**Proceedings of ISFOG 2025**
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025
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ISBN 978-2-85782-758-0

# A Methodology for Estimating Anchor Penetration in Layered Soils for Cable Burial Risk Assessments

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**ABSTRACT:** Anchors represent a significant hazard to subsea cables as they are designed to penetrate the seabed to generate sufficient holding capacity to moor vessels safely. Cable burial risk assessments (CBRA) are required in order to develop a suitable burial protection strategy for subsea cables, and this requires estimation of the potential penetration of an anchor. Where practical and technically feasible, cables are ideally located beneath the potential anchor penetration depth. Anchor penetration is a function of anchor type and size as well as the soil type and geotechnical characteristics. General anchor holding capacity estimation methods, such as the Naval Civil Engineering Laboratory's Techdata Sheet on drag embedment anchors for moorings, provide guidance on the anchor penetration trajectory for specific soil types. This may underestimate or overestimate anchor penetration as in reality the shallow geology often consists of layered sediments where the soil type and geotechnical characteristics vary with depth, thereby impacting anchor penetration trajectory. This paper presents a simplified conceptual method for estimating the anchor penetration depth in layered soils based on relationships between drag distance, holding capacity and anchor penetration for different anchor types in different soil types. Stockless, fixed, drag embedment anchors are utilized to illustrate the concept. The aim of this method is to provide a further boundary to the envelope of anchor penetration estimation to help understand the potential risk to cables and enable a more considered approach to the cable protection strategy.

**Keywords:** Anchor Penetration; Layered Soils; CBRA

## 1 INTRODUCTION

The renewable energy industry uses subsea cables to transmit offshore generated electricity to and between grid sectors. Globally, an estimated 200 to 300 subsea cable faults occur annually (e.g. Clare et al., 2023). Cable fault reduction is critical for network resilience and supply continuity. Burial of the cable below seabed elevation protects cables from many natural and anthropogenic threats that lead to faults and Shapiro et al (1997) noted that cable fault occurrences typically reduce due to burial. Moore et al (2021) noted that cable armour does not generally protect against dropped or dragged anchors and additional protection such as rock installation, or mattresses, may be more effective, but attracts higher cost which can vary with water depth. Cable burial, however, is reasonably straightforward, economical and effective (Sharif et al, 2023), although attracts additional risk to cable integrity through cable handling, management, physical burial and thermal impact on cable life.

Allan (1998a) highlighted the importance of balancing the protection provided by burial and the ease of cable recovery for maintenance. Furthermore, overspecifying burial depths that are not acheivable in practice can increase costs and be problematic for projects, particularly if burial depth and additional protection measures are linked to consent conditions.

Whilst the depth a drag embedment anchor (DEA) can penetrate is limited, it is often not cost-effective or achievable to bury the cable below the largest anchor penetration anticipated. Cable Burial Risk Assessments (CBRA) typically focus on vessels tansiting across or operating in the project area and the majority of these vessels utilise DEA. CBRAs assess the likely anchor size (mass, fluke length etc.) and utilise probablilistic assessment to evaluate risk to cables from different anchor sizes and other external threats. This balances risk and protection associated with different burial depths, enabling a project-specific compromise between cost and probabilisitc risk (Sharif et al, 2023).

Modelling vessel anchor penetration is complex and is typically approximated through simplified theoretical and numerical methods, which generally utilise single-layer soil models. Models of two or three soil layers are available (e.g. Haertsch & Knight, 2022), Peng et al (2021)), and are often backed by experimental data.

Test data from field trials provide realistic penetration paths and capacity for specific anchors, however understanding the soil conditions throughout the anchor trajectory and relating this to general anchor behaviour can be challenging. The current test database is relatively restricted in terms of DEA types, soil types, geotechnical characteristics and layer configuration.

