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Research paper

Drag embedment anchor penetration in layered sands and through cable and pipeline trenches

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ABSTRACT

Cable Burial Risk assessment (CBRA) is undertaken to identify risks to offshore renewable energy cable infrastructure. CBRA assumes uniform soil conditions and does not recognise the effect of the cable installation methods. Centrifuge model testing was undertaken to explore the performance of a shipping anchor (AC-14) when encountering layered sand soil profiles. In addition, anchor interaction with both cable plough trenches and backfilled V-shaped pipeline plough trench routes were investigated. For a specific anchor, in loose over dense sand layers, penetration is stopped with minimal penetration into the underlying dense layer irrespective of the thickness of the loose layer for the anchor size investigated. Testing a recent layered soil CBRA approach indicated that it performed well when inputs were based upon well-characterised model anchor performance. Anchor interaction with vertical cable plough trenches showed limited modification of anchor behaviour. Similar observations were made for the V-shaped backfilled trenches where the anchor approached at 90 or 45° to the trench. When the anchor followed the route of the trench it dived through the trench and backfilled material and into the underlying dense soil. For CBRA methods to improve there is a need for high-quality characterisation of different anchor types in a wider range of soil conditions where realistic installation practices are considered.

1. Introduction

Cable burial risk assessment (CBRA) is an important stage in the development of both offshore renewable energy power distribution systems and major undersea telecommunication routes. The cable burial risk assessment process is used to determine how to protect the cables, and if burial is an option, how deep such a cable should be buried (Burley et al., 2023). Burial is an expensive process with cable or pipeline plough forces related to the square or cube of the plough depth. Thus, the deeper a plough goes the greater the tow forces required, this may increase the size of an offshore vessel or reduce available installation plant options, and the deeper the plough the slower progress may be due to soil rate effects (Lauder et al., 2012, 2013). Thus, to address all of these issues, installers target the lowest depth of burial to reduce cost, allow flexibility of plant use, whilst balancing the threat to the buried asset. Therefore, there is a need for accurate CBRA processes that can deal with complex site conditions e.g. layered soils (Haertsch and Knight, 2022), and the effects of previous cable or pipeline installation methodology.

Currently CBRA approaches such as Cable Burial Risk Assessment Methodology - Guidance for the Preparation of Cable Depth of Lowering Specification CTC835 (Carbon Trust, 2015) does not tackle the issue of anchor penetration in layered soils or interaction with real cable or pipeline installations. Current approaches to assessing anchor penetration in Carbon Trust (2015) are relatively simplistic. Final or ultimate penetration, H_{ult} of an anchor may be calculated based upon a simple formula as shown in Equation (1).

$$H_{ult} = SF \times \sin \beta \times FL \quad (1)$$

where β is the anchor fluke opening angle (normally assumed to be the maximum anchor opening angle for a particular anchor design, or 45° if

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unknown) and *FL* is the anchor's fluke length (See Fig. 1). *SF* represents the soil encountered and refers to a simple Soil Factor (*SF*). Typical soil factors based upon Carbon Trust (2015) guidance and interpreted from Naval Civil Engineering Laboratory (1982)are either a fixed value of 1 in sand or selected so the method returns H_{ult} equivalent to one anchor fluke length in sand. The above equation assumes the anchor's shank is horizontal, and the anchor does not roll.

How the anchor depth of penetration is calculated in Carbon Trust (2015) has been drawn into question particularly in loose to very loose sand by Sharif et al. (2023) where far greater penetration depths were encountered during centrifuge tests under drained conditions. This was also verified numerically by Bird et al. (2026). Interpretation of guidance in NCEL (1982) suggests that penetration should be limited to 1 anchor fluke length in sand and stiff clays and 3-4 in silts and soft clays. Sharif et al. (2023) showed penetration depths in loose sand of 2.45 times these recommendations for an 8 tonne AC-14 anchor with a fluke length of 1.715 m. It is notable though that Sharif et al. (2023)'s results compared well with the Carbon Trust (2015) approach in medium dense sands and the previous drum centrifuge study of Moore et al. (2021).

Previous examples of attempting to incorporate layering into CBRA approaches seem limited with little published or in the public domain. That said there are some limited existing models that have recently been developed that vary in complexity (e.g. Peng et al., 2021; Haertsch and Knight, 2022; Davies et al., 2025). For example, choosing the simpler Davies et al. (2025) approach requires utilising Equation (1) but with an attempt to incorporate layering by considering the energy or force lost by the anchor in each layer. To do this, knowledge of the anchor's depth-drag distance and load drag distance relationships are required, which may not be readily available for all anchor types in different soil conditions. The method also requires assumptions about the anchor's kinematics e.g. the shank is horizontal and that the anchors maximum opening angle (Fig. 1) is assumed. Sharif et al. (2023) showed that depending on the depth of penetration, the shank can be significantly inclined and the anchor's opening angle can tend to the anchor's maximum opening angle in loose sand, but that the value is typically very low in dense sands (e.g. 11° for an AC-14 anchor that had a maximum opening angle of 35°). Thus, CBRA approaches and those designed to deal with layering seem overly simplistic and do not reflect real anchor kinematics.

Even more sparse are public domain accessible examples of physical modelling studies looking at anchor penetration in layered soils or through installation features e.g. backfilled trenches. Bransby et al. (2005) did consider the effect of soil layering on pipeline plough penetration and showed that additional soil layers may increase tow forces where this was attributed to different sands in the layers with different frictional properties rather than relative density, since relative density was not recorded. One major difference though between a pipeline or cable plough and an anchor is that the plough can control its depth via skids that can be actuated during the operation, so on encountering a hard layer the plough tow force would increase, and the plough would tend to reduce depth to compensate for this. The skids would then be used to force the plough back to the target depth, increasing tow force and requiring the towing vessel to work harder or slow down. In contrast, anchors tend to change depth to maintain a force equilibrium, thus in loose soil they go deep and in dense soil they end up in a shallow position with little overall effect on the tow or drag force required (Sharif et al., 2024; Robinson et al., 2019).

Based upon the complex geometry and variety of anchors of different mass that are available on the market it would seem a significant task to predict anchor penetration based upon analytical approaches. Thus, modelling of anchor penetration and realistic behaviour prediction seem to require computationally efficient simulation techniques to realistically deal with various soil variations and anchor permutations. Recent attempts at capturing this behaviour for similar penetrating objects rely on large deformation modelling techniques such as CEL (Dao and Grabe, 2024) or the Material Point Method (MPM), (Bird et al., 2025, 2026). However, such approaches may currently be computationally expensive and require further evolution. They have the advantage, however, of enabling a wide range of scenarios to be evaluated beyond uniform soils. To develop such approaches requires high quality validation cases and data sets which this paper aims to contribute to.

To inform the evolution of CBRA approaches and the broader realistic modelling of anchor penetration behaviour, whilst providing various cases for validation of numerical approaches, a series of limited centrifuge tests with full continuous anchor tracking have been undertaken in dry sand to look at the effects of soil layering likely to be encountered in the North Sea. This is informed by the layering profiles identified by Johnson et al. (2024) and MacDonald et al. (2023). Additional tests have been undertaken through cable or pipeline routes where the trench formation and backfilling have been replicated at model scale to reflect the realistic installation process that may be adopted in the field, to investigate the effects on anchor penetration and to see if these pose an additional component that requires consideration in future CBRA approaches. Previous approaches to CBRA consider the ground as uniform and do not consider cable installation.

2. Methodology

Scaled physical modelling of the anchoring process was undertaken on the University of Dundee 3 m radius Actidyn Centrifuge. All testing was undertaken in dry sand. Anchor testing in layered sand was undertaken at 16.4g but with a scaling factor of 1/24th or N = 24 (Table 2). The test g level was lower than the scaling factor in order to recreate the effective stress of a fully saturated drained soil bed without the need for pore fluid or waterproofing of the model anchor instrumentation. This reduction of g level approach in dry sand to mimic drained saturated

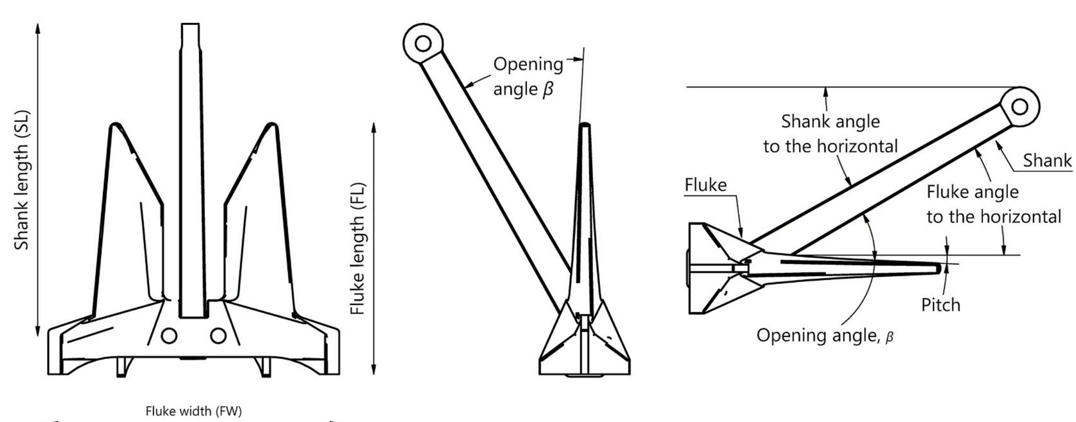


Fig. 1. Schematic of the AC-14 anchor used and definitions of anchor orientation terminology (dimensions can be seen in Table 1).

