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B1 INSULATED CABLES
PS1 / Learning from experiences

Failure cause analysis and prevention of subsea cable failures in a joint industry project (JIP CALM)

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SUMMARY

The joint industry project for cable lifetime monitoring was initiated by the author's companies in collaboration with international industry partners to reduce subsea power cable failures and make offshore wind energy more reliable. The project consisted of four main tasks. For the first task, a highly secure environment to safeguard all received sensitive cable system failure data was used. In total more than 100 failure cases were analysed, comprising of both power cables and accessories. Every failure case was thoroughly analysed to isolate the main failure initiating component, classify the associated failure mechanism and provide recommendations. The results were analysed, anonymised, and released to the consortium to highlight the immediate risks and their prevention for submarine power cables throughout all life cycles. These results highlight key aspects requiring attention during the cable system design, manufacturing, installation, and operation stages to prevent failures.

The second task is to develop and test a Fibre-Optic (FO) based sensing technology that continuously monitors the mechanical loading of submarine power cables to prevent failures throughout the lifetime, as were identified in the first work task. Finite-Element modelling (FEM) has been applied to verify the unambiguous sensor response to critical parameters such as minimum bending radius, axial strain and twisting, as well as sensor integrity. Available FO read-out technologies have been investigated and their accuracy and response time were practically verified up till 50km distance using a dedicated test frame. The FO-sensor unit concepts are under production and will be integrated in a submarine power cable and undergo full scale testing, in collaboration with the industrial participants.

The third task focusses on the assessment of seabed and its importance for submarine cables. Sand wave dynamics is key importance for both the submarine cables. Significant advances have been made in applying a 3D morphological model for a sand wave field. It results in better understanding of the driving forces and predictions for future seabed levels and associated uncertainties relevant for cable burial assessments. Using smart algorithms and satellite imagery, heat maps have been generated showing nearshore seabed dynamics. The long-term morphological changes can affect cable burial and its thermal dynamics, for which a model is developed. This model is tested against DTS measurements. Finally, a cable routing tool is developed, which considers expected seabed dynamics in the design of cable routes. The fourth task deals with the cost and impact assessment of the proposed innovations in this project. To make a sound assessment of the impact of the innovations proposed, the team developed a detailed model of the cable installation process and validated it with real wind farm cases. The model makes use of a discrete event approach for simulation of the transport and installation logistics planning and cost, ensuring realistic estimates and a view on the spread in results considering the operational state of art and weather conditions. The impact of the innovations, including the developed FO monitoring system, will be assessed in comparison to a reference offshore wind farm case.

KEYWORDS

Cable failure cause, cable lifetime monitoring, Fibre optic, distributed sensing, strain, bending, power cable, interrogator seabed mobility, landfall, cable route optimization, cable burial detection, LCOE

1. CABLE FAILURE CAUSE ANALYSIS (WP1)

The first work task of this joint industrial project involved the secure collection, storage and in-depth root cause analysis of cable system failure data shared with the consortium.

1.1. Confidentiality requirements of the failure data and analysis

To ensure the confidentiality of the failure data on one side while enabling the analysis of this failure data on the other side, a secure environment was ensured existed both from a physical perspective (secure room with restricted and monitored access) and from an electronic perspective (data containers housed in a cloud with IPv4 machine-mapped access). In this way, the analysis of the failure data could happen fully secured while generic, anonymized results could be shared with the consortium in order to take learnings from the failures in submarine power cables. Some of these learnings are shared below.

1.2. Failure data sets and statistics

A total of 135 unique and different submarine power cable system failures were analysed by experts, comprising of 114 failures in the cable sections (85% of the entire dataset- 45% with AC-XLPE insulation, 4% with DC-XLPE insulation, 2% with EPR insulation, 1% of SCFF, 6% of MIND, and 42% could not be disclosed by insulation type), 10 joint failures (7% of the entire dataset) and 11 termination failures (8% of the entire dataset). It is worth noticing that the percentages show failures related to the whole dataset, not the percentages related to the subpopulation of one specific insulation material. Hence, it cannot be concluded that XLPE tends to fail more often than other materials.

