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A study into cable-seabed interaction in offshore cable decommissioning

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ABSTRACT: Offshore wind energy has become a crucial element of the global energy transition, with the North Sea being a major hub for offshore wind farms. As first-generation farms approach the end of their operational life, decommissioning offshore wind export cables has emerged as a significant technical challenge. There is no industrial standard available (yet) to assess decommissioning of offshore power cables. A thorough understanding of the soil-cable interaction is essential to identify the limitations in the cable pull-out process, enabling cost-effective and safe operations. Factors such as shear strength, burial depth, pull-out velocity and cable stiffness are analyzed to assess the forces that oppose cable recovery. An analytical model of the cable-seabed interaction is developed and implemented in OrcaFlex. The model includes scenarios for fully drained, fully undrained, and partially drained uplift resistance, to simulate real-time resistance during pullout operations, allowing dynamic simulations of soil resistance during cable-pullout. Additionally, experiments have been performed to investigate the influence of flexibility of the cable, pull-out rate and burial depth. These results show that two regimes can be identified, based on the ratio of bending stiffness over burial depth. 1) the cable behaves as a rigid object, and 2) the cable bends within the seabed and exits the seabed with an angle close to being vertical, resulting in a smaller area where sediment is mobilized and a lower pull-out force. These simulations and experiments provide valuable insights, aiming to support the offshore wind industry's evolving needs and enhance the sustainability of decommissioning processes.

Keywords: dilation, pullout, cable,

1 INTRODUCTION

Offshore wind energy has become a crucial element of the global energy transition, with the North Sea being a major hub for offshore wind farms. As first-generation farms approach the end of their operational life, it needs to be considered whether offshore power cables would need to be decommissioned, e.g. because of circularity and re-use of the materials in the seabed. Decommissioning at a large and cost-effective scale remains a challenge. The limited experience makes that the decommissioning of offshore wind power cables has not yet emerged (Topham, et al. 2019). To date, only a few experimental or small wind farms have been decommissioned (Ove Arup & Partners Ltd. 2018). Experience with the removal of subsea power cables is very limited and virtually non-existent for offshore wind farms cable systems (DNV AS 2016). Although, the sector has some experience with repairs of failures in offshore power cables, cable pull-out is required, be it in a different context and value proposition. For decommissioning purposes, the value proposition is low, and emphasis should be on low environmental and financial costs. This paper focuses on the feasibility and limitations of using the cable pullout method for decommissioning offshore wind export cables, particularly examining the influence of burial depth and soil conditions, yet without considering methods to relieve the resistance exerted by the seabed, e.g. jetting, deburial.

2 BACKGROUND

So far, limited research has been done to assess cable-pullout forces. However, there is an industry standard available of a process that is somewhat related, i.e. uplift resistance in upheaval buckling of buried pipelines (DNV AS 2021). The cable soil interaction is assumed to be comparable to the pipeline soil interaction, with the main difference that a cable has a lower bending stiffness, thus behaves more flexible. As a result, when a cable is pulled out of the seabed at one end, the cable will start to bend rather than being uplifted, and thus the orientation can change from horizontal to vertical.

The drainage condition of a sandy, non-cohesive soil largely determines the uplift resistance, together with the soil's relative density and burial depth. The extremes can be distinguished as drained and undrained behaviour. In fully drained conditions, there is sufficient time for the porewater to redistribute and equilibrate with the applied load, while for fully undrained conditions the reduced flow of porewater results in dilatant strengthening of the soil.

Bransby and Ireland (Bransby and Ireland 2009) conducted the first study on the uplift resistance of pipelines for various drainage conditions (soil deformation rates). Through their experiments, they identified the two regimes through the normalised peak uplift resistance $W_u/_{\gamma' HD}$ with respect to the normalized velocity $\frac{vD}{c_v}$, where W_u is the soil uplift resistance, submerged weight of the soil γ', velocity v, burial depth H, pipe diameter D and coefficient of consolidation c_v. (Bransby and Ireland 2009). High permeability sands in combination with slow pullout of the cable result in a small normalized velocity with drained conditions, whereas a high pullout velocity in low permeability sands result in undrained conditions. Due to the effect of shearing, dense sands dilate, which causes an increase in soil resistance (White, et al. 2018). These results are shown in Figure 1.**Error! Reference source not found.** The fully drained resistance, i.e. 'vertical slip' method and fully undrained resistance are also plotted.

