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Performance of subsea mechanical trenching systems

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ABSTRACT: The growth of offshore renewable power generation and sharing of power between countries has led to a significant increase in the length of cables to be buried into the seabed over the last 20 years. Burial is particularly difficult in glacial till deposits which contain cobbles and boulders, and weak rocks. However achieving burial in these materials can be key to cable protection and is preferred to rock placement with consequent increased environmental and cost impact. The generally preferred solution is use of a mechanical cutter to form a trench. This paper indicates how performance prediction models can be developed on a machine specific basis and also some of the practical aspects to consider when selecting a mechanical cutter for a project.

Keywords: Trenching; Cable Burial, Stiff Clay, Rock Cutting

1 INTRODUCTION

The growth of the offshore wind power generation and interconnectors to allow sharing of power between countries across bodies of water has led to a significant increase in the number of power cables being installed. The time required for repair and the consequent financial impact makes protection a particular concern. As many of these cables cross areas of relatively hard seabed geology, burial is particular concern.

Jetting is the generally preferred trenching method for power cables in sands and soft and firm clays, but this technique is generally limited to clays with an undrained shear strength of less than between 75 and 100 kPa and depending on the required depth. The alternative methods to trench cables in these soils are ploughing, either prior to laying the cable, or after laying the cable, or mechanical cutting.

Ploughing of cables caries certain risks, with pre-lay ploughing leaving an open trench, which may infill prior to lay, and require a much tighter than normal lay tolerance during the cable lay operation, and a requirement to backfill the cable. At least one cable is known to have been damaged during the backfill process. Alternatively, post lay ploughing carries several risks including a very narrow tolerance for cable ‘slack’, potential risks in cable handling, particularly for bundled cables and limited options for remedial trenching, should depth not be achieved.

As a result, mechanical trenching is often preferred as a trenching technique as the risk to the cable is much reduced and the cutting process can usually be relied upon to achieve greater depth than possible with a cable plough.

This paper describes how mechanical trenchers operate and discusses the power requirements for successful trenching operations. These can be based on theoretical models, however the preference is to develop performance correlation based on a back analysis of trenching data.

2 EXAMPLE MECHANICAL CUTTER TRENCHERS

Mechanical trenchers are based around either a chain cutter or a wheel cutter. Wheel cutters have some advantages in that the rigid wheel supporting the cutting picks has many fewer components subject to wear, however depth is limited due to the physical size of cutting wheel required. As a result, the trench depth is typically limited to between 1.0 to 1.5 m. An example of a typical wheel cutter is shown in Figure 1.

The more common option for subsea trenchers is to use a chain cutter as the primary trenching tool. While this has many more wear components, including cutting pick, the cutting chain and some parts of the chain boom, all of which need replacing at regular intervals, advantages include an ability to cut to greater depth, often over 2 m, including new build trenchers currently being built with a depth capability of 5 m. Another advantage is the reduced height to which the cable has to be lifted, reducing the excess length of cable required for loading. A typical mechanical cutter is shown as Figure 2.

For the purposes of this paper, emphasis has been placed on the performance and operation of chain cutters as these are the more common trenchers in use at this time. However the principles discussed are also applicable to the operation of wheel cutters.

Figure 1. Typical subsea wheel cutter

Figure 2. Typical subsea mechanical chain cutter

When considering different trenchers, a useful exercise is to consider the input power available to the cutting chain and the cross sectional area of the trench as shown in Figure 3, and including results for a selection of onshore trenchers, as published by Sweeney et al (2004).