The dataset comprised failures in cable systems of the MV(AC) class ($1.2\ \text{kV} \leq U_m \leq 36\ \text{kV}$- 31% of the cable dataset), the HV(AC) class ($36\ \text{kV} < U_m \leq 170\ \text{kV}$- 25% of the cable dataset), the EHV(AC) class ($170\ \text{kV} < U_m$- 6% of the cable dataset) as well as HVDC (12% of the cable dataset) cable systems. In addition, 26% of the failures could not be disclosed by voltage range.

The termination failures are all from the MV(AC) class, and for the joint failure records, 70%, 20% and 10% belong to the MV(AC), HV(AC) and EHV(AC) classes, respectively. The entire failure dataset is of an international nature, with multiple records in the EU and UK regions.

1.3. Failure analysis and findings

The failures have been related to dominant failure mechanisms, which occurred mainly during (in diminishing order): the installation phase, the production phase, the transportation phase, the operation phase, and the design phase.

It is noted that the root cause of these failure mechanisms may have been formed in earlier lifetime phases than mentioned here (for example, a failure mechanism related to the installation phase could have been caused by a root cause in the design, meaning that the phase in which the root cause is created would be the design phase instead of the installation phase).

Upon examining the dominant failure mechanisms leading to failures in cable sections (not in accessories), the following was seen as most important reasons and factors for failures:

- Related to the design phase:
  - For MV cable sections: failure to correctly design for fatigue experienced at J tubes.
  - For HV cable sections, components deviating from type tested components (so no representative design test), cables not being designed to cope with the appropriate forces or platform vibrations.
  - For EHV cable sections, cables being designed for inappropriate mechanical forces.
- Related to the manufacturing phase:
  - For MV cable sections, material or production problems such as extrusion errors, insulation material impurities or inclusions.
  - For HV cable sections, contaminations of raw materials and incorrect cable assembly in combination with insufficient QA/QC procedures.
  - For HVDC cable sections, material or production problems such as extrusion errors, insulation material impurities or inclusions.
- Related to the installation phase:
  - External damage arising from a variety of origins including application of excessive forces during cable handling, faulty cable installation equipment, insufficient cable protection during

    heavy weather conditions, unexpected objects on the sea floor and impaired visibility of operators during cable laying.
  - Incorrect handling of cable systems arising from a variety of origins including not adequately monitoring the installation process, overrunning the cable by the installation equipment, incorrect operator inputs and decisions in various control software, breakdown of the cable pulling machinery, dragging cables over a rough surface.
  - Incorrect installation of cable components, for example incorrect earthing and bonding of the cable system during installation, incorrect connection of the earth screen and incorrect repair methodologies.
- Related to the operational phase:
  - External mechanical damage.
  - Overloading of cable systems by not adhering to design limits.

Analysing the failures towards their technical cause learned that 74% of the failures in the dataset (all life phases combined) can be attributed to mechanical failure mechanisms. The most affected parts of the cable system are the outer sheaths of the power cables and the (integrated) fibre optic cables. Also, often a mechanical cause is found when evaluating cable insulation material failures, lead sheath failures, water blocking layer failures, earth screen wires/tapes/connections failures, armour wire failures and clamp and conductor connector failures. Another 8% of the failures in the dataset (all life phases combined) can be attributed to electrical failure mechanisms which are mostly connected to the power cable insulation impurities or inclusions.

Analysing the individual sub-components and their dominant failure causes, showed the following:

- Most of the cable system electrical insulation failures result from either material impurities or from water tree growth due to water ingress through outer cable layers.
- Most of the cable system lead sheath failures result from incorrect handling during production or during repair and from insufficient mechanical withstand capabilities against the forces at play. For example, metal fatigue due to excessive platform vibrations in combination to water current induced vibrations right after leaving the J-tube, resulting in a failed lead sheath leading to full cable failure.
- Most of the cable outer sheath failures were observed to occur for reasons such as damage occurring due to pulling of the cable in ducts or impacts and cuts caused by the installation equipment. Also, problems during the extrusion of the outer sheath were identified causing severe necking of the outer sheath.
- Most of the fibre optic cable failures result from cable twisting, from spooling the power cable on a turn table with a too small inner diameter and from damage caused by adjacent cable layers. Other regular causes are incorrect fibre optic cable production leading to faulty insulation of the metal tube, corrosion of the metal tube, local overheating of the full cable system and limited mechanical strength of the fibre optic cable.

