the size of the centrifuge. Access to centrifuge modelling is not always available due to their limited number, and the cost associated with conducting an experiment. The only alternative to this would be conduct 1-g experiments in larger and longer boxes.

The purpose of using a geotechnical centrifuge to conduct geotechnical model scale experiments is to ensure that the stress field within the soil surrounding a structure (anchor, pile, plough, etc.) corresponds to the stress field a full-scale structure would experience. This supresses the near surface dilation that naturally occurs in the field from effecting the results of deep problems and as such, the model scale experiment is able to represent a highly controlled full-scale experiment accurately. For near surface problems such as anchoring or ploughing the suppression of the high dilation angle of the near surface soil may not be required as the majority of the large deformation or high strain problem occurs within this region at full scale (Lauder & Brown, 2014; Lauder et al., 2013). This has previously been shown by (Robinson et al., 2019) to be the case for cable and pipeline ploughs, as they were able to recreate centrifuge experiments at 1-g.

Therefore, it may be possible to replicate the behaviour of anchors tested in the centrifuge through the use of 1-g experiments and the scaling Laws proposed by Bransby *et al.* (2005). This paper explores that hypothesis.

2 MODEL SCALE TESTING METHODOLOGY

In order to test the applicability of 1-g model testing for use in characterising the behaviour of a model scale anchor, two model scale experiments were conducted in a loose soil bed ($D_r = 25\%$) using the same testing equipment but at 1-g on the lab floor and at 16.1g using the University of Dundee 3 m radius geotechnical beam centrifuge. The centrifuge test was conducted in dry sand (effectively drained conditions) at 16.1g resulting in situ effective stresses equivalent to saturated sand at 24g due to the increased dry unit weight (Li et al., 2010) It is assumed that no pore pressures are generated during dragging due to the low drag velocity.

The experiments were conducted in a strong box of internal dimensions 1400 mm x 400 mm x 640 mm using a dedicated large displacement actuator developed to investigate the performance of drag embedment anchors and ploughs (Davidson et al., 2023; Robinson et al., 2019; Sharif et al., 2023). The tow force/holding capacity of the anchor was measured using a 5kN loadcell (Tedea Huntleigh type 616) positioned at the surface of the soil bed. Such that the anchor forerunner cable was pulled from the soil surface. The loadcell was attached to a towing arm mounted to a moving platform controlled by a Paralux SD12-LWS high torque 220 V DC motor (capacity of 63 Nm at 13 rev/min). The displacement of the platform was measured using a draw wire transducer (DWT) (Multicomp SPI-50). A swivel and shackle were located at the end of the loadcell end of the forerunner to remove the possibility of the connection detail from influencing the orientation of the anchor and minimise torsional forces from tensioning of the twisted rope. The anchor pad-eye to loadcell distance was 420 mm (length of cable).

To measure the inclination of the towline and in turn the shank of the anchor a 200-g 3 axis accelerometer was mounted to the swivel between the anchor and the loadcell. Continuous measurements of the inclination of the fluke were recorded through out the experiments using a 6-axis accelerometer-gyroscope, which was mounted inside the anchor and transmitted to the CompactRio through a Bluetooth connection.

Labview 2018 was used to create a purpose-built control and logging programme for the actuator. The data acquisition system consisted of a National Instruments 9047 CompactRio programmed using hybrid mode (simultaneous use of scan engine and FPGA modes) and a 9202 C-series module was used to read the data obtained from the analogue sensors at a frequency of 250Hz.

2.1 Soil bed properties

The two soil beds were created using dry slot pluviation method to a depth of 300mm. To ensure the density of both soil beds was consistent the mass of the pluviated bed and the strong box was measured before commencing the experiment. HST95 sand was used in the experiments which is a fine-grained quartz laboratory sand commonly used in the geotechnical laboratories of the University of Dundee for physical modelling (Lauder 2010), Physical properties are provided in Table 1.