conditions was proposed by Li et al. (2010) and fully validated by Klinkvort and Hededal (2013). This approach is explained in more detail by Li et al. (2010) where in saturated sand, the effective vertical stress of soil is expressed as:

$$\sigma_v{}' = \rho' \times g_{sat} \times z \quad (2)$$

where g_{sat} is the acceleration in a centrifuge test in saturated sand e.g. $g_{sat} = 24g$; ρ' is the buoyant density of the saturated sand and z is the depth of the soil in an 1/24 scale model. To achieve the equivalent soil conditions, the vertical stress of dry sand expressed in Eq. (2) should be equal to the effective vertical stress of saturated sand in Eq. (3):

$$\sigma_v' = \rho_d \times g_d \times z \quad (3)$$

where g_d is the acceleration to be imposed in a centrifuge test on dry sand; ρ_d = the dry density of the sand and z = the depth of soil in scale model. Thus, the g_d value is 16.4g, obtained by Eq. (4):

$$g_d = \rho'/\rho_d. \times g_{sat} = 16.4g \quad (4)$$

Further validation for the anchor tested here by Brown et al. (2026) showed no observable differences between dry reduced g testing and water saturated testing where g level was the same as the scaling factor. It should be noted though that dry or drained testing reflects the worst case or greatest penetration depth. Brown et al. (2026) showed that anchor penetration depths reduced by up to 25% in loose soils but only 4% in dense soils when moving from slow mooring speeds to emergency deployment speeds. Scaling for the trench interaction study differed in that the plough models for cable, pipeline and backfill ploughs already existed as they have been used in previous ploughing performance studies (Lauder et al., 2013; Robinson et al., 2017, 2019). These were designed with a scaling factor of 1/50th or N = 50 so testing was undertaken at 32g to achieve saturated test behaviour following the approach described above. The tests undertaken are outlined in Table 2.

Tests were conducted within a strong box of internal dimensions of 1400 mm × 400 mm x 650 mm with a dedicated large displacement actuator, developed to investigate the performance of ploughs and anchors (Robinson et al., 2017, 2019; Davidson et al., 2023) (Fig. 2). The tow force was measured using a 5 kN S-type loadcell positioned at the surface of the sand bed, which was attached to the towing arm mounted to a moving platform. The moving platform was belt driven via a Paralux137 SD12-LWS high torque 220V DC motor. The displacement of the platform was measured by a draw wire transducer (DWT). The anchor pad-eye was connected to the loadcell by a forerunner (tow cable)

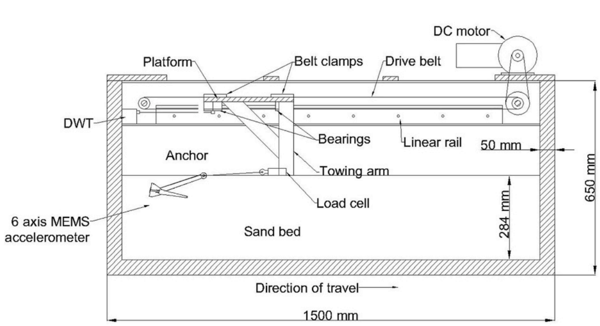


Fig. 2. Schematic showing a cross section of the large displacement centrifuge anchoring actuator and model.

consisting of a 1.5 mm diameter steel wire rope of length 420 mm. A swivel and shackle were located at the loadcell end of the forerunner cable to which a 200 g 3 axis accelerometer (Analogue Devices 150 ADXL377) was mounted to measure the inclination of the forerunner as an indication of the shank angle of the anchor. It is noted that chains may also be used between the mooring line and the anchor. These were not adopted in this study as at the scales used in this study model anchor chain could not be sourced that had appropriate dimensions and the strength to survive the loads applied. To control the actuator and record the signals from the analogue sensors a National Instruments (NI) based control and data acquisition system was used with a purpose built Labview 2018 virtual instrument (VI). The system is based around a National Instruments CompactRio, cRIO-9024. A logging rate of 50 Hz was used for all instrumentation, with measurements taken simultaneously using a NI-9202 C-series module.

2.1. *Description of anchor type and modelling*

An AC-14 anchor was chosen for this study (Fig. 1), as it is reported to be the most widely deployed anchor in the shipping industry (Luger, 2023), in addition to having previously been investigated by physical modelling (Moore et al., 2021), numerical modelling (Dao and Grabe, 2024) and field scale tests (Luger and Harkes, 2013). In this study the anchor was scaled at two sizes by varying the centrifuge g level as discussed above which resulted in the anchor being scaled at 1/24th and 1/50th size for the layered soils and plough trench interaction, respectively. This resulted in the anchor representing an 8.7 tonne and 18.1 tonne anchor respectively in dry conditions. The key dimensions at model and prototype scale are shown in Table 1. The initial model anchor mass was 0.11 kg which increased to 0.35 kg when internal instrumentation was added and the rear cover plate, designed to protect the instrumentation, was attached. The total mass of the anchor was designed to reflect its buoyant weight whilst testing at reduced g under dry conditions. This then gave the appropriate prototype buoyant unit weight during centrifuge testing. The anchor model was created by 3D metal printing in steel (Fig. 3). Anchor instrumentation included a Seeed Studio XIAO nRF 52840 Sense Bluetooth development board with a 6-axis inertial measurement unit (IMU) containing a 3-axis accelerometer and a 3-axis gyroscope. This allowed continuous wireless tracking of the anchors position in the box as well as its pitch and roll. Anchor installation progressed by advancing the platform away from the anchor at a rate of 20 mm/min. The test was typically stopped after 1000 mm of displacement. More detail on the experimental procedures and instrumentation analysis can be found in Sharif et al. (2024).

2.2. *Layered soil modelling*

The sand beds used to test the anchor penetration, were dry slot pluviated (Ueno, 2000) into the strong box described above. For layered soil sand beds, two layers were formed to mimic field conditions. These consisted of loose layers of various thicknesses over dense layers (as shown later). The lower dense layers were first pluviated at $D_r = 82\%$ to the required depth and then a hopper pluviator with mesh grids selected to control density positioned at a fixed height above the sand was

Table 1
Length dimensions of the model and prototype AC-14 anchor geometry investigated in this study.

Dimension	Model Scale	Prototype (1/24th scale)	Prototype (1/50th scale)
Shank length (mm)	137.80	3308	6890
Fluke length (mm)	71.46	1715	3573
Fluke width (mm)	90.25	2166	4513

Table 2
Summary of centrifuge testing (all results shown at prototype scale).

Test ID[a]	Scaling factor	g level	Soil Profile	Relative density profile, D_r (%)	Final penetration depth, H_{ult} (m)[b]	Final anchor tow force (tonnes)	Comment
T1-U-25%-24	24	16.4	Uniform	25	4.201 (2.45FL)	35.7	
T2-U-82%-24	24	16.4	Uniform	82	0.707 (0.41FL)	33.1	
T3-L-0.5-24	24	16.4	Layered (0.5 m loose layer)	25/82	0.558 (0.33FL)	29.3	0.5 m think loose layer over dense
T4-L-1.0-24	24	16.4	Layered (1.0 m loose layer)	25/82	1.430 (0.83FL)	35.9	1.0 m think loose layer over dense
T5-L-1.5-24	24	16.4	Layered (1.5 m loose layer)	25/82	1.765 (1.03FL)	35.3	1.5 m think loose layer over dense
T6-U-82%-50	50	32	Uniform	82	1.439 (0.66FL)	140.3	
T7-CT-0°-50	50	32	Cable trench (in-line)	82	1.425 (0.66FL)	138.5	Anchor following trench route
T8-CT-90°-50	50	32	Cable trench (Perpendicular)	82	1.362 (0.63FL)	138.7	Anchor at 90° to trench route
T9-VT-0°-50	50	32	V shaped trench (in-line)	82	2.258 (1.04FL)	159.2	Anchor following trench route
T10-VT-90°-50	50	32	V shaped trench (perpendicular)	82	1.516 (0.69FL)	159.8	Anchor at 90° to trench route
T11-VT-45°-50	50	32	V shaped trench (in-line)	82	1.318 (0.61FL)	113.9	Anchor at 45° to trench route

Notes.
[a] Test ID nomenclature, T: Test Number-Soil profile-Soil profile specific information-Scaling factor. U = Uniform soil, L = Layered, CT = Cable trench, VT = V shaped trench.
[b] Final penetration depth in parenthesis shows depth normalised by fluke length, FL.

