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Anchor Damage to Offshore Cables

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I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

Signed ________________________________ *Date* ______________________

Technical Abstract

The offshore cable network currently consists of over 1 million km of subsea cables, providing power, communication and data worldwide. Modern society is dependent on offshore cables and consequently cable faults lead to major disruption and economic loss. External aggression is the leading cause of cable damage, with anchors causing 30-40% of offshore cable faults. Two major cable damage incidents occurred in UK waters in November 2016, both as a result of anchors and both having significant social and financial impacts. This demonstrates the importance and relevance of the investigation of this issue.

The most effective way to protect offshore cables from anchor damage is to bury them in the seabed, out of reach of anchors being dragged by ships. The current guideline for cable burial depth was produced by Cable and Wireless Marine (CWM) in 1997. It uses data from ploughs rather than anchors and advises burial depths based on the ambiguous metric of Burial Protection Index, therefore the guideline is deemed to be inadequate.

This report details the investigation completed into the behaviour of anchors in sand. The results from experimental work are compared to the existing cable burial guidelines and other relevant research. A new guideline is produced to suggest suitable burial depths for cables, based on the more useful metrics of anchor and ship size.

Models of the AC-14 and Halls anchors were 3D-printed in stainless-steel, both identified to be anchors which have caused cable damage. Preliminary testing was carried out with the anchors in a sand tank at 1g, alongside finite element analysis. These methods were valuable in giving an initial understanding of the interaction between the anchor and the sand. It was hypothesised that anchors have an equilibrium position in the seabed where the stresses above and below are equal, and that anchors will move towards this equilibrium position.

The main part of the investigation involved 18 tests done in the minidrum centrifuge at the Schofield Centre. In each of these, the anchor was dragged through saturated sand at realistic subsea stresses, with parameters such as anchor size, sand density and particle size being varied. This allowed for accurate analysis of the problem.

The results show that initial anchor depth does not impact ultimate anchor depth, with an identical final position observed whether the anchor was placed at the surface or at the base of the model. In addition, the sand particle size has no impact on anchor penetration, despite a factor of two difference being suggested by the CWM guide. A linear relationship was observed

between sand density and anchor penetration, with denser sand leading to a reduced final depth. This is due to the higher peak friction angle of dense sand which resists penetration of the anchor. The difference in depth between loose and dense sand was an order of magnitude smaller than the absolute penetration depths, however, so would not be significant when deciding on cable burial depths.

The most significant factor that influences anchor penetration depth is the size of the anchor, investigated by completing centrifuge tests at different g-levels. A linear relationship was recorded between anchor size and penetration depth. Plotting this against existing sources allowed for a useful comparison. The experimental data was most similar to the Naval Civil Engineering Laboratory guide, which suggests a 1:1 relationship between anchor fluke length and penetration. The existing CWM guideline was deemed to be unsuitable, with the coarse sand guideline being too conservative and the fine sand guideline being insufficient, putting cables at risk of being damaged.

By taking all sources into account, a new guideline for cable burial is suggested, shown in Figure i. The guideline uses the experimental results with a 400mm safety margin, to allow for variations in environment and installation. The new chart is clear and easy to use, with the cable burial depths given in relation to anchor size, anchor mass and ship mass, all less ambiguous metrics than the Burial Protection Index used in the current guideline. It is believed that use of this chart will enable the safe and economic burial of cables, and lead to a decrease in the incidence of anchor damage to offshore cables.

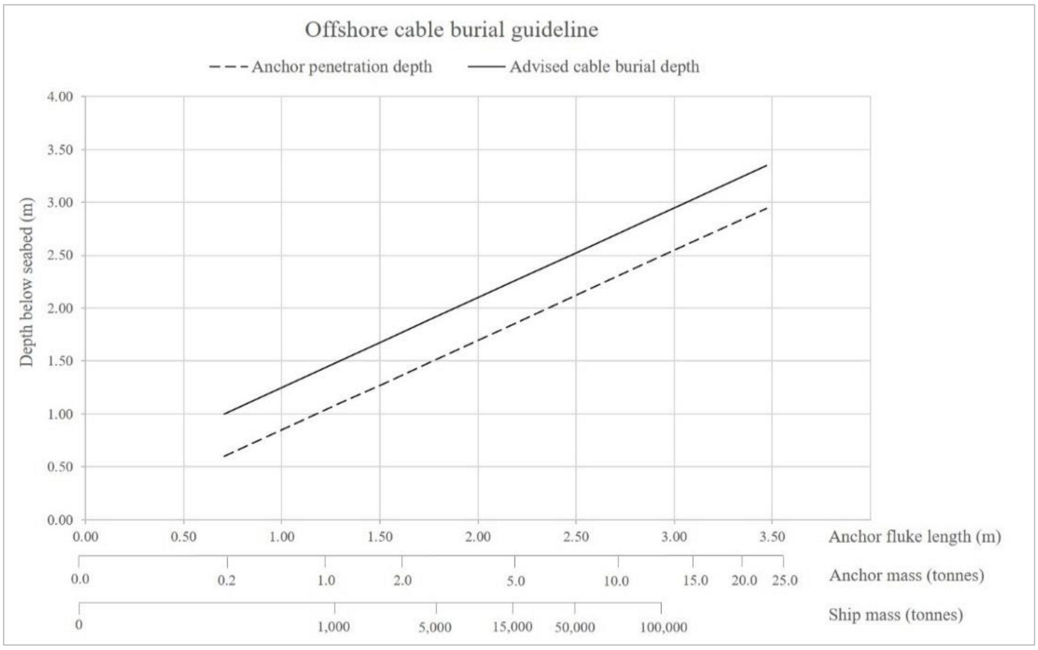

Figure i: New guideline for burial depths of offshore cables

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1 Introduction

1.1 Anchor damage to offshore cables

Over 1 million km of offshore cables exist worldwide (Figure 1) and modern society would not be able to operate without them. As a result of the rise in offshore power generation, in addition to increasing communication links to developing countries, the offshore transmission network is growing rapidly with new cables constantly being installed in already congested offshore areas. Consequently, the risk of damage to offshore cables is also increasing.

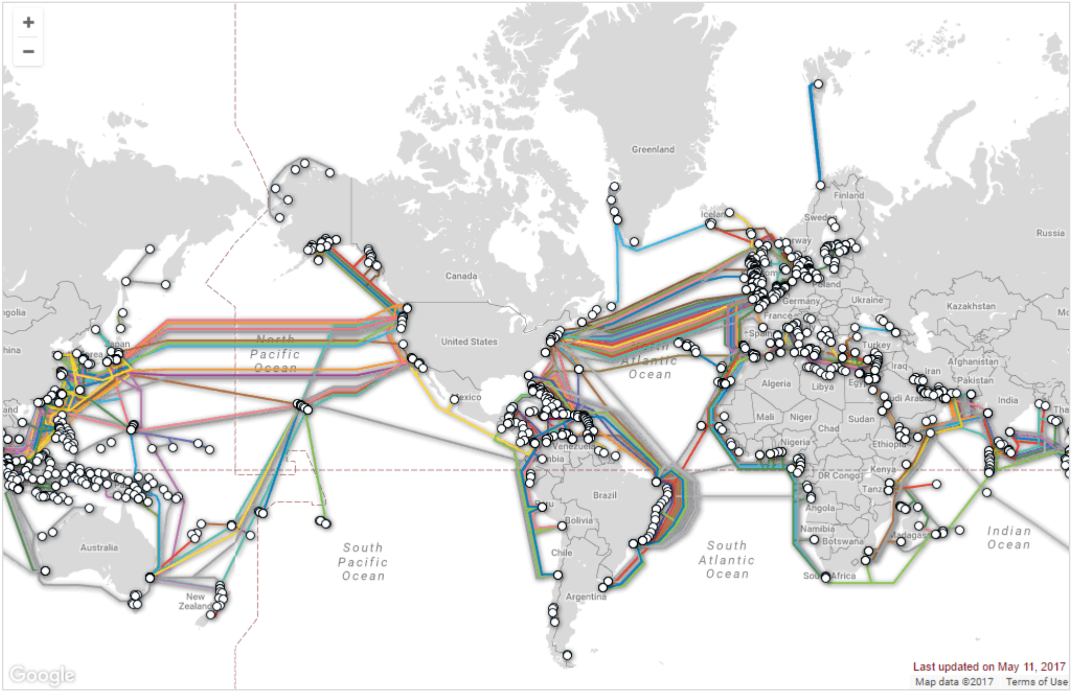

Figure 1: Submarine Cable Map [1]

External aggression is the largest threat to offshore cables, accounting for 72-86% of total faults, with the remainder being caused by component failure [2]. The majority of external aggression cases result from human activity, with fishing equipment and anchors being the two main contributors. Before 2007, it was thought that only 8% of cable faults were caused by anchors, however, the International Committee for the Protection of Cables (ICPC) introduced an Automatic Identification System (AIS) to diagnose cable problems, which showed that anchor damage is more prevalent than previously thought [3]. Revised figures indicate that anchors cause 30-40% of cable damage. Between 2007 and 2010, 53 telecoms faults were recorded around the UK, 19 of which were caused by anchors [4]. Therefore, it is clear that anchors pose a definite threat to offshore cables.

Damage can occur either by an anchor being deployed directly onto a cable or by an anchor being dragged across a cable as a ship tries to secure itself. It is also possible for ships to unknowingly drag their anchors long distances, which can be more serious as several cables in a row could be damaged.

A cable may fail instantly if it is completely severed by the anchor (Figure 2), alternatively the anchor could cause minor mechanical damage which is initially unnoticed but over time leads to deterioration of operation and subsequent failure of the cable. Large ships pose a more severe threat as their larger anchors go deeper in the soil and so are more likely to snag a cable. However, smaller ships have a higher likelihood of causing damage as they sometimes do not securely fasten their anchors due to frequent port calls, and hence, the anchor can become loose and deploy without the captain realising. Additionally, anchors can be dropped during an emergency, regardless of whether there are cables present below the ship.

Figure 2: Cable damage caused by an anchor [3]

Although efforts can be made to better secure anchors and check charts for the presence of cables, these measures are all susceptible to human error. The only way to ensure that cable damage is avoided completely is to protect all cables against the potential presence of anchors. Already a major global issue, the ICPC predicts that the incidence of cable damage is set to increase as cable numbers increase. Evidently, there is scope for further investigation and implementation of measures to protect cables from anchor damage.

1.2 Motivation for work

Offshore cables are deemed to be critical infrastructure in modern society, providing worldwide communication, data and power. When sending an email or booking a flight, there is a 95% chance that an offshore cable will be used, either to power the computer, connect to the internet or transfer data to another party [5]. Damage to cables therefore has significant impacts, both financially and socially.

Worldwide, many people and businesses are dependent on offshore cables. In 2008, two major cables that run under the Mediterranean Sea between Italy and Egypt were damaged, affecting an estimated 70% of the internet and telephone connections between Europe, Africa and Asia [6]. The event was likened to "severing a major artery" and caused problems for 75 million people [7]. The resulting damage to local businesses and society as a whole was devastating, with the total indirect cost of such a fault being immeasurable. Whilst there was speculation that the damage could have been caused by a ship unknowingly dragging its anchor, the actual cause of the fault was never confirmed. Nevertheless, this incident still demonstrates the severe impacts resulting from cable damage.

In addition to these consequences, the time and money required to repair a damaged cable are significant. The fault must first be located, after which ships travel to the site of the damage to raise the cable off the seabed, replace the damaged length and splice it back together before returning it to the seabed. Altogether, these tasks can take several weeks or months, costing an average of £1-2million per fault [8]. There are thus several major incentives to minimise the risk of anchor damage to offshore cables.

1.3 Project aims

This project aims to investigate the hazard posed to offshore cables in sand by ship anchors and use experimental results to advise measures to manage this risk. There are three key stages in the development of the project.

1. ***Investigate anchor interaction with the seabed***

   Consider the anchors in use globally and the typical seabed conditions that they encounter. Investigate the interaction between the anchor and the sand when the anchor is subjected to a horizontal force as though being pulled by a ship.

2. ***Quantify anchor behaviour***

   In addition to qualitative investigation of the behaviour, this project aims to quantify anchor behaviour in sand in order to build a useful model which can be applied to various anchors in various locations. Centrifuge modelling will be used to accurately model the scenario and provide representative data.

3. ***Suggest measures to reduce cable damage***

   Current cable protection methods should be considered and evaluated, with alternatives suggested if necessary. The ideal method would be one that ensures protection of all cables against anchor damage whilst minimising the cost of installation and maintenance.

2 Literature Review

2.1 Anchor operation

Anchors are large metal devices used to keep a ship in place when it wishes to remain stationary in a body of water, securing it to the seabed in order to resist currents and strong winds. There are many different types of anchor in operation across the world, the most common of which are shown in Figure 3.

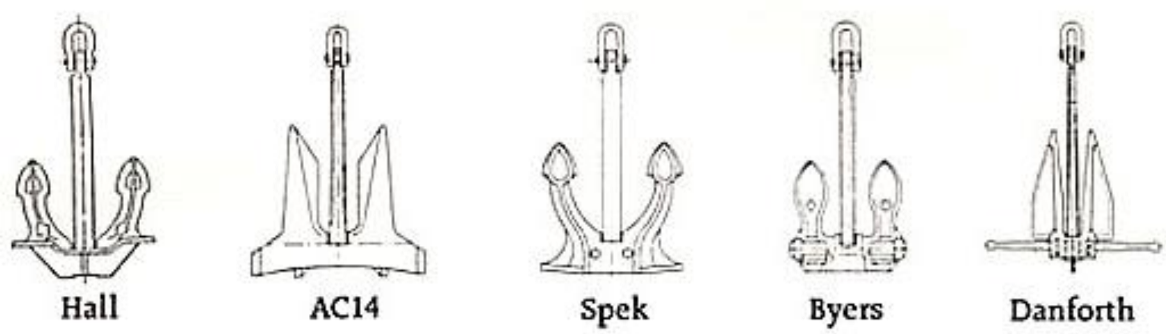

Figure 3: Common types of anchor [9]

The anchors shown each consist of a central column called a shank with two arms known as flukes which dig into the soil to secure the anchor. This type of anchor has an excellent holding power to weight ratio and hence is a popular choice for ships.

Anchors achieve their high holding power by first 'setting' into the seabed [10]. This is achieved by the ship dragging the anchor a short distance along the seabed after it has been deployed, in order for the flukes to enter into the soil and firmly secure themselves. The anchor is attached to the ship by a rode, the length of which is typically 5-10 times the expected depth of the water (Figure 4). The rode consists of a 2-12m length of chain close to the anchor, with the remainder being fibre rope. The self-weight of the chain causes the rode to form a catenary shape in the water such that the force on the anchor is horizontal. The chain also resists abrasion from any rocks on the seabed. The fibre rope is more lightweight so it is easier to store on the ship when the anchor is undeployed, however a rode made solely from rope would pull the anchor out of the soil rather than applying a horizontal force, due to its minimal self-weight.

The horizontal force on the anchor as a result of the rode catenary allows the anchor to use both its self-weight and the strength of the soil which it is set into. The horizontal resistance of the seabed is the main contributor to overall anchor resistance. To raise the anchor, the ship manoeuvres itself to be vertically above the anchor and the anchor is hauled back onto the ship, made easier by the elimination of the horizontal resistance.

