On The Pre-Lay Trench Tool Design

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Abstract

The significant growth in offshore wind activities in boulder clay areas requires suitable cable protection solutions. It is desirable to create a trench prior installation of the cable in order to guarantee the target depth of burial. Modern equipment of available on the market can be refined in order to create a reduced footprint, both economical and environmental. For this thesis there is looked into an innovative solution to create a pre-trench by utilization of a classic dredging vessel. Several alternatives are investigated. However, eventually two different mechanical cutting methods were selected for detailed investigation as a consequence of a multi criterion analysis. One uses counter rotating shredders and the other concept consists of an inclined screw conveyor. After physical considerations it turns out the screw conveyor has the best potential and is therefore subjected to a detailed design.

1 Introduction

Offshore wind power is the use of wind farms located offshore, for harvesting wind energy in order to generate electricity. The offshore wind farms are connected to the onshore grid via power cables. The wind turbines are connected to an offshore substation by means of infield cables and consequently the offshore substation is connected to the onshore grid via export cables. Cable protection is required in order to avoid economic losses as much as possible due to damage on the cable.

Various techniques can be deployed to bury the cable, such as rock placement, installation of mattresses, mechanical trenching, ploughing and jetting. Among other things depending on soil conditions, one method can be more suitable than another one.

Furthermore, the cable can be installed either after trenching (pre-lay), simultaneously (simultaneous lay and burial) or prior trenching (post-lay). Post-Lay is cost-effective, however, deploying dedicated burial tools, such as trenchers in stiff soils could result in unsatisfactory burial depths due to the cohesive character of the soil. Therefore in these areas is a pre-lay burial method more desirable. Creating a trench can be done by the use of classic dredging.

The scope of this thesis includes a pre-lay operation for export power cables, executed by a trailing suction hopper dredging vessel exerted in cohesive soils. Utilizing the conventional dredging equipment available on the market results in oversized trenches in terms of volume. In general the trench profiles generated are disproportionable compared to the required dimensions for cable installation. Figure 1 depicts a conventional trench profile containing an export power cable.

Figure 1: Trench profile created with conventional draghead  Figure 2: Reduced trench profile

Consequently, from both an economical and environmental point of view the operation can be optimized.

The aim of the thesis study is to acknowledge the most optimal concept design solution, to create
a reduced trench profile, by utilization of a trailing suction hopper dredger (TSHD), for subsea power cable burial in stiff cohesive soil types with the potential occurrence of boulders. Boulders are defined as a separate rock mass, having a diameter larger than 200 mm. However, on the present seabed they usually don’t exceed values of 2 m. Problem statement as mentioned, is established with regards to power cable protection for offshore wind activities in the North-Sea areas, were the seabed consists of boulder clay. Possible geometry of a reduced trench profile can be obtained from Figure 2.

2 Approach

The strategy of approaching the problem can be obtained from the Kite model depicted in Figure 3. Herein the main stages during the project are listed, starting with the literature review.

A Literature review on relevant topics like offshore site investigation, subsea cable installation, TSHD and dragheads, soil mechanics and physics on excavation formed the basis for the thesis. Additional there is looked into onshore trenching applications, for instance in the agricultural industry. The review includes the current knowledge including substantive findings, as well as theoretical and methodological contributions to the topics in consideration. The gained information is used directly or indirectly in the following stages. Hereafter a multi criterion analysis (MCA) is carried out including requirements, functional analysis and concept morphology. The two best most conceptual designs out of the MCA are subjected to further detail analysis by physical considerations, i.e. cutting forces, power calculations, physical working. The one concept which turned out to have the best potential was selected for more detailed design. And finally there was an implementation stage.

2.1 Multi Criterion Analysis

Design requirements were drafted including trench geometry, limitations of TSHD, soil properties, area conditions, operability and so on. A distinction is made between fixed requirements and variable requirements. The latter were assessed to each other in order to assign importance factors to them. Main function of the tool is obviously Creating the trench. Subsequently, 9 partial functions contribute to perform the main function. For each partial function multiple concepts to fulfill the function were considered. A morphological overview containing the above was the result. Hereafter ten solution structures were selected from the overview. Ten potential concept designs were assessed to the requirements including weigh factors. After assessment, the concepts which had the highest score were the Shredder Bucket and the Hybrid Auger.