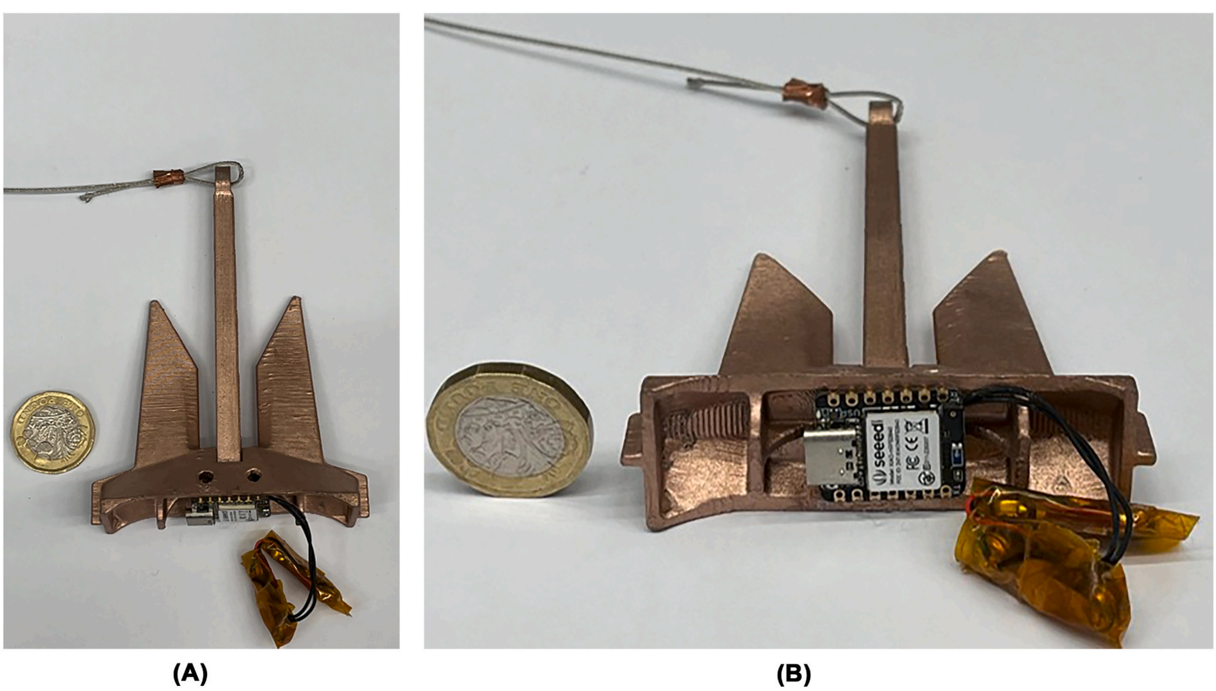
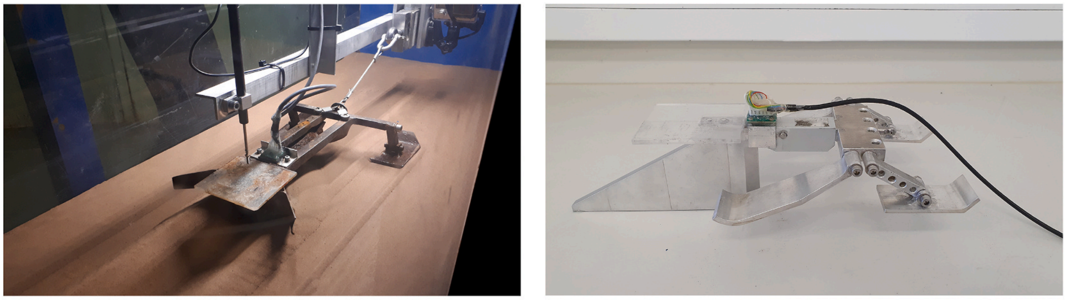


Fig. 3. Image of 3D printed metal AC-14 anchor a) image of anchor as its placed on the sand surface, b) image of anchor and wireless instrumentation (GB pound coin shown for scale).

utilised to complete the formation of the loose overlying layer at a D_r = 25%. The final depth of the soil was 284 mm.

2.3. Plough trench formation and backfilling

As well as testing anchors in layered soil horizons, tests were undertaken in pluviated soil beds that were initially uniformly prepared at a relative density of 82% but were then subject to realistic cable ploughing in-flight or V-shaped trench formation and then backfilling of the latter all at g. To create a cable plough installation along the length of the centrifuge box a 1/50th scale model of a SMD HD3-300 cable plough was used as previously described in detail by Robinson et al. (2021) and SMD (2018). The cable plough (Fig. 4) had a plough share width of 7.5 mm (375 mm at prototype scale), a penetration depth of 60 mm (3 m prototype) and a triangular leading edge with a 40° apex angle. For in-line V-shaped trench formation a 1/50th model scale pipeline plough was used as described by Robinson et al. (2019) and Lauder et al. (2013). The plough had a maximum trench depth of 40 mm



(A) (B)

Fig. 4. Images of the a) pipeline and b) cable plough used in the study (described in more detail by Robinson et al., 2021).

(2 m prototype) and formed a V-shaped trench with side walls inclined at approximately 29-30° above the horizontal (Bransby et al., 2018). This trench was then backfilled in-flight by channelling the spoil heaps formed into the trench using a set of realistic backfill blades (Fig. 5, Boyes, 2011) mounted on the anchor towing frame (Fig. 2). For a 39.2 mm deep trench (1.960m prototype) this resulted in a backfilled trench width at the seabed surface of 133.4 mm (6.672 m prototype). Trenching and backfilling was undertaken at an advance rate of 20 mm/min. Once the backfilling process had been completed the centrifuge was "g'd down" (decelerated), the backfill blades removed and a specially designed mini CPT rig (described later) mounted on the towing frame to allow inflight CPT characterisation of the backfilled trench. All of these operations were undertaken at 32 g in dry sand conditions as described previously.

The CPT backfill characterisation was then used to inform the creation of the V-shape trenches that were created directly across the strong box (90° to the anchor path or perpendicular) and at 45° to the anchor path. These V-shaped trenches could not be formed realistically with a model pipeline plough due to the nature of the actuation and space constraints within the strong box. To form these short trenches, preparation occurred at 1g and, for a cable plough, involved manually embedding a detachable plough share into the dense sand and manually moving the share element across the box at the correct depth. For the V-shaped trench, the trench geometry was defined based upon post installation inspection of the trench by laser scanning (Robinson et al., 2016) after centrifuge ploughing as described above. A V-shaped trench was then manually excavated to match this geometry following which the trench was filled in with a miniature hopper pluviator maintained at a fixed depth above the trench at the relative density of that found from the centrifuge installation and CPT testing (discussed later in the paper).

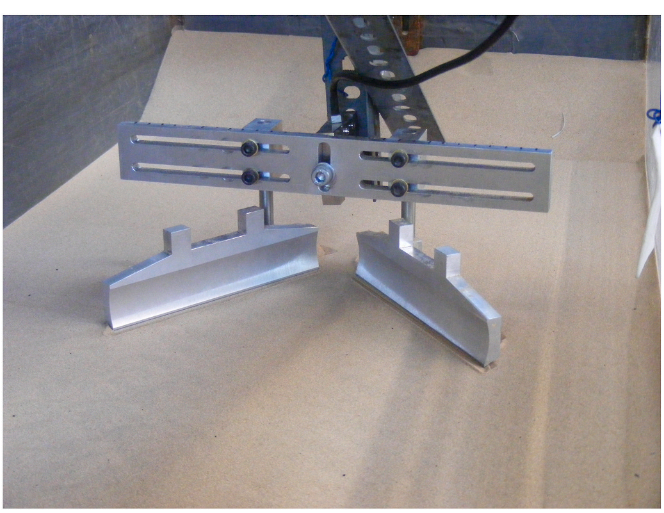


Fig. 5. Image of the pipeline plough backfilling blades designed to be mounted on the towing platform (described in more detail by Boyes, 2011).

2.4. Sand used and characterisation

The sand used in the experiments was HST95 sand which is a fine-grained quartz laboratory sand commonly used in the geotechnical laboratories of the University of Dundee (Table 3).

Separate in-situ characterisation of the sand was undertaken in the backfilled V-shaped trenches (as discussed above) using a specifically designed min inflight CPT device mounted to the towing arm of the actuator. This consisted of a mini CPT of 11 mm diameter, that has the ability to measure both the cone resistance and sleeve friction. The CPT was actuated by a stepper motor which was attached to a lead screw and driven by a Geckodrive Microstep controller, and the displacement of the CPT was measured by a draw wire transducer (DWT). CPT characterisation was initially conducted at locations outside of the area influenced by anchor installation or trenching where the CPT penetrated the soil beds at 10 mm/min. After V-shaped trenching, CPT characterisation was also undertaken of the backfilled material. Relative density of backfilled sand in the ploughing study was derived from in-situ CPT measurements at g using the approach outlined in Knappett and Craig (2020).

3. Results and discussion

3.1. Layered soils

Prior to commencing the layered soil study, it was necessary to establish the specific layering combinations to be examined and to define the thickness of each layer. Based upon previous work by Sharif et al. (2024) it has been shown that the AC-14 anchor penetrates to a significant depth in loose sands (4.21 m, 2.46FL) and to a limited extent in dense sand (0.71 m, 0.41FL). The adopted layering scheme was informed by previous studies of the North Sea, which report significant layering in the upper subsurface, or within 2 m below the seabed.