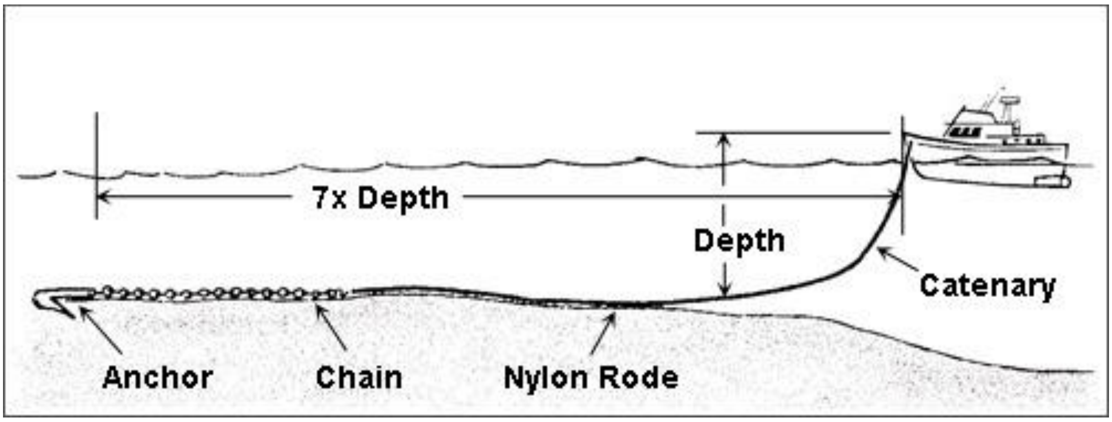

Figure 4: Diagram showing a deployed anchor [10]

Most cable damage is caused by anchors that are fully deployed and being dragged along the seabed [4], as this causes the flukes to penetrate the maximum distance into the seabed. Therefore, the investigation will focus on anchor behaviour under horizontal force in order to obtain the most relevant results.

2.2 Cable protection

At present, there are three main methods used to protect offshore cables:

1. **Armouring**

   Offshore cables are manufactured with a substantial outer casing, or ‘armour’ before they are laid on the seabed [11]. However, this method is only suitable for providing protection against fishing and trawling equipment and is not sufficient to protect against forces from even the smallest anchors.

2. **Rock installation or mattresses**

   Offshore cables are shielded from external threats by laying large rocks along their length or by covering them in a flexible layer of concrete blocks known as a mattress. These methods offer effective protection against anchor damage but are expensive and often not carried out in deep water as accurate placement of the rocks is challenging. As a result, this method is only feasible close to the shore [12].

3. **Burial**

   Offshore cables are buried beneath the seabed, typically up to depths of 3m to protect them from ship anchors. Burial is effective, straightforward to implement and economical, though optimising burial depths can save substantial sums of money [13].

This project will focus on cable burial, as the above information has identified it to be the most common and cost-effective form of cable protection. Since the introduction and widespread adoption of cable burial in the 1980s, a dramatic drop in the number of cable faults has been observed (Figure 5). The spike in faults/1000km of fibre optic cable seen in 1989 does not fit this pattern of fault reduction, however that was soon after the introduction of fibre optic cables so there would have been a small number in existence, meaning that a few faults would give a large number of faults/1000km. Overall, this graph demonstrates the efficacy of cable burial in reducing cable faults.

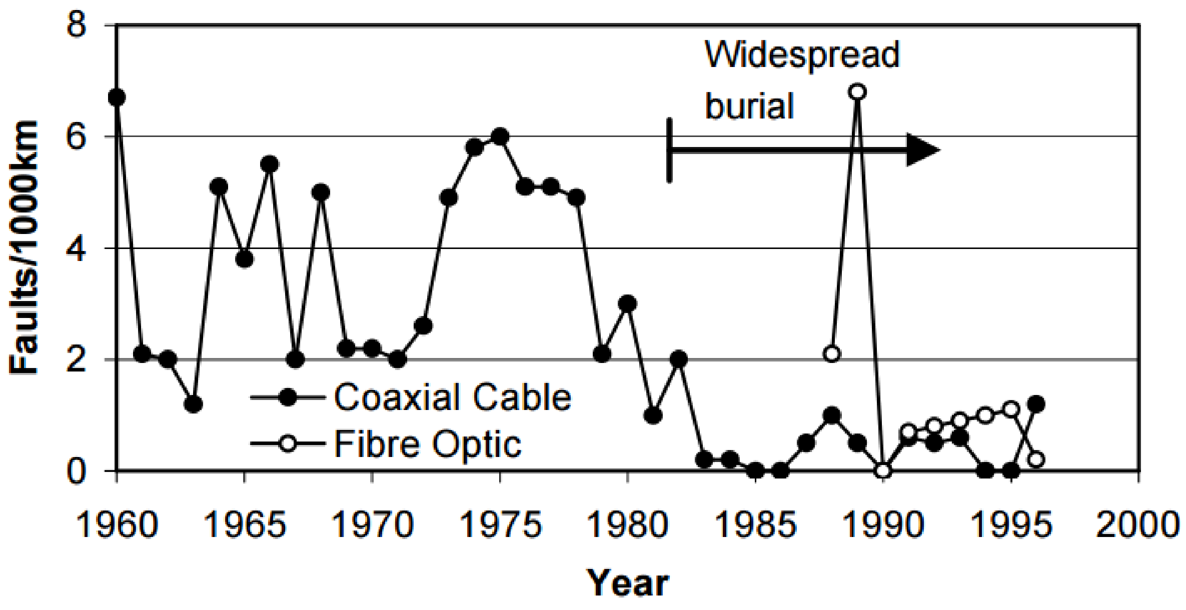

Figure 5: Graph of cable fault occurrence since the introduction of cable burial [13]

There are several ways in which cables can be buried, with the chosen method depending on the water depth and the type of seabed [5].

1. **Ploughs**

   A plough is used to form a trench in the seabed which the cable is laid into (Figure 6). The plough is pulled by a ship and the cable is fed from the ship through the plough and into the trench, with the tension carefully controlled so that the cable is not damaged but that slack is minimised to reduce cable wastage. Displacement ploughs form large V-shaped trenches up to 5m wide and non-displacement ploughs cut small trenches between 0.3 and 1m wide. The trench is left open after ploughing, but sedimentation leads to the cable being covered over time without the need for machinery.

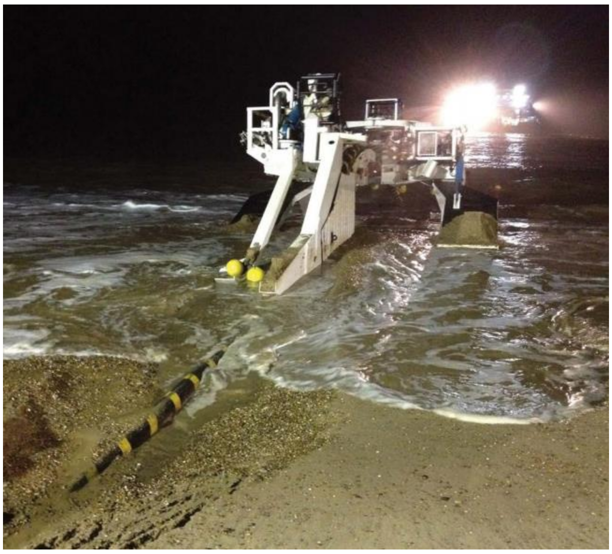

Figure 6: Cable plough beginning operation at the shore [4]

2. **Water jetting**

   A concentrated jet of water creates a slit in the seabed which the cable is then inserted into. This is typically used for sandy seabeds and can be done with both new and existing cables, which is beneficial for protecting old cables that are at risk. It is performed with a device similar to a plough, dragged behind a ship.

3. **ROVs**

   Remotely Operated Vehicles (ROVs) cut away the soil on the seabed and create a trench for the cable. The ROV is an unmanned device which is attached to an above ship via a control cable. These are used in delicate areas close to other cables or pipelines as they can be more carefully controlled than ploughs.

Displacement methods remove soil from the seabed meaning that the horizontal stresses in the surrounding soil will decrease. In sand, this will lead to an instant reduction in effective stresses whereas in clay it will take time for the excess pore pressure to dissipate and the effective stress to decrease. Non-displacement methods shear the soil, leading to dilation of the soil around the cut and therefore a slight increase in effective strength. Overall, any changes in strength of the soil are neglected during consideration of anchor penetration as the changes are minor and limited to a small area compared to the size of the anchor.

2.3 Existing guidelines

Figure 7 shows the only available chart which provides a guideline for cable burial depth.

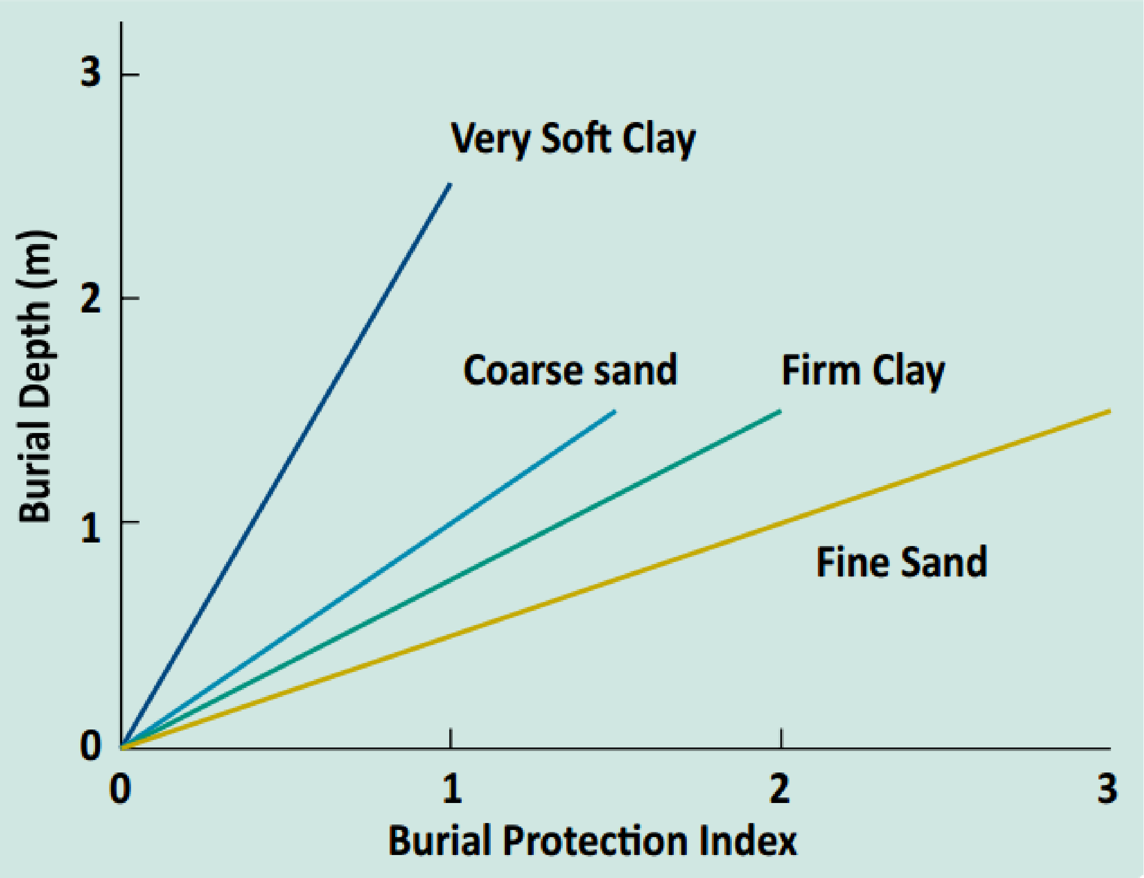

Figure 7: Cable and Wireless Marine guideline for cable burial depth [4]

This chart was produced by Cable and Wireless Marine (CWM) in 1997. Prior to this, the nominal burial depth was 0.6m but it was found that this was insufficient to protect cables from anchors, only fishing gear. The chart was therefore developed from the CWM database of ploughing and survey operations. In the original paper, this guideline is introduced as only a rough concept rather than a definitive model [14]. However, with no updated charts available, this is the best existing guideline for cable burial depths.

This chart has several limitations:

Firstly, there is no record of the methodology used to measure penetration depths, or the amount of data used to create the chart. It was also produced from records of ploughing operations, which are likely to give different penetration depths to anchors. However, this chart is still in use, suggesting that the burial depths given are generally conservative, otherwise it would have been revised or rejected. Using conservative burial depths does minimise cable damage, but could lead to unnecessarily high burial costs. Cable failures still occur, however, so in some circumstances the prescribed burial depths may be insufficient.

The second limitation is the way in which the seabed is classified. Grouping soils by type is ambiguous as it relies on human judgement to classify the seabed. Using a quantitative measure such as strength or particle size would be more useful in this situation. In addition, the differentiation between fine and coarse sands is seemingly unwarranted, given that when compared to the enormity of an anchor, the difference in grain size between coarse and fine sand would be expected to make negligible difference to anchor penetration depths.

The final limitation is the metric of 'Burial Protection Index'. This is an arbitrary measure which is unhelpful when deciding on the desired burial depth, due to the ambiguous definition of each BPI value. For example, BPI 3 is said to protect against 'anchors of all but the largest ships' which lacks clarity. A more useful metric would be the size of anchor against which the cable is protected, or the percentage certainty that the cable will be safe.

Overall, while the chart is an improvement on the prior situation, a more scientific approach to the problem could generate guidance which is more directly linked to the appropriate parameters and therefore more suitable.

2.4 Previous work

There has been minimal previous work carried out to study anchor penetration depths, leading to the problems seen with the existing guidelines. Three different sources have been found which attempt to quantify anchor penetration.

2.4.1 TenneT tests

In May 2013, testing was done by TenneT, a company responsible for connecting offshore windfarms to the grid in the German sector of the North Sea [15]. The existing regulation was to bury cables at 3m within shipping lanes and at 1.5m otherwise, however there were concerns that this was overly conservative and that money could be saved by reducing burial depths. A 12-tonne Halls anchor and an 8-tonne AC-14 anchor were tested, with each being dragged three times at three different test sites in the North Sea.

Penetration depths were determined using Side Scan Sonar (SSS), Sediment Echosounder Surveying (SES) and visual inspection using ROVs. Figure 8 shows the surveys of the seabed that were completed before and after each pull. Boat 1 completed SSS surveys of the entire pull area and then Boat 2 completed SES to measure the specific depth at certain points along the anchor tracks. A clear limitation of this method is that some sand could collapse back into the anchor tracks after the anchor has been pulled through, leading to an underestimate of penetration depth.

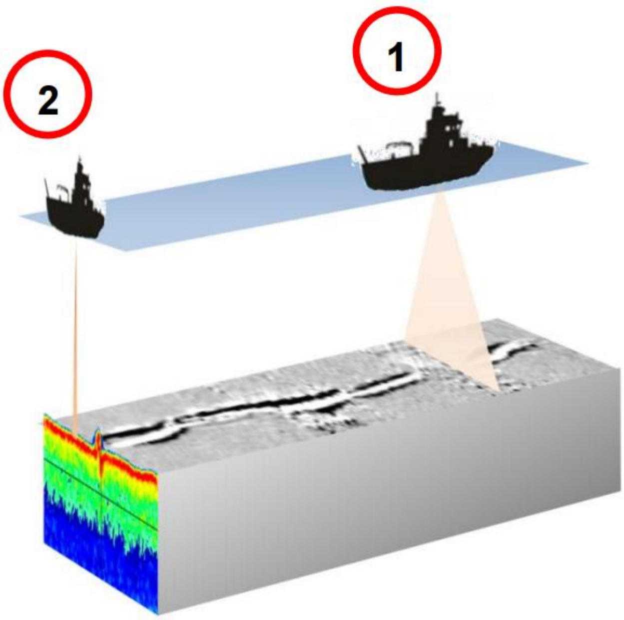

Figure 8: Combined SSS and SES approach to tracking anchor penetration depths [15]

It was found that the Halls and AC-14 anchors had maximum penetration depths of 0.88m and 0.67m respectively which were achieved in the loosest sand. As a result of this research, burial depth guidelines were reduced to 1.5m everywhere in the region from 2014, resulting in huge savings in cable burial costs. These tests were not extensive, however, so are unreliable and only valid for the areas in which the tests were performed.

2.4.2 IEEE mathematical model

A paper published for the Institute of Electrical and Electronic Engineers (IEEE) in Japan in 1992 gives penetration depths of anchors in different soils, based on anchor weight (Figure 9).