2.2 Shredder Bucket

The concept contains a trapezoidal bucket with two counter rotating shredder bodies, located at the end of the vessel’s suction pipe. The tool will be lowered from the vessel to the seabed by
means of a steel cable connected to the onboard deck winch. A skid plate touches the seabed and consequently, the tool will be dragged over the seafloor. An actuator, mounted on top enables transit in of the bucket into the soil. Simultaneously, the counter rotating shredders, mounted inside the bucket are activated. The undisturbed seabed soil will be cut into lumps and as the soil has passed the shredders, water flow enabled by water jets will contribute to both transport of the lumps into the suction pipe and cleaning of the shredder bodies. The latter is inevitable for preventing clogging of the bucket. In the initial design, the soil will be sucked into the hopper. The purpose of using two shredder bodies, is that they cross the cutting line in the soil of each other, which makes it possible to produce lumps. Counter rotating shredders are used to eliminate undesirable lateral forces. Furthermore, the clay sticking to one shredder will come of the shredder body since the other rotating shredder body will take the lump away.

2.3 Hybrid Auger

The second concept uses an inclined screw conveyor (auger) for both cutting and transport of the soil out of the trench. The tool is located at the end of the suction pipe as well. A hydraulic system enables the required cutting depth can be achieved by moving the auger up or down. The housing in were the auger can be retracted, is suspended with a steel wire rope which in turn is connected to the swell compensator of the operating vessel. The compensated wire force guarantees for a constant force between tool and seabed. Furthermore, the housing is connected to the suction pipe via a cardan joint. This joint captures the ranges of angles, the pipe can admit as a retinue of the potential differences in water depth. Once the tool touches the seafloor, the auger will be moved into the seabed. The concept design supports both suction and sidecast operation, making it an hybrid design.

3 Physical Considerations

3.1 General

In this section, general information is shown which is applicable for both concepts.

3.1.1 Soil parameters

The maximum cohesion value applied is derived out of general survey data within the region. The adhesion can be expected as a fraction of the cohesion. Figure 4 shows this relation, exposed by Tomlinson (1957). On the left vertical an empirical adhesion factor is shown. On the horizontal, the cohesion values of the clay are shown. The chart is generated for foundation piles penetrating into clay grounds. The pile adhesion is derived from the contact surface area and the shaft resistance for penetration.

For cohesion values above 150 kPa, the adhesion factor converges to 0.25 according to the chart. However, it is doubtful what physically happens. How stiffer the clay, the less tendency it contains to stick to another material. Considering this effect, the 25 % as shown in the figure will be most likely caused by friction and not by adhesion. For this study, however, the true physical meaning is left outside the scope.

Figure 4: Adhesion factor, Tomlinson (1957)

Figure 5: Definitions of cutting process, Miedema (2014)
3.2 Cutting forces

Applying the physics behind the cutting process during a mechanical trenching operation, is inevitable to determine the reaction forces and consequently the energy required for excavation. Cutting forces are determined based on the equilibrium of forces on a layer or chip of soil cut ([Miedema, 2014]). The derivation is valid under the assumption that the stresses on the shear plane and the blade are constant and equal to the average stresses acting on the surfaces. Another condition is that in this chapter only 2-dimensional situations will be described. Clay cutting definitions on a single blade can be obtained from Figure 5.

Where:

- \( A \) = blade tip
- \( h_i \) = layer cut thickness
- \( B \) = shear plane
- \( v_c \) = cutting velocity
- \( C \) = top of blade
- \( \alpha \) = blade angle
- \( A-B \) = shear plane
- \( \beta \) = shear angle
- \( A-C \) = surface of blade
- \( F_h \) = horizontal force
- \( h_b \) = blade height
- \( F_v \) = vertical force

As per Miedema, the cutting processes in clay are dominated by cohesion and adhesion. Cohesion meaning the sticky effect between two objects of the same material, in this case the clay particles. Adhesion meaning the sticky effect between two objects of a different material in this case the clay and the material of the tool. Miedema presents 3 different types of failure in his book when cutting clay namely, the flow type, the curling type and the tear type. When cutting under normal conditions, the flow type occurs. The curling type takes place when the adhesion is high compared to the cohesion. This forces the clay peel to 'curl' from the blade. The tear type is present when there is a relatively small blade angle \( \alpha \) and the adhesion is small compared to the cohesion.