Table 1 Properties of the HST95 sand (adopted from Lauder (2010)*)*

Properties	**Symbol**	**Value**
Effective particle size [mm]	d_{10}	0.090
Mean particle size [mm]	d_{50}	0.141
Particle specific gravity [-]	G_s	2.63
Minimum void ratio [-]	e_{min}	0.467
Maximum void ratio [-]	e_{max}	0.769
Dry unit weight [kg/m^3]	γ_{dry}	16.0
Saturated unit weight [kg/m^3]	γ_{sat}	19.7
Critical state friction angle [°]	φ_c	32
Peak friction angle [°]	φ_p	39.0
Peak dilation angle [°]	ψ_p	8.6
Steel-sand interface friction angle [°]	δ	24

2.2 Anchor model

The model anchor utilised in this study is a 1/24th scale 316L stainless steel replica of an 8.5-tonne AC-14 anchor that was previously used by (Sharif et al., 2023). The model was 3D metal printed and scale such that both the dimensions and mass were scaled down in accordance with the scaling laws of (Garnier et al., 2007). This is to ensure that the mass and centre of gravity of the anchor were true to the prototype model such that the behaviour of the model anchor accurately replicated that of the full-scale anchor. The model was created in a manner in which the fluke was able to open during testing and a fluke opening angle was not set prior to dragging. At the start of the test the anchor was placed flat on the soil surface.

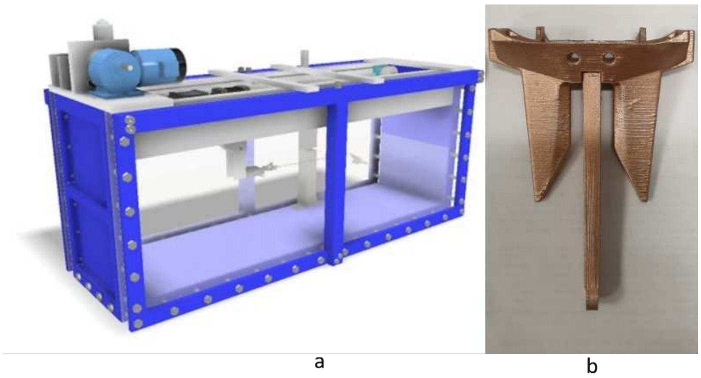

Figure 1: a) Image of long strong box and actuator used for the centrifuge experiments (soil not shown for clarity).b)3D metal printed model anchor used in the model scale experiments

2.3 Scaling Laws for 1-g and Centrifuge experiments

To be able to compare the results of the 1-g and centrifuge experiments and scale them up to field scale values a series of scaling laws are required for the recorded force and displacement of the experiments. The inclination of the anchors would be the same for all scales and only the kinematic behaviour of the anchor may be different due to the reduction in stress within the soil.

For the outputs of the centrifuge experiment, the scaling laws proposed and collated by Garnier *et al.* (2007) will be used and can be seen in Table 2 below. Where N is the scaling factor of the model anchor.

Table 2: Scaling factors for 1-g and centrifuge model anchor tests

Parameter	**Scaling factor for centrifuge model tests**	**Scaling factor for 1-g model tests**
Displacement.Length	N	N
Force	N^2	N^3
Mass	N^3	N^3

For the 1g experiments the scaling laws used are those that were initially proposed by Brown *et al.* (2006) for ploughing experiments. These scaling laws have previously been verified for ploughing by (Brown et al., 2006) and against centrifuge experiments by (Robinson et al., 2019). Table 2 shows the scaling factors used for the 1-g experiments.

3 RESULTS AND DISCUSSION

To assess the applicability of the 1-g model scale testing ability to replicate the centrifuge model tests, the holding capacity/tow force, penetration depth and the attitude of the anchor must all be compared.

Figure 1 shows the comparison of towing force required. Both of the experiments have been scaled to prototype values using the factors identified in Table 2.

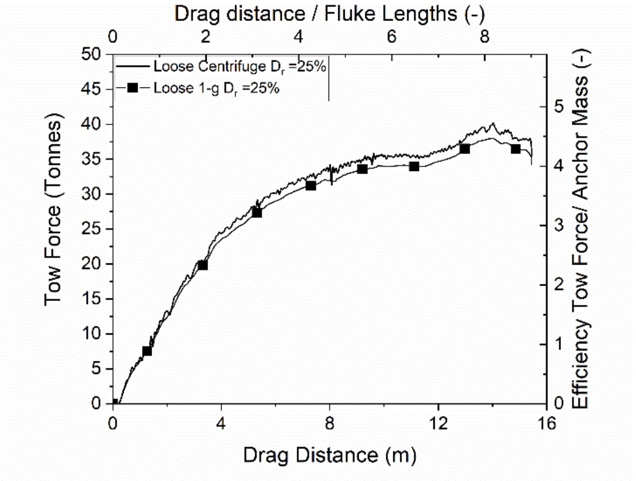

Figure 2: Comparison of tow force recorded from the 1-g and centrifuge model tests