The results were gained from the development of a simple mathematical model which calculates the expected failure rate of a length of cable by considering external mechanical hazards. By specifying the desired failure rate and imposing variations on critical parameters, it was possible to find a safe limit for parameter values such as cable burial depth. The parameter of ‘external mechanical protection’ was considered too complex to model and so instead a new parameter was defined, ‘equivalent protection’ which combined mechanical protection and seabed properties to give five distinct levels. For example, the first level of equivalent protection is burying a cable 0.5m deep in mud or laying it on the surface for sand. The final results gained from the model were justified by reverse application on existing data.

Ship Weight(tons)	Anchor Weight(tons)	Anchor Head(m)	Depth of penetration of anchor(m)			
			Mud	Sand	Gravel	Rock
1,000	1.0	1.0	~ 1.0	~ 0.5	~ 0.5	-
5,000	2.8	1.6	~ 2.0	~ 1.0	~ 0.8	-
15,000	4.8	2.0	~ 3.0	~ 1.5	~ 1.0	-
50,000	8.2	2.4	~ 4.0	~ 2.0	~ 1.2	-
100,000	12.4	2.6	~ 5.0	~ 2.5	~ 1.4	-

Figure 9: Depth of ship anchor penetration, estimated from numerical modelling [16]

The paper highlights the drawbacks of this method, explaining that some of the parameters were too complex to be modelled perfectly, hence the results are only rough estimates. In addition, the existing data used was exclusively from cable failures around Japan, meaning that it may not be applicable worldwide owing to variations in both geotechnical parameters and maritime traffic patterns.

2.4.3 NCEL guide

The Naval Civil Engineering Laboratory (NCEL) published a paper in 1984 that advised on the maximum expected penetration depths of anchors (Figure 10). The normalised fluke tip penetration is seen to be 1 for all anchors in sands or stiff clays, indicating that the penetration depth is equal to the length of the anchor fluke. The paper does not specify the source of the data, and it is possible that safety factors have been applied. However, it is still an additional prediction for anchor penetration depth, so will be useful in the analysis stage of the project.

Anchor Type	Normalized Fluke Tip Penetration, (d_{tm}/L) (fluke lengths)	
	Sands/Stiff Clays	Mud (e.g., Soft Silts and Clays)
Stockless[a]	1	3
Moorfast Offdrill II	1	4
Stato Stevfix[a] Flipper Delta Boss Danforth LWT[a] G.S. (type 2)	1	4-1/2
Bruce Twin Shank Stevmud	1	5-1/2
Hook	1	6

Figure 10: NCEL normalised fluke tip penetrations [17]

2.5 Recent case histories

There are two recent examples of anchor damage to offshore cables which demonstrate the importance of continuing investigation of this issue.

The first occurred during Storm Angus in November 2016 when a ship deployed its anchor in an emergency and cut four of the eight cables in the crucial HVDC interconnector power link between Folkestone and Calais [18]. Consequently, the 2-gigawatt connection ran at half its capacity until February, resulting in a rise in UK electricity prices over winter as the National Grid had to make use of back-up coal-fired power stations. This incident raises concerns over the protection of these vital power links and shows the significance of having accurate information about appropriate cable burial depths.

The second event occurred on 28th November 2016. This involved an anchor being dragged across the seabed, damaging three of the four internet cables to Jersey [19]. The first cable was severed at 4pm and the third at 9pm, leaving just one cable to provide the island with internet, resulting in slower broadband and some residents losing internet completely. Repair of the cables was a complex job, with ships having to travel in bad weather to raise the cables and splice them back together, taking three weeks overall. Reportedly, there were clear warnings in place not to deploy anchors in the area where this damage occurred, however this event highlights the need to physically protect the cables as warnings alone are not sufficient.

3 Theory and Design of Experiment

3.1 Centrifuge modelling

Centrifuge modelling is an experimental method used to simulate large scale problems with smaller physical models. The aim is to induce stresses in the model which are equal to those that would be experienced in the real-life situation being investigated, known as the prototype. The centrifuge is rotated in order to apply an inertial radial acceleration field which affects the model like a strong gravitational acceleration field, leading to identical stresses in the model and prototype. Centrifuge modelling is used as soils have non-linear mechanical properties that are dependent on the stresses present. It is not valid to use results from tests done at lower stresses and so centrifuge modelling offers a more accurate representation of soil behaviour [20]. In this project, the Schofield Centre minidrum centrifuge will be used (Figure 11).

Figure 11: Minidrum centrifuge

3.1.1 Scaling laws

To deduce the behaviour of the field problem, scaling laws relate the properties of the model (m) to that of the prototype (p) based on the rotational speed of the centrifuge, as follows:

$$a_m = Na_p \qquad L_m = \frac{L_p}{N} \qquad M_m = \frac{M_p}{N^3}$$

Where a is acceleration, L is length, M is mass and N is the multiplier of normal gravitational acceleration, g, that is experienced by the model.

For example, a 60-gram model anchor in 10cm of sand spun at 20g represents a prototype anchor of 480kg in 2m of sand. It is appropriate to use the 1m diameter minidrum centrifuge for testing, as this will allow modelling of sand depths of up to 8m and drag distances of up to 16m.

3.1.2 Limitations of centrifuge modelling

During centrifuge testing, ideally the only force acting on the model is the gravitational acceleration exerted by the rotation of the drum. However, there are limitations associated with centrifuge modelling which mean that this is not always the case.

Soil particle size

As seen from the scaling laws in Section 3.1.1, the centrifuge scales up the size of all components of the model, including the sand particles used. Therefore, the use of fine sand at 80g could be assumed to represent a gravel. For exact modelling of the prototype, smaller particles would be needed that still exhibit the behaviour of sand. However, this is not possible. Whilst clay particles would be the correct size, clay has a different stress-strain characteristic to sand and so would not give accurate results for sand behaviour.

Comparing the size of the sand particles to the size of the model anchor shows that there is a factor of 4,000 difference. This is acceptably large such that the sand in the model can be assumed to act as a continuum and therefore results are still valid despite the scaling laws.

Variation of acceleration within the model

The gravitational acceleration experienced at any point in the centrifuge varies linearly with radial distance from the centre. The minidrum has a radius of 0.5m and the height of the model is 0.1m, leading to a 20% difference in the gravitational acceleration across the model, with the top of the model experiencing a lower acceleration than the bottom.

Work by Taylor [20] has found that there is an exact correspondence in stress between the model and prototype at two-thirds model depth, i.e. the depth h_i in Figure 12 is equal to 2H/3. The effective centrifuge radius should therefore be taken as the distance from the centre of rotation to one-third of the model depth, the location of the maximum under-stress. Hence, when calculating the speed for each centrifuge test, the required gravitational acceleration will be calculated at one-third of the initial depth of the anchor.

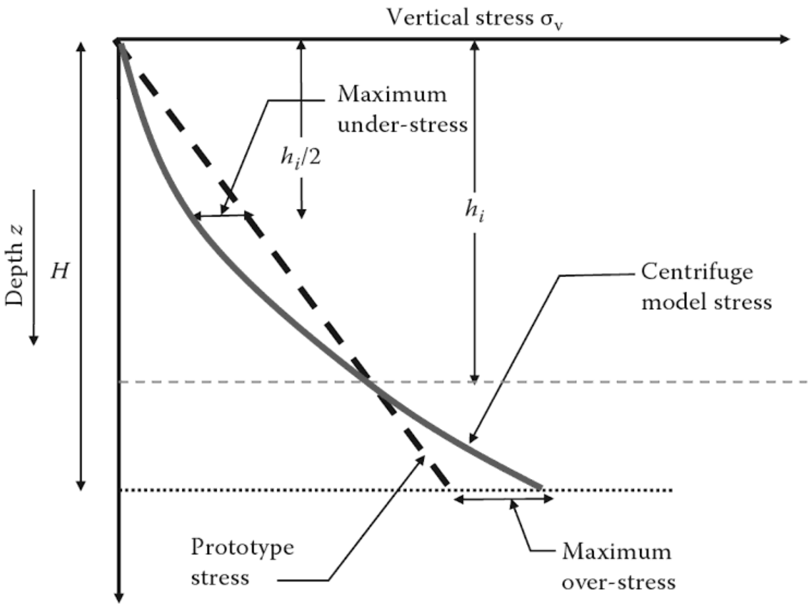

Figure 12: Graph of stress variation in centrifuge model [21]

The error due to variation of acceleration across the entire model can be calculated as below:

$$\varepsilon_{variation} = \frac{H}{6R_e} \text{ x } 100 = \frac{95}{6\left(405 + 95 \text{ x } \frac{2}{3}\right)} \text{ x } 100 = 3.4\%$$

Whilst 3.4% is not an insignificant error, the anchor will be positioned close to the effective depth R_e and is not expected to deviate far from this position meaning that, in reality, this error will be lower. As a result, it can be concluded that this error is acceptable.

Coriolis acceleration

The radial movement of the anchor relative to the rotating acceleration field will lead to the model anchor experiencing Coriolis acceleration, which could affect its behaviour. The error due to Coriolis acceleration is the ratio between the inertial acceleration and the Coriolis acceleration:

$$\varepsilon_{coriolis} = \frac{a_{coriolis}}{a_{inertial}} = \frac{2v\dot{\theta}}{V\dot{\theta}} \text{ x } 100 = \frac{2v}{V} \text{ x } 100$$

where v is the velocity of the anchor and V is the linear velocity of the model. In this case, the anchor is being pulled at a speed of v = 0.33mm/second and the surface of the model is moving at V = 8500mm/second. Consequently, the error due to Coriolis acceleration is 0.008% which is negligible.

Earth's gravitational pull

The centrifuge exerts a force on the model which is horizontal, yet the earth is still exerting a 1g pull vertically downwards. However, this force is always at least 20 times lower than the horizontal acceleration experienced by the model, as the minimum test speed is 20g, so it is neglected. It is possible that the anchor will move downwards slightly in its path but this movement would be too small to affect the results for final penetration depth.

Overall, the limitations discussed have been proven to be negligible for the centrifuge modelling to be completed in this project. Therefore, the results from the tests carried out can be taken as accurate and will not need any adjustment.

3.2 Anchor models

The Halls and AC-14 anchors were chosen to be modelled for experimentation. These were identified as two common anchors known to have caused cable damage, with an AC-14 anchor being responsible for the damage to Jersey's cables in November 2016 (Figure 14). Models of these anchors were drawn in SolidWorks, using realistic proportions to ensure that the models would behave representatively (Figure 13a). As well as 3D models, plane strains versions were printed to allow for testing against a glass panel to observe behaviour more clearly. The anchors are at 1:20 and 1:80 scale of the smallest and largest typical anchor sizes respectively [22].

The drawings were sent to be printed in stainless-steel, so that they would mimic the properties of real anchors, but in the meantime plastic versions were printed for preliminary testing. The plastic anchors were lightweight and so were reprinted hollow and filled with lead shot (Figure 13b) to increase their mass and therefore make them more useful for preliminary tests.

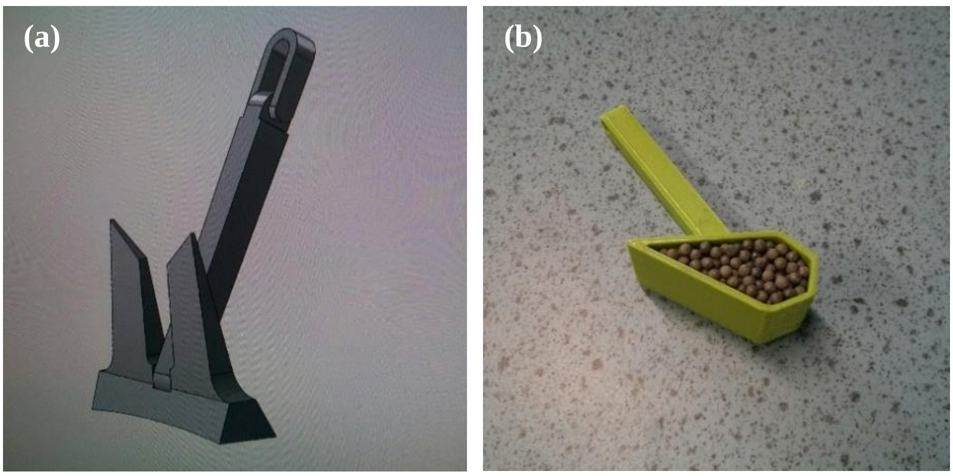

Figure 13: (a) AC-14 anchor modelled in SolidWorks (b) Plastic plane strain Halls anchor filled with lead shot

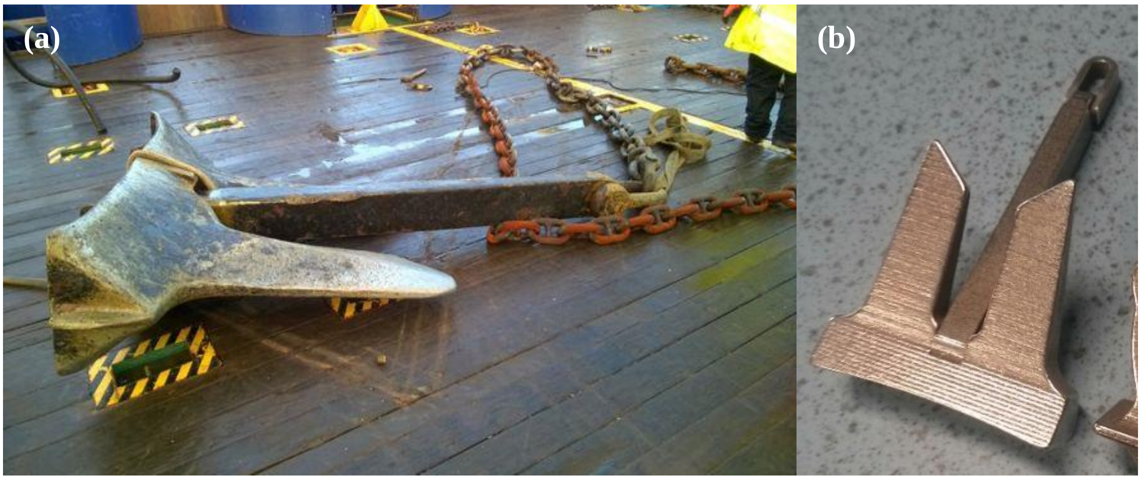

Figure 14: (a) AC-14 anchor that damaged Jersey's cables in November 2016 [19]
(b) Model AC-14 anchor, 3D-printed in stainless-steel

3.3 Experimental setup

Based on the theory and aims of the project, an experimental setup has been designed which will model an anchor being pulled behind a ship in sand. The tests will take place inside the 1m diameter minidrum centrifuge, located at the Schofield Centre, such that the stresses in the model will match the prototype. The experiment will aim to quantify the depth of anchor penetration in sand whilst investigating influencing factors by varying the following parameters: type and size of anchor, initial depth, sand particle size and density.

The components of the test rig are described below and shown in Figure 15:

1. **Centrifuge body:** The model is placed inside a 1m diameter drum which is then rotated in the horizontal plane to apply a radial acceleration field to the model, allowing it to simulate a gravitational pull of up to 100g.
2. **Model box:** A metal box contains the experimental model and is placed inside the centrifuge drum and secured in place. The box makes up one sixth of the drum area, meaning that the distance the anchor can be dragged is limited.
3. **Counterweight box:** A counterweight is required on the opposite side of the drum so that the centrifuge is in balance when running. Therefore, the model must be weighed and the counterweight box filled with the required weights to match it, accounting for the weight of the water which will be added during operation.
4. **Water layer:** Water is added to the model via a tap once the centrifuge is running. This ensures that there is a layer of water above the sand such that the sand is completely saturated and the experiment accurately models subsea conditions.

5. **Actuator:** A servo motor sits at the centre of the drum and powers a linear actuator which is attached to the anchor via a pulley, allowing the anchor to be pulled horizontally across the model, as though being dragged along the seabed.
6. **Anchor rode:** The anchor rode consists of chain close to the anchor and then wire which would be attached to the ship. This reflects the typical composition of anchor rode as described in Section 2.1.
7. **Anchor:** Two anchor types are to be tested, the Halls and AC-14 anchors. The anchors are 3D-printed in stainless-steel, as described in Section 3.2 (Figure 19).