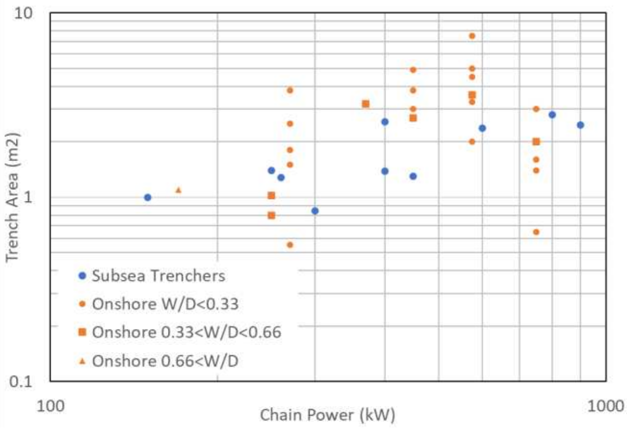


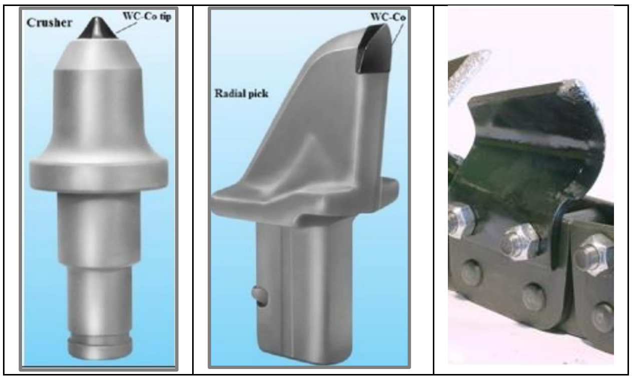
Figure 3. Typical power output of mechanical cutters
W is chain width, D is trench depth

As can be seen there are a wide range of power outputs used for subsea mechanical trenchers ranging from 150 kW to 900 kW, with the power spread only partially compensated by the trench area. However there is a broad comparison and similar trends in trench area between onshore and subsea trenchers. Note is also made that in this case, the more power trenchers in terms of power to trench area plot lower and to the right on this graph.

3 CUTTING TOOL SELECTION

The cutting process relies on the use of a tool, commonly referred to as a pick to cut into the trench face, and remove material to form the trench. The pick types available comprise three main types as described below and illustrated in Figure 4:

a) Conical Picks – these are widely used in rock cutting tools and are designed to rotate progressively in their holder under the cutting action. This in theory helps maintain their sharpness and they are generally considered relatively robust.
b) Drag Picks – when new, these can be quite efficient at cutting and transporting material, however a wear flat can quickly develop on the base of the tip; this then requires an increased normal force to push the pick into the surface being cut, translating to a loss of efficiency and a requirement for an increased tractive effort.
c) Clay Cutters – are intended for clean soils which are relatively soft or loose offering improved transport of spoil but limited cutting ability.



a) Conical Pick b) Drag Pick c) Clay Cutter
Figure 4. Principal types of cutting tool

In practice, we normally recommend conical picks in most circumstances. These offer the most robust solution and while transport capability may not be as great as some other types of pick, they can survive cutting through or displacing cobbles and boulders in most instances.

Clay cutters may be considered as an option, but it is suggested these are only suitable for projects which can be confirmed as free of cobbles and boulders (both surface and subsurface) with confidence. They do not have the ability or robustness to reliably deal with such inclusions and once they lose their cutting edge, greater tractive effort may be required to advance the trench face.

The author is aware a number of trenching contractors who employ a combination of conical picks and clay cutters. However, conical picks typically have a lower overall height than a clay cutter. As a result, if a cobble or boulder is present in the trench profile, this will generally be encountered by the clay cutter in advance of the conical pick. Thus the less robust part of the cutting system is having to do the harder work. As result the clay cutters often get flattened and become effectively redundant.

The picks do have to be mounted on a chain and the distribution of the picks needs to be in a pattern such that the full cross sectional area is cleared as shown in Figure 5.

Note is made that the chain illustrated in Figure 5 includes some horizontal strips, the purpose of these is to asist transport of material out of the trench.