1.4. Recommendations

From the analysis of the submarine power cable system failures, it thus has been possible to deduce a number of commonalities behind failures of different types of cable systems. For these generic findings, also a set of recommendations could be deduced with the aim to help preventing such failures.
Some of the generic recommendations are:

- Ensure that the type tests for qualification of the cable system in general and the water blocking components specifically are properly defined for the application and are correctly performed.
- Avoid any undefined electrical potentials in the cable system, since they lead to unwanted current flows which can damage cable components by heating and chemical (corrosion) reactions.
- Much greater attention needs to be directed towards proper cable handling practices, to make sure no overbending or twisting of the cables occur.
- The installation/layout route should be well investigated before installation and this information should be used to prepare the installation equipment in advance.

- Proper knowledge of all design limits should be communicated to installation and repair personnel so that the cable integrity is not jeopardized due to exceeding design limits whilst various installation procedures are active.
- Proper QA/QC procedures should be adopted during the production phase and especially also during the installation phase. To take actual installation conditions properly into account, the type tests and further special design tests should be relevant for the situation which is expected in reality. During manufacturing a focus on the verification of the cable sheath integrity over the whole cable length is important.

Further recommendations exist for cable accessories and more detailed information was developed for the joint industry project participants.

2. CABLE LIFETIME MONITORING SYSTEM DEVELOPMENT (WP2)

2.1. Problem formulation and concept description

Monitoring the strains, loads and deformations continuously and timely during the full life cycle of an electric power cable allows to detect critical conditions that help to prevent possible failures, which is key to integrity management and qualification. At several stages during the following process, input from the failure and root cause analysis in the first work package (WP1) has been used. One of the key parameters, amongst others, to ensure cable integrity during load-out and installation is the minimum bending radius (see Figure 1). This has initially been selected as main design driver for the sensor system concept.