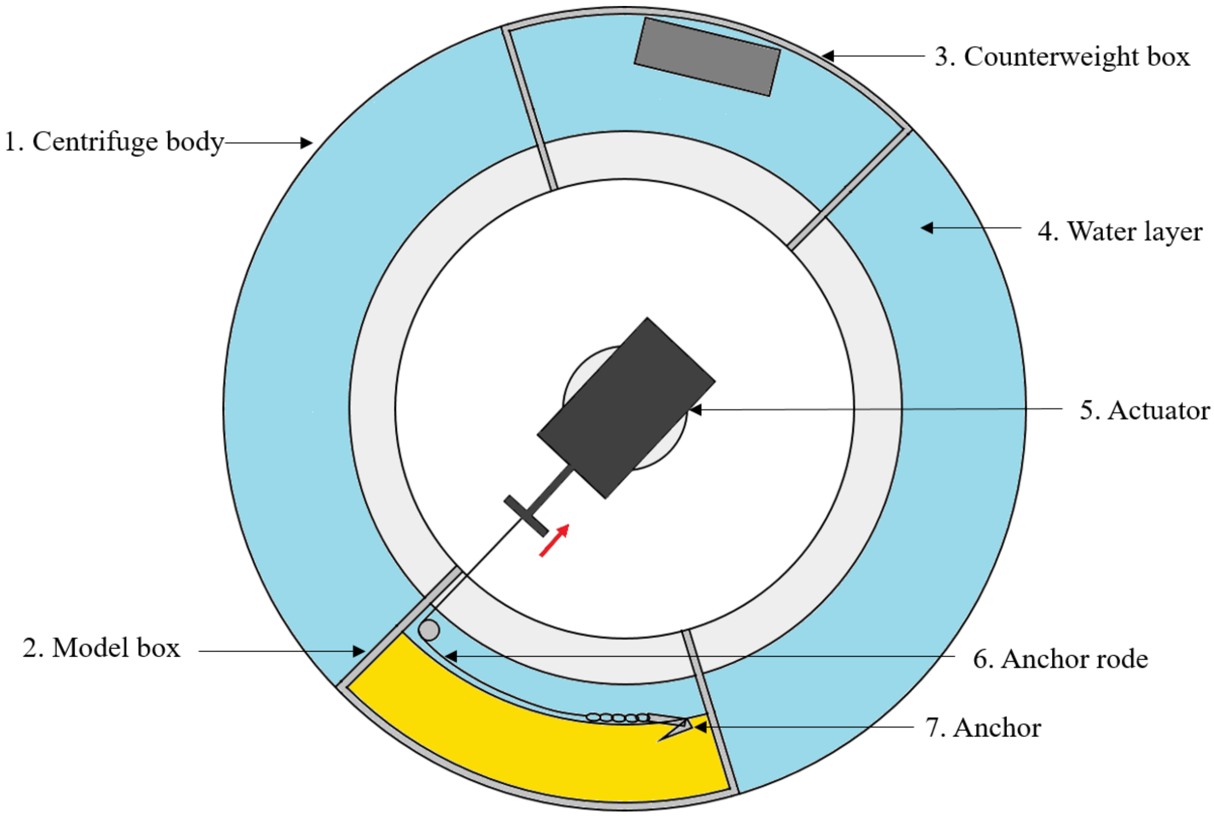

Figure 15: Plan view of the experimental setup

3.4 Experimental method

The following procedure was carried out to complete a full experiment:

1. The model was constructed by pouring sand at a constant rate into the model box and positioning the anchor at the required depth at the far end of the box.
2. The model was placed in a tray of water and left for an hour to saturate via capillary action (Figure 16).

3. Once saturated, the model was drained for 30 minutes to ensure that the sand was under suction and thus would remain in place when tilted to the horizontal position in the centrifuge.
4. The counterweight box and the model box were placed into the centrifuge on opposite sides of the drum and secured by tightening the bolts on the side of the box. The end of the anchor rode was attached to the actuator (Figure 17).
5. The safety screen was bolted into place.
6. The minidrum was tilted to the horizontal position (Figure 18), a check was made to ensure the model was still intact and then the centrifuge was sped up to 10g to fill with water.
7. The minidrum was sped up to the test speed and the actuator switched on to drag the anchor through the sand. This was observed using a strobe light to check for problems and indicate when the actuator should be stopped.
8. At the end of the drag, the actuator was switched off and the water drained from the drum at 10g.
9. The minidrum was stopped, tilted back to the vertical position and the model removed from the drum.
10. The anchor was carefully excavated and penetration depth recorded.

Figure 16: Model box during saturation

Figure 17: Model box secured in place in the centrifuge drum

Figure 18: Centrifuge being tilted to the horizontal position for testing

Figure 19: 3D-printed stainless-steel anchor models

3.5 Experimental accuracy

In setting up the model, the depth of the sand layer was measured with a ruler, and is therefore accurate to +/- 0.5mm. The other dimensions of the box were also measured to +/- 0.5mm meaning that the volume of sand is accurate to +/- 0.87mm^2. The weight of the box was measured using a balance which is accurate to +/- 0.0005kg. Combining the above, the relative density of the sand is accurate to 0.001 which is negligible.

During testing, the centrifuge speed is accurate to +/- 0.5rpm, meaning that the rotational acceleration field imposed on the model is accurate to +/- 0.05g. This gives a maximum error in the prototype penetration depths of 0.25% which is acceptably small.

To measure the penetration depth of the anchor, sand was carefully excavated and photos taken of the anchor embedded in the sand. These were analysed by obtaining the angle between the sand surface and the anchor shank and using trigonometry to determine the final depth, as the anchor dimensions are known precisely to 0.1mm. The measured angle is accurate to +/- 0.5^o, meaning that the depth is accurate to a minimum of +/- 0.48mm. Therefore, the prototype depths calculated are accurate to +/- 0.0096m at 20g and +/- 0.038m at 80g. When combined with the error from the variation in centrifuge speed, this gives an overall maximum depth error of 1.75% which is acceptable.

4 Results and Discussion

4.1 Preliminary testing

Due to the minidrum centrifuge being under repair during Michaelmas term, preliminary tests were completed in a sand tank at 1g to gain an initial understanding of anchor behaviour in sand (Figure 20). At this point, the stainless-steel anchors had not arrived and so the lead-filled plastic anchors were used for testing - specifically the plane strain versions as they could be placed against the glass side of the tank, allowing clear observation of the behaviour.

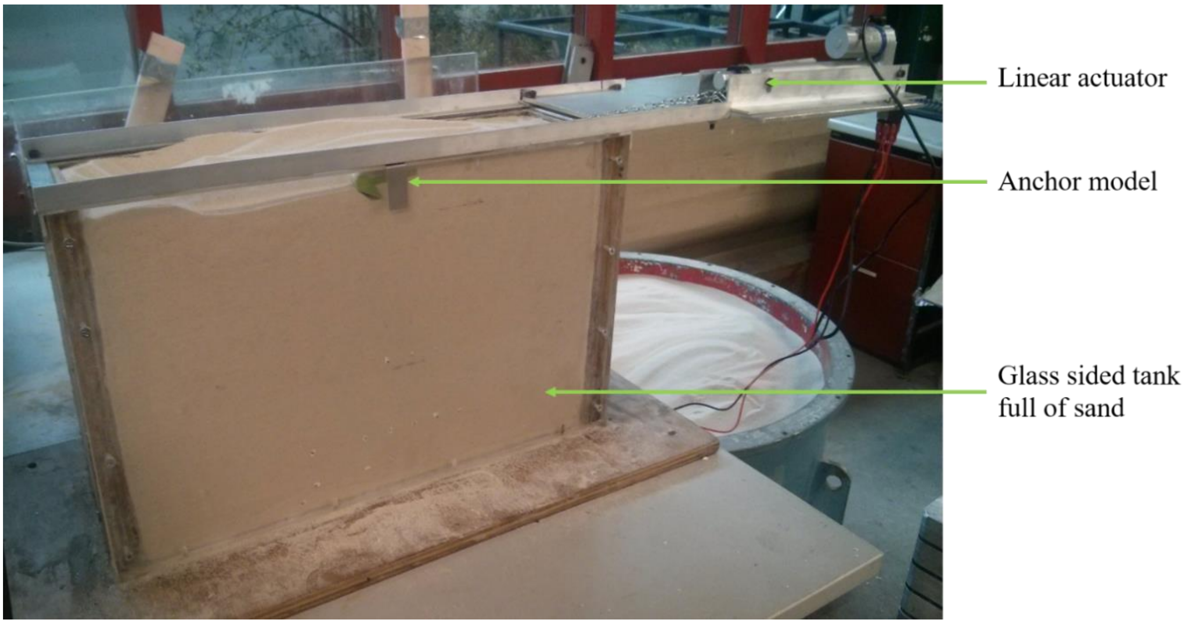

Figure 20: Preliminary test setup

The preliminary tests involved dragging the anchor across the tank via a chain attached to a linear actuator at one end of the tank. The anchor was positioned at varying initial depths and dragged 200mm across the sand tank before the final penetration depth was recorded. The penetration depth is defined as the vertical distance from the surface of the sand to the deepest point of penetration of the anchor, usually the tip of the fluke.

When the Halls anchor was placed on the surface of the sand, it initially penetrated downwards into the sand before moving horizontally across the tank, seen from the sand profile highlighted in Figure 21. This suggests that the anchor moves towards an equilibrium position and then remains at this depth after reaching equilibrium. If this equilibrium position could be quantified, it could be used to anticipate the penetration depths of varying sizes of anchor.

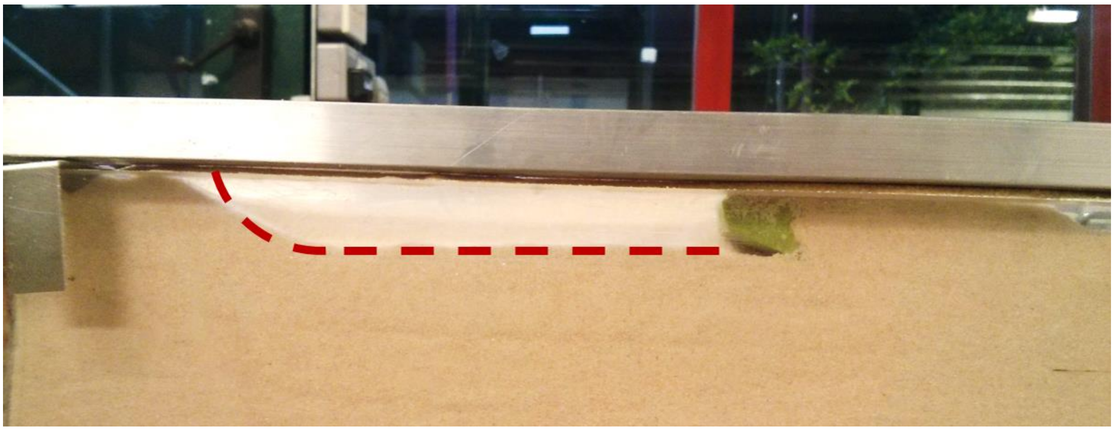

Figure 21: Sand profile after Halls plane strain anchor dragged through sand

There was a concern that the plastic anchors were still too lightweight for this test, and that the chain was too large in proportion to the anchor. Therefore, it is possible that the anchor was not providing sufficient downwards force or that the chain was providing resistance against the dragging force, rising up out of the sand and pulling the anchor with it. To consider the effect of these issues, the tests were repeated with the stainless-steel anchors once they had arrived, initially with chain and then with wire which was expected to lead to lower resistance.

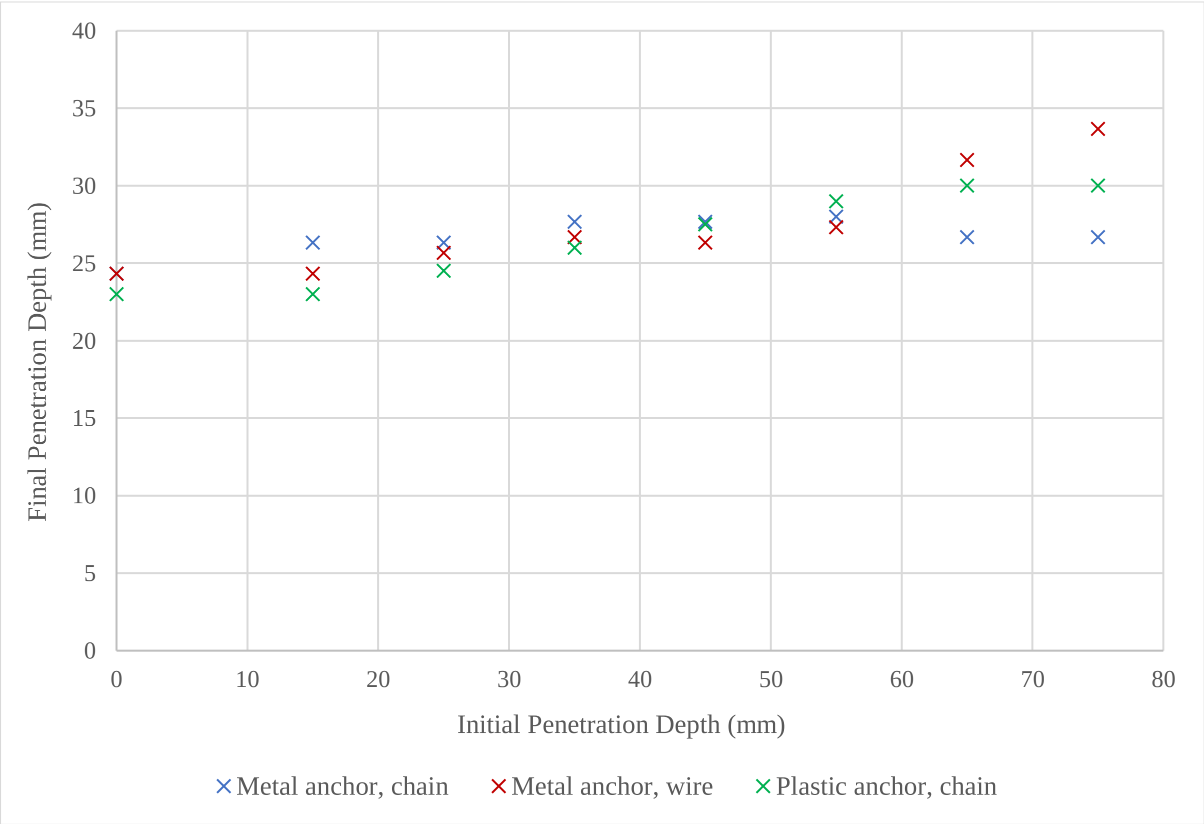

Figure 22: Graph of Halls anchor final penetration depth with varying initial depth in dry sand at 1g, no trendlines have been drawn as there is no clear trend to the data

Figure 22 shows that all results for final penetration depth lie between 23 and 34mm despite the greater range of initial depths. When initial depth is less than 55mm, all three test setups display similar final depth results. For initial depths greater than 55mm, the metal anchor dragged by wire remains deeper, as does the plastic anchor though to a lesser extent. The metal anchor dragged by the chain displays a more constant final depth across all initial depths.

This difference is expected to be due to the limited drag length available in the tank, which means that the equilibrium position may not always be reached. Each anchor configuration has a different resistance, with a lower resistance setup taking longer to reach equilibrium, due to the lower stress imbalance causing slower movement through the sand. In this case, the metal anchor dragged by wire has the lowest resistance, suggesting that it did not always reach equilibrium and hence gave the greatest final depth for high initial depth. If a longer tank were used, it is expected that all three anchor configurations would reach a consistent equilibrium position.