Figure 5. Cutting chain to show pick pattern

4 THEORECTICAL ASSESSMENT OF CUTTING FORCE

An estimate can also be made of the power required to cut into a trench face. The primary load on the cutting chain is the force required for the pick to penetrate the trench face and cut into the material. Research has been performed by various workers, and summarised by Bilgin et al (2006). Bilgin identified the Evans (1984) method as providing a reasonable correlation with test data, with the only input parameters being unixial compressive strength and tensile strength. While other models are available, these require additional variables which are rarely defined and therefore our preference is to use this method.

The form of equation propsoed by Evans is presented in Equation 1.

$$FC = \frac{16 \cdot d^2 \cdot \sigma_t^2}{Cos^2(^{\varphi}/_2) \cdot \sigma_c} \quad (1)$$

Where FC is cutting force (kN), d is depth of cut (mm), σ_t is tensile strength (kPa), σ_c is uniaxial compressive strength (kPa) and φ is rake angle of tool (degrees).

The available cutting models have been developed for cutting rock, however, much of the use of offshore trenchers is though clay soils. For such soils, strength is typically presented as an undrained shear strength (su). By using Mohr's circles, undrained shear strength can be approximated as half the uniaxial compressive strength, thus an undrained shear strength of 350 kPa approximates to a uniaxial compressive strength of 0.7 MPa.

The analysis also requires input of a tensile strength. For rock this is typically estimated as one tenth of the compressive strength; to provide a little conservatism in the analysis, our practice is to assume a tensile strength equivalent to one eighth of the compressive strength. The same analogy could be applied to a stiff or very stiff clay soil, however in practice, this may result in an underestimate of tensile strength for a cohesive material. To address this, a sensitivity analysis has been included, assuming that in clay soils (with an undrained shear strength of 350 kPa) using a reduced ratio of tensile strength to uniaxial compressive strength of six.

The results of a typical analysis for a 2m cutting chain in clays of 350 and 500 kPa are shown in Figure 6. This shows the signficant impact of the assumption regarding tensile to comnpressive stength, with tensile strength being the dominant factor in the cutting force requirement.

The plot also includes a limitation imposed by the available power and the ability of the chain to transport material out of the trench. In this example the power output from the chain drive motor would be 500 kW, however allowance must be made for frictional losses in the chain mechanism, meaning that typically only 70% (or approximately 350 kW) of the power is actually available for cutting. The transport limit assumes a certain volume of soil is removed by each pick, with the supporting value being based largely on experience of different pick types and arrays and in this example speed would be limited to just under 300 m/hr.

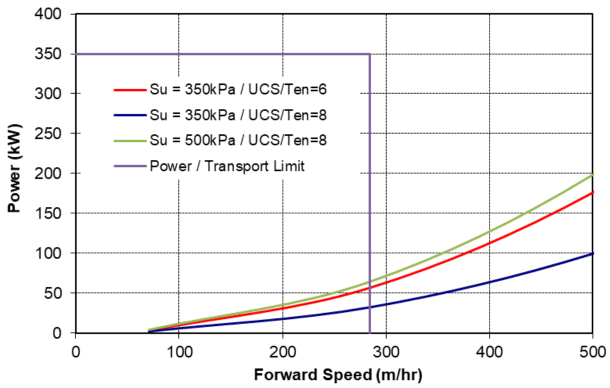


Figure 6. Example theoretical assessment of cutting chain performance

This analysis would suggest that the power requirement is actually quite low, and the chain drive motor has been somewhat conservatively sized at 500 kW. However, our experience is that these calculations, while useful, should only be considered as a first indication and that the theoretical analyses underestimate the cutting forces required, particularly if cobbles and boulders are to be expected within the trench profile. This is discussed further in the following section.

5 A SPECIFIC ENERGY APPROACH

The concept of specific energy is to consider the energy input required to excavate a given volume of soil or rock, and is a concept widely used in the drilling industry (see e.g. Rabia, 1986). As well as providing a useful performance assessment, the drilling industry also uses the concept to predict the useful life of drill bits, eliminating or reducing any requirement to recover them for inspection.