In this stage as a starting point the calculations derived for the flow type are used. All the forces are per unit width \( (w) \), since a 2-dimensional situation is considered. Both the adhesion force and cohesion force are completely depended on the surface area they are acting on. The expression for the cohesion force reads:

\[
C = \frac{\lambda \cdot c \cdot h_i \cdot w}{\sin(\beta)}
\]

Consequently the adhesion force can be calculated by:

\[
A = \frac{\lambda \cdot a \cdot h_b \cdot w}{\sin(\alpha)}
\]

When cutting clay, the internal and external shear strength increase over the time, also known as strengthening. Accounting for the strengthening phenomena, a strengthening factor is included in the calculation, \( \lambda \). Since \( \lambda_c \) and \( \lambda_a \) are nearly identical in magnitude, an average quantity \( \lambda \) is used for the calculations. The equation reads:

\[
\lambda = 1 + \frac{\tau_0}{\tau_y} \cdot ln\left(1 + \frac{1.4 \cdot \varphi_c \cdot h_i}{\tau_y \cdot \sin(\alpha) \cdot \sin(\alpha + \beta)}\right)
\]

With: \( \tau_0 / \tau_y = 0.1428 \) and \( \epsilon_0 = 0.03 \). The relation between the adhesion and cohesion is known as the ac ratio \( r \).

\[
r = \frac{a \cdot h_b}{c \cdot h_i}
\]

The standard cutting theories available for clay cutting processes are modified in order to be applicable for the chosen concept designs.

3.2.1 Torque

From the cutting forces, the required torque to rotate a cutting body can be determined. Torque, also known as the moment of force, is the rotational analog of force. A force is required to change an object’s state of motion in the same way a torque is required to change an object’s state of rotation.

The torque on a shaft can be computed as a force normal to the shaft multiplied with the distance
between the acting point of the force and the rotation point. In general vector form the equation for torque reads:

\[ \vec{T} = \vec{F} \cdot \vec{r} \]

In where \( \vec{T} \) is the torque vector, \( \vec{F} \) is the force vector and \( \vec{r} \) is the position vector of the point where the force is applied relative to the axis of rotation. The torque direction is perpendicular to the plane in which it is acting.

### 3.3 Shredder Bucket

For the shredders, the driving forces are dominated by adhesion between the shredder blade and the clay. Adhesion force is directed in opposite direction of rotation, obtainable in Figure 6.

![Figure 6: Adhesion on a single shredder](image)

At first sight the strengthening factor is omitted for determining the adhesion force, since it is challenging to determine some of the relevant parameters, i.e. shear angle and layer cut. Hence, the expression for the adhesive force reads: \( (A_{shred}) \):

\[ A_{shred} = a \cdot S_{tot} \]

\( S_{tot} \) is the total surface area of one shredder body (top face and bottom face of the plates) and is obtained from a CAD model. \( S_{tot} \) is approximately 3 m\(^2\). The surface area is not constant in the direction of \( z \), and can be presented as a function of the height. For simplicity, first the total surface area is divided by the total height \( (h) \) which turns in the gradient \( q = \frac{S_{tot}}{h} \). \( S_{shred} \) as a function of the height can be estimated by the following equation.

\[ S_{shred}(z) = q \cdot z \]

The adhesion can now be integrated over the height.

\[ A_{shred}(z) = \int_0^h a \cdot S_{shred}(z) \cdot dz \]

### 3.4 Torque

Once the cutting forces are determined, the torque balance can be derived. Purpose is to define the required amount of torque for rotation of both shredders. The torque can be estimated by multiplying the total resistance force with the distance between the rotation point and the acting point of the force \( (r_t) \). For simplicity the top view of one shredder can be seen as a square plate with length of the sides equal to \( W \). Figure 7 shows this top view.