Despite this variation, the graph clearly shows that anchors at the surface move downwards and that anchors buried deep move upwards, indicating that there is a depth where an anchor will cease to move vertically. Therefore, it can be hypothesised that anchors have an equilibrium depth that they will move towards, regardless of initial depth in sand.

The final orientation of the anchor was with the shank horizontal, close to the surface of the sand. This was consistent across all tests where the initial depth was less than 55mm. For the remaining tests, the shank was positioned pointing slightly upwards rather than completely horizontal. As discussed above, this may be due to the anchor not reaching equilibrium. If the equilibrium position always consists of the anchor shank being horizontal at the surface, penetration depth could be easily calculated from the anchor geometry.

These tests have significant limitations, the most obvious being that the sand is dry rather than saturated and that the stresses are lower than those present at the seabed. In addition, the anchors may be too lightweight to penetrate any deeper into the sand. Therefore, the results are not taken to accurately represent the behaviour of real anchors being pulled behind ships. However, the tests are still useful for observing the interaction between the anchor and the sand and suggest the idea of an equilibrium position, which can be investigated further in the centrifuge tests.

4.2 Finite element analysis

In addition to the preliminary testing, Finite Element Analysis (FEA) was used to provide analysis of the problem. Numerical modelling is a powerful tool to use alongside experimental work, as it can be used to compare theory with experimental findings. The programme ABAQUS was used to simulate a 2D analogue of the Halls anchor being dragged across the sand box, as was done in the preliminary testing (Section 4.1).

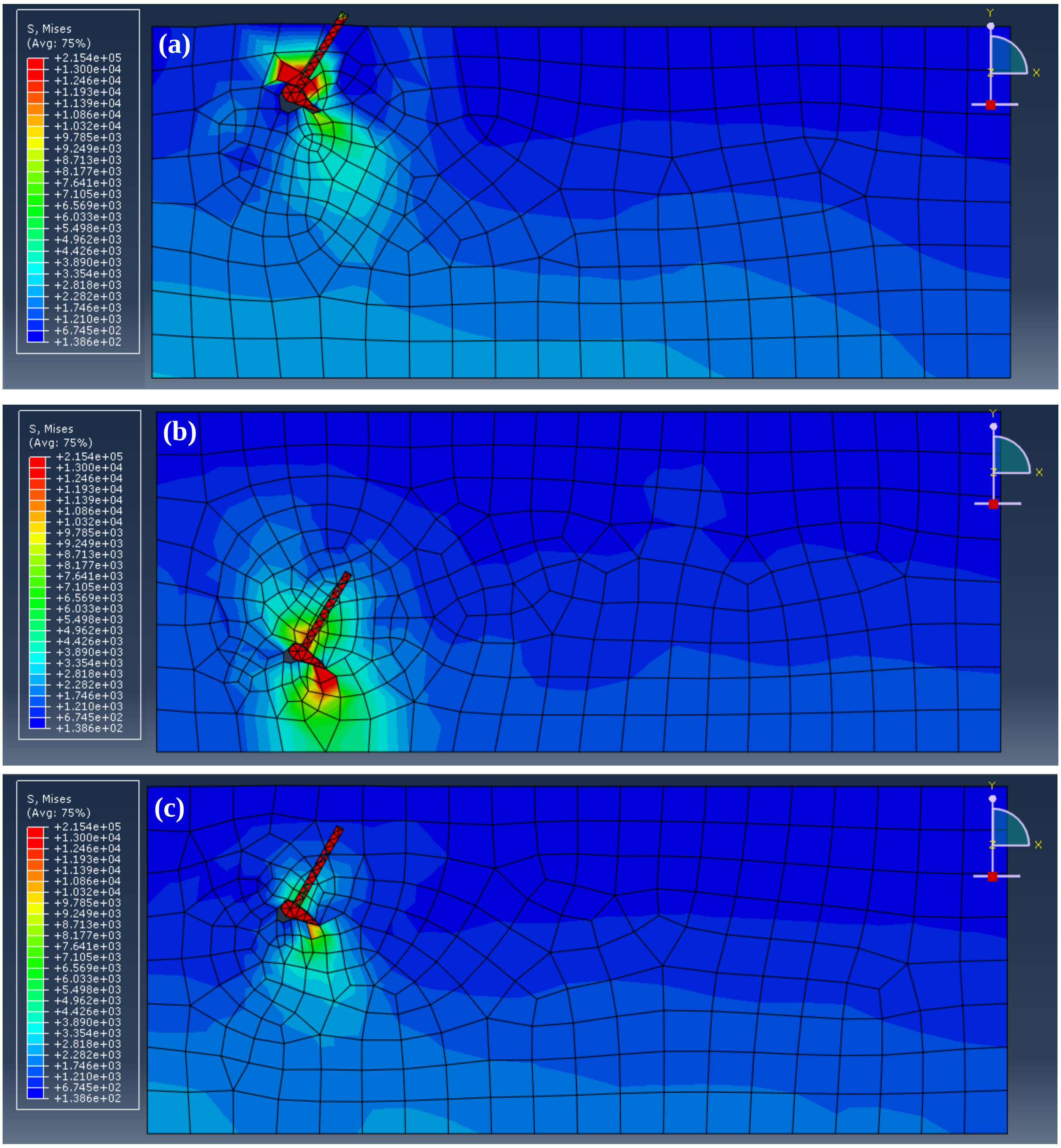

Figure 23: FEA simulation showing the stresses in the sand around the Halls anchor when (a) anchor is buried deep in the sand (b) anchor is near the surface of the sand (c) anchor is close to equilibrium

Figure 23 shows the FEA results for a Halls anchor in sand, with a horizontal force applied to the top of the shank. Regions of high stress are indicated by areas with red and yellow shading, as specified by the key on the left-hand side. In Figure 23a, where the anchor is closer to the surface, the stresses are greatest above the fluke, either side of the shank. The higher stress above the anchor will lead to the anchor moving downwards, seeking a position where the stress below is equal to the stress above. In Figure 23b, where the anchor is buried deep in the sand, the stresses are greatest under the tip of the fluke and above the junction between the base of the shank and the rear of the fluke. The higher stress below the anchor shows that the anchor will move upwards, again to seek a position with equal stresses. This agrees with the preliminary testing by indicating that the anchor moves towards an equilibrium position within the sand, irrespective of initial depth.

To test this, a simulation was run with the anchor positioned between the two depths from (a) and (b) such that it was close to the expected equilibrium position. This is shown in Figure 23c, where it can be seen that the stresses above and below the anchor are close to equal and lower than the stresses in the other two images, show by the absence of red shading. This confirms that the equilibrium position in the sand results in a lower stress imbalance and thus no vertical movement of the anchor.

The location of the point where the stresses are equal has several influencing factors, including sand density and anchor size. The effective stresses in the sand increase with depth and are influenced by the unit weight of the sand, itself influenced by the density. Denser sand has a higher unit weight and a higher peak friction angle, making it more resistant to penetration. It is anticipated that looser sand will lead to a deeper equilibrium position as the effective stresses and the peak friction angle of the sand will be lower and so the anchor will reach a greater depth before penetration is resisted. In addition, the equilibrium position will be influenced by the weight of the anchor. It is predicted that larger anchors will have a deeper equilibrium position as they will exert a higher stress on the sand and so will penetrate deeper before this stress is balanced by the effective stresses in the sand.

It was not possible to complete full simulations and quantify the anchor penetration depth, due to instability of the finite element model. This caused each simulation to run for a different amount of time meaning that the final depth of the anchor was not reached and so could not be measured or compared. Furthermore, this meant that it was not possible to observe the final orientation of the anchor, although it was seen that the anchor rotated clockwise so that the shank was closer to horizontal than its initial position. This agrees with the preliminary test findings.

There are limitations of using FEA to model geotechnical problems. For instance, it is difficult to model sand numerically due to its non-linear properties and thus the model was unstable during simulations and often crashed rapidly. Parameters were fine-tuned in order to stabilise the simulation and obtain useful results, however this may have compromised the accuracy of the model. Taking this into account, the model was used to understand anchor behaviour and investigate the idea of an equilibrium position, rather than obtain quantitative anchor penetration depths. It was useful in the formulation of hypotheses which can be investigated in the centrifuge testing.

4.3 Centrifuge testing

The main part of the experimental work was completed in Lent term, using the minidrum centrifuge located at the Schofield Centre as described in Section 3.

4.3.1 Experiment record

Eighteen tests were run in the minidrum centrifuge in total, all with varying parameters. Table 1 shows the details and results of each test performed, along with comments and any problems encountered.

Test	Date	Anchor type	Sand type	Sand relative density	g-level (g)	Starting location	Final penetration depth (mm)	Comments
1	12/01/17	AC-14	Hostun (fine)	0.55	20	Surface	32.00	
2	17/01/17	AC-14	Hostun (fine)	0.46	20	30mm deep	N/A	*Failed:* chain snapped. Replaced with longer wire threaded through chain to prevent repeated failure.
3	19/01/17	AC-14	Hostun (fine)	0.47	20	30mm deep	32.25	
4	24/01/17	AC-14	Hostun (fine)	0.51	20	60mm deep	32.25	
5	27/01/17	AC-14	Hostun (fine)	0.52	80	Surface	N/A	*Failed:* actuator belt came off, suspected to be as a result of high g-level. Actuator fitted with new belt.
6	30/01/17	AC-14	Hostun (fine)	0.52	80	Surface	32.25	
7	01/02/17	AC-14	Fraction B (Coarse)	0.57	20	30mm deep	32.00	
8	07/02/17	AC-14	Hostun (fine)	0.51	40	Surface	32.25	
9	08/02/17	Halls	Hostun (fine)	0.52	20	Surface	N/A	*Failed:* Anchor twisted so penetration depth could not be obtained. Anchor heated and straightened using a vice.
10	09/02/17	Halls	Hostun (fine)	0.49	20	Surface	N/A	*Failed:* Anchor twisted again despite attempt to straighten, penetration depth could not be obtained.

Test	Date	Anchor type	Sand type	Sand relative density	g-level (g)	Starting location	Final penetration depth (mm)	Comments
11	15/02/17	AC-14 plane strain	Hostun (fine)	0.50	20	Surface	N/A	*Failed:* Go-pro view was distorted due to water so anchor could not be seen. Anchor twisted away from glass when dragged. Go-pro mount adapted so that camera is higher. Metal guard made to keep anchor against glass without impeding movement.
12	16/02/17	AC-14	Hostun (fine)	0.74	20	Surface	29.70	
13	21/02/17	AC-14 plane strain	Hostun (fine)	0.50	20	Surface	N/A	Go-pro view better after mount adapted, metal guard insufficient to keep anchor against glass for the entire test. Tighter brass guard made and soldered onto anchor.
14	24/02/17	AC-14 plane strain	Hostun (fine)	0.52	20	Surface	N/A	New guard better at keeping anchor against glass but still not entirely successful.
15	27/02/17	AC-14 plane strain	Fraction B (Coarse)	0.57	20	Surface	N/A	Same behaviour seen as in Test 14 despite using coarser sand.
16	28/02/17	AC-14	Hostun (fine)	0.10	20	Surface	33.20	
17	02/03/17	AC-14	Hostun (fine)	0.26	20	Surface	32.50	
18	07/03/17	AC-14	Hostun (fine)	0.64	20	Surface	30.00	

Table 1: Summary of centrifuge tests

4.3.2 Impact of initial anchor depth

In Section 4.1, it was hypothesised that anchors have an equilibrium position in the sand which they move towards, regardless of initial depth. To investigate this hypothesis, tests were completed with the anchor at varying initial depths in the sand: at the surface and at depths of 30mm and 60mm, see Table 2.

Test (from Table 1)	**Model initial depth (mm)**	**Model final depth (mm)**	**g-level (g)**	**Prototype initial depth (m)**	**Prototype final depth (m)**
1	0	32.00	20	0.0	0.640
3	30	32.25	20	0.6	0.645
4	60	32.25	20	1.2	0.645

Table 2: Results of anchor penetration depth from varying initial anchor depth

The final anchor position was almost identical in each case, with the 0.25mm difference in Test 1 being negligible when compared to the experimental accuracy. This consistency in final depth supports the concept of an equilibrium position. However, the final orientation of the anchor in the centrifuge tests differed from that seen in preliminary testing. The preliminary testing showed the shank being parallel to the surface of the sand whereas in the centrifuge tests, the anchor shank was in the region of 21^{o} to the horizontal below the sand surface (Figure 24). This highlights the limitations of dry testing at 1g, as the same behaviour is not necessarily seen at higher stresses in saturated sand. The tests completed in the minidrum centrifuge therefore provide a more representative model.

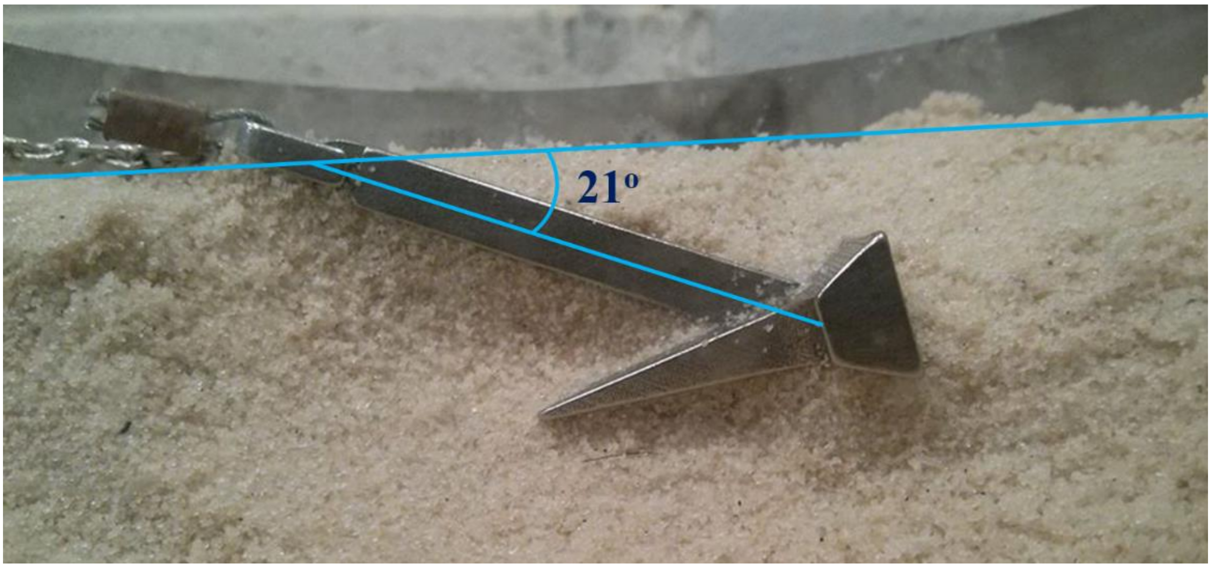

Figure 24: Final orientation of AC-14 anchor after centrifuge Test 1

The results show that initial depth does not impact final anchor penetration depth in sand, with anchors moving towards the same equilibrium position whether this is above or below their current position. Therefore, it is clear that anchor penetration is limited and that anchors will not continue to penetrate indefinitely into the seabed. Applying this to cable damage, it is advised that cables are buried below the anchor equilibrium position to ensure their safety. Additionally, it is possible that an anchor could become buried under a layer of sand if a ship is anchored for a long time. However, this is not a major concern as any movement of the ship will lead to upwards movement of the anchor through the sand towards its equilibrium position, rather than remaining at a deeper level or penetrating further.

4.3.3 Impact of anchor size

The size of an anchor varies greatly depending on the size of the ship that it belongs to, with larger ships needing larger anchors to give sufficiently high holding power. It is therefore important that the relationship between anchor size and maximum penetration depth is known in order to protect cables from the sizes of anchors used in the surrounding area.