The specific energy concept considers the amount of work required to excavate a given volume material. In drilling terms, the two components of the specific energy equation are torque and axial thrust and these are normalised by the volume of material excavated (ie borehole area times depth). This may be expressed mathematically as:

$$SE = \frac{2 \cdot \pi \cdot r \cdot F \cdot N}{R \cdot A} + \frac{T \cdot R}{R \cdot A} \quad (2)$$

Where SE is specific energy (drill), r is the operating radius (m), F is the force on cutting picks (kN), N is the rotary speed (rpm), R is the penetration rate (m/min), A is the area excavated (m^2) and T is the thrust load (kN)

The r.F expression (operating radius times force) provides an equivalent cutting force for the pick array on a drilling bit. The distance travelled by the rotating picks is significantly greater than the vertical distance travelled by a bit drilling a hole. As the vertical force is generally less than the horizontal force (expressed in this case as a torque), the torque component of the above equation is the significant component.

Investigation of the two components of torque and thrust indicates that the torque component comprises more the 95% of the total energy input to the cutting process (Rowlands, 1971). The torque may be likened to the cutting force required by the chain cutter, and this cutting force is related to the strength of the material being cut. Hence the approriate equation for a mechanical trenching tool is:

$$SE = \frac{M_P \cdot C_S}{V \cdot A} \quad (3)$$

Where SE is specific energy (mech. trencher), M_P chain drive motor pressure, C_S is the chain speed, V is the forward speed and A is the trench area (width x depth). As the calculation is essentially emprirical, provided units are consistently adopted, the actual units can be those which are most convenient.

Using this concept it is possible to illustrate the changing nature of soils along a trench route, and ultimately to develop a correlation between specific energy and soil strength. These factors do need to be considered on a machine specific basis as the input energy is estimated from the chain speed and hydraulic pressure, but the volume of hydraulic oil circulated is not considered, hence there will be significant differences between individual machines. With knowledge of the specific hydraulic motors used, it may be possible to address this variation but such detail is not always readily provided by trenching contractors / equipment manufacturers.

An example of the typical output for a mechanical trencher on typical stiff clays encountered within the North Sea, is shown in Figure 7 showing the key parameters of chain depth (and hence trench area), cutter motor pressure, chain speed and trencher speed.

This data has then been processed to provide a specific energy analysis as shown in Figure 8. A point to note is that to make sense of the data, some averaging of the data, which is typically recorded at between 10 and 30 seconds intervals, needs to be performed. In this case, data has been averaged over two minutes. Ground speed and chain depth are used to assess volumetric rate of excavation. Ground speed may be assessed from track speed, however our preference is to use survey positioning and average this over a similar time period to the chain motor pressure and speed. Too short a time period in both cases simply results in excessive scatter in the data. The input energy is a function of the chain drive motor pressure and the chain speed, in this case the rotational speed of the drive motor, but this may be presented as a chain speed.