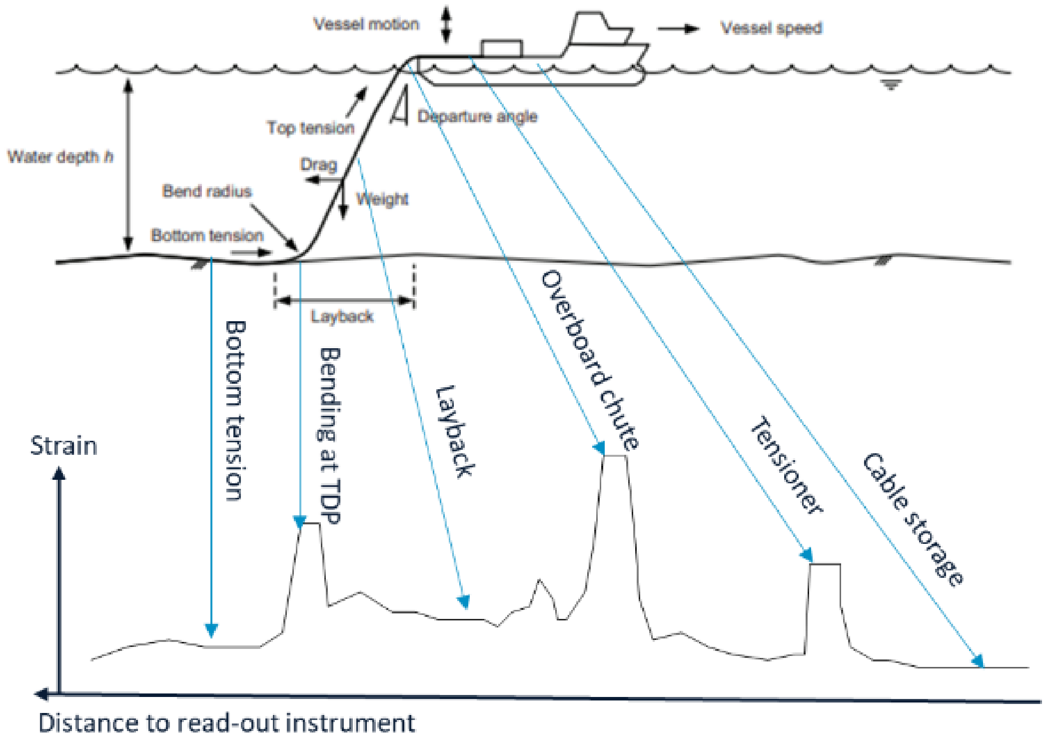


Figure 1: Representation of various strain exposures to the power cable during the offshore cable installation. Source: Recommended Practice (RP-0360)- Subsea power cables in shallow water *[1].*

The proposed concept makes use of a sensor unit that contains several tight-buffered optical fibres mounted in a well-defined geometry. The strain distribution over the full length of the sensing fibres is continuously recorded using e.g., Brillouin Optical Time Domain Reflectometry (BOTDR) [2]. This DSS (Distributed Strain Sensing) allows real-time monitoring of the strain, enabling to calculate the estimated shape of the sensor unit and (under the assumption of shape similarity) of the power cable it is mounted in. Distributed Acoustic Sensing (DAS), which only measures relative strain variations, could also be considered for the estimation of the shape, provided that some initial shape calibration can be made available. The following goals are set to develop the concept into a successful monitoring solution (due to confidentiality of this project, only global aspects/features can be disclosed):

- The measurement concepts should be capable to monitor cable length typically up to 50km
- The monitoring concept shall provide control of power cable integrity over the total lifecycle of the cable, spanning production, transport, deployment and operation
- The main parameters to monitor for early warning on failure-endangering are, e.g., strain, bending, torsion, and temperature
- The FO sensing unit shall be produced such that it can be integrated into various submarine power cable designs

Technology for the interrogation of the sensing cable must be accurate in position and response to events exposed to the power cable, reacting within seconds to the events

2.2. Approach: design methodology and modelling

Three cable-specific sensor unit designs have been modelled in collaboration with cable manufacturers. The unambiguous sensor response to critical parameters such as minimum bending radius, axial strain and twisting has been evaluated using analytical and Finite-Element modelling (see Figure 2).

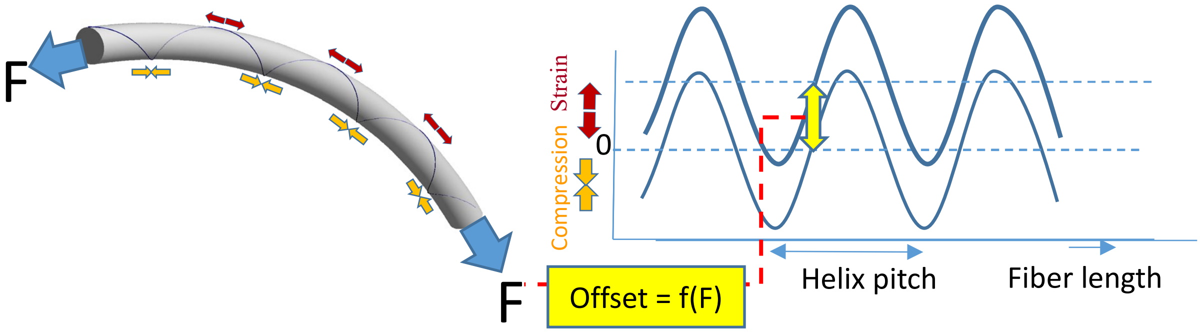


Figure 2: Impression of the strain in a fibre wound in a helix attached to the outside of a bent and stretched flexible component.

The models showed importance of the sensor unit geometry and interaction with the cable to ensure sensor accuracy, while maintaining its integrity. Also, some properties of the sensor read-out and post-processing, such as averaging over non infinitely small distance with a given cable lay-length, have been investigated. Although these models have been very useful during the initial design, a test plan has been prepared and started to verify the performance of the components and system for proof of concept. Two fibre optic sensing unit designs were made to the level of prototyping.