Variation of penetration depth with anchor size was investigated by completing centrifuge tests at varying g-levels, allowing simulation of different anchor sizes with the same model. From the scaling laws explained in Section 3.1.1, it is known that the prototype length is the model length multiplied by the g-level. Therefore, tests done between 20g and 80g with the AC-14 model (38mm fluke length) allowed for testing of prototype anchors with fluke lengths between 0.76m and 3.04m. The linear actuator, used to pull the anchor in the centrifuge, struggled to operate at high g-levels, highlighted by the belt slipping in the first 80g test (Test 5, Table 1). Therefore, only two further high g-level tests were completed (Tests 6 and 8, Table 1) and Table 3 summarises the results.

Test (from Table 1)	**Model fluke length (m)**	**Model final depth (mm)**	**g-level (g)**	**Prototype fluke length (m)**	**Prototype final depth (m)**
3	0.038	32.25	20	0.76	0.645
8	0.038	32.25	40	1.52	1.290
6	0.038	32.25	80	3.04	2.580

Table 3: Results of anchor penetration depth from varying anchor size

Figure 25 shows the measured penetration depth against anchor size, using the metric of anchor fluke length as this is a standard used in the shipping industry. Evidently, there is a linear relationship between fluke length and penetration depth, which fits with what was expected from these tests. Therefore, there was no need to complete further tests.

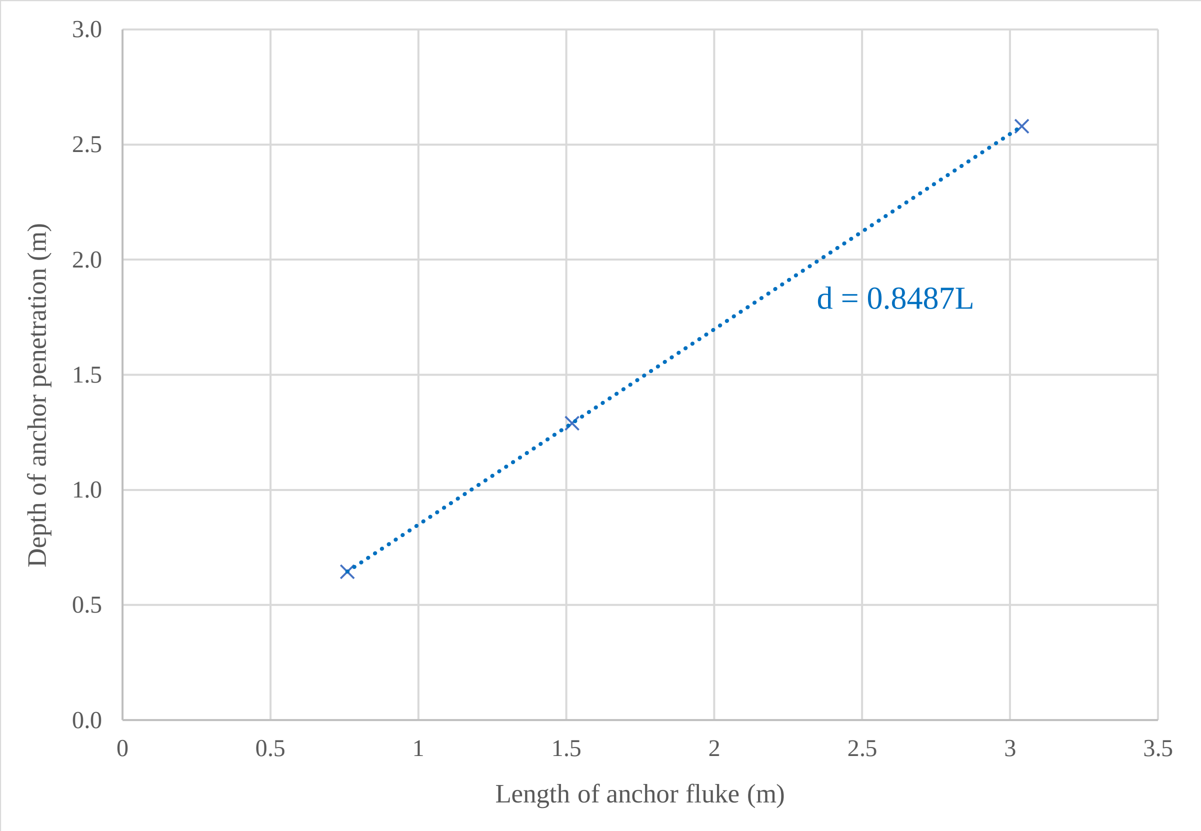

Figure 25: Graph of final anchor penetration depth with varying AC-14 anchor size

AC-14 anchors typically range from 0.7m to 3.4m fluke length [22]. Therefore, Figure 25 covers almost the entire range of possible anchor sizes and, assuming the linear relationship continues, predicts a maximum penetration depth of 2.9m in sand for the largest AC-14 anchor. The data suggests the following relationship between anchor size (L) and penetration depth (d):

$$d = 0.8487L$$

When considering cable burial, knowledge of the typical anchor size for ships in the region will enable calculation of the expected penetration depth using this formula and therefore it can be ensured that cables are buried to safe depths.

The experimental data obtained can be compared to the existing guidelines and previous studies discussed in Sections 2.3 and 2.4. The four known predictions are plotted alongside the experimental results in Figure 26:

1. The **US Naval Civil Engineering Laboratory** (NCEL) suggests that maximum fluke tip penetration is equal to one fluke length in sands [17].

2. The **TenneT** tests in the North Sea were done in three different areas with loose, medium and dense sand – the medium result for the AC-14 anchor has been plotted on the graph as the experimental data being considered here applies to medium density sand so it is the most appropriate comparison [15].

3. The **CWM** chart (Figure 7) is harder to compare as it provides burial depths against the Burial Protection Index, rather than size or weight of the anchor [4].

   BPI 1 applies only to fishing gear meaning that it is irrelevant to anchors.

   BPI 2 applies to 2-tonne anchors so the corresponding fluke length of a 2-tonne AC-14 anchor was found and the burial depth read from the CWM graph for BPI 2.

   BPI 3 applies to 'anchors of all but the largest ships' which is an ambiguous statement. From the IEEE results in Figure 9, the largest ships are indicated to be 100,000 tonnes, so it is assumed that BPI 3 does not apply to this size of vessel and instead applies to the next largest which is a 50,000-tonne ship with an anchor of 8.2 tonnes. Therefore, the size of an 8.2-tonne AC-14 anchor was found and plotted against the burial depth for BPI 3.

   Both the fine and coarse sand burial depths for BPI 2 and 3 have been plotted to show the contrast. The points have not been joined as there is no knowledge of the variation between these points. The line for coarse sand on the CWM graph was extrapolated to reach BPI 3, assuming it remains linear.

   The above procedure required to adapt the CWM data in order to enable comparisons was complex and time-consuming. This demonstrates how unhelpful it is as a guideline, with BPI being an ambiguous metric.

4. The **IEEE** results developed from mathematical modelling in Japan were given in relation to anchor weight. These were converted to equivalent fluke lengths for the AC-14 anchor and plotted on the graph [16].

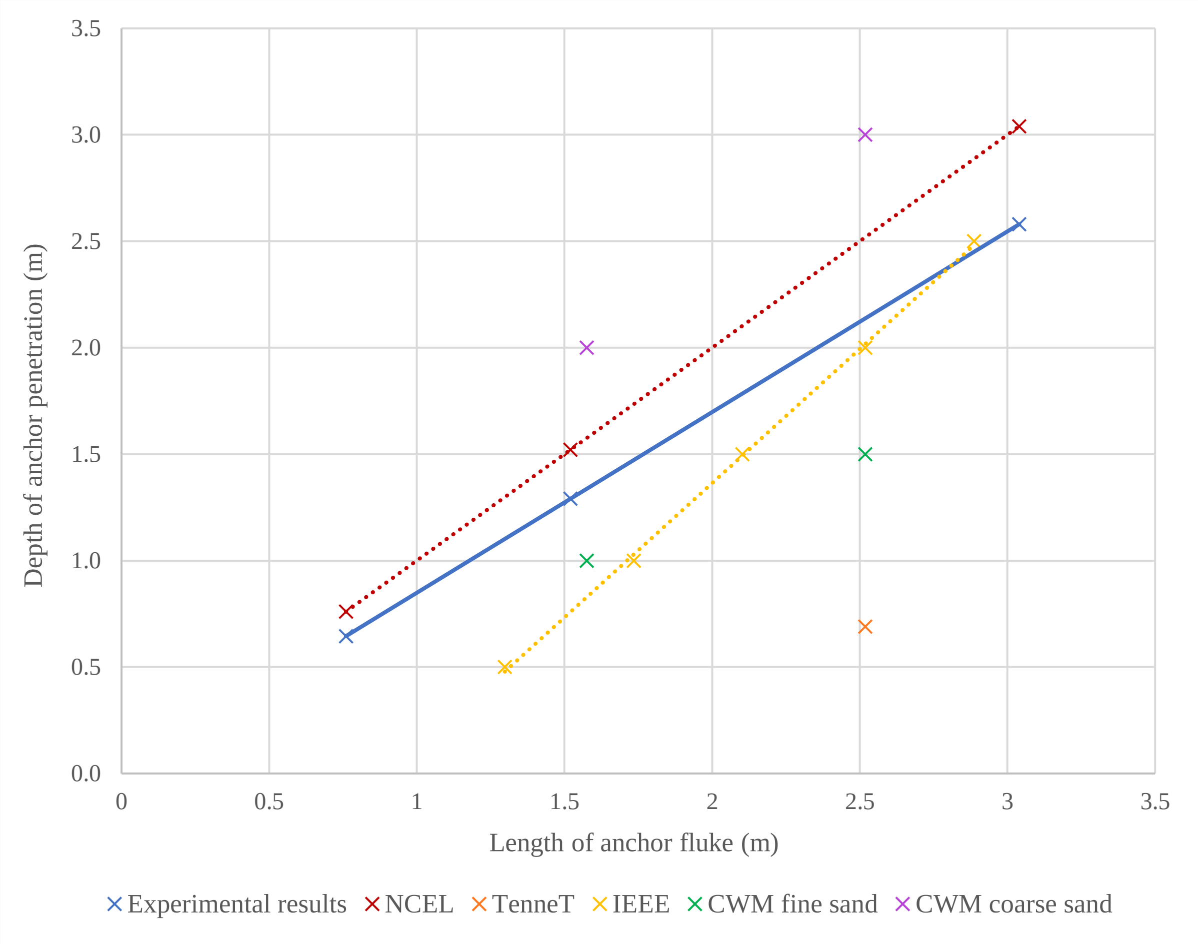

Figure 26: Graph of anchor penetration depth with varying AC-14 anchor size, from various sources

All sources, apart from the TenneT result which only has one data point, show an increase in anchor penetration depth for larger anchors. This agrees with the hypothesis made in Section 4.2, as larger anchors are heavier and so will penetrate deeper into the sand before the effective stresses equilibrate with the anchor weight. All sources show results in a similar range, confirming that the experimental results are reasonable and that a valid comparison can be made with the other sources.

The closest fit to the experimental data is the NCEL guide which suggests a 1:1 relationship between fluke length and penetration depth, 18% higher than the experimental results which gave a ratio of 1:0.8487. The exact source of the NCEL data is unknown; therefore, this difference could be due to a safety factor having already been applied to the data such that it is a conservative estimate rather than the measured penetration depth.

The IEEE data also has a linear increase of penetration depth with anchor size, though with a steeper gradient than the NCEL and experimental results. Based on the experimental results, it is expected that the IEEE line would underestimate the penetration of small anchors, but suggest a more suitable value for large anchors. This inconsistency highlights the challenges faced in trying to accurately model the behaviour of the seabed using numerical modelling.

The result from the TenneT North Sea test is significantly lower than the other sources for an anchor of 2.5m fluke length, indicating that it could be inaccurate. With such a low penetration depth, the anchor would protrude a long way above the seabed, which disagrees with the results seen from testing. However, there were several limitations of these tests identified in Section 2.4.1, notably that the method of measuring the anchor tracks after the anchor drag is likely to underestimate the penetration depth. In addition, the data is from one test in one location, which means that it is unreliable and lacks validity when considering all types of sandy seabed. Figure 26 confirms that this result is an underestimate, with the measured anchor depth being less than half the value of the next lowest result.

The CWM results are shown as separate points for fine and coarse sand, neither of which agree with the experimental data, though it should be noted that these results are burial depths rather than penetration depths so are expected to be slightly higher than the other results. The coarse sand results suggest the highest depths of all sources, indicating that this is an overestimate of the burial depth needed to protect cables against these anchors. This will result in cables being buried unnecessarily deep and money being wasted. The fine sand results are significantly lower, suggesting that cables buried in fine sand using this guideline may not be protected from anchor damage. The difference between the experimental and CWM results is unsurprising as the CWM chart was based on plough penetration depths and was never intended to be a widely-used guideline.

Overall, all sources agree that larger anchors result in greater penetration depths, however there is disagreement as to the exact penetration depths.

4.3.4 Impact of anchor type

Two different types of anchor were 3D-printed in stainless-steel for testing: the Halls and AC-14 anchor. Unfortunately, the Halls anchor model arrived with a slightly bent shank and so there was a concern that it would not be useful for testing. The first test with this anchor (Test 9, Table 1) resulted in twisting of the anchor about the direction of pull, as the bent shank led to a stress imbalance across the anchor flukes which prevented it from moving in a straight line, seen in Figure 27. In an attempt to rectify this problem, the anchor was heated and straightened in a vice to reduce the shank defect. The shank of the anchor was visibly straighter after this effort but regrettably proved unsuccessful as the Halls anchor exhibited the same twisting behaviour in the subsequent test (Test 10, Table 1).

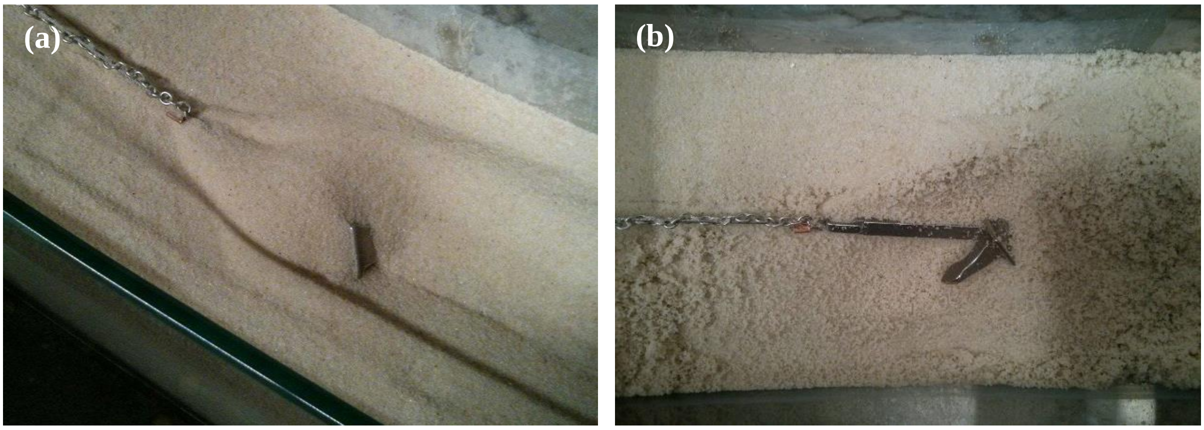

Figure 27: (a) After testing, one side of fluke seen to have twisted out of the sand (b) After excavation, view of the twisted anchor from above

As a result of these issues, it was decided that no further tests would be carried out with the Halls anchor and that it would be more productive for the remainder of the experimental work to focus solely on the AC-14 anchor. Whilst this deviated from the original plan, it maximised efficiency by allowing time for more in-depth analysis of the AC-14 anchor, enabling investigation of relationships between other parameters that can be applied to all anchors, regardless of type.

The Halls anchor would be expected to exhibit similar behaviour to the AC-14 anchor, with the relationships between parameters being constant across the anchor types. The only variation may be the exact penetration depths, due to the different geometry and the slight difference in angle between the fluke and the shank. However, this is anticipated to make negligible difference when deciding on safe cable burial depths.