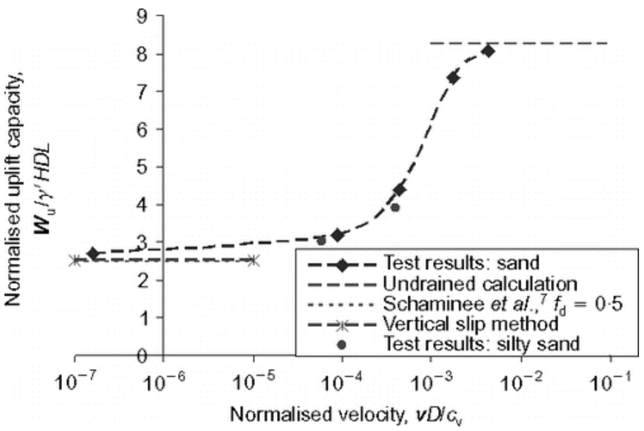

Figure 1:Normalised peak uplift resistance versus normalised velocity (Bransby and Ireland 2009)

2.1 Fully drained uplift resistance

When assuming vertical slip surfaces under fully drained conditions (see Figure 2), the total drained uplift resistance in terms of weight and integrated shear resistance follows from:

$$F_{uD} = \gamma' HD + \gamma' D^2\left(\frac{1}{2} - \frac{\pi}{8}\right) + f\gamma'\left(H + \frac{D}{2}\right)^2$$

Where f is the uplift resistance factor related to the soil's relative density (DNV AS 2021). The first two terms account for the soil weight that is mobilized. The third term relates to the shear resistance, and thus friction angle of the soil.

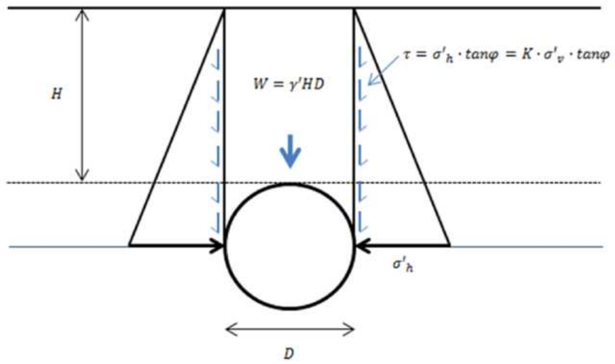

Figure 2: Vertical slip model (DNV AS 2021)

2.2 Fully undrained uplift resistance

For fully undrained conditions, two different failure modes govern the uplift resistance (DNV AS 2021), being 1) global soil failure where a wedge extending to the surface of the soil is lifted together with the cable, 2) local soil failure where the soil directly above the cable is displaced around and under the cable, see Figure 3 for the two failure modes. Global failure can be modelled with a vertical slip model that is adapted for dilation, and thus underpressure in the pores, along the failure planes. For larger burial depths, local failure is more likely to occur, while for shallow burial depths, global failure provides the least resistance.

The undrained lifting resistance for global failure is provided by:

$$F_{uU0} = \gamma' HD + \gamma' D^2\left(\frac{1}{2} - \frac{\pi}{8}\right) + 2s_u\left(H + \frac{D}{2}\right)^2$$

And in the case of local failure:

$$F_{uU0} = N_c s_u D - \gamma' A_p$$

2.3 Mobilisation

The mobilisation distance z_{mob} is the displacement required to mobilise the peak uplift resistance. According to (DNV AS 2021), $z_{mob} = 0.01H$ for gravel and rock backfill, but this value would be too conservative for sandy soils. (Bransby and Ireland 2009) found that the mobilisation distance in sandy soil not only depends on burial depth, but also on velocity, as is shown in Figure 4. They also showed in their experiments that for uplift velocities larger than 0.01 m/s, the mobilisation distance was in the order of $0.1H$.