With the assumption that the adhesion force is equally distributed over the surface, the magnitude of the arm \( r_t \) can be estimated by finding the centroidal line, which basically means that the surface area on the left of the line and on the right of the line are equal in magnitude. The position of this line is depicted in Figure 7 as well. The derivation for the length of the arm holds:
Since the shredders are conical shaped, the width \((W)\) and therefore, the radius of the shredder is a function of the height. This leads to the following expression:

\[
r_t(z) = r_{t, \text{min}} + \left( \frac{r_{t, \text{max}} - r_{t, \text{min}}}{h} \right) \cdot z
\]

Involved parameters can be seen in Figure 8. The torque equation as a function of the height reads:

\[
T_{\text{shred}}(z) = A_{\text{shred}}(z) \cdot r_t(z)
\]

The expression requires integration over the total height in order to determine the total amount of torque. Filling in all the above derived equations and adding the integral boundaries, the torque balance becomes:

\[
T_{\text{shred}}(z) = \int_{0}^{h} a \cdot q \cdot z \cdot (r_{t, \text{min}} + \frac{r_{t, \text{max}} - r_{t, \text{min}}}{h}) \cdot z \cdot dz
\]

### 3.4.1 Result

Combining the equations turns in the results obtainable in Figure 9 for the required shaft power to drive the shredders. The chart illustrates the required power in relation to the forward velocity of the tool.

### 3.5 Hybrid Auger

#### 3.5.1 Pitch

According to Kase Custom Conveyors, Bulk Material Handling Equipment and their online Screw Conveyor Engineering Guide, a wide variety of pitch to diameter ratios are present in the industry.
Pitch may vary from \( p = \frac{1}{2} \cdot Do \), for handling extremely fluid materials to \( p = 1 \frac{1}{2} \cdot Do \), for transporting fluid materials or for rapid movement of very free-flowing materials. Other specific designs, furthermore, are not surprising e.g. variable pitch, double flights, tapered outer diameter, cut & folded flights and so on. Augers with a pitch equal to the outer diameter are defined as standard. They can be deployed in a broad range of applications and materials including vertical and inclined conveying of material. Therefore, a pitch to diameter ratio of \( p = Do \), will be taken at first sight. Later on the pitch value will be optimized.

### 3.6 Cutting Forces

A schematic side view of the auger approaching the undisturbed seabed is depicted in Figure 10. As per Miedema (2014), cutting processes in clay are dominated by cohesion and adhesion. First the cohesion contribution is exposed followed by the adhesion. As the tool moves forward, only half of the auger’s perimeter is in contact with undisturbed soil (Fig. 11). The other half is facing an empty trench.

![Figure 10: Side view auger in soil](image1)

![Figure 11: Top view auger in soil](image2)

For the cohesion force this contact area is governing. In order to determine the quantity of this surface area, the parameters involved can be seen in Figure 10. The right hand side of Figure 10 is a section view of the contact area.

When projecting this area in a 2-dimensional plane, it can be subdivided into a rectangular piece and a triangular piece. For the total contact area \( S_{coh} \) it can be said:

\[
S_{coh} = S_{rect} + S_{tria} = \frac{\pi}{2} \cdot Do \left( \frac{h_{cut}}{\sin(\alpha_{aug})} - \frac{Do}{2 \cdot \tan(\alpha_{aug})} \right)
\]

With:

- \( Do \) = outer diameter auger
- \( h_{cut} \) = depth of cut
- \( \alpha_{aug} \) = angle of attack auger

The cohesion force \( (C_{aug}) \) can be determined by:

\[
C_{aug} = S_{coh} \cdot c.
\]

As with the shredder calculations, the strengthening factor \( (\lambda) \) will be omitted at first sight, since it is a concept design and it is challenging to determine the exact value of the shear angle and the layer cut of the auger.

### 3.6.1 Adhesion

The adhesion force \( (A_{aug}) \), is depended on the contact area between the soil and the tool. The sum of the flight areas is governing the adhesion force. Both the top side and the bottom side of the flights are in contact with the soil. During operation, the soil is constantly sliding over the auger. The amount of flights within the given auger length is depended on the pitch \( (p) \). Number of flights is given by total length of auger \( (l_{aug}) \) (including the part inside the housing) divided by the pitch. The total surface area of the flights can be computed by:
To be completely accurate, the shaft diameter \((D_i)\) should be subtracted in calculating the surface of the flight. However, the total surface area of the inner shaft contributes to the adhesion force as well. In this stage of the design, it is appropriate to use the simplified \(S_{\text{aug}}\). The adhesion force \((A_{\text{aug}})\) can be computed with:

\[
A_{\text{aug}} = S_{\text{aug}} \cdot a
\]