4.3.5 Impact of sand density

The density of the sand was varied by changing the pouring speed during preparation of the model, allowing for investigation of the effect of sand density on penetration depth. Loose sand was obtained by rapid pouring and dense sand by slow pouring close to the model using the sand hopper and a fine nozzle. Table 4 shows the results obtained from the eight tests done at 20g with varying relative density.

Test (from Table 1)	**Sand relative density**	**Model final depth (mm)**	**g-level (g)**	**Prototype final depth (m)**
16	0.10	33.20	20	0.664
17	0.26	32.50	20	0.650
3	0.47	32.25	20	0.645
4	0.51	32.25	20	0.645
1	0.55	32.00	20	0.640
18	0.64	30.20	20	0.604
12	0.74	29.70	20	0.594

Table 4: Results of anchor penetration depth from varying sand density

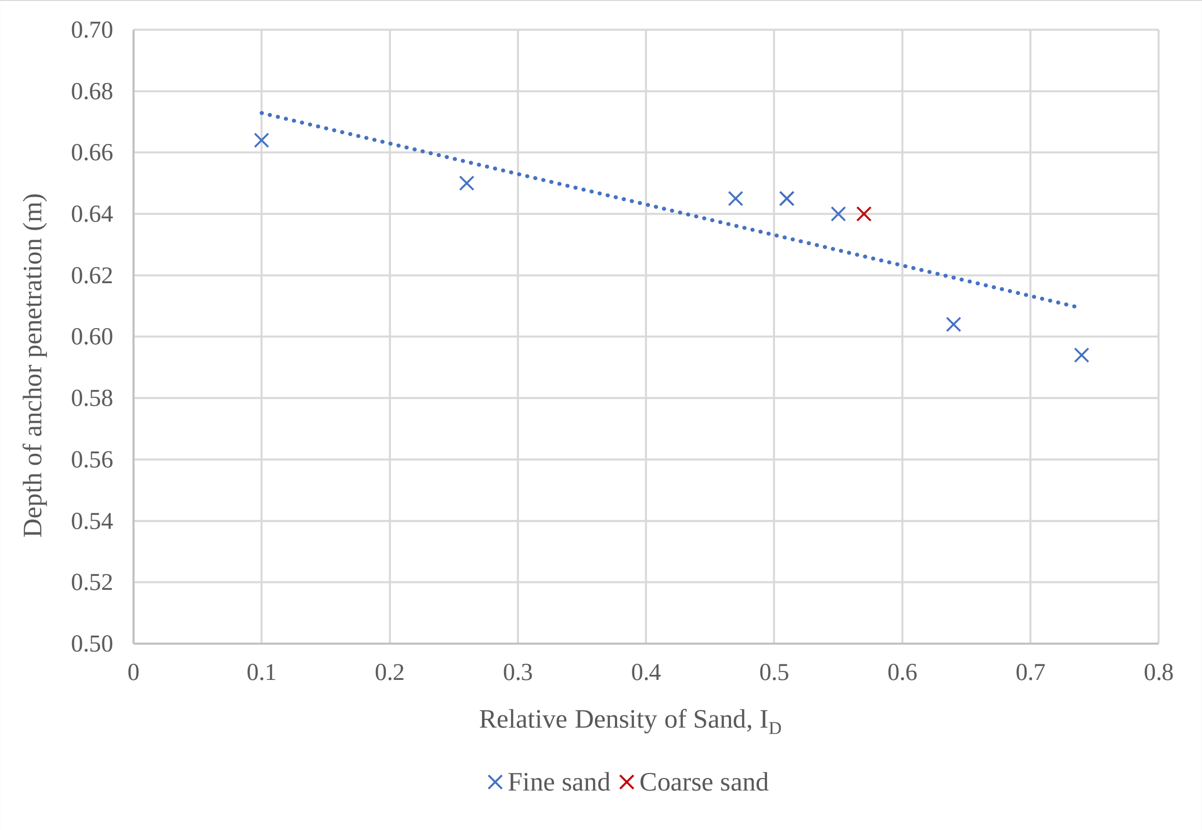

Figure 28: Graph of final anchor penetration depth with varying sand density

The red point in Figure 28 is discussed in Section 4.3.6. The graph in Figure 28 shows a linear relationship between relative density of sand and anchor penetration depth, with denser sand leading to shallower penetration depths. This agrees with the hypothesis made in Section 4.2 which suggested that denser sand will lead to a shallower final depth due to its higher effective stress and peak friction angle making it more resistant to anchor penetration as a result of dilatancy. From Bolton's stress dilatancy formulae [23], the range of peak friction angles for the Hostun sand can be calculated:

$$\emptyset_{peak} - \emptyset_{crit} = 3I_R \qquad \text{where} \qquad I_R = I_C I_D - 1$$

The critical state friction angle is taken as 35°. Assuming the effective unit weight of the sand to be 6kPa, the range of peak friction angles can be calculated at 0.664m depth, the deepest penetration depth observed in the tests. This gives p' to be 4kPa and so I_C is 8.5. Thus, I_R varies from 0 to 5.29 (though is limited to 4) and the range of peak friction angles for the range of relative densities tested is 35° – 47°. This is a significant range which shows that the peak friction angle of the sand is clearly influential in determining the depth of anchor penetration, plotted in Figure 29.

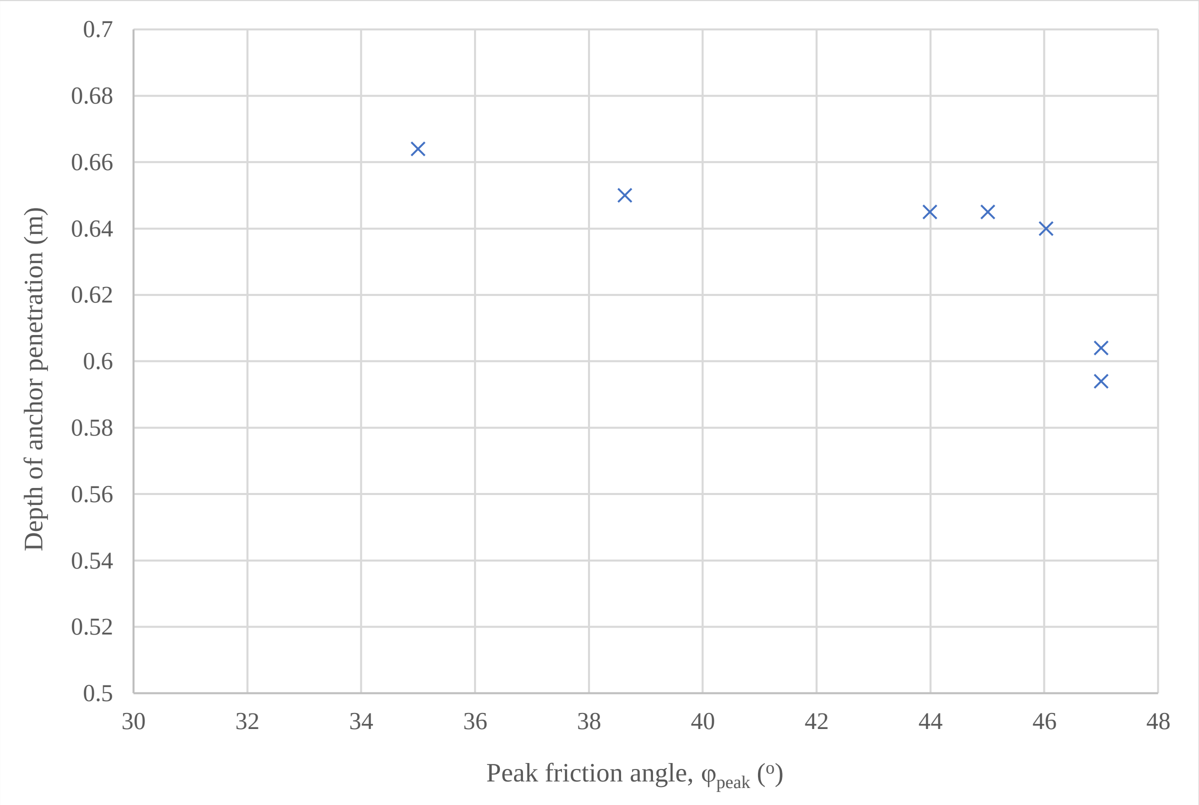

Figure 29: Graph of final anchor penetration depth with varying peak friction angle of sand

Figure 29 shows that higher peak friction angles lead to lower penetration depths, due to the greater resistance provided by the sand. The peak friction angle is influenced by the sand weight and density but also by the critical state friction angle. The minimum value of ϕ_{crit} for sands is 32^{o} which would give a minimum ϕ_{peak} of 32^{o} for the loosest sand. From the graph, this minimum ϕ_{peak} value would lead to a greater penetration depth than those observed in the Hostun sand tests, expected to be around 0.68m.

Evidently, anchor penetration depth is influenced by the density and critical state friction angle of sand, however the difference in depth due to variations in these properties is small, with only a 70mm difference between sand with relative density 0.10 compared to 0.74. This difference is around 10% of the predicted penetration depths and so whilst the difference is not negligible, it is expected to be insignificant when deciding on cable burial depths. As a result, measuring the sand properties at the location of cable burial is deemed to be unnecessary. This would be a costly and time-consuming process that would lead to minimal difference in the suggested burial depth.

4.3.6 Impact of sand particle size

The existing Cable and Wireless Marine guideline advises different burial depths depending on whether the sand is coarse or fine (Figure 7). However, it is hypothesised that the sand particle size will have no effect on penetration depth, as anchors will be in the region of ten thousand times larger than the sand particles so a slight change in particle size would be negligible. To investigate this, a test was done with Fraction B sand (Test 7, Table 1), which has particles ten times larger than the Hostun sand used for the other tests. By calculating the relative density of the coarse sand, this result was plotted on the graph of relative density against penetration depth, to be compared to the fine sand results (Figure 28).

The graph confirms that the coarse sand test, shown in red, does not differ dramatically from the fine sand tests, indicating that particle size does not have an impact on penetration depth of the anchor in sand.

To further consider the difference shown on the CWM guideline, Figure 30 shows the same experimental results as above but with the addition of the CWM burial guidelines for an anchor of this size in both coarse and fine sand. These are shown as horizontal lines on the graph as the CWM guideline does not differentiate between loose and dense sand.

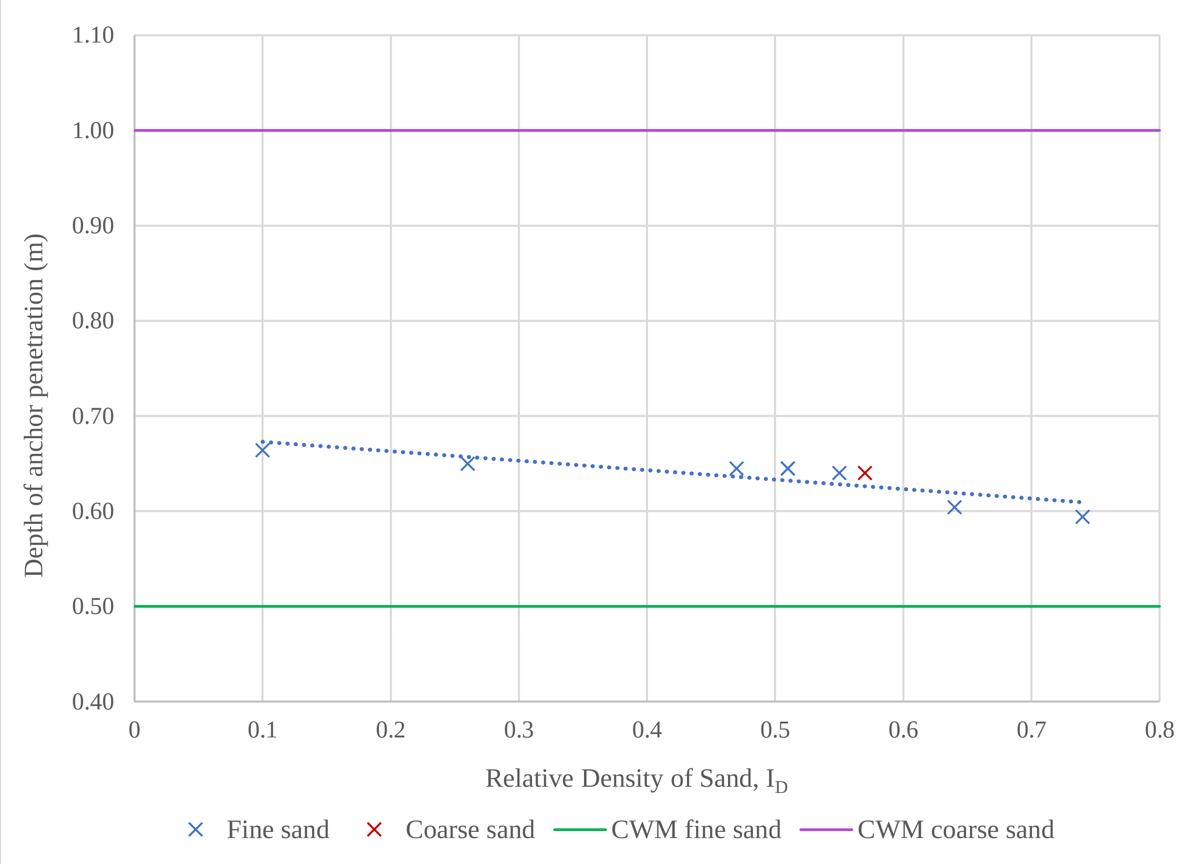

Figure 30: Graph of experimental results and CWM guidelines for fine and coarse sand

There is a factor of two difference between the advised CWM cable burial depth in coarse and fine sand, whereas the penetration depth found from testing can be considered the same for coarse and fine sand (Figure 30). Therefore, it is deemed unnecessary to have different burial guidelines based on the size of sand particles. Furthermore, it is dangerous to have such a contrast between coarse and fine sand. This graph suggests that cables buried to be protected from anchors in fine sand would in fact be at risk of damage, with the experimental results showing deeper penetration than the CWM fine sand guideline of 0.5m. Conversely, cables buried to be protected from anchors in coarse sand would be buried too deep at 1m which, whilst safe, is uneconomic. In this particular case, an average of the coarse and fine sand burial depths would give an appropriate burial depth based on the experimental results. However, this may not be true for all anchor sizes, as was seen in Section 4.3.3.

These results confirm that the CWM guideline is incorrect to give different burial depths based on sand particle size. Therefore, the CWM guideline is not an appropriate chart to use when deciding on cable burial depths in sand.

4.3.7 Plane view tests

In addition to using the 3D model anchors, tests were carried out using the plane strain versions of the anchors to allow closer observation of the interaction between the sand and the anchor. By changing the position of the pulley in the model box, the plane strain anchor could be pulled against the side of the central glass panel with a go-pro camera mounted in the other half of the box to record the anchor movement. Information from these tests is detailed in Table 1 (Tests 11, 13, 14 and 15).

There were several issues related to this test setup. The initial positioning of the go-pro camera meant that the anchor could not be seen when the centrifuge filled with water, as the water distorted the view. The camera mount was adapted to rectify this.

Furthermore, the dragging of the anchor led to problems, as the anchor twisted away from the glass when it was dragged rather than remaining against the glass, meaning that it could not be seen after the first few seconds. This problem was tackled by creating a guard for the anchor which effectively clipped it onto the glass panel. Grease was also added between the anchor and the glass in an attempt to create a seal to prevent sand from getting in the way. Unfortunately, these measures did not give a perfect result as the sand still came between the glass and the anchor. However, it was possible to make some useful observations.