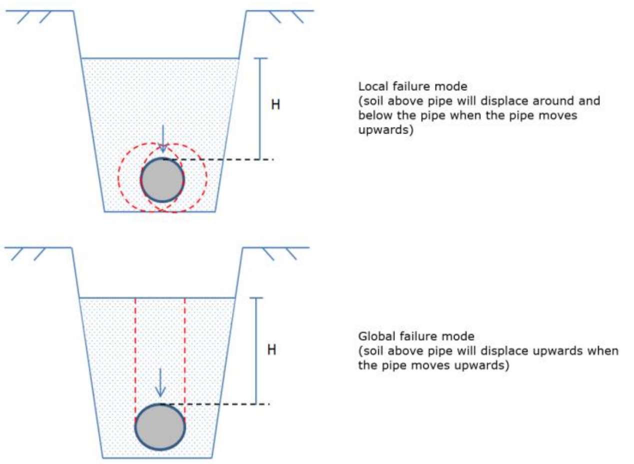

Figure 3:Uplift resistance failure modes for undrained conditions (DNV AS 2021)

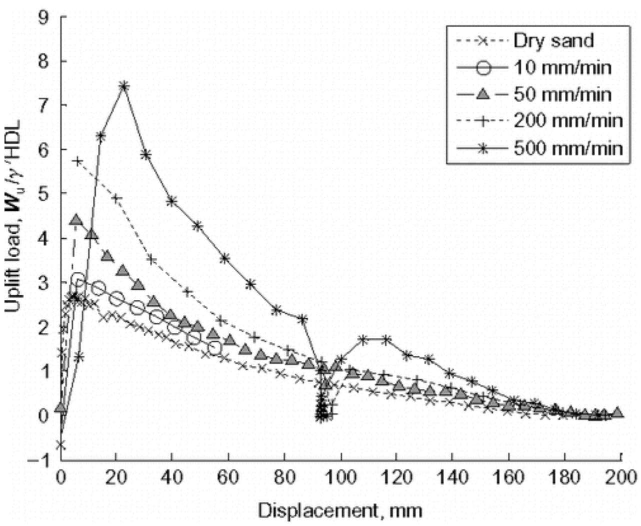

Figure 4: normalised uplift resistance versus. displacement of pipeline tests carried out at different vertical velocities with saturated sand, H/D=3, and $D = 0.048m$ (Bransby and Ireland 2009)

3 EXPERIMENTS

In order to assess to what extent the upheaval buckling would be a fair starting point for the cable pull-out response, simple look and feel experiments are executed. This is done within the Offshore and Dreding Engineering laboratory at TU Delft. Within these experiments, scaled cables are buried within a bed of sand and these cables are pulled out with a set load, in the form of mass blocks in the range of 2-35 kg. To study the effect of cable stiffness, objects of the same diameter (16 mm outer diameter) have been used, but with varying stiffness, i.e. steel rod, PVC tube and a garden hose (which was capped at both ends to avoid buckling), which are respectively referred to as stiff, intermediate and flexible cable. The setup is shown in Figure 5. The experiments are executed in a tank of 80x80x80 cm. In order for this short length of experiment to be representative, the cables are clamped on a hinge in the sediment at one side. Sand with $d_{50} = 180\mu m$ and $d_{10} = 63\ \mu m$ is used, which is loosely deposited around the cables and the cables are installed level, laying loosely on top, which is further filled up with loosely deposited sediment until the desired burial depth is reached.