2.3. Test program and first results

The test plan for evaluation of the sensor system consists of tests at different levels, from component, through small-scale to full scale. The component and small-scale tests have been performed for different samples and read-out equipment from different manufacturers. The full-scale tests are planned for the second quarter of 2022. The concept as described in the first section consists of several components, from the bare fibre, the sensor unit, the read-out equipment and the postprocessing tools. Figure 3 (Left) shows a static test frame (STF) as well as a test bench in Figure 3 (Right; to apply and define the radius of the curvature) that have been developed to perform dedicated tests in a controlled setup.

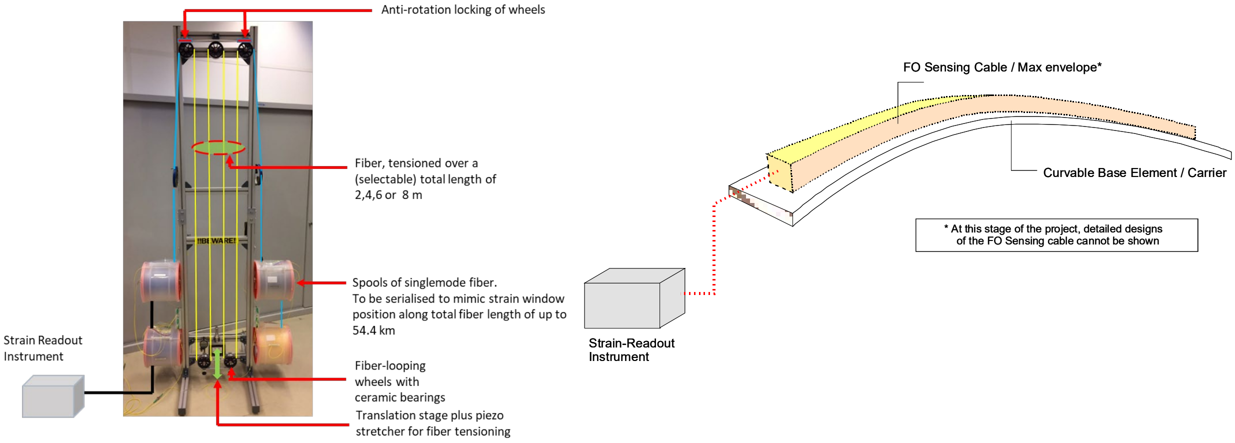


Figure 3: (Left) Static Test Frame (STF) that used for validating the strain reading performance ofvarious read-out technologies. (Right) Test bench adjustable for different radius of curvature.

The first results from component and small-scale tests are listed below:

- These optimized-tight buffer fibres using OTDR and BOTDR, specifically produced for this joint industry project are suitable to be integrated into a prototype fibre sensing cable.
- The results on DSS and DAS using the STF showed the suitability of these techniques for read-out of the FO sensing cable response, providing absolute strain measurement for the first one and relative strain measurement for the second one. Future work: improve read-out speed and reduce minimum window length, dynamic window shift with modified STF.
- Small-scale tests showed that the applied bending radius can be retrieved from the measured strain. From these tests, more detailed area of improvements on FO sensing cable production for long lengths have been identified and will be tested in a similar way.

To pre-qualify the power cable including the integrated FO sensing cable, a full-scale test program will be executed and documented in the coming period. The aim is to use both DSS and DAS technologies to detect various critical conditions that are applied to the power cable.

3. CABLE-SEABED INTERACTION (WP3)

3.1. Sand wave modelling

The assessment of seabed and sand wave dynamics can be of key importance for both the inter-array and export cables [3], [4]. Various offshore infrastructural projects, like offshore wind farms, demand long term (30-50 years) predictions of the seabed dynamics. Currently data-driven methods are used to determine the range of expected bed levels. However, the uncertainty in these predictions is significant, with sand waves being the largest source of uncertainty. Most of the planned wind farms in the (e.g., Dutch) North Sea are located in areas where the seabed is covered with sand waves, where these sand waves have lengths of 100-1000 m, heights of 1-8 m and they migrate with rates of up to 10 m/year [5]. Sand wave migration and changes in the shape of the sand wave, may cause a significant change in the local bed levels, which can decrease the stability of foundations or bed protections or cause exposure of cables and pipelines.