Soil conditions often vary laterally and vertically across cable routes and consequently anchor penetration trajectories are non-linear (e.g. Peng 2021). Anchor penetration assessment is therefore typically idealised by zoning the cable route according to the generalised geological conditions and considering the dominant soil type within the zone. Advanced analysis methods, such as finite element analysis, are generally used for geotechnical modelling in complex soil conditions and require advanced geotechnical data. Acquisition of this data and performing advanced analysis can be impractical over long routes with high variation in ground conditions; these are therefore not generally undertaken for CBRA and Burial Assessment Studies (BAS).

The method presented in this paper is a simplified semi-empirical method aimed at estimating the potential envelope of DEA penetration into layered soils. It is based on in-house and publicly available data on anchor penetration in soils of different types and geotechnical characteristics and this paper focusses on US Navy Stockless, fixed drag embedment anchors.

## 2 DEA INSTALLATION AND HOLDING CAPACITY

There is a wide variety of DEA types available, which share similar characteristics, but have different design concepts. The three main designs are stockless anchors, admiralty (stocked) and fluked anchors. As illustrated in Figure 1, key elements of these anchors include the fluke, shank and crown; the different configurations and geometries influence penetration depth and holding capacity (e.g. Miedema et al, 2006) and suitability in different seabed substrate and shallow geology.

DEA are installed by dragging the anchor along the seabed until it trips and engages with the seabed and penetrates into the seabed (American Bureau of Shipping (ABS), 2018). The theoretical ideal is that anchors penetrate in an exponential decay curve manner (Figure 2) along a horizontal distance, called the drag distance, or drag length, and the holding capacity increases with depth. The anchor moves parallel to the fluke, which incrementally rotates as the anchor penetrates until the fluke becomes horizontal. At this point the anchor cannot penetrate further and the ultimate holding capacity is achieved. Further load increases cause failure and the anchor drags through the soil with no additional penetration.

In reality, anchor holding capacity is more complex, depending on a variety of factors, such as anchor type, design geometry, weight, seabed penetration and soil types, characteristics and layering. A further factor is the mooring line itself, where the size and type, e.g. chain or wire, can impact penetration and resistance.

The Naval Civil Engineering Laboratory (NCEL) performed field trials investigating DEAs for navy moorings, partly supplemented with commercial data (NCEL, 1987). They related maximum embedment depth of the anchor to the anchor fluke length in mud and sand. The background dataset is not provided for further assessment, however the holding capacity for different DEAs of different weights in mud and sand were presented and illustrates a power function relationship for holding capacity with anchor weight for both sediment types.

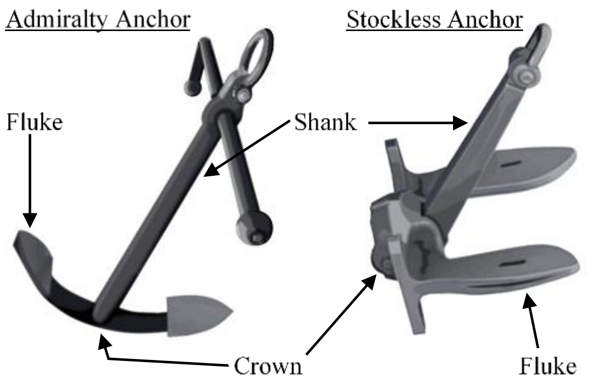


*Figure 1. Illustration of Anchor Types*

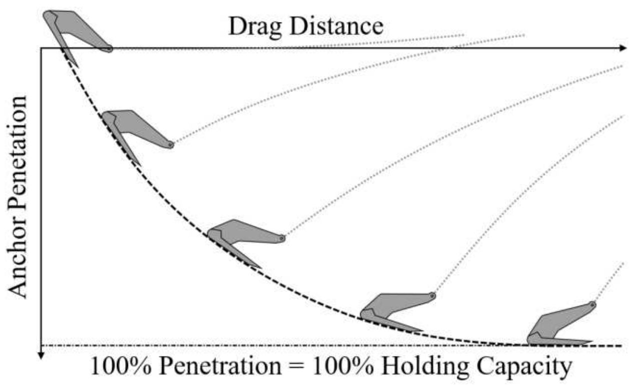


*Figure 2. Idealised Anchor Penetration Trajectory*

The Naval Facilities Engineering Service Centre (NFESC) and ABS present similar power function design charts for a variety of DEAs in “soft” and “hard” soil, which are often replicated in standards and guidance such as API (2008) and ISO (2013).