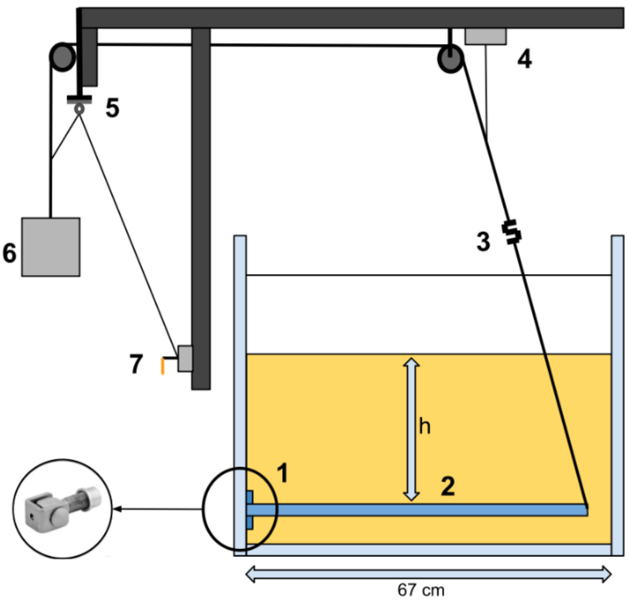

Figure 5:Experimental setup used for first estimates of cable pull-out behavior. 1) Hinge connection, 2) scaled offshore cable, 3) load sensor, 4) displacement sensor, 5,6,7) pull out wire, mass and release

Table 1: Test settings, applied to stiff, intermediate and flexible cable pull-out

Tested burial depths [cm]	Applied loads [kg]
5	1.1, 1.4, 2.5
17	8.6, 17.5, 26
25	8.6, 17.5, 26

Pull-out response has been measured for various initial loadings and burial depths. Figure 6 shows some results of these pull-out tests. Two regimes can be distinguished. 1) In the case of a rigid cable, the soil is mobilized along the entire length of the cable. As a result, a slow initial pullout is observed, together with a rapid increase as soon as the cable tends to get free of the bed, see Figure 7. 2) in the case of a more flexible cable, a more linear displacement of the end of the cable is observed. Simultaneously, we observe that the soil failure around the cable is more localised, as the cable tends to be pulled out in a more vertical direction, see Figures 8 and 9. As an effect, required pull-out force for a flexible cable is lower than that of a rigid cable. Furthermore, it is observed that the cable will be pulled out faster with the same pulling force exerted on the cable. Whether a cable behaves as rigid, depends on its bending stiffness as well as burial depth (not shown in this paper). Next step in experiments would be to conduct more representative pull-out tests, by having a winch moving along with the cable pull-out .

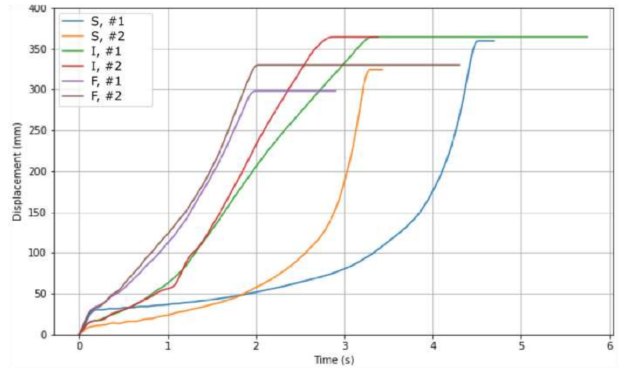

Figure 6:pull-out results of two runs for each of the 3 cables with load of 17.5 kg attached. S=stiff, I=intermediate, F=flexible. for various loads

Figure 7: pullout of rigid cable (steel rod). Dilation observed along entire length of rod

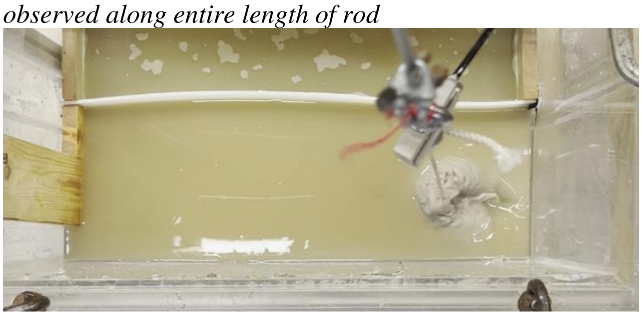

Figure 8: pullout of garden hose (flexible cable).Bed disturbance only observed close to where the cable is protruding from the bed (localized failure)

4 MODEL

The experiments have shown that upheaval buckling of pipelines provides a fair comparison for the pull-out process of rather stiff cables, or at shallow burial depths. Due to the complexity of the geometry and the large soil deformations, our first step is based on upheaval buckling to model the cable-soil interactions. By doing this, we effectively simplify the cable pull-out process by assuming that the cable remains in a horizontal orientation as long as it is within the seabed.