Once the magnitudes of the two dominating forces have been exposed, it is important to determine the direction in which they act. The cohesion force \(C_{\text{aug}}\) will act in axial direction of the auger (Fig. 12), since the shear strength of the clay has to failed in that direction. The point of acting is on the edge of the blade. Furthermore, a normal component can be seen \((C_{\text{aug},n})\) as well as an horizontal component \((C_{\text{aug},h})\). The latter is important for the torque calculation since it is acting in the same plane as the rotational movement. The horizontal component of the cohesion force reads:

\[
C_{\text{aug},h} = \tan(\theta_{\text{aug}}) \cdot C_{\text{aug}}
\]

The pitch angle \((\theta_{\text{aug}})\) plays a dominant role in the value of this parameter and is depended on the pitch - diameter ratio. The expression reads:

\[
\theta_{\text{aug}} = \tan^{-1} \left( \frac{p}{2 \cdot D_o} \right)
\]

Figure 13 shows were the adhesion force \((A_{\text{aug}})\) is acting. This force contribution is acting over the complete surface of the auger and is directed in opposite direction of rotation.

3.7 Lateral Reaction Forces

Since there is 1 auger considered, the reaction forces in the horizontal plane contribute to lateral movement of the complete tool during operation. Therefore, it is vital to expose the magnitude of this force.

Accounting for both the angle of attack and the pitch angle, the tangential component \((R_{\text{tan},\text{tot}})\) in the horizontal plane of the total cohesion force can be calculated by:

\[
R_{\text{tan},\text{tot}} = \cos(\alpha_{\text{aug}} - \theta_{\text{aug}}) \cdot C_{\text{aug},n}
\]

The tangential force acting on a point on the cutting edge is depicted in blue in Figure 15. The tangential component, however, will act over the complete auger - soil interaction line (i.e. \(\pi\) in radians). A top view of the situation considered can be seen in Figure 15. The component in direction of \(Y\) is governing for the lateral movement of the tool. The magnitude of this force is varying over the interaction line and is a function of the angle, \(\phi\). Hence, the expression reads:

\[
R_{\text{f}_y} = \sin(\phi) \cdot R_{\text{tan}}
\]

When taking the integral over the contact area, the total can be exposed as:

\[
R_{\text{f}_{y,\text{tot}}} = \int_{0}^{\pi} \sin(\phi) \cdot R_{\text{tan}} \cdot d\phi
\]
The individual components \( (R_{f_{tan}}) \) are not known, the total \( (R_{f_{tan,tot}}) \), however is. Therefore, the total magnitude in \( Y \) direction can be calculated by using the following ratio:

\[
R_{f_{y,tot}} = \frac{\int_{0}^{\pi} \sin(\phi) \cdot d\phi}{\pi} \cdot R_{f_{tan,tot}}
\]

With this expression, an optimum for the pitch - diameter ratio can be obtained. The adhesion and cohesion components, which are governing for the required shaft power and the lateral force are plotted in function of the pitch to diameter ratio \( (p/Do) \), for an angle of attack equal to 55 degrees and a soil cohesion of 200 kPa.

For larger ratios, the adhesion and cohesion sum is significant lower. Hence the required shaft power to drive the auger is lower. The lateral reaction force, however, slightly increases with increasing pitch ratio. Consequently, as a trade-off a smaller ratio than 1 is not recommended.

### 3.8 Torque

The vector form torque equation can be simplified to:

\[
T = F \cdot r
\]

In order to estimate the torque balance, required for the operation, three contributions can be distinguished, namely:

1. Cohesion
2. Adhesion
3. Inertia of soil inside auger

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Figure 14: Tangential component cohesion force  
Figure 15: \( Y \) - component cohesion force