Table 3
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
Peak friction angle[a], φ'_{pk}, at 25% relative density: °	34
Peak friction angle[a], φ'_{pk}, at 57% relative density: °	40
Peak friction angle[a], φ'_{pk}, at 84% relative density: °	45
Critical state friction angle, φ'_{crit}: °	32
Sand–steel interface friction angle, δ'_{crit}: °	24
Maximum dry density, ρ_{max}: kN/m^3	17.58
Minimum dry density, ρ_{min}: kN/m^3	14.59

[a] Strength properties are from direct shear box tests at effective normal stresses up to 25 kPa.

Approximately 45% of core sample sites analysed by Johnson et al. (2024) contained more than one layer within this 2 m window, with individual layer thicknesses varying across the 0-2 m interval. On this basis it was decided to study three thicknesses of loose sand 0.5, 1.0 and 1.5 m (or in terms of fluke length 0.29, 0.58 & 0.88FL) to give some contrast to the results. The lower dense layer was prepared at 82% relative density and the loose layers at 25% relative density (as described above).

In each case (Fig. 6) encountering the dense layer quickly limits the penetration of the anchor with the anchor penetration-distance track following that of the uniform loose soil profile until entering the dense sand or just before in the case of the 1.0 m thick layer. The anchors penetrated 0.56 m (0.33FL), 1.46 m (0.85FL) or 1.77 m (1.03FL) in the 0.5 m, 1.0 m & 1.5 m scenarios, respectively. Greatest penetration into the dense layer was observed for the scenario where a 1.0 m thick layer loose sand overlays the dense layer.

The reason for the greater penetration in the 1.0 m thick layer is not immediately obvious from the results as Fig. 7a shows relatively similar final anchor opening angles and orientation (Fig. 7b) for the 1.0 and 1.5 m cases. Inspection of the shank inclinations (not shown here) also showed very similar behaviour between these two layering cases but for the 1.0m layer case the fluke inclination was only 20° and the anchor shank had reduced cover which may have initially reduced anchor resistance and allowed depth increase to maintain the force equilibrium seen in Fig. 8. Results for anchor opening of the 0.5 m layered case are not shown as the anchor tipped over immediately on the fluke tip contacting the dense layer making continuous tracking challenging. As the penetration is very shallow in this case there was not enough soil above the fluke to stop this rotation. The orientation shown in Fig. 7b is that based upon the final excavated orientation. It is notable that in each case considered the anchor shank is never horizontal or the anchor open to its maximum angle (35°) as assumed in the Carbon Trust (2015) methodology.

The effect of layering on tow force (Fig. 8) is less noticeable, with the anchors generally tending to a steady state force irrespective of soil conditions, as observed by Sharif et al. (2024). This shows that the anchors tend to a set holding capacity irrespective of the soil conditions if the anchor can maintain a normal orientation. There is some reduction in the tow force for the shallow 0.5 m layer conditions, but this may be a result of the unusual final orientation as noted above. Although the data is “noisy” in Fig. 8 similar perturbation of the tow force was noted for the

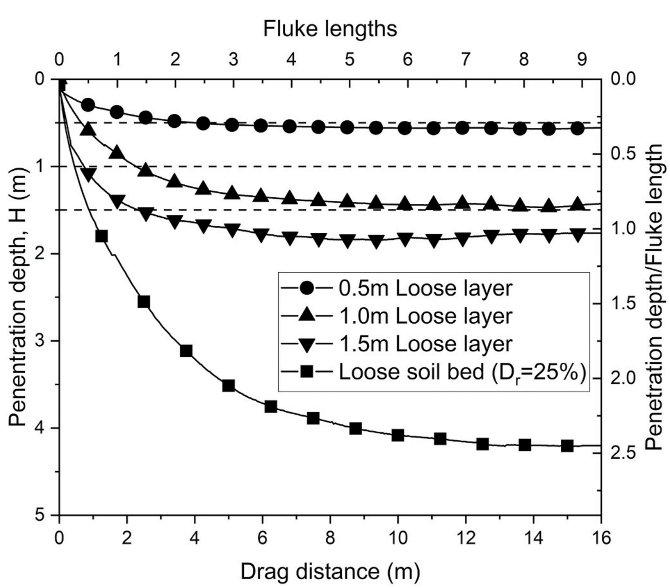


Fig. 6. Results of anchor penetration in layered sands of different thicknesses compared to penetration in uniform loose soil.

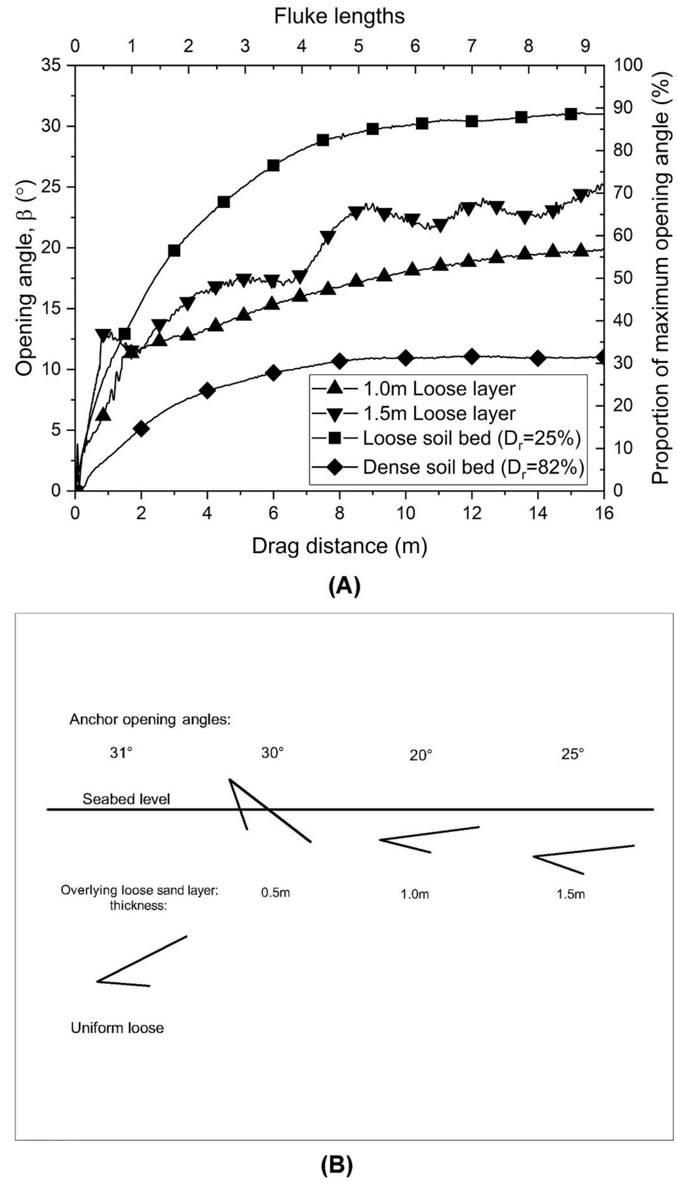


Fig. 7. Comparison of a, anchor opening angles (0.5 m layer opening angles not shown due to difficulties in deduction with the overturning anchor behaviour in this case) and b, schematic of final anchor orientation when testing in layered sands.

1.5 m loose layer corresponding to similar perturbations observed in the opening angle measurements (Fig. 7a).

On obtaining this layered soil data it is possible to test and comment on layered penetration prediction methods such as the one recently proposed by Davies et al. (2025). One drawback of the Davies et al. (2025) methodology is it requires knowledge of the evolution of specific anchor drag depth with drag distance and how this relates to the evolution of ultimate holding capacity (UHC) for a specific anchor. This information may be published for some anchors, for example in the Vryhof Anchor Manual (Vryhof, 2018) for their products, but it is not necessarily easy information to find for different anchor types/manufacturers. The Vryhof Manual assumes the same evolution of depth and force across all its anchor types and does not appear to reflect any differences in soil conditions. It is also not clear how this varies with mass of the anchor (which in turn effects geometry) as such information is not reported. Bird et al. (2026) suggest that penetration scales well across a broad range of anchor sizes/mass, but capacity efficiency may increase at a reduced rate compared with some published sources as

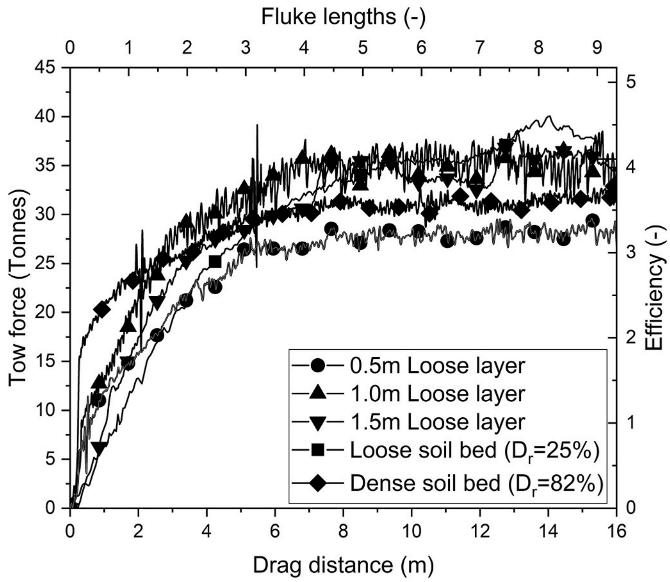


Fig. 8. Comparison of effect of soil layering on anchor tow force.

anchor mass increases. With access to physical modelling data such relationships are straight forward to create and are shown in Fig. 9 for the AC-14 anchor tested compared to a Vryhof standard evolution curve based upon the uniform soil test data published by Sharif et al. (2024).