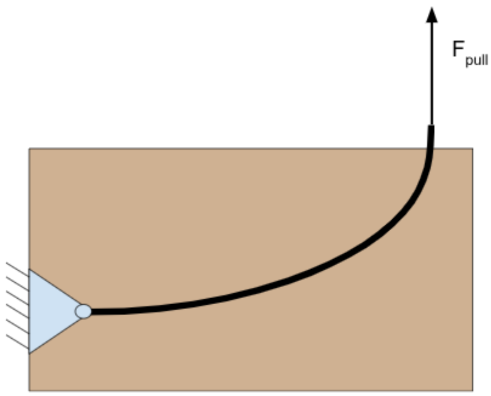

Figure 9: Effect of cable bending within the bed

4.1 Orcaflex implementation

OrcaFlex was selected to use as a simulation environment, mainly because of its suitability for cable-ship interactions during the pull-out process and it is commonly used for cable installation simulations. On its own, OrcaFlex does not have soil interaction models available for buried components, let alone consider soil deformation. Thus the soil-resistance acting on the cable is modelled as a spring-damper force that is applied on a discretized cable.

This soil-cable interaction is then implemented as a user defined function (UDF) to include the drained, undrained and mobilisation effects as described in section 2, consisting of mobilization ($< 0.01H$) and the normalized peak uplift force, depending on the normalized deformation rate. The concept of the UDF is shown in figure 10. For sake of simplicity, within this soil-cable interaction, it is assumed that the orientation of the cable remains horizontal, although the shape of the cable will be updated based on tension, soil resistance and its bending stiffness. .

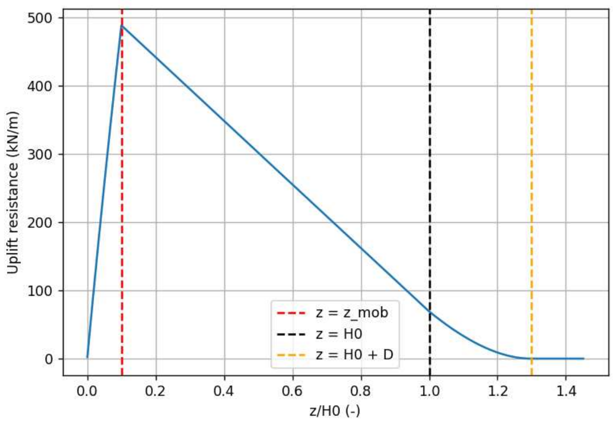

Figure 10: Uplift resistance model with $H_0 = 0.5m$, I_D=0.5, $v = 0.2\ m/s$, and $D = 0.149m$

As the spring-damper model does not recognize the deformation of a seabed, an virtual seabed is programmed within the UDF. This is a conservative approach, as the settling of the sediment underneath the cable is not accurately considered. The schematic of including the virtual seabed deformations within the UDF is shown in Figure 11

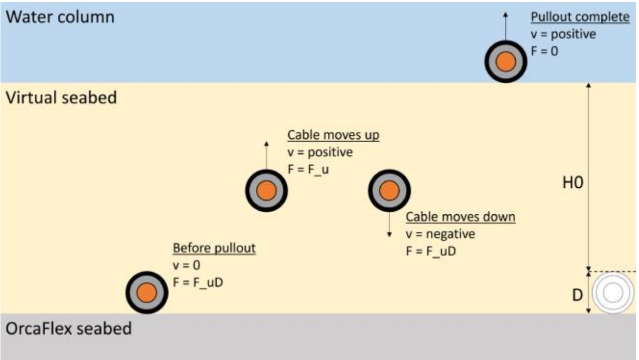

Figure 11: Visualisation of the resulting soil resistances in the virtual seabed computed by the UDF