From Figure 1 it can be seen that using the proposed scaling factors in loose sand the required towing force of the anchor is similar in the 1-g and centrifuge experiments, with only a small reduction in the ultimate holding capacity (approximately 4%) in the 1-g experiment. It can also be seen that the distance required to mobilise the force is also the same. Therefore, in loose sand, it can be stated that the 1-g testing can be used to determine the holding capacity of a model scale anchor.

The next property that needs to be assessed is the kinematics of the anchor movements during the dragging event. From Figure 3 the overall orientation of the anchor in the loose soil bed is similar in both the centrifuge and 1-g experiments. The only difference in the data being the fluctuation in the shank and fluke angle which is most likely due to the difficulties in preparing loose soil bed. From this it can also be stated that the kinematic behaviour is similar for the 1-g and centrifuge tests on the anchor in loose soil, with the final check being the anchors penetration depth.

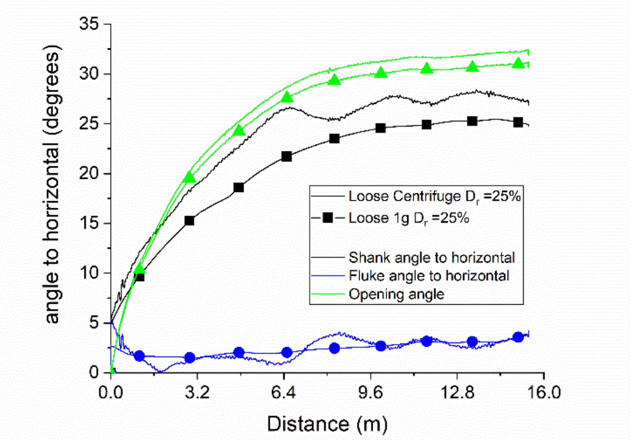

Figure 3: Comparison of 1-g and centrifuge orientation of anchor during anchor pull.

Figure 4 shows the penetration depth of the anchor for both experiments. The penetration depth is calculated using the orientation data from the accelerometers and gyroscope and, as Figure 3 shows, the attitude of the anchor is similar for both experiments, the penetration depth is also very similar.

Figure 4 shows that the penetration depth only varies by 6% at the end of drag with the transitional behaviour remaining the same throughout. This shows that both the scaling of the tow force and the kinematic behaviour of the anchor can be replicated at 1-g

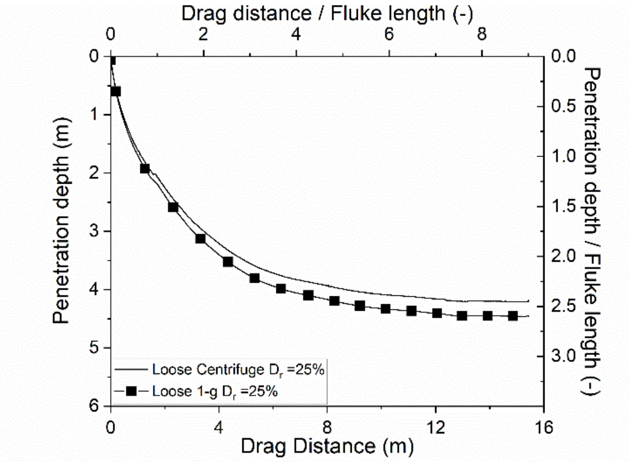

Figure 4: Comparison of penetration depth for the 1-g and centrifuge model anchor experiments

4 CONCLUSION

This study has shown that 1-g testing can be used to replicate the behaviour of an anchor tested in a geotechnical centrifuge under drained conditions in loose sand beds. The 1-g model test was able to replicate the holding capacity of the anchor when scaled up to full size using the scaling factors proposed by Bransby et al. (2005)Bransby et al. (2005) for ploughing which have previously been validated by Robinson *et al.* (2017). Further work is required to check the applicability of 1-g model scale testing in soil beds of different relative densities in addition to other soil types such as clays and layered soils.

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