For this reason, a numerical modelling approach is adopted for predicting the migration of sand wave fields. For multiple sites in the North Sea, a 2DV transect model has been set up using bathymetry surveys and local current conditions induced by tides, wind and storms [6]. Through these case studies the influence of various combinations of tidal forcing was analyzed for real-life situations (see Figure 4). Clear dependencies of sand wave growth and migration on boundary conditions were found. The M4 tidal component is identified as an important driving force for the local sand wave migration. Moreover, the addition of a residual current caused further migration of the sand waves. The differences in morphological results with the simulation including the full tidal signal indicate that other tidal components might also be of importance.

By applying a full 3D model, it was found that even in a regular sand wave field, without much variation in sand wave migration direction, 3D effects in hydrodynamics can be of importance to morphology. In a 3D flow field, the variations in flow velocity and direction over a sand wave field are better represented [6]. At the location of steep sand waves slopes the direction of sediment transport is significantly influenced by bed slope transport. This might cause deviations between the sediment transport direction and the flow direction at the bed. These factors make the inclusion of a third dimension in sand wave modelling essential for a good representation of hydrodynamics and sediment transport.

To summarize, these significant advances in applying a process-based 3D morphological model for a sand wave field result in better understanding of the driving forces and quantitative predictions for future seabed levels and associated uncertainties relevant for cable burial (risk) assessments, while it also allows studying the effect of human activities, such as dredging.

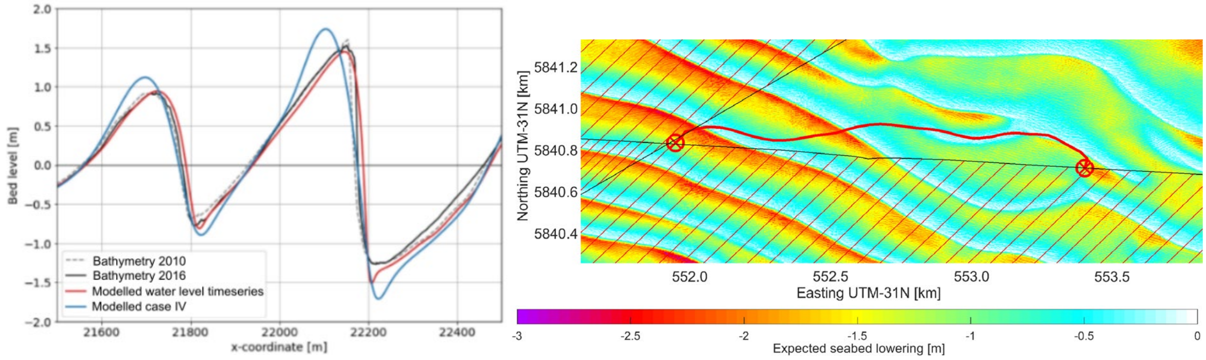


Figure 4: a) Measured and computed bed levels after 6 years with water level timeseries and Case IV forcing (combination of M2, S2, M4 and residual current), b) Cable route between two turbine locations avoiding areas of significant seabed mobility & constraints (red hatched areas).

3.2. *Satellite derived bathymetry (SDB) for seabed mobility*

In the nearshore area, where submarine cables landing onshore, complex interactions between winds, waves, currents, and sediment induce large uncertainties in cable burial depth assessments. Extensive (historic) measurement campaigns with multi or single-beam sensors in the shallow nearshore are difficult to perform, time-consuming and costly, cover only a limited spatial extent and have limited temporal coverage. The use of optical satellite imagery to supplement available bathymetric data in data sparse environments is more apparent nowadays, as data from space sensors is publicly available and more easily accessible. By using smart algorithms, the automatic generation of clean, high-quality multispectral (composite) satellