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Characterization of anchor penetration behaviour for Cable burial risk assessment

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ABSTRACT: Offshore wind (OSW) power cable failure currently accounts for 75% of the cost of all insurance claims associated with OSW projects and faults typically take 100+ days to rectify. The most effective method for protecting the cables from anchor 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 depth of anchors, such as the anchor size (considered as the weight in kg), fluke length, fluke angle and the soil type and properties. The fluke length and angle vary depending on anchor size, the type of anchor and the manufacturer. Current industrial guidance suggests that an anchor's penetration behaviour can be predicted based upon its fluke length and vessel displacement and the soil type but this does not consider the physical properties of the soil. In this paper the penetration behaviour of a Class F (AC-14) anchor has been investigated in sand soil beds of varying relative densities. The results indicate that the penetration depth of the anchor is density dependent and that the anchor penetrates deeper than may be anticipated in very loose sands.

1 Introduction

In order to transmit electrical power and data across the world's oceans and from offshore assets such as wind turbines, large lengths of submarine cables are required. Damage to these cables can cause extreme disruption to global connectivity and to power grids, as faults to power transmission cables typically take 100+ days to repair(Moore et al., 2021) . Over the next 30 years there is expected to be a large increase in the installed offshore wind (OSW) capacity surrounding the U.K which will results in a large increase in the number of cables spanning over shipping lanes and fishing grounds which makes them susceptible to damage from drag embedment anchors (DEA) and fishing equipment.

1.1 *Methods for protecting submarine cables from anchor snagging*

Protection for submarine cables typically consists of either burying them below the soil surface or applying rock armour on top of the cable, which gives physical protection to impacts but only provides minimal protect against snagging from a dragged object, although the mechanism behind this is not very well understood.

In the majority of cases the most cost-effective way to protect a cable is to bury it up to a depth of up to 3m beneath the seabed, such that the anchor is unable to reach the cable. Although this method is considered to be relatively cheap, there is a substantial cost associated with increasing burial depths across the entire length of the cable. The increase in cost is a result of the increase in time required to install the cable through methods such as plough and trenching to greater depths as lower towing velocities may be required to maintain the stability of the plough, which results in longer vessel hiring times and therefore additional fuel costs. In addition to this in certain soil conditions multiple passes with a plough or other burial equipment is required to achieve greater burial depths (Robinson et al., 2017, 2019).

To predict the appropriate burial depth of the cable along a given route, a cable burial risk assessment CBRA, (Carbon Trust, 2015) is conducted. This consists of splitting the proposed route into sections based upon available site investigation, with the required depth of burial assessed independently on the level of activity (frequency of vessel movements and likelihood off emergency anchor deployment), soil conditions and size of vessels likely to be present in each of the sections. Once the size of vessels has been determined, it is then possible to approximate the mass of anchor required to stop the aforementioned vessel based upon existing design charts. Once the mass is known the physical properties of potential anchors used by a vessel can be found from manufacturer specifications(Carbon Trust, 2015).

From the dimensions of the anchor and data on soil type from the ground investigation, existing prediction methods can be used to approximate the depth of burial when the anchor is deployed. Using the approximated burial depth of the anchor during dragging a target embedment depth of the cable can be specified. Although it would be ideal for the cable to buried below the penetration depth of all anchors likely to cross the path of the cable, it is not always financially viable or physically practical for this to occur. Therefore, a statistical analysis is undertaken to determine the probabilistic risk to a cable and a compromise between cost and risk is achieved.

1.2 *Previous studies on the penetration depth of anchors in sand*

Very few studies exist on the penetration behaviour of anchors, which has led to the 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 in which the penetration depth was not directly measured but rather inferred using other sensing techniques, such as water pressure or seabed sonar scans.

One such study was conducted at the United States of America Naval Civil Engineering Laboratories, (1982,1984) in which a variety of anchors were tested to determine their holding capacity and the attitude (orientation) of the anchors when dragged (the inclination and roll of the anchor). To measure the depth of the anchors when in their final position, the water pressure at the fluke depth was measured using pressure sensors, and from this reading a depth of the anchor fluke was inferred. The depths of the anchors in various soil conditions at different sites were reported and compared to the fluke length of the anchor. The recommendation from this study suggests that anchors in sands and stiff clays penetrate to a depth equal to one fluke length and for looser soils (soft clays and silts) the penetration was reported to be three fluke lengths. No physical characteristics or properties of the soils were reported and therefore it is difficult to determine the soil conditions in which the tests were conducted or under what conditions these anchor penetration values are likely to occur.

A common study used by industry is the Anchor tests, German Bight study conducted in the North Sea (Luger & Harkes, 2013). This study consisted of testing a 12-tonne Hall anchor and an 8-tonne AC-14 anchor at three test sites to aid in determining the required depth of lowering of a subsea cable in shipping lanes for a new wind farm in Germany. Similar to the study conducted by the Naval Civil Engineering Laboratory (1982), the depth of the anchor was not directly measured but was inferred through different sensing methods. In this case the authors used side scan sonar (SSS), sediment echosounder surveying (SES) and visual inspection to determine the penetration of the anchors. These methods were used to scan the surface of the seabed before and after the anchor test had been conducted and a comparison of the trench left in the wake of the anchor was used to determine penetration depth. The method is unable to account for any of the soil that has collapsed back into the trench formed by the anchor and therefore would underestimate the penetration depth.

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

Moore et al. (2021) conducted a centrifuge study on the penetration depth of an AC-14 anchor in sand. Unlike previous studies the depth of the anchor was measured directly after the drag had been conducted, rather than being inferred from other sensors. The results indicated that as the fluke length increases there is an increase in penetration depth, as would be expected, and that as relative density increased there was a decrease in penetration depth. Although this study investigated the effect of relative density on the penetration depth of the anchor, it was conducted at a low g-level and therefore represents a relatively small anchor (720 kg) in comparison to those that would be used in a shipping lane.

1.3 *Existing penetration prediction techniques*

Although several empirical methods exist for predicting the penetration depth of DEAs, they are typically rudimentary and do not consider the overall geometry of the anchor or the presence of layers within the soil profile (Macdonald et al., 2023). Generally, the fluke length is used, alongside a multiplier (determined by the soil type, as shown in Table 1).

Table 1: anchor penetration multiplier for different soil types (Laboratories, 1984)

Soil type	Anchor penetration (Fluke lengths)
Sands	1
Stiff clay	1
Soft clay and silts	3-5

The values shown in Table 1, were developed through full scale testing on various anchor designs by the US Navy Civil Engineering Laboratories ((Naval Civil Engineering Laboratory, 1982). The penetration depth was determined using a pressure sensor, although it should be noted that the authors questioned the reliability of the depth data due to kinking of the hose attached to the pressure sensor, in addition to “soft soil” entering the hose causing it to become clogged, altering the readings.

Another prediction method that is typically used is shown in Equations (1) & (2).

$$P = 1 \times L_f \times sin(\theta) \text{ "}Hard\ soils\text{"} \quad (1)$$
$$P = 3 \times L_f \times \sin(\theta) \text{ "}Soft\ soils\text{"} \quad (2)$$

Where P is the final embedment depth, L_f is the fluke length and θ is the fluke opening angle. The current guidelines for cable burial risk assessment (CBRA) (Carbon Trust, 2015) recommends that the fluke angle be set to 45˚ to conservatively account for different anchor types and soil conditions. No guidance is given for what constitutes a “Soft” or “Hard” soil, and thus the method can predict a required depth of lowering that is deeper than necessary in addition to a depth of lowering that is too shallow, depending upon the user’s assumptions of whether a seabed is considered to be “Hard” or “Soft”. Neither of the methods specified have recommendations for how layered soils should be included within the analysis, and from Macdonald et al. (2023) it can be seen that there are many areas of the North Sea where layered soils are present as would be expected in reality.

In addition to the empirical relationships discussed above, analytical models such as those summarised by Pretti et al. (2022) , in which the forces on acting on an anchor at a given displacement point and its current position are used to determine the position of the anchor at the next timestep (a fixed horizontal drag distance). These methods typically require the use of a computer to compute the predicted embedment depth and require a range of soil parameters, which may not be available from the limited data obtained through a typical site investigation report. These methods are able to accommodate the presence of layered soils and a specific anchor geometry or type, but calibration data may be required for the input parameters for different anchor geometries which may not be readily available. One such method is that proposed by Neubecker & Randolph (1996a).

In order to investigate the validity of current CBRA approaches and penetration depth of an anchor in sand soil beds of varying relative densities a series of geotechnical centrifuge experiments were conducted on a AC-14 model scale anchor. The AC-14 anchor was chosen based upon its regular use by larger vessels commonly found in shipping lanes. The results of the investigation are presented within this paper.

2 Centrifuge modelling methodology

To replicate the prototype stress conditions, geotechnical centrifuge testing of a scaled model of an 8.5T AC14 anchor was conducted. The model anchor was 3D metal printed in 316L stainless steel (Figure 1), ensuring that the mass and centre of gravity were accurately scaled down, such that the behaviour of the anchor accurately replicated that of the real 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.

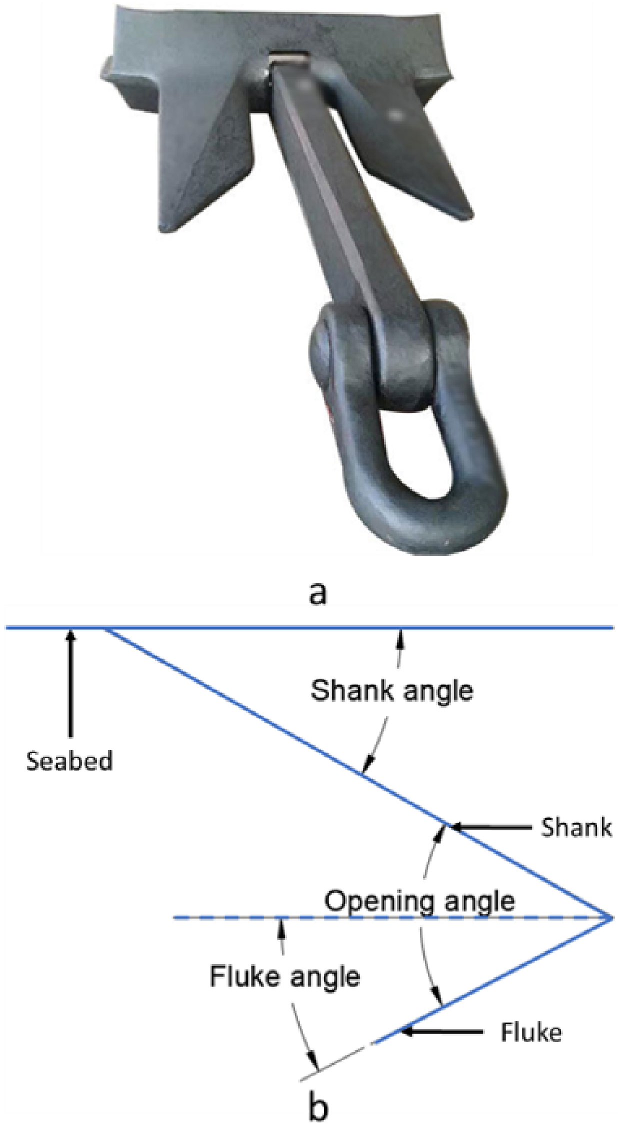

Figure 1: a) Image of AC-14 anchor used in this study b) Diagram of anchor angle definitions used in this study

The experiments were conducted on the University of Dundee’s 3 m radius beam geotechnical centrifuge in a strong box of internal dimensions 1400 mm x 400 mm x 650 mm using a dedicated large displacement actuator develop to investigate the performance of anchors and ploughs (Davidson et al., 2023; Robinson et al., 2017, 2019). The tow force was measured using a 5kN loadcell (Tedea Huntleigh type 616) positioned at the surface of the sand bed, which was attached to a towing arm mounted to a moving platform. The displacement of the platform was measured using a draw wire transducer (DWT) (Multicomp SP1-50), see Figure 2. A swivel and shackle were located at the loadcell end of the forerunner (the cable used to attach the towing arm to the padeye of the anchor) to minimize potential torsional forces from tensioning of the twisted wire rope. The anchor padeye to loadcell distance was 420mm.

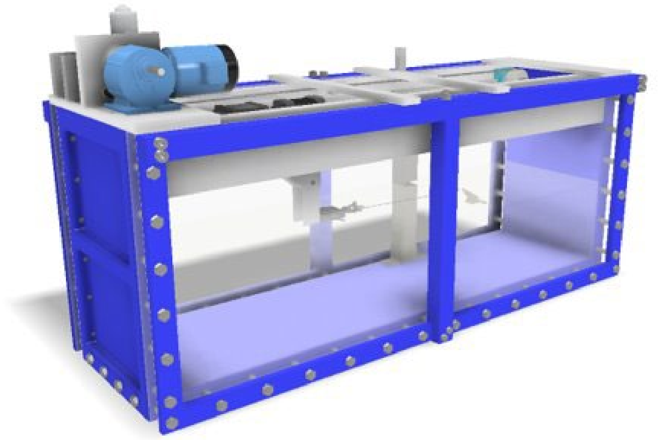

Figure 2: Image of long strong box and actuator used for the centrifuge experiments (soil not shown for clarity).

To measure the inclination of the towline and in turn the shank of the anchor a 200g 3-axis accelerometer was mounted to a swivel between the loadcell and tow cable. To continuously measure the inclination of the fluke a 6-axis accelerometer – gyroscope was mounted inside the fluke of the anchor, with the data transmitted to a logging PC via Bluetooth.

Sand beds pluviated to depths of 400 mm were created in four relative densities to assess how density affects the penetration of the AC14 anchor. The relative densities (D_r) chosen were 25%, 38%, 55% and 82% to represent sand beds in the loose, medium dense and very dense categories. 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 (physical properties provided in Table 2).

Table 2: HST95 sand material properties(Al-Defae et al., 2013; Lauder et al., 2013)

Property	Value
Effective particle size D_{10} mm	0.09
Average particle size, D_{50}: mm	0.14
Critical state friction angle, φ'_{crit}: degrees	32
Sand–steel interface friction angle, δ'_{crit}: degrees	24
Angle of dilation*, ψ: degrees	16
Maximum dry density, ρ_{max}: kN/m^3	17.58
Minimum dry density, ρ_{min}: kN/m^3	14.59

Tests were 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 pressure are generated during dragging due to the low drag velocity. This produces a prototype mass of anchor of 8.5 tonnes and a fluke length of 0.976 m. On this basis tests and models were scaled at 1:24 from the prototype case. All results presented in this paper are in prototype scale (full scale) unless directly specified.

The towing platform was displaced at a rate of 20mm per minute, which in turn dragged the anchor along the soil bed. The onboard Bluetooth instrumentation continuously logged at a rate of 50hz, while the remainder of the instrumentation (loadcell, DWT and 200g accelerometer) was logged at a rate of 250hz. The higher frequency logging of the wired instrumentation was to ease the synchronization of the two data sets during post processing. Once the test had been conducted, and the centrifuge had spun down, the soil surrounding the anchor was saturated and the anchor was carefully excavated in such a way that it was possible to take measurements of the final penetration depth, shank angle and fluke angle to confirm the readings recorded during the test. To process the data from the accelerometer and gyroscope to find the penetration depth of the anchor a Kalman filter was used.

3 Results and discussion

The tow force and penetration depth (measured at the fluke tip) of the anchor can be seen in Figure 3 and 4 respectively. Figure 3 shows that for all soil densities there is very little change in the tow force required to pull the anchor over the 16m drag length. Suggesting that the anchor has a preferred holding capacity and the position and attitude of the anchor in the soil (shank angle, fluke opening angle and penetration depth) changes depending on the soil bed properties.

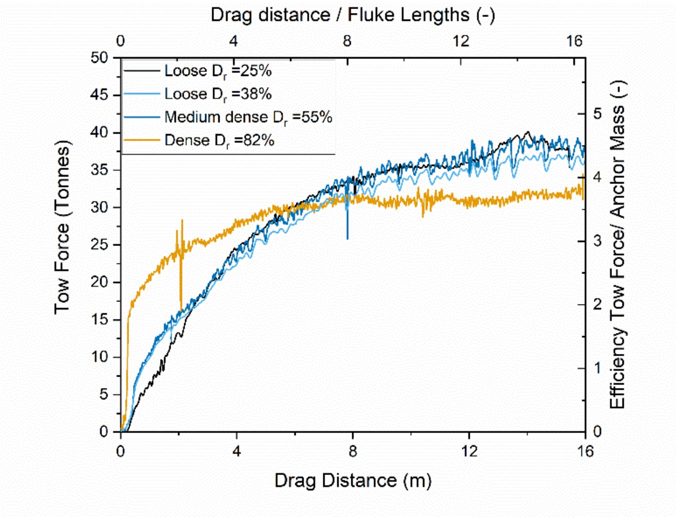

Figure 3: Tow force vs horizontal displacement for centrifuge tests (All values are shown in prototype scale)

This can be seen in the penetration depth that is achieved by the anchor (Figure 4), with the looser soils having much larger penetration depths than that of the anchor in the medium dense and dense soil beds. From Figure 4 it can be seen that the anchor tested in the loose soil bed penetrated to a depth of approximately 4.0m below surface, which is larger than maximum 3.0m depth specified for cable trenching and ploughing equipment, suggesting that in the loose soil it is possible that a buried cable is susceptible to snagging by an anchor similar in size to that tested in this study.

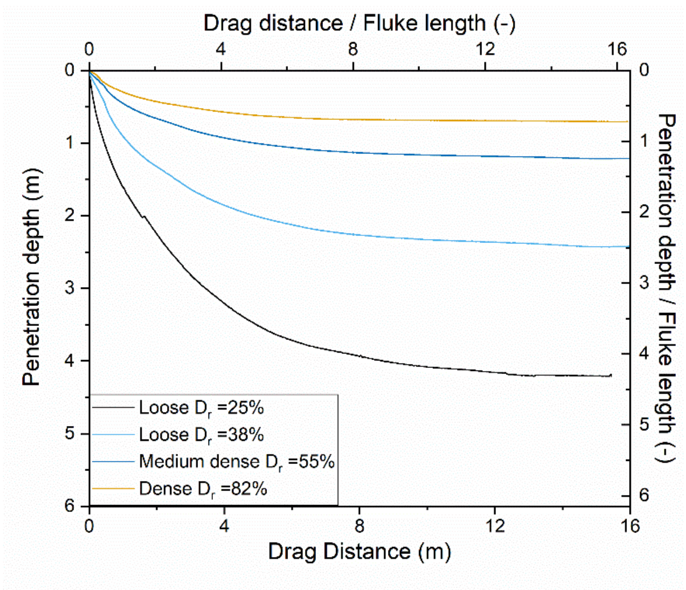

Figure 4: Penetration depth against drag distance for AC-14 anchor in sand beds of different relative densities. (All values are shown in prototype scale)

Figure 5a and 5b show the shank and fluke angles, for the anchors in the loose and dense soil beds, relative to the soil surface during the dragging process. From these figures it can be seen that the fluke angle does not vary significantly during the drag process in both densities shown, whereas a large difference can be seen in the shank angle (26˚ for the loose and 5˚ in dense at full displacement). Showing that the fluke of the anchor stays relatively flat during the embedment and that the opening angle increases to enable the anchor to dive into the soil to reach the desired holding capacity. The oscillations seen in Figure 5 are most likely due to the challenges with forming a uniform loose soil bed, may represent small pockets of sand that have a slight variation in relative density. as

Figure 5 also shows that after a displacement of approximately 5m-6m (5-6 fluke lengths) the anchor transitions from a rotational and translational displacement to simply a translational behaviour (as the angle of the fluke and shank do not change significantly after this displacement).

The images on Figure 5c shows the final orientation of the anchor in reference to the soil surface, as an indicator of attitude of the anchor at the final depth.

Data such as that shown in Figure 5 can be used to aid in informing analytical approaches such as Neubecker & Randolph (1996a) as it is possible to determine the orientation of both the fluke and shank over the displaced distance. By plotting the change in angle over a given displacement it would be possible to determine the incremental path of an anchor and from there an equilibrium approach can be used to assess

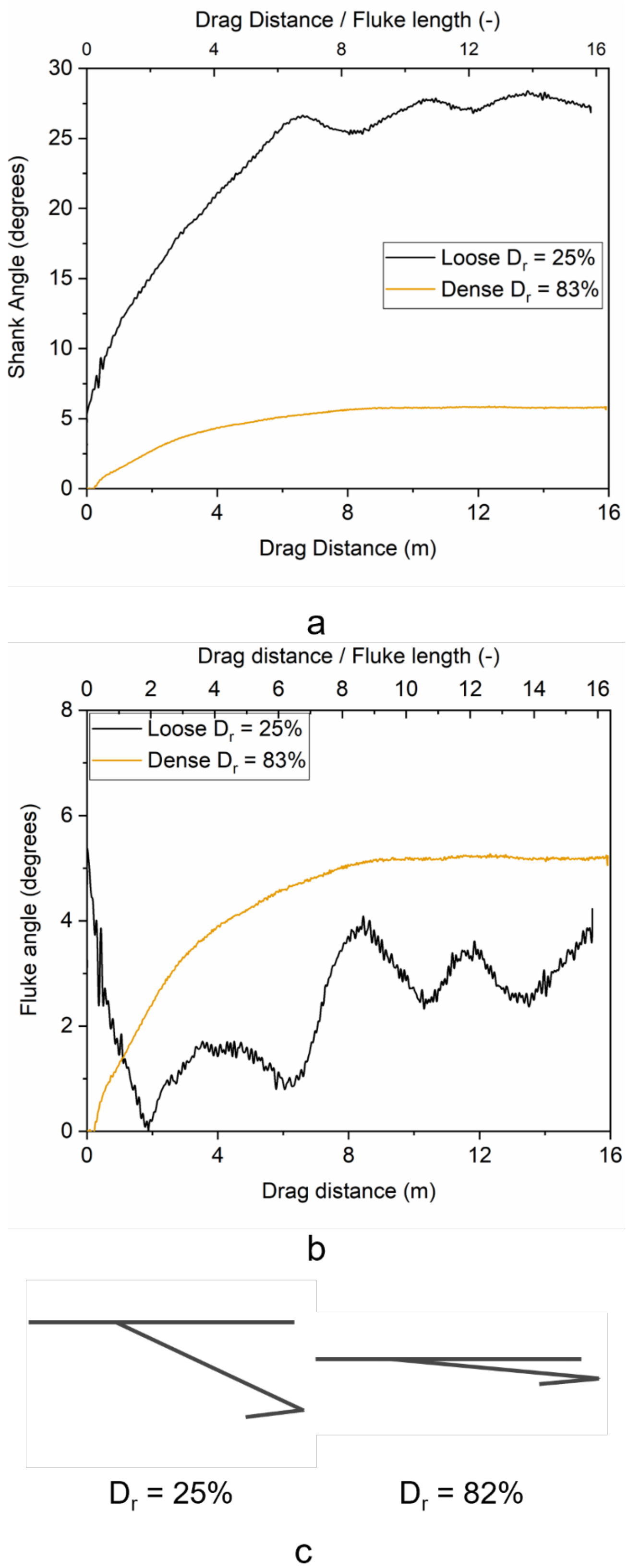

Figure 5: attitude of anchor at the end of drag. a) angle of shank relative to soil surface b) angle of fluke relative to soil surface c) orientation of anchor at the end of the drag (All values are shown in prototype scale)

how the anchor moves in the next displacement increment.

3.1 *Comparison of centrifuge results to existing methods and data.*

When comparing the results of the centrifuge study to existing prediction methods (as outlined in Section 1.2 and combined in Figure 6) it can be seen that the methods tend to be similar at higher densities or significantly underpredict the penetration depth of the anchors in looser sands.

When using Equation (1) the authors have decided that “Soft soil” is a sand below a D_r of 40% and “Hard soil” is determined as a sand with a D_r greater than 40% (as existing guidance appears vague on the actual soil type/state referred to). Figure 6 shows that in all instances Equations (1) & (2) underpredict the penetration depth of the anchor in each of the soil beds when using both the recommended 45° opening angle and the actual recorded opening angle from the centrifuge tests, although it can be stated that the predicted depth using the 45° opening angle is close to that measured in the centrifuge for the relative densities larger than 25%. This may appear a better approach but it does not recognise the real opening angle of the anchor and how this varies with relative density. The largest underprediction is from the D_r = 25% test, with Equation (2) predicting a penetration depth half of that recorded experimentally.

When using the fluke angle multiplier specified by NCEL (1987) to predict the embedment depth, the D_r of 38% and 55% lie within the region of prediction whereas the anchor in the loose soil is once again under predicted, although to a much less extent then when using Equations (1) & (2).

Assessing the results of both prediction methods it could be concluded that fluke length is not a good method for predicting the penetration depth and that dilation angle (or relative density or CPT data, e.g. as per Robinson et al., (2021)) and fluke opening may be a better alternative. This shows that further investigation into the penetration behaviour of drag embedment anchors is required, in order to accurately predict the embedment depth of the various anchor geometries in sand beds of different relative densities.

The centrifuge results match well with the medium dense drum centrifuge test of Moore et al., (2021) although the field tests of Luger and Harkes (2013) significantly underpredict the penetration depth of the AC-14 anchor in the loose soil which is of concern as there appears to be a trend of industry adopting this data set in CBRA. The soil characterization for the field tests of Luger and Harkes (2013) is very limited within the report and the authors of the current paper were unable to source the underlying CPT data, so it is unclear what the exact relative density of the sands were and the overall soil profile at the test sites was for the “loose” sand tests. Therefore, a grey box has been placed on Figure 6 to indicate the range of possible relative densities this data point could indicate.

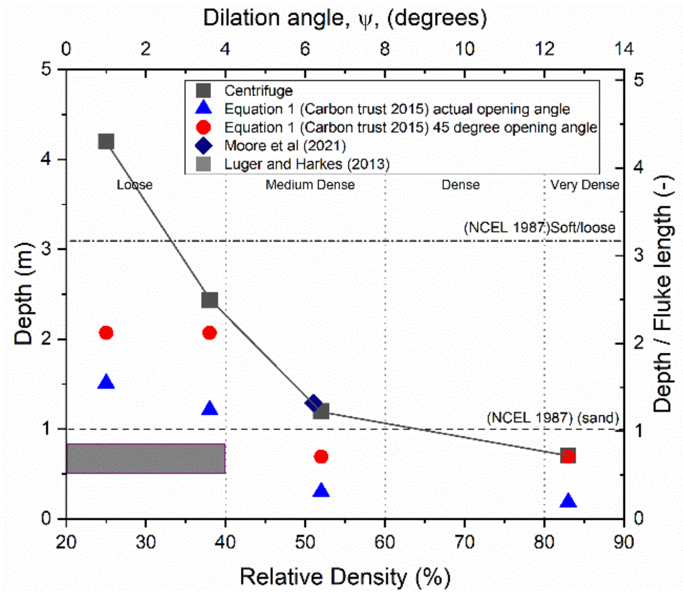

Figure 6: Comparison of centrifuge experiments with previous studies and existing prediction methods (All values are shown in prototype scale)

Although current CBRA practice would appear to be none conservative in loose and very loose sands it is acknowledged that the whole process is a probabilistic and the chances of encountering this depth of loose to very loose sand in the field may be low. That said it would appear preferential to at least start the CBRA process with accurate input parameters. Hopefully the work by MacDonald et al (2023) will shed light on the potential for encountering such horizons in the North Sea. It should also be noted that the study here has been undertaken mimicking drained soil conditions which do not allow for any form of rate effects that may occur in practice if the anchor is dragged at higher speeds, particularly in emergency deployment. This means that the penetration depths shown are likely to represent maximum values. Rate effects may be significant in silty sands but are more likely to be greater in dense rather than loose soils due to reducing dilation with reducing density or dilation. The rate effect will act to increase the strength of the soil encountered by the anchor and reduce depth as shown for offshore pipeline ploughs by Lauder et al. (2013). The form of relationship derived by Lauder et al (2013) and verified by Robinson et al (2019) could be used to inform the Neubecker & Randolph (1996a) & Neubecker & Randolph, (1996b) approach for predicting more reliable anchor penetration predictions subject to appropriate calibration for different anchor types. The results shown herein are only shown for an 8500 kg AC 14 anchor. This may require centrifuge calibration testing at different g levels to simulate different anchor masses (and their resulting penetration) and requires testing of a wider set of anchor types.

4 Conclusion

This paper presents the results of a series of centrifuge model tests of an 8.5-tonne AC-14 anchor in sand beds of varying relative densities. The results of the experiments show that the relative density of the soil plays a significant role in the achieved penetration depth of the anchor during dragging, with looser soils having larger penetration depths and denser soils restricting the anchor to relatively shallow depths.

The additional onboard sensors with continuous data feed were able to identify that the attitude of the anchor (fluke angle and shank angle) is density dependent and that larger fluke openings occur when the anchor is able to penetrate the soil to a deeper depth as would be expected.

From this study it can be stated that the existing guidance and prediction methods on anchor penetration is not applicable to loose and very loose drained sand conditions, due to the underprediction of penetration depth. The results indicate that the use of fluke length alone to predict the anchor penetration depth is not applicable and that it would be much better to use the opening angle and an indication of soil strength (in the case of sand friction/dilation angle) to predict the penetration depth of a given anchor. The use of opening angle would require additional characterisation of multiple anchor behaviour to determine the opening angle for each soil type and relative density.

Further work is required to understand the penetration behaviour of anchors, including the characterisation of different anchor geometries to understand how the individual geometric features of an anchor effect the mechanistic and kinematic behaviour when deployed.

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