Fig. 9 shows that that in medium dense and loose soils evolution is similar for the AC-14 anchor but a different profile is obtained in dense sand where capacity increases at an initially rapid rate up to approximately 50% UHC at sub 20% penetration. As Vryhof only publish a single evolution curve and there is no mention of a density effect or curves for different relative densities, it would seem there is a need to characterise anchor depth-force evolution under different soil conditions. The rapid increase in the anchor load (Fig. 9) in the dense sand for the AC-14 was observed by Sharif et al. (2024) in both centrifuge and repeat testing at 1g and thus appears to be an artefact of the anchor type "biting into" or "snagging" in dense soil rather than a testing issue.

Based upon the insights from Fig. 9 the performance of the layered-soil penetration prediction approach proposed by Davies et al. (2025) can be tested and in this case the 1.5 m thick loose layer over dense was

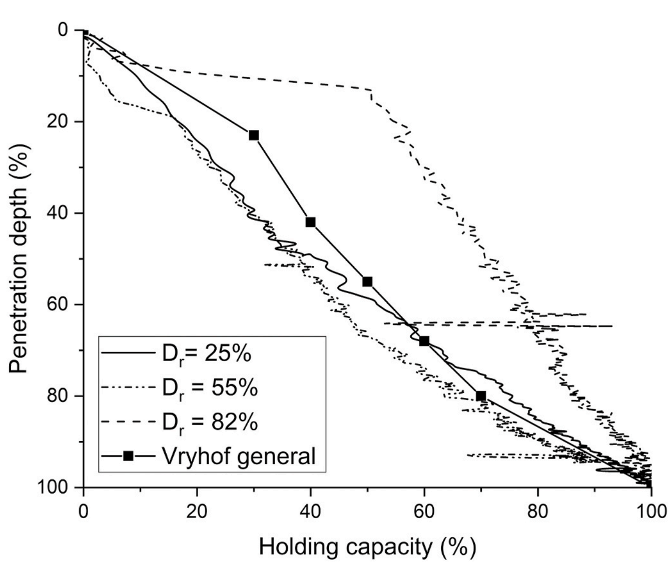


Fig. 9. Comparison of evolution of penetration depth and relationship to anchor holding capacity for the AC14 anchor tested in different relative densities compared to a Vryhof standard curve.

chosen (Fig. 6) as this represents a relatively significant depth of loose sand. Purely, following the approach outlined in the Carbon Trust methodology with a 45° opening angle (Equation (1)) the anchor would only penetrate to 1.212 m and not leave the loose sand layer ($SF = 1$ irrespective of sand density). This is at odds with the loose sand only penetration results as shown in Fig. 6. It is also significantly lower than the results obtained from centrifuge testing in the layered soil profile where final penetration was recorded in the dense layer at 1.767 m. Thus, in terms of cable protection a cable would require burial in the dense underlying layer which may require different burial plant or reduced installation progress rates (Robinson et al., 2021).

Fig. 10 shows the results of the approach outlined by Davies et al. (2025). The method proceeds by working out how much of the anchor's ultimate holding capacity (UHC) is "used up" in each soil layer and assumes 100% UHC occurs at the final calculated penetration (H_{ult}), however the method requires published penetration-UHC evolution relationships. In this methodology the normalised penetration depth and holding capacity are determined based upon the maximum penetration

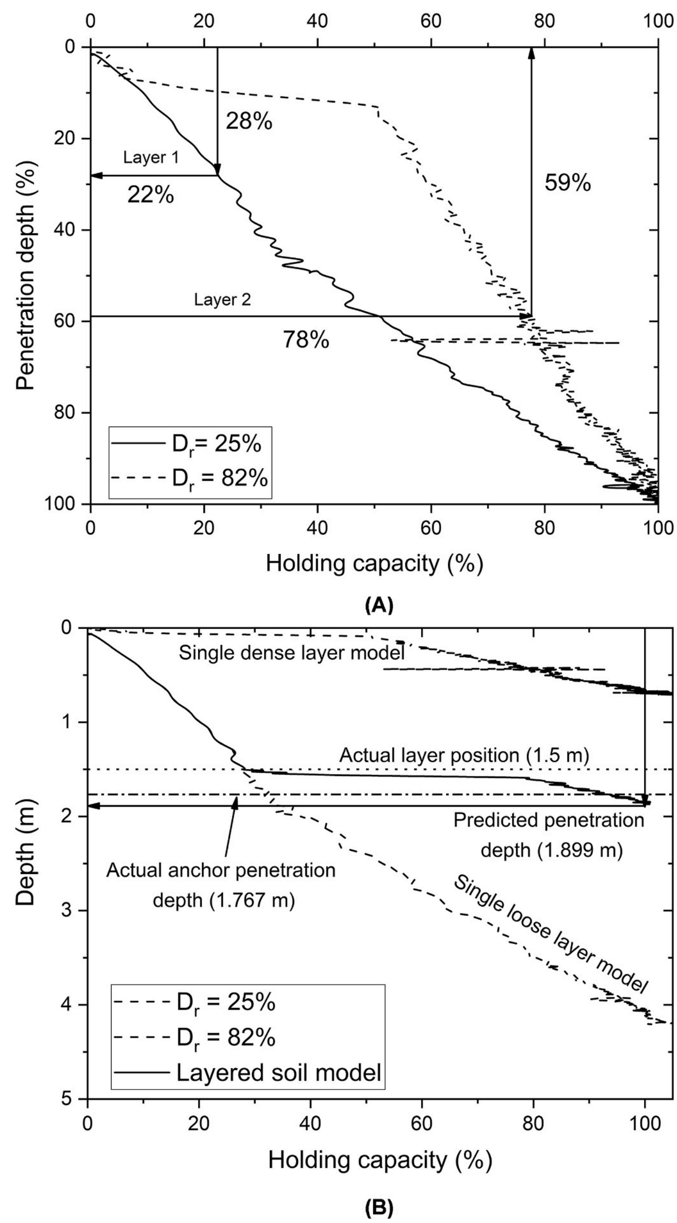


Fig. 10. Figures highlighting Davies et al. (2025) approach to CBRA a, UHC "used up" in each layer, b, Comparison of predicted penetration to measured.

and holding capacity determined in the uniform soil conditions determined by Sharif et al. (2024) and re-interpreted in Fig. 9. In this case the centrifuge test data was used to inform this and the anchor penetration calculated based upon realistic back figured soil factors ($SF_{\text{loose}} = 4.4$ adopted, rather than 1 in CBRA guidance, with a fixed 45° anchor opening angle). Fig. 10a shows in the overlying 1.5 m deep loose sand that penetration would be 28% of the total anchor penetration depth when passing into the dense soil and that 22% of the UHC would be "used up". This then requires 78% of the remaining UHC to be used up in the underlying dense layer which corresponds to 59% penetration into the dense layer (Fig. 10a). As both the loose and dense data shown in Fig. 10a are normalised these % penetrations do not relate directly to % penetration into a layer. The effect of the approach in terms of absolute penetration depth is shown in Fig. 10b. The results show with the real anchor penetration data that this method predicts a penetration of 1.889 m which is an overprediction of 7% and safe. Without access to the measured data and based purely upon the Vryhof relationship (Fig. 9) the method would have predicted greater burial depth, increased cost and limitations on installation plant.

Although the Davies et al. (2025) approach appears to have performed well and to have some merit, it has in some part only done so based upon detailed knowledge of the realistic AC-14 kinematics through prior characterisation in uniform soils. This has then been used with a correction to the current CBRA methodology and uses specific soil factors for the AC-14 anchor final/limiting penetration depth in each layer density (Brown et al. (2026)). The latter themselves mask the complexity of the anchor kinematics which are shown to vary in the layered soils (Fig. 7b) and do not conform to the fixed opening angles adopted in the analysis. It is also clear that at no stage (Fig. 7b) does the anchor shank become horizontal, which is the basis of Equation (1).

3.2. Ploughed route-Anchor interaction

Fig. 11 shows the results of the anchor penetrating through a cable ploughed installation with the anchor interacting with a deep cable trench (3 m) at different approach angles. This is compared with anchor behaviour in uniform dense soil ($D_r = 82\%$). It can be clearly seen that there is little impact on the anchor penetration behaviour, tow force or roll (Figs. 12 and 13) due to the limited width of the plough share and associated disturbance zone/trench (trench width = 0.11FL). In Fig. 12, tow force is also shown as anchor efficiency which is the anchor tow

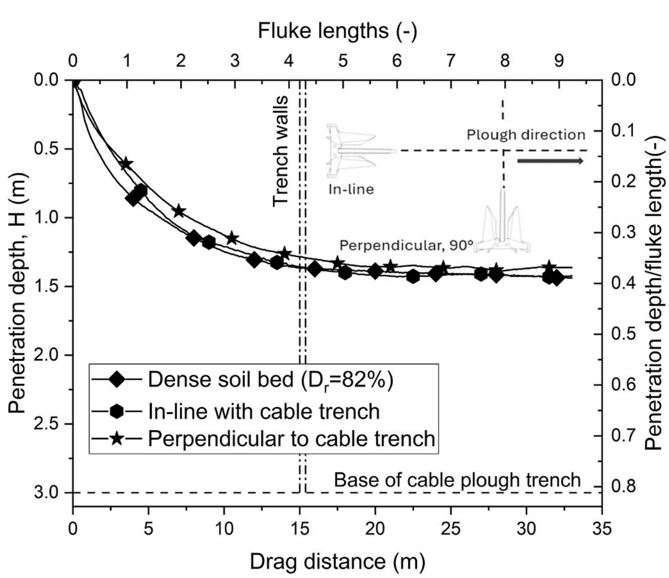


Fig. 11. Comparison of effect of cable plough trenches on anchor penetration depth with different anchor approach directions (note: trench wall position not relevant for in-line case).