The NCEL also presented percentage holding capacities with drag distance/fluke length ratio for different DEAs in mud. From these data, stockless, fixed DEAs were noted to provide the lowest holding capacity of the anchors considered but are the most efficient in terms of rapidly achieving holding capacity with drag distance.

Some anchor manufacturers provide physical properties of their anchors and often provide an indication of anchor drag distance, penetration depth and holding capacity in single-layered soils (e.g. Vryhof, 2018).

This paper considers US Navy stockless, fixed drag embedment anchors, which are anchors commonly carried by vessels and exhibit drag distances to maximum holding capacity (and therefore maximum penetration) which are relatively short. US Navy stockless anchors generally have large fluke lengths and fluke length is a key parameter for estimating anchor penetration in line with NCEL (1984), Carbon Trust (2015) etc.

## 3 ANCHOR PENETRATION TRAJECTORY

The presented method is specific for estimating the maximum likely penetration of a DEA for CBRA and BAS. This paper considers the idealised anchor trajectory in terms of the percentage holding capacity generated at a percentage penetration depth within a particular soil type. The drag distance and holding capacity is not assessed. Complex behaviours, such as interactions between various anchor elements for example chain effects (e.g. Thorne, 1998); layer interface effects such as tripping along a soft/stiff soil interface, or transition effects through an interface; destabilisation; pull-out; post-installation effects etc. are not considered.

The idealised penetration trajectory of a DEA into a specific seabed sediment type, e.g. dense sand, soft clay, stiff clay etc., is typically presented in two ways:

1. Holding capacity with drag distance: the idealised path is an exponential decay curve, where after a certain drag distance the ultimate holding capacity is achieved, i.e. 100% capacity.
2. Anchor penetration with drag distance: the idealised increase in anchor penetration with drag distance follows an exponential decay curve where after a certain drag distance the maximum penetration depth is reached, i.e. 100% anchor penetration.

Such curves may be taken from publicly available data, or in-house data and are used to construct idealised curves of percentage holding capacity versus percentage anchor penetration within a specific sediment type.

The underlying principle is that irrespective of anchor size, 100% embedment depth will be achieved at 100% holding capacity within a particular soil type. The method is therefore dependent upon a database of the embedment trajectory and holding capacity for different anchors within different soil types.

Cables are typically recorded in navigation charts etc. and therefore to maintain cable integrity and supply security as far as possible, the likely anchor penetration depth typically considers an emergency or malicious anchoring case for different vessels transiting near the cable.

## 4 ESTIMATION OF PENETRATION IN LAYERED SOILS

The method presented considers that :

- The seabed is flat over the required drag distance, with no features or obstacles.
- The soil boundaries/interfaces are horizontal and even over the required drag distance.
- Soil layer boundary effects are not exhibited.
- The DEA is fully deployed and set on the seabed.
- Mooring line influences are not exhibited.
- The DEA is being dragged into the seabed.
- Complex DEA behaviours are not exhibited.
- The maximum penetration can be achieved.
- Soil strength is uniform within each layer, although sensitivity assessments can be undertaken using lower bound and upper bound strengths to bound the potential penetration.

For CBRA, deadweight tonnage (DWT) banding is used to determine the size of the anchors present (i.e. fluke length and mass) and therefore the maximum anchor penetration using anchor penetration factors for different soil types, according to NCEL, 1987:

$$z_{ult} = f_a \cdot F_L \cdot \sin \delta_a \quad (1)$$

where: $z_{ult}$ is the maximum anchor penetration; $f_a$ is the anchor penetration factor; $F_L$ is the fluke length, and $\delta_a$ is the fluke angle.