4.2 Reference case

For this paper, a reference case is selected that is based on a 525 kV HVDC subsea cable. The relevant mechanical properties are shown in Table 1. All these material parameters are assumed as constant and uniform along the length of the cable. Based on the experiments of Ehlers et al. on a similar cable, ultimate tensile strength of the cable is approximately 1000kN.Excessive bending of the cable can result in local buckling destruction of the cable, as the armour wires interfere and touch each other (Fergestad 2017). Although buckling is less of an issue in decommissioning, it is likely to slow down the cable pullout process, unnecessarily complicating the operation and thus costs. The locking radius ρ_l follows from

$$\rho_l = \frac{R}{1 - Ff}$$

With cable radius R and fill factor F_f. For the cable properties as here, this results in a locking radius of approximately 1 m.

The scenario that is studied here is as if the cable was pulled out of the seabed as if it were an anchor line, hence the pull from the vessel as visualized in Figure 12. For now, it is assumed that there is no wave interaction influencing the vessel response.

Table 2:cable properties

Property	Unit	Value
Outer diameter	mm	149
Mass in water	kg/m	42.0
Axial stiffness (no rotation)	kN	390e3
Bending stiffness	kNm2	39
Torsion stiffness	kNm2	155
Pull-out velocity	m/s	0.2
Burial depth	m	1
Water depth	m	30

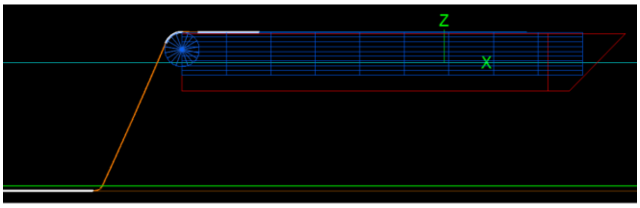

Figure 12:OrcaFlex simulation of pulling out a buried cable from the virtual seabed (green) with $H_0 = 1\,m$ and $I_D = 0.5$.

The cable is discretized in segments of length 0.05m. At the start of the dynamic simulation, all nodes have an applied load equal to the drained resistance. Once the node at 58m arc lengths starts moving, the partially undrained resistance is applied, which increases with increasing displacement and velocity at first until it starts decreasing due to time-dependent drainage and the declining burial depth. One by one, the nodes are mobilised. After mobilizing the node at arc length 61m, the simulation enters an approximate steady state where uplift resistance of each node follows a similar pattern. Results for the cable curvature are shown in Figure 13.

Limitations in pull out performance have been explored, identifying max tension and max bending radius of the cable during operation. This has been tested for various burial depths and relative soil densities. The results are presented in Figures 14 and 15. Based on those results, it is likely that most concern of damaging the cable is in tensile failure while pulling, which highly depends on relative soil density and the burial depth. These results indicate that in most practical cases, some equipment or processes are required to relieve the soil resistance force on the cable. This could be done by e.g. use of water jets to fluidize the soil, or by combining pullout with deburial activities.

5 CONCLUSIONS & RECOMMENDATIONS

Upheaval buckling is a good starting point to study the cable-seabed interaction in the case of pull-out. Due to the rate of the pullout process the effect of dilation of the sediment significantly influences the pull-out response. Experiments have shown that lower pull-out forces are required for more flexible cables.

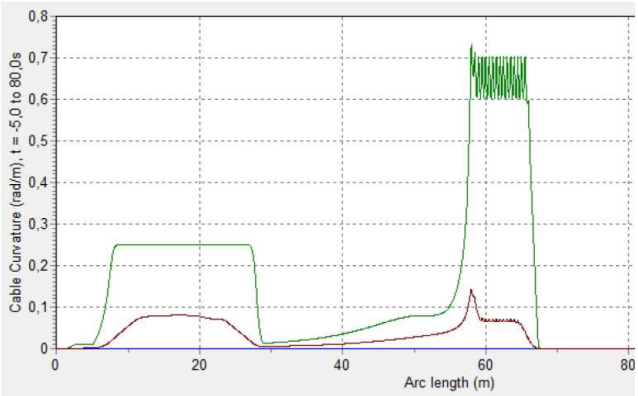

Figure 133: Range graph of the cable curvature with blue as minimum, red as mean and green as maximum curvature