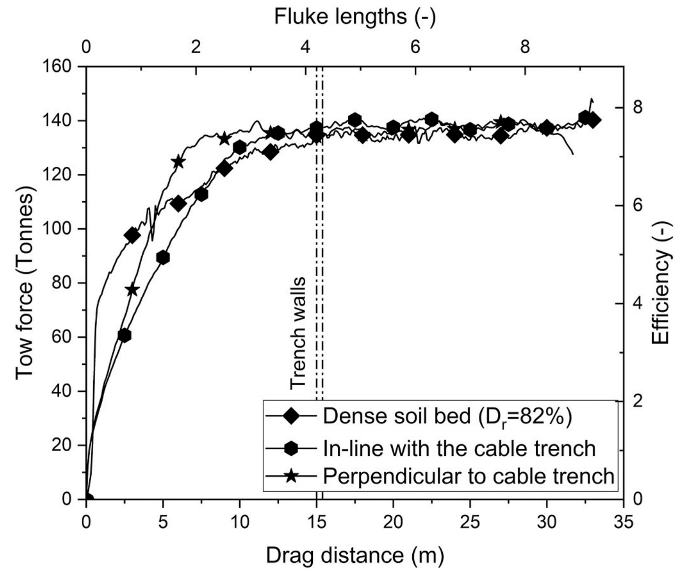


Fig. 12. Comparison of effect of cable plough trenches on anchor tow forces with different anchor approach directions (note: trench wall position not relevant for in-line case).

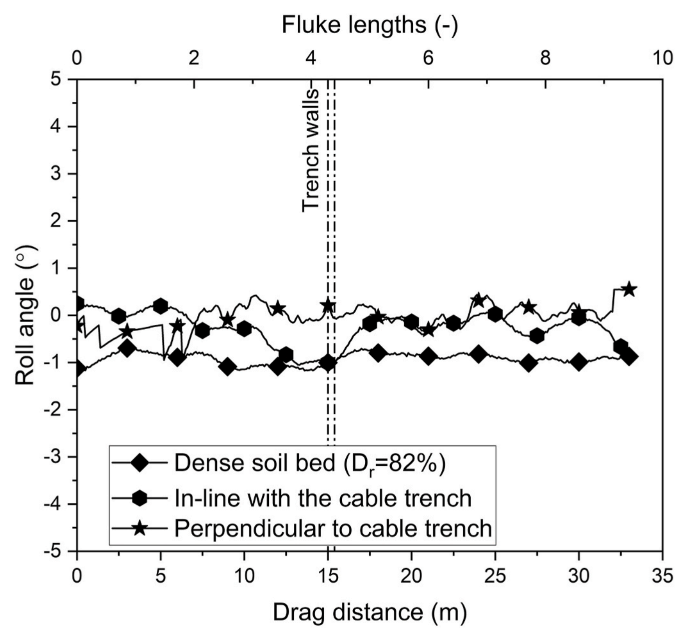


Fig. 13. Comparison of effect of cable plough trenches on anchor roll with different anchor approach directions (note: trench wall position not relevant for in-line case).

force or holding capacity normalised by the anchor mass.

In this assessment, only the added effect of the trench and backfill material are considered, with no cable present. While a cable within the anchor's penetration depth would interact with the anchor, anchor penetration appears unaffected by cable ploughing. Therefore, the results from uniform soil CBRA appears not to require any additional modification for cable plough trenches. Intersection of the cable plough trench at 45° was not attempted due to the limited trench width relative to anchor fluke length. However, this approach was used in V-shaped ploughs as described in the following.

In contrast to anchor interactions with cable ploughed routes, when ploughing through the backfilled V-shaped pipeline trench (6.672 m wide or 1.87FL at the surface and 1.960 m deep) there is some apparent affect with respect to depth, but this is limited when crossing the trench at 45 or 90°. Though the depth in the perpendicular case does increase by 6.5% (Fig. 14). When the anchor runs along the trench (in-line), the anchor penetrates much deeper as the trench at the surface is 1.47 times wider than the anchor and the anchor does not interact with the trench walls until at least 0.61 m penetration. As a result, the anchor penetrates the soil below the trench which would result in definite interaction with the cable or pipeline. This appears similar to the loose over dense layered soil case (1.5 m) where penetration is limited by the underlying dense layer (Fig. 6). It is noted that the penetration depth within the trench will depend on the width of the anchor relative to the width of the trench and the specific seabed material encountered and further investigation is required for different anchor sizes and soil types.

The pattern of anchor tow force is also consistent, with in-line anchoring showing a less "stiff" response in the loose backfill material but tending to a similar final tow force as seen in the denser materials (Fig. 15). However, this is not the case for the anchor interacting with the ploughed trench at 45° where lower tow forces are generated. This behaviour is a result of the anchor initially interacting with the inclined walls of the trench which induces a significant roll in the starboard direction or right side of the anchor tipping downwards (Fig. 16) that only stabilises as the fluke leaves the trench. This seems consistent with the onset of the small reduction in anchor depth seen in Fig. 14.

Interaction with a pipeline trench at 90° or 45° suggests that CBRA approaches in uniform or layered soil CBRA do not require significant additional modification (6.5% depth increase for perpendicular case). In contrast, anchoring along the direction of the cable or pipeline seems to have a high potential for damage but potentially a low probability of occurrence. The reason for the varying anchor behaviour for pipeline type trenches can be seen in the changes to soil backfill density relative to the surrounding soil shown in Fig. 17, which is initially significantly different from the far-field dense soil being very loose near-surface and tending to loose with increasing depth. The CPT senses the base of the trench 1.3 diameters before penetrating the dense underlying soil. Fig. 17 shows the depth to which the plough penetrated, and the post-plough trench depth prior to backfilling where some trench wall collapse and trench infill is often encountered. The difference between the relative density profiles for the in-line and perpendicular trenches reflects the difference in formation methodology in the model study where in-line trenches were created by model ploughing and perpendicular (across the centrifuge box) were created manually to mimic the

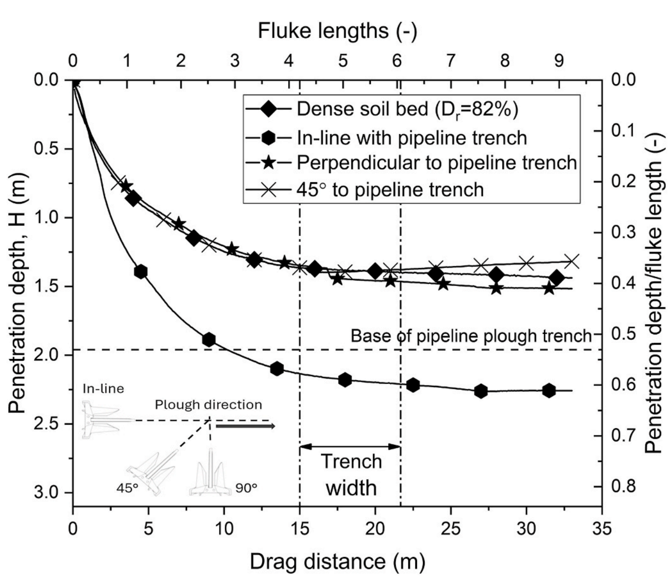


Fig. 14. Comparison of effect of pipeline plough trenches on anchor penetration depth with different anchor approach directions (note: trench wall position not relevant for in-line case).

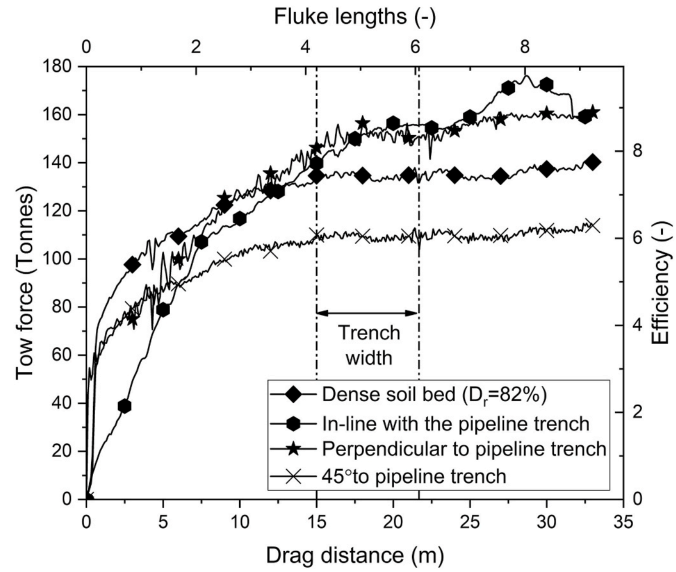


Fig. 15. Comparison of effect of pipeline plough trenches on anchor tow forces with different anchor approach directions (note: trench wall position not relevant for in-line case).