Definition of anchor penetration factors are beyond the scope of this paper, but examples can be found in NCEL, 1984, Carbon Trust, 2015 etc.

The thickness of each layer is used to determine the percentage utilisation of holding capacity and the residual anchor holding capacity available to penetrate into the next layer. The holding capacity generated from each layer is determined and an overall anchor penetration derived once the ultimate holding capacity is reached i.e. 100% holding capacity. The process is outlined in Figure 3.

The method is illustrated by considering two soil categories: hard and soft. Examples of hard soils include medium dense sand and stiff clays. Both soil categories have an idealised, non-linear percentage anchor penetration versus percentage holding capacity curve, as illustrated in Figure 4. The example ground model is presented in Table 1.

In this example, two DWT bands are adopted: DWT 6 and DWT 9, with corresponding esimated fluke lengths of 1.52 m and 2.43 m respectively.

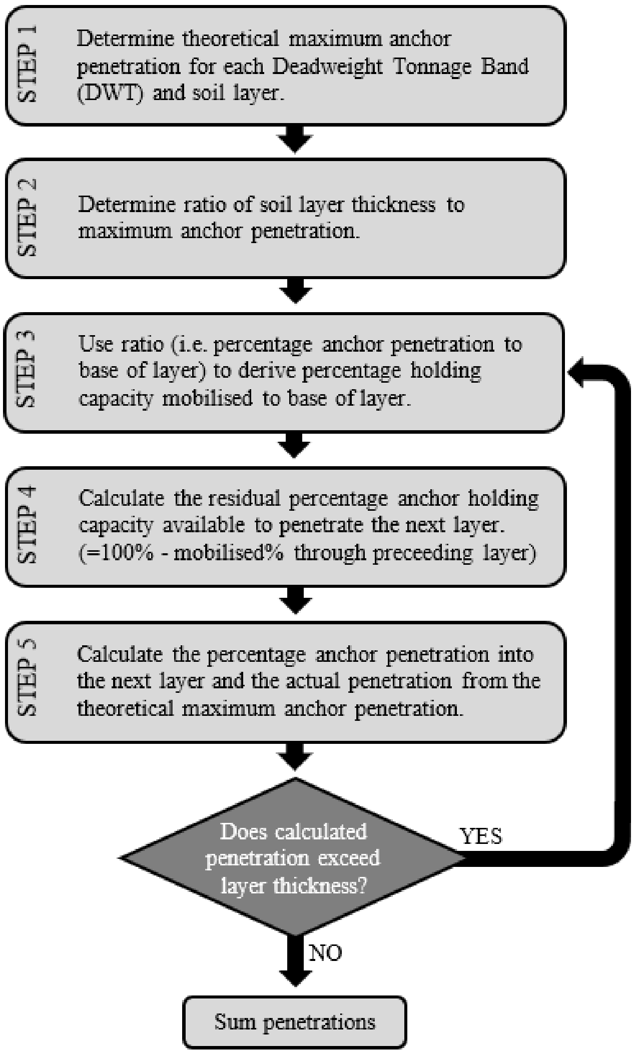


*Figure 3. Anchor Penetration Assessment Process*

**Step1:** Determine the maximum anchor penetration for each DWT band and soil layer using eq. (1):

*Table 1. Ground Model*

Layer 1, DWT6: $z_{ult} = 3 \cdot 1.52 \cdot \sin 50 = 3.49\,m$
Layer 1, DWT9: $z_{ult} = 3 \cdot 2.43 \cdot \sin 50 = 7.88\,m$
Layer 2, DWT6: $z_{ult} = 1 \cdot 1.52 \cdot \sin 32 = 0.81\,m$
Layer 2, DWT9: $z_{ult} = 1 \cdot 2.43 \cdot \sin 32 = 1.82\,m$
.