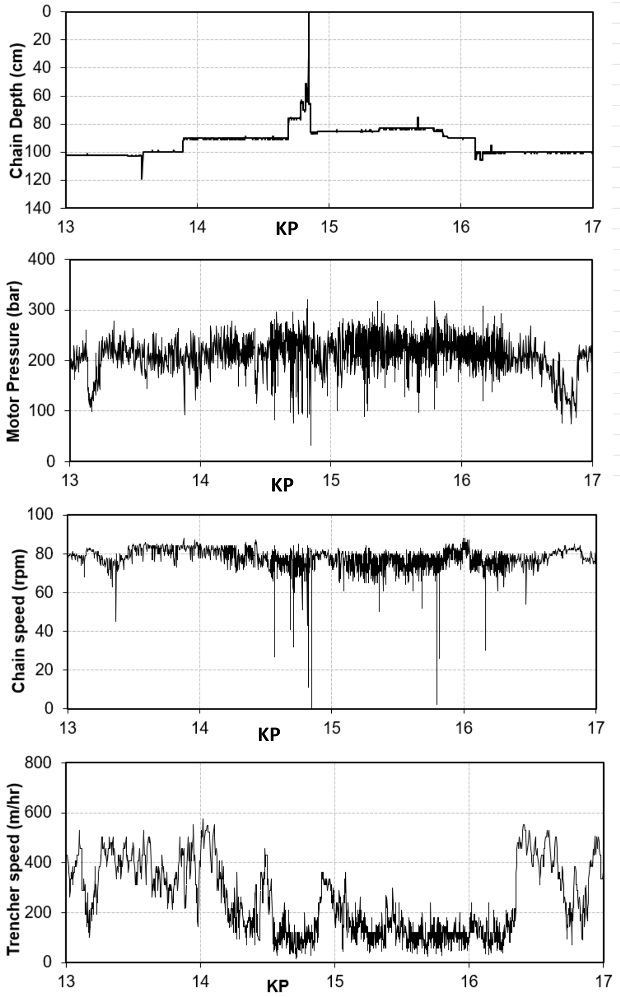


Figure 7. Example Mechanical Trencher Output

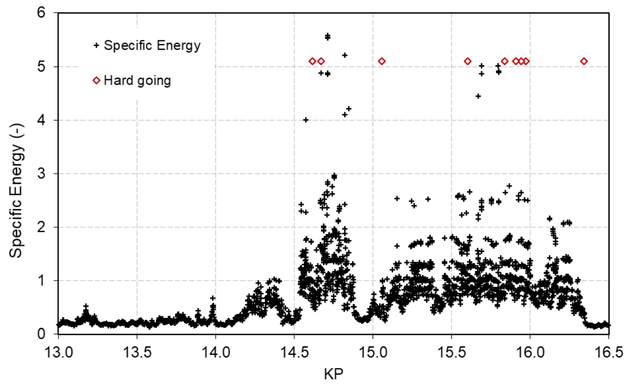


Figure 8. Example Specific Energy Assessment

It can be seen in this example that the specific energy required for the first section of this route between KP 13.0 and KP 14.2 was relatively easy to trench with a low specific energy required of around 0.2 with only minor increases. However, from KP 14.5 to KP 16.3, there is significant scatter in the data with occasional points exceeding a specific energy of 4.0 and a baseline average of around 1.0. Between KP 16.3 and KP 17.0, the specific energy decreases back to the level experienced on the first section of this example.

In the example, the trencher logs were reviewed and reports of `hard going′ are noted. It can be seen these correlate well with the spikes in specific energy. It is also expected that the higher spikes in specific energy are associated with boulders being encountered within the trench profile and either being broken up, or being rolled out of the trench or pushed aside. This factor illustrates why the relatively low power requirement associated with theoretical models shown in Figure 6 should only be used with caution as in reality much greater power is required to reliably form a trench, particularly in glacial soils containing cobbles and boulders.

6 SPECIFIC ENERGY FOR PERFORMANCE ASSESSMENT

The specific energy assessment can be back analysed, and where sufficient data is available, correlated to soil strength. This can then be used to inform a performance assessment and develop a schedule for a project.

For the data shown in the exmaple, a series of CPTs had been done at regualr intervals along the route and it was possible to make a reliable assessment of the strength of the clay soils present. The strength has then been plotted against the specific energy reported (Figure 9). As can be seen the correlation achieved is good for a full range of clay strengths up to 350 kPa. It is then possible to use this data to improve performance predictions for future projects. However, as noted above, without detailed knowledge of the chain drive motor this is a machine specific analysis.