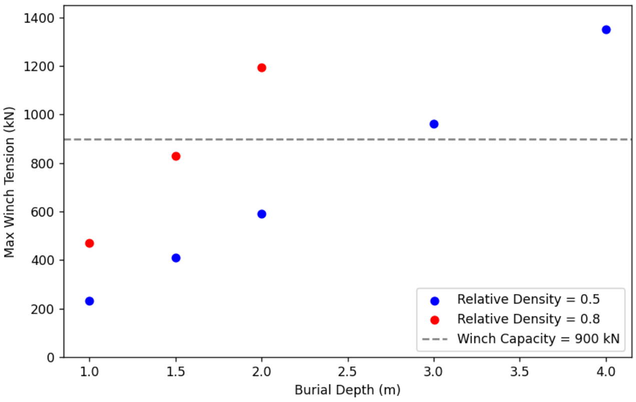

Figure 14: Maximum winch tension versus burial depth for medium and dense sand

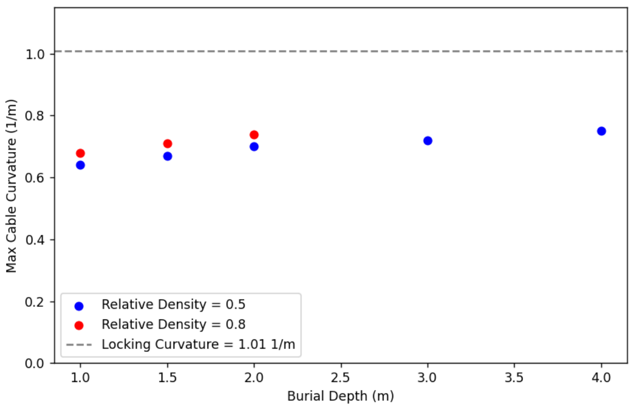

Figure 15: Maximum cable curvature versus burial depth for medium and dense sand

The pullout process is likely to be limited by the tensile strength of the cable. So far, the model results hint at limited cable curvature. However, the experiments indicate that for higher curvature, the pull-out force reduces. This requires further study to determine whether interlocking of the cable during pull-out might be a risk Techniques or processes that relieve the soil resistance force might be necessary for economic decommissioning of the offshore power cables.

Although OrcaFlex might be suitable for the cable-equipment interaction, it is less suitable for seabed interactions. In this paper it is shown that OrcaFlex can be adapted for this. However, if a more thorough analysis of the cable-seabed interaction is desired, it is advised to use a solver that allows for more detailed analysis of the cable-seabed interaction, e.g. computational fluid dynamics solvers or geotechnical solvers.

AUTHOR CONTRIBUTION STATEMENT

RH: Data curation, Experiments, Methodology, Formal Analysis, Writing- Original draft. Supervision **WB**.: Software, Simulations, Methodology, Reviewing and Editing, **EBP, OK, SS:** Methodology, Reviewing and Editing

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6 REFERENCES

Bransby, M.F., og J. Ireland. 2009. „Rate effects during pipeline upheaval buckling in sand.“ *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering.* doi:10.1680/geng.2009.162.5.247.

DNV AS. 2016. *Recommended practice - DNV-RP-0.360 Subsea power cables in shallow water.* Tech. rep.

DNV AS. 2021. *Recommended practice - DNV-RP-F114 Pipe-soil interaction for submarine pipelines.* DNV.

Fergestad, Dag. 2017. *Handbook on design and operation of flexible pipes.*

Ove Arup & Partners Ltd. 2018. *Review of Approaches and Costs of Decommissionning Offshore Wind Installations.* Tech. Rep.

Topham, E., E. Gonzalex, D. McMilan, og E. Joao. 2019. „Challenges of decommissioing offshore wind farms: Overview of the European experience.“ *Journal of Physics: Conference Series (vol 1222, No. 1 p012035).*

White, D.J., C.D. O'Loughlin, N. Stark, og S.H. Chow. 2018. „Free fall penetrometer tests in sand: Determining the equivalent static resistance.“ Í *Cone Penetration Testing 2018*, 7. CRC Press.