**Step 2:** Determine the ratio of soil layer thickness to maximum anchor penetration:

Layer 1, DWT6: $l_t/z_{ult} = 0.5/3.49 = 0.14$
Layer 1, DWT9: $l_t/z_{ult} = 0.5/7.88 = 0.06$
Layer 2, DWT6: $l_t/z_{ult} = 0.5/0.81 = 0.62$
Layer 2, DWT9: $l_t/z_{ult} = 0.5/1.82 = 0.28$

**Step 3:** Use ratio to derive the percentage holding capacity mobilised to base of layer using the relevant soft or hard soil idealised curves relating percentage anchor penetration to percentage holding capacity:

Layer 1, DWT6: $HC_{mob} = 17\%$
Layer 1, DWT9: $HC_{mob} = 6\%$

**Step 4**: Calculate the residual percentage anchor holding capacity at the top of the underlying layer:

Layer 1, DWT6: $HC_{res} = 100 - 17 = 83\%$
Layer 1, DWT9: $HC_{res} = 100 - 6 = 94\%$

**Step 5:** Calculate the percentage penetration into the underlying layer using the residual percentage holding capacity using the relevant soft or hard soil idealised curves relating percentage anchor penetration to percentage holding capacity, as illustrated inFigure 5.

Layer 2, DWT6: $z_{pen} = 75\%\ of\ theoretical\ z_{ult}$
Layer 2, DWT9: $z_{pen} = 91\%\ of\ theoretical\ z_{ult}$

**Step 6:** Calculate the actual penetration into the layer based on the theoretical maximum penetration into the layer:

Layer 2, DWT6: $z_{pen} = 0.75 \times 0.81 = 0.61\,m$
Layer 2, DWT9: $z_{pen} = 0.91 \times 1.82 = 1.66\,m$

As Layer 2 is only 0.5 m thick, anchors for both DWT band 6 and 9 will fully penetrate Layer 2 and begin to penetrate into Layer 3. As illustrated in Figure 3, the process returns to Step 3 to estimate the percentage holding capacity mobilised through Layer 3 and re-peats until the ultimate holding capacity and therefore ultimate anchor penetration, $z_{ult}$, is achieved. The penetration result is illustrated in Figure 4, along with single layer hard and soft soil models for comparison.

| Layer | Depth (mbsb) | | Thickness (m) | Soil Model | | | Anchor Penetration Factor (-) | Fluke Angle, δ (°) [b] |
|---|---|---|---|---|---|---|---|---|
| | | | | Type | Description | Category | | |
| 1 | Top<br>Base | 0.0<br>0.5 | 0.5 | CLAY | Low Strength | SOFT | 3 | 50 |
| 2 | Top<br>Base | 0.5<br>1.0 | 0.5 | SAND | Medium Dense | HARD | 1 | 32 |
| 3 | Top<br>Base | 1.0<br>1.5 | 0.5 | CLAY | Low Strength | SOFT | 3 | 50 |
| 4 | Top<br>Base | 1.5<br>2.5 | 1.0 | SAND | Dense | HARD | 1 | 32 |
| 5 | Top<br>Base | 2.5<br>α [a] | β [a] | CLAY | High Strength | HARD | 1 | 32 |

Notes:
- **a.** Unless underlain by an impenetrable stratum, the depth of the base layer, α, and the corresponding thickness, β, is taken as the maximum possible anchor penetration in that soil
- **b.** Vryhof 2018

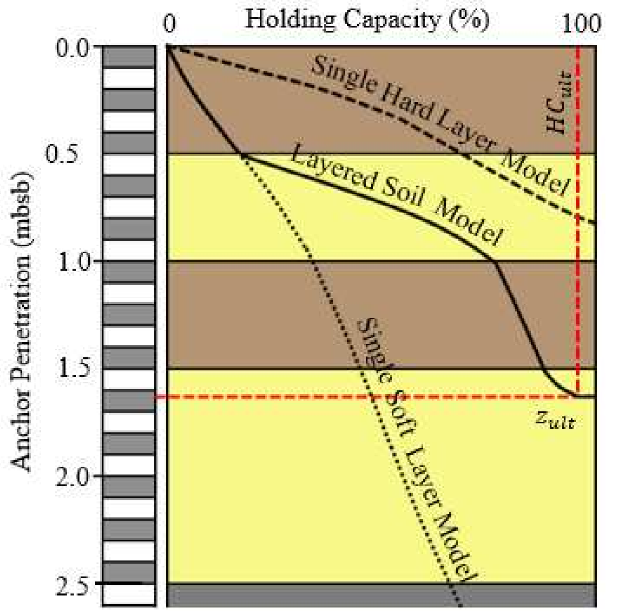


*Figure 4. Illustration of Simplified Anchor Penetration Through a Layered Soil Profile*

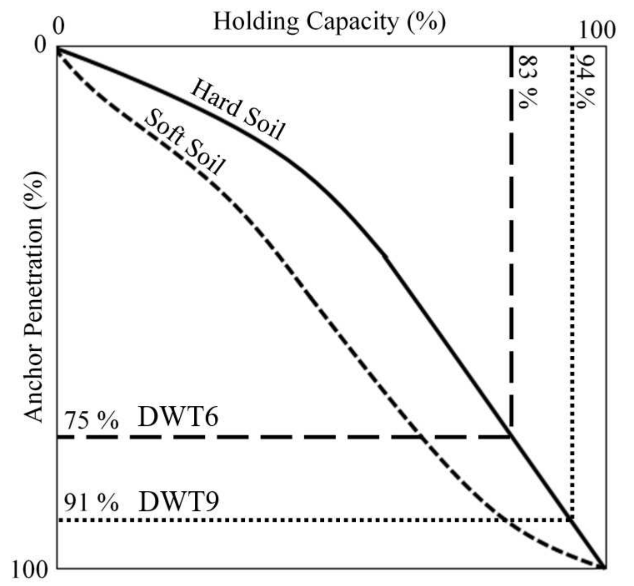


*Figure 5. Utilising Idealised Soil Curves to Derive % Anchor Penetration from % Residual Holding Capacity*

## 5 CONCLUSIONS

This paper presents a simplified method to assess theoretical anchor penetration into a layered seabed using data relating anchor holding capacity and anchor penetration for specific soil categories and specific anchor types.

As an idealised method, other effects such as anchor chain influence, soil stresses, deformation mechanisms, destabilising effects of non-uniform soil layers, etc. are not explicitly considered.

The method aims to provide additional insight into DEA penetration assessment design envelopes for buried asset protection in cases where detailed assessments or analysis, such as finite element analysis, may not be possible due to limitations such as the availability of the required geotechnical parameters.

The method is consistent with the anchor penetration factor method commonly used within the industry, e.g. Carbon Trust, 2015. To refine estimates further, soils intermediate between "soft" and "hard" could be assigned additional categories, or anchor penetration factors could be linked to soil strength and density, etc. However, the majority of publicly available data for anchor holding capacity versus anchor penetration typically covers "soft" or "hard" soils and is not specific to soil types and geotechnical characteristics.

Method validation against other calculation methods, advanced analysis, physical modeling or anchor testing has not been comprehensively completed and is the subject of future study.

Ulitimately, the recommended depth of lowering for a buried asset should be selected based on asset risk assessment and balanced with the costs of installation and retreival for maintenance or decommissioning.

## AUTHOR CONTRIBUTION STATEMENT

**Simon Davies**: Conceptualisation and methodology, Data curation, Writing- original draft. **Louis Duménil**: Model implementation, Conceptualization, Writing- original draft. **Peter Syrda**: Model review, Writing- review and editing.

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*The paper was published in the proceedings of the 5th International Symposium on Frontiers in Offshore Geotechnics (ISFOG2025) and was edited by Christelle Abadie, Zheng Li, Matthieu Blanc and Luc Thorel. The conference was held from June 9th to June 13th 2025 in Nantes, France.*