Figure 16: Forces in function of pitch ratio

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To encounter the addition of the cohesion, the force normal to the shaft is equal to $C_{\text{aug},h}$ and the position of the acting point is the outer edge of the auger. Which means the distance between rotation point and acting point is equal to half the outer diameter. The torque required is equal to:

$$T_{\text{coh}} = C_{\text{aug},h} \cdot \frac{D_o}{2}$$

As can be seen in Figure 13, the adhesion force acts on the complete surface of the flights. To find the position of the centroidal, the surface on both sides of the line have to be equal. This leads to the following expression for the torque arm, when encountering the shaft diameter ($D_i$) as well:

$$r_{\text{adh}} = \sqrt{\frac{D_o^2 + D_i^2}{8}}$$

The torque balance to overcome the adhesion is equal to:

$$T_{\text{adh}} = A_{\text{aug}} \cdot r_{\text{adh}}$$

Finally there is a contribution from the inertia due to the mass of the soil inside auger. However, not the total amount of soil inside the auger has to be taken. When the auger is rotating, every time-step a new amount of soil mass is entering the auger. Only this part has to be accelerated from zero to the rotational speed of the auger. The amount of soil what is inside the auger by that time, already moves with the rotational speed.

Experience from calculations in previous projects, learns that this contribution is disproportional to the cohesion and adhesion. Therefore it will be omitted in the torque calculation.

The total torque required to drive the auger during operation is said to be:

$$T_{\text{aug}} = T_{\text{coh}} + T_{\text{adh}}$$

### 3.8.1 Production

The in-situ volume production in function of the forward velocity can be computed by:

$$Q_{\text{aug}}(v_t) = \frac{D_o \cdot d_{\text{tren}}}{n_p} \cdot v_t$$

With $v_t$ the forward velocity of the tool and $n_p$ the number of passes to complete the trench. The target depth of the trench ($d_{\text{tren}}$) is also in direct relation with the depth of the cut $h_{\text{cut}} = \frac{d_{\text{tren}}}{n_p \cdot n_{\text{pa}}}$. 

### 3.8.2 Fill rate

Fill rate ($i$) of the auger is not constant over the height. At the bottom side the auger is filled half (Fig. 10), meaning $i = 0.5$. At the top the auger is completely filled and therefore $i_{\text{max}} = 1$. Hence, $i_{\text{min}} = 0.5$.

### 3.8.3 Angular velocity

The required amount of revolutions is directly proportional with the forward velocity of the tool. The amount of revolutions in radians per second can be expressed as:

$$\omega_{\text{aug}}(v_t) = \frac{4 \cdot D_o \cdot d_{\text{tren}}}{n_p \cdot p \cdot \pi \cdot (D_o^2 - D_i^2) \cdot i_{\text{min}}} \cdot v_t$$

### 3.8.4 Power

From the torque, subsequently, the required shaft power to drive the auger can be determined by using following expression:

$$P_{\text{aug}}(v_t) = T_{\text{aug}} \cdot \omega_{\text{aug}}(v_t)$$

The results of the calculations can be observed in Figure 17. The contribution of the adhesion and cohesion are shown and the total power consumption as well. All the above in function of the forward velocity of the tool. Two passes are considered.
4 Conclusion

Using the information of the previous sections, a choice is made between the shredder bucket concept and the auger concept. Accounting for reliability, the amount of moving parts in earth processing devices is vital in the comparison. Also other aspects are taken into consideration.

4.1 Shredder bucket

- For the shredder bucket design, there are at least two main moving parts, namely the shredder bodies
- Risk with the shredder bucket is that if one shredder stops functioning, the other one instantly hits the failed shredder, resulting in damage
- Boulders of sizes larger than the potential cut clay lumps can not be handled and result in damage to the tool
- Significant force required to push bucket into soil, providing stable cutting process. Furthermore, significant amount of mass of the tool is vital, required to ensure all the mechanical energy can be used for cutting instead of unwanted movements of the tool

4.2 Hybrid Auger

- For the auger concept, at first sight there is only one moving part, the auger
- In case of power breakdown the auger can not be retracted easily, this can be solved by suspend the auger frame hinge able
- Boulders of size equal to the pitch can be handled, larger ones require specific handling which should be looked further into
- Auger will pull itself into the soil, owing to downward pointing cutting forces
4.3 Power Consumption

Considering, the required power for the two concepts, the auger concepts requires least amount of mechanical energy at the same forward velocity, as depicted in Figure 18. The shredder bucket, additionally, requires also power to drive the water jets.

![Figure 18: Required shaft power in function of forward velocity](image)

References