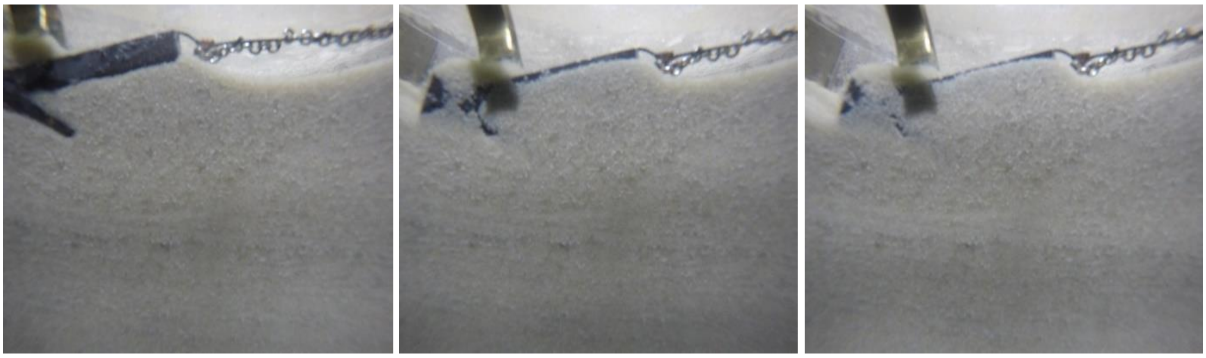

Figure 31: Images of the AC-14 plane strain anchor being dragged against the glass during a centrifuge test, taken by a go-pro camera

Figure 31 shows the progression of the anchor through the sand against the glass panel. The images highlight the problem that was encountered with sand coming in between the anchor and the glass, resulting in the anchor being less visible by the last image. However, the general path of the anchor can still be observed, with a clear downwards movement across the images as the anchor moves towards its equilibrium position. In addition, Figure 31 shows that the chain pulling the anchor is not perfectly level with the sand surface and is instead pulling upwards slightly on the anchor, a piece of information which could not be gained from the 3D tests. This shows that the force on the anchor is not horizontal as desired and so the results of the tests may have slight inaccuracies, though this is not a concern as any difference will be minimal. The experimental setup meant that it was hard to achieve a perfectly horizontal force - a heavier length of chain could be used to improve this.

Overall, the plane view tests had limited value but there is significant potential for future work to be done to improve this method and obtain more useful results.

4.4 Cable burial guideline

The results from this project can be combined to provide a design guideline for the burial of offshore cables. The guideline will give an advised burial depth for cables in sand in relation to the size of the anchors expected to be present in the cable vicinity. The burial depth will not vary based on properties of the sand such as density, critical state friction angle and particle size, as these were seen to make minimal difference to anchor penetration. The guideline will be based on the experimental results, as well as taking into account the other sources of data discussed in Section 4.3.3.

The experimental results give the anchor penetration depth rather than a cable burial depth; therefore, the advised burial depths will be greater than the results gained to give a margin of safety between the tip of the anchor fluke and the cable. This safety margin will allow for variations in the level of the seabed, different anchor types and potential under-ploughing during burial. For clarity, the guideline will display both the anchor penetration depth and the advised cable burial depth with the safety margin added, to prevent companies from increasing costs unnecessarily by adding their own safety factor. It is decided that the results will be extrapolated for the full range of AC-14 anchor sizes and that a 400mm safety margin will be added to the experimental results to produce the design guideline. This is deemed to be a suitable margin of safety between the fluke tip and the cable, to allow for variations in environment and installation without incurring large excess costs.

Figure 32 shows how the guideline compares to the existing sources of data. This indicates that cables would be considered safe by all sources apart from the overly conservative CWM coarse sand guideline, though this is thought to be incorrect. In addition, the NCEL guideline suggests that the largest anchors could cause damage, however there is only a small overlap and the likelihood of this being an issue is low.

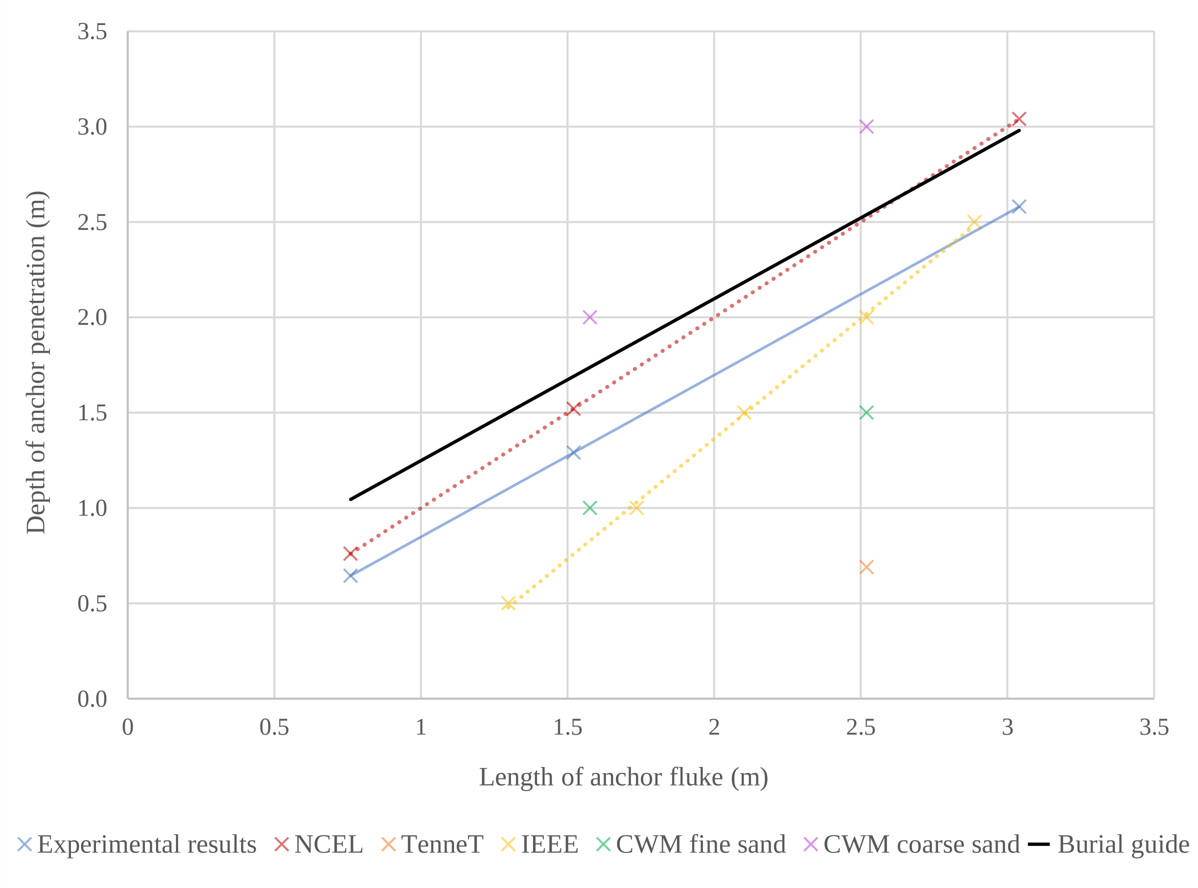

Figure 32: Graph of burial guideline, shown in relation to known sources

The final chart for selecting cable burial depths is shown in Figure 33. The burial depths are provided in relation to three variables: anchor fluke length, anchor mass and ship mass. This means that the chart is easy to use, with only one of those three pieces of information required to identify the appropriate burial depth. In comparison to the CWM guideline, this new guideline is more straightforward to use and less ambiguous, meaning that it will minimise errors and result in fewer incidents of anchor damage to offshore cables.

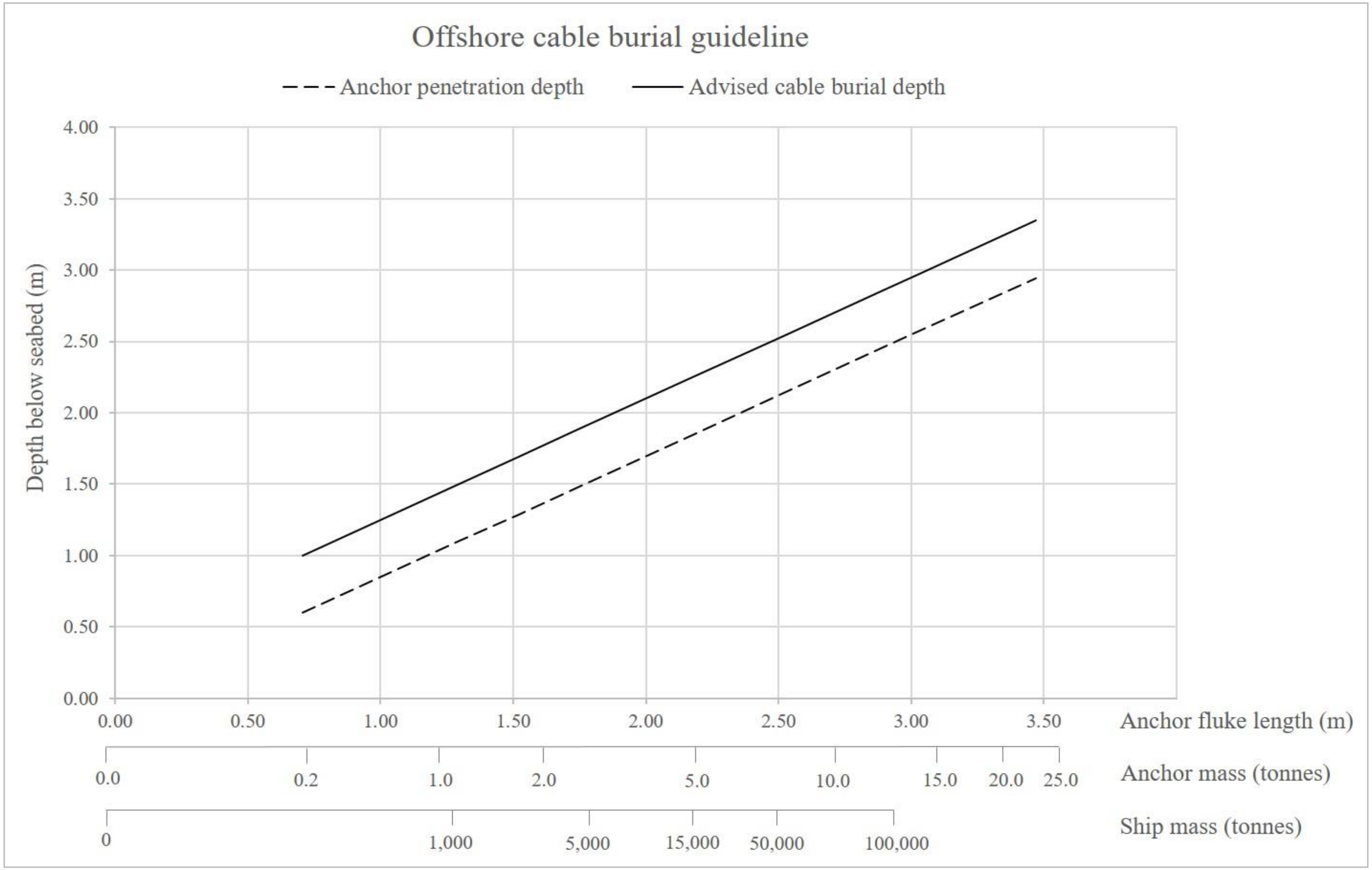

Figure 33:Final guideline for cable burial depth

5 Conclusions

A variety of experimental and analytical techniques were used during the project to investigate anchor damage to offshore cables. Due to the worldwide use of offshore cables and the severe impacts that result from their damage, the practical implications for protecting cables have been considered throughout. The following conclusions can be made, drawing on the literature review and both numerical and physical modelling:

- Centrifuge modelling is an effective method for collecting data relating to geotechnical problems - in this project specifically the situation of a ship's anchor being dragged through a sandy seabed.

- Preliminary tests and numerical modelling are useful tools for investigation of a problem. They should not always be relied upon for accurate results, but they can indicate trends which allows for focused design of experimental tests.

- An anchor dragged through sand has an equilibrium position in the seabed where the effective stresses in the sand are in balance with the self-weight of the anchor and the horizontal force on the anchor. If the anchor is above this equilibrium position, it will penetrate downwards into the soil. If the anchor is below this equilibrium position, it will rise upwards through the soil. Hence the initial depth does not impact the final penetration depth of the anchor.

- The penetration depth of an anchor increases linearly with the fluke length. This is true for the typical known range of anchor sizes.

- The penetration depth of an anchor decreases as the density of the sand increases due to the increased peak friction angle, although this difference can be taken to be negligible compared to the absolute depth. No difference in penetration depth is seen between fine and coarse sand, despite the factor of two difference suggested by the CWM guideline.

- A final guideline for cable burial depths in sand has been developed, taking into account existing research as well as the experimental results (Figure 33). This is a simpler chart than the existing CWM guideline which will reduce anchor damage by ensuring safe but economic burial of all offshore cables.

6 Future Work

There is significant scope for continuation of the investigation of this issue to provide a more comprehensive study of anchor damage to offshore cables.

Physical Modelling

The existing equipment and method used for centrifuge testing has proved to be successful in providing good results, and could be used further:

- Complete tests with clay using the same anchor models to quantify anchor penetration in clay as well as sand.
- Replace the actuator with a stronger pulling mechanism such that tests can be done up to 100g to model the largest anchors in use, instead of extrapolating data for smaller anchors.
- Re-print the Halls anchor model or other anchors in stainless-steel and complete the same tests as were done for the AC-14 anchor, to offer a comparison between anchor types.
- Test the burial depth guidelines gained from centrifuge testing by including a cable in the model at the advised burial depth and checking that the anchor does not damage it.
- Refine the plane view method such that clearer images of the anchor moving through the sand can be gained. Potentially use Particle Image Velocimetry methods to track the sand.

Numerical modelling

The FEA completed in this project has the potential to be extended for future work:

- Analyse the forces acting on the anchor as a result of the effective stress in the soil, the horizontal force from the anchor rode and the self-weight of the anchor. Attempt to quantify and compare these forces to find the expected equilibrium depth.
- Create a detailed three-dimensional finite element model which can be used to give quantitative rather than qualitative information. Parameters should be modelled as accurately as possible whilst giving a stable model that can complete full simulations.

Data analysis

The data available about anchor damage to cables is limited. However, submarine cable companies are likely to have more detailed records which could be used for the following:

- Analyse the burial depths of cables which have been damaged by anchors. Consider if they were buried deep enough given the new guideline created.
- Identify the types of anchors which cause the most faults. Analyse if they penetrate deeper than others and the reason for this.

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Appendix: Risk Assessment Retrospective

The initial risk assessment (Table 5) considered all aspects of the practical work to be undertaken and took into account existing safety routines at the Schofield Centre.

Hazard	**Control measures**
Fast moving machinery	Hair was tied back and no loose clothing worn during operation of the centrifuge.
Fast moving parts	The safety screen was bolted in place before the centrifuge was switched on for each test. The safety stop was clearly marked in case of emergency.
Centrifuge operation	The centrifuge was checked by a trained operator before each test to ensure that it was safe to run.
Centrifuge out of balance	Calculations were done before each test to ensure the centrifuge would be balanced, these were approved before testing. Automatic cut outs were in place to stop machine in case of excess vibration.
Use of clay power/sand	Pouring was done in a sealed room and a dust hood was worn to protect against dust.

Table 5: Hazards and control measures from initial risk assessment

The risk assessment was found to be suitable for the project work. In the end, clay was not used as the project focussed only on sand, however the same safety measures were implemented as sand also creates dust when poured. The use of sand led to the further hazard of lifting heavy models of saturated sand, detailed in Table 6.

Hazard	**Control Measures**
Heavy lifting	Correct manual lifting procedure was followed to insert and remove model box from centrifuge. Help was sought from another individual if the load was too heavy.

Table 6: Addition to risk assessment

No injuries were sustained during the project. Overall, the risk assessment was accurate. The only hazard omitted came as a result of altering the experiment. If repeated in future, the risk assessment for this project should be done in the same way but with further consideration of potential changes to the practical work. It should also be kept as a live document and updated throughout the project.