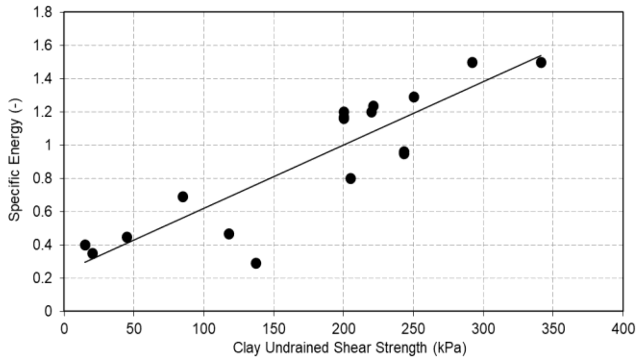


Figure 9. Undrained Shear Strength vs Specific Energy

7 PRACTICAL CONSIDERATIONS

Subsea trenching is an expensive operation and to maintain cost effectiveness, a reasonable ground speed must be achieved together with an acceptable chain life. We have used the Pettifer and Fookes (1994) chart as a basis for typically achievable trenching operations as shown in Figure 10. Clay soils are generally trenchable subject to boulder content.

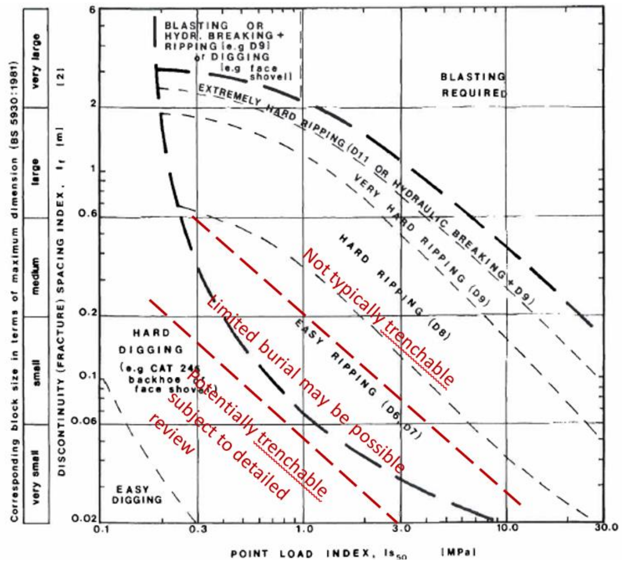


Figure 10. Typical Practical Limits on Trenching Operations

Mechanical trenchers are the most complicated form of subsea trenchers with key factors to consider when selecting them for use discussed below.

Cable Loading – A mechanical cutter requires that the cable is lifted over the cutting tool. The lifting process requires that the lay tension allows lifting of the cable. Some length is also required for a cable guide or depressor to place the cable to depth at the base of the trench a short distance behind the cutting tool. However, too much length means a bight of cable is pushed forwards in front of the trench, and this may result in the cable exceeding its minimum bend radius. Conversely, insufficient length and the cable is not placed at depth.

Chain Stalls and Chain Wear – If a boulder is encountered, a chain stall can occur. While the chain may be able to withstand this, the effect on the hydraulic motor can be significant with the momentum of the hydraulic oil in the supply hoses creating a vacuum which can cause cavitation and damage to the drive motor. Careful design of the hydraulic systems is required to mitigate this.

Typically a chain will require servicing every 4 to 6 km, but we are aware of chains which have lasted less than 2 km in hard trenching conditions and over 8 km in easier trenching conditions.

Chain Clearance – It is important to clear spoil from the front of the chain. This is typically achieved with eductors. However these can become blocked in stoney ground and often limit the overall trenching speed.

8 CONCLUSIONS

The paper has illustrated that theoretical models to predict cutting forces typically underestimate the input power required for practical trenching purposes and proposed that a specific energy approach can provide reliable performance predictions.

An indication has also been provided on the overall capability of mechanical trenchers and some of the practical aspects to consider in their use.

AUTHOR CONTRIBUTION STATEMENT

This paper was prepared in its entirety by the author.

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