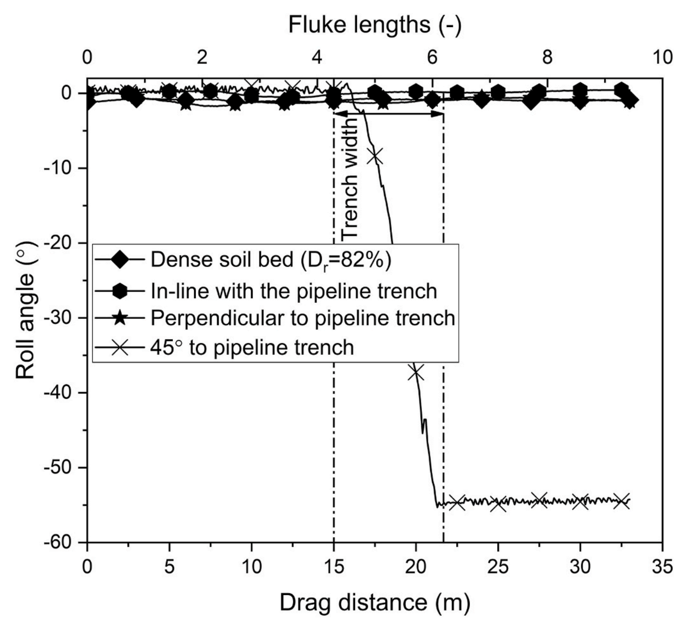


Fig. 16. Comparison of effect of pipeline plough trenches on anchor roll with different anchor approach directions (note: trench wall position not relevant for in-line case).

ploughed trench profile and relative density (as described previously). Characterisation of the cable plough trench was not undertaken during this study due to the relative diameter of the CPT to the width of the unsupported trench formed (1.47 times).

It is noted that the CPT based derivation of the density in the dense soil bed suggests relative density approximately 7% under that which it was actually prepared at (calibrated by sand density pots as part of the pluviation and soil bed preparation process). This is thought to be due to issues with the CPT density correlations (Knappett and Craig, 2020) where these are based upon normalised CPT data ($q_c/\acute{\sigma}_v$) over the range 300-6000, where at the shallow depths and low effective stresses encountered during anchoring or ploughing values of the order of 200 may be more common.

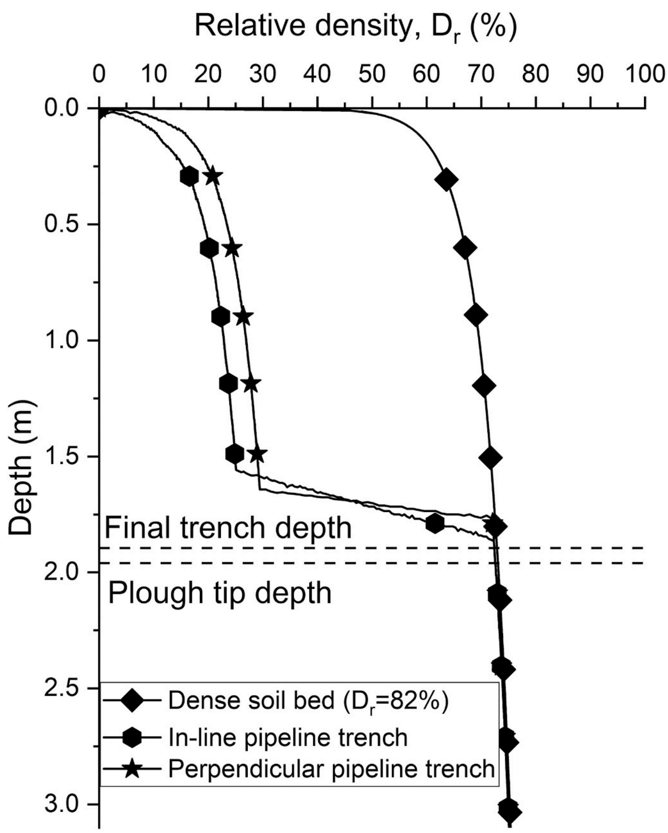


Fig. 17. Post trench formation and backfilling characterisation of the backfilled trenches based upon CPT correlation.

Such low relative densities have been noted previously in field studies after trench formation in sands by jetting, where the study by Powell et al. (2023) showed that the sands in question regained up to 50% of their initial pre-trenching density after 7 months and 65 months (or approximately 5.5 years) respectively. In the case of the relatively free draining sands encountered this varying time for strength regain was predominantly attributed to wave action with combined effects of sea state and water depth influencing induced seabed shear stresses at the two sites studied. Such modification in sand density with time may be another variable that CBRA needs to be aware of especially where V-shaped ploughs or wide jet trenches are formed or CBRA approaches are applied to pipeline (rather than cable) depths of lowering. This also suggests that buried assets are most vulnerable just after they have been installed but risks may reduce with time at considerably different rates based upon wave action and local site conditions.

4. conclusions

Based upon the results presented in this study the current approach to cable burial risk assessment (CBRA) adopted for uniform soils does not reflect the behaviour seen in layered soils. Therefore, there is scope to improve current CBRA methodologies, but this requires well characterised recorded anchor behaviour for different anchor types, mass and in different soil conditions, which may not be in the public domain for many common anchor types.

Anchoring in layered sand consisting of loose over dense sand, as commonly encountered in the North Sea, shows that anchor penetration is quickly limited by the dense underlying layer. Penetration in loose sand is much greater than the current CBRA approach suggests, and loose and dense sand cannot be “classified” as having the same behaviour as in the current approach. Using a recently developed method for CBRA in layered soils shows good performance where this approach is based upon well characterised model anchor characterisation and adoption of optimised CBRA input parameters, but the method does not mirror true anchor kinematics.

For the single anchor and cable plough trench geometry in sand investigated here, and in the absence of a physical cable, there appears to be a limited, effect on anchor behaviour when encountering a vertical cable plough trench path, irrespective of the anchor approach direction/orientation. Similarly, for a backfilled V-shaped trench, which results in looser backfill compared to the native soil, there appears to be limited effect on anchor depth where the anchor interacts with the ploughed route at 90° and 45° (6.5% increase in depth when interacting at 90°). Although anchors may roll significantly at approach angles less than 90°, this appeared to reduce anchor penetration depth and anchor capacity, with roll stabilisation not occurring until after the trench was exited. Whereas when the anchor follows the trench route the anchor dives to the base of the trench and the fluke passes through it to approximately 1.15 times the trench depth into the underlying dense sand, in the case investigated. It is noted that this risk may reduce with time after cable or pipeline plough installation due to wave induced soil trench backfill density changes. The penetration depth will also depend on the width of the anchor relative to the width of the trench and further investigation is required for different anchor sizes and soil types.

This study shows that both layered sand and trenched sands may have a significant impact on current CBRA approaches depending on the nature of the layering, type of trenching methodology and how the anchor approaches a trench. Current CBRA approaches may, in the main, be overly simplistic and not reflect true anchor behaviour in different soil types or cable installation scenarios. For CBRA methods to improve there is a need for broader high-quality characterisation of different anchor types and mass in a wider range of soil conditions.

It is noted that only one anchor type was selected for study due to it being a common anchor type in shipping applications. The behaviour of other anchor types and geometries, in a wider set of soil types may vary from that shown here and would require further investigation to allow generalisation of the findings. It is hoped though that in the near future that this will occur through efficient numerical simulation techniques and that the results of the study can be used to aid development and validation of such techniques.

Data statement

All of the data used are available from the corresponding author by request.

CRediT authorship contribution statement

Yaseen Umar Sharif: Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Michael John Brown:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **Duncan Stevens:** Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Robert E. Bird:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **William M. Coombs:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Charles E. Augarde:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Catriona Macdonald:** Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Al-Defae, A.H., Caucis, K., Knappett, J.A., 2013. Aftershocks and the whole-life seismic performance of granular slopes. Geotechnique 63 (14), 1230–1244. https://doi.org/10.1680/geot.12.P.149.

Bird, R.E., Coombs, W.M., Brown, M.J., Augarde, C.E., Sharif, Y.U., Prettia, G., Macdonald, C., Stevens, D., Carter, G., 2026. Three-dimensional modelling of drag anchor penetration using the material point method. Ocean Eng. 358 (2). https://doi.org/10.1016/j.oceaneng.2026.125456.

Bird, R.E., Prettia, G., Coombs, W.M., Augarde, C.E., Sharif, Y.U., Brown, M.J., Carter, G., Macdonald, C., Johnson, K., 2025. A dynamic implicit 3D material point-to-rigid body contact approach for large deformation analysis. Int. J. Numer. Methods Eng. 126 (14). https://doi.org/10.1002/nme.70080.

Boyes, S., 2011. Physical Modelling of the Mechanical Backfilling Process. University of Dundee, UK. MSc Dissertation.

Bransby, M.F., Barlow, D., Brown, M.J., Davidson, J., Brankin, S., Robinson, S., 2018. The performance of pipeline ploughs traversing seabed slopes. Ocean Eng. J. 148, 125–135. https://doi.org/10.1016/j.oceaneng.2017.11.028.

Bransby, M.F., Yun, G.J., Morrow, D., Brunning, P., 2005. The performance of pipeline ploughs in layered soils. In: Gourvenec, S., Cassidy, M. (Eds.), International Symposium on Frontiers in Offshore Geotechnics. CRC Press, Perth, Australia, pp. 597–606.

Brown, M.J., Sharif, Y.U., Bird, R., Coombs, W.M., Augarde, C.E., Macdonald, C., Stevens, D., 2026. Effect of drag rates on drag embedment anchor penetration for cable burial risk assessment. Géotech. Lett. https://doi.org/10.1680/jgele.25.00069. E-ISSN 2045-2543. Published AOP 15/12/25.

Burley, L.J., Terente, V.A., Hewiston, L.J., Stuart, H.J.M., 2023. Cable integrity risk assessment (CIRA). Offshore Site Investigation Geotechnics 9th International Conference Proceeding. Society for Underwater Technology, London, pp. 468–475.

Carbon Trust, 2015. Cable burial risk assessment methodology - guidance for the preparation of cable depth of lowering specification CTC835. Available at: https://www.carbontrust.com/our-work-and-impact/guides-reports-and-tools/cable-burial-risk-assessment-cbra-guidance-and.

Dao, D.A., Grabe, J., 2024. Numerical assessment of ship anchor penetration depth in Baltic Sea sand: implications for subsea cable burial. Ocean Eng. 314 (3). https://doi.org/10.1016/j.oceaneng.2024.119674.

Davidson, C., Brennan, A., Brown, M.J., Inglis, L., Vasudevan, S., 2023. Out of plane loading of drag embedment anchors for floating renewable energy technologies. 9th Int. SUT OSIG Conference “Innovative Geotechnologies for Energy Transition”. 12-14 September, 2023, pp. 1241–1248. London. ISSN 2754-6322.

Davies, S.R., Duménil, L., Syrda, P., 2025. A methodology for estimating anchor penetration in layered soils for cable burial risk assessments. Proceedings of ISFOG 2025 5th International Symposium on Frontiers in Offshore Geotechnics. Nantes, France. June 9-13th, 2025.

Haertsch, M., Knight, P., 2022. Cable burial risk assessment methods for layered soil. Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering, pp. 2633–2637. Sydney, Australia.

Johnson, K.R., Carter, G.D.O., Macdonald, C., 2024. Layered soil units of the shallow subsurface (<6.0m). In: Coombs, W.M., Bird, R.E., Augarde, C.E., Brown, M.J., Sharif, Y.U., Arnhardt, R. (Eds.), North Sea; A Data Report. British Geological Survey Open Report, OR/24/031.

Klinkvort, R.T., Hededal, O., 2013. Lateral response of monopile supporting an offshore wind turbine. Proc. Inst. Civ. Eng.: Geotech. Eng. 166 (2), 147–158. https://doi.org/10.1680/geng.12.00033. http://www.emerald.com/jgeen/article/166/2/147-158/392839.

Knappett, J., Craig, R., 2020. Craig's Soil Mechanics, ninth ed. CRC Press, London.

Lauder, K., Brown, M.J., Bransby, M.F., Boyes, S., 2013. The influence of incorporating a forecutter on the performance of offshore pipeline ploughs. Appl. Ocean Res. J. 39, 121–130. https://doi.org/10.1016/j.apor.2012.11.001. ISSN: 0141-1187.

Lauder, K., Brown, M.J., Bransby, M.F., Gooding, S., 2012. The variation of tow force with velocity during offshore ploughing in granular materials. Can. Geotech. J. 49 (11), 1244–1255. https://doi.org/10.1139/t2012-086.

Li, Z., Haigh, S.K., Bolton, M.D., 2010. Centrifuge modelling of mono-pile under cyclic lateral loads, Physical Modelling in Geotechnics - Proceedings of the 7th International Conference on Physical Modelling in Geotechnics. ICPMG 2, 965–970. https://doi.org/10.1201/b10554-159.

Luger, H., 2023. Impact of anchor type on anchor hazard assessment. Offshore Site Investigation Geotechnics 9th International Conference Proceeding. Society for Underwater Technology, London, pp. 1233–1240.

Luger, D., Harkes, M., 2013. Anchor tests German bight - detecting the penetration depth of ship anchors, hydrographische nachrichten. Available at: https://www.iscpc.org/information/marine-resources/anchors-and-anchoring/.

Macdonald, C., Carter, G., Johnson, K., Augarde, C.E., Coombs, W.M., Bird, R., Brown, M.J., Sharif, Y.U., 2023. Depth of lowering and layered soils; a case study from across the North Sea. 9th Int. SUT OSIG Conference “Innovative Geotechnologies for Energy Transition”. 12-14 September, 2023. London.

Moore, E., Haigh, S.K., Eichhorn, G.N., 2021. Anchor penetration depth in sandy soils and its implications for cable burial. Ocean Eng. 35, 109411. https://doi.org/10.1016/J.OCEANENG.2021.109411.

Naval Civil Engineering Laboratory, 1982. Drag Embedment Anchor Tests in Sand and Mud - NCEL Techdata Sheet. Port, Hueneme, CA, USA. Available at: https://apps.dtic.mil/sti/citations/ADB068224. (Accessed 15 July 2025).

Peng, j., Liu, H., Liang, K., Xiao, Z., 2021. A theoretical model for analyzing the behavior of drag anchors in layered soils. Ocean Eng. 222 (2021), 108568.

Powell, T.A., White, D.J., Alvarez-Borges, F., Fearn, M., 2023. In-situ testing in trench backfill: evidence of evolving backfill density. 9th Int. SUT OSIG Conference “Innovative Geotechnologies for Energy Transition”. 12-14 September, pp. 476–483, 2023. London. ISSN 2754-6322.

Robinson, S., Brown, M.J., Brennan, A.J., Cortis, M., Augarde, C.E., Coombs, W.M., 2017. Improvement of seabed cable plough tow force prediction models. 8th Int. Conf. on Offshore Site Investigation & Geotechnics (SUT OSIG), 12-14th Sept 2, 914–921, 2017. London, UK. ISBN 13 978 0 906940 58 7.

Robinson, S., Brown, M.J., Matsui, H., Brennan, A., Augarde, C., Coombs, W., Cortis, M., 2019. Centrifuge testing to verify scaling of offshore pipeline ploughs. Int. J. Phys. Model. Geotech. 19 (6), 305–317. https://doi.org/10.1680/jphmg.17.00075.

Robinson, S., Brown, M.J., Matsui, H., Brennan, A.J., Augarde, C., Coombs, W.M., Cortis, M., 2021. A CPT approach to cable plough performance prediction based upon centrifuge model testing. Can. Geotech. J. 58 (10), 1466–1477. https://doi.org/10.1139/cgj-2020-0366. ISSN 0008-3674.

Robinson, T., Brown, M.J., Brennan, A.J., Cortis, M., Augarde, C.E., Coombs, W.M., 2016. Development of low cost 3D soil surface scanning for physical modelling. In: Thorel, L., Bretschneider, A., Blanc, M., Escofier, S. (Eds.), 3rd European Conference on Physical Modelling in Geotechnics (Eurofuge 2016). Nantes, France, pp. 159–164, 1-3 June 2016. ISBN 978-2-85782-716-0.

Sharif, Y.U., Brown, M.J., Coombs, W.M., Augarde, C.E., Bird, R., Carter, G., Macdonald, C., Johnson, K., 2023. Characterization of anchor penetration behaviour for Cable burial risk assessment. 9th Int. SUT OSIG Conference “Innovative Geotechnologies for Energy Transition”. 12-14 September, 2023, pp. 555–562. London. ISSN 2754-6322.

Sharif, Y.U., Brown, M.J., Davidson, C.D., Knappett, J.A., Coombs, W.M., Augarde, C.E., Bird, R., Carter, G., Macdonald, C., Johnson, K.R., 2024. Comparison of 1g and centrifuge modelling of drag embedment anchors with subsurface wireless tracking. Int. J. Phys. Model. Geotech. 25 (2), 102–114. https://doi.org/10.1680/jphmg.24.00029.

SMD, 2018. HD3-300 Heavy Duty Plough Specifications, Soil Machine Dynamics Ltd. Newcastle-upon-Tyne, UK. https://www.smd.co.uk/wp-content/uploads/2017/01/HD3-300.pdf_0.pdf. (Accessed 6 January 2026).

Ueno, K., 2000. Methods for preparation of sand samples. In: Kusakabe, Kimura, Takemura (Eds.), Proceedings of the International Conference Centrifuge 98, 23-25 September 1998. Tokyo, Japan, Vryhof 2018. Vryhof Manual: the Guide to Anchoring. Vryhof. Available to down load from. https://insights.delmarsystems.com/download-the-vryhof-manual. (Accessed 12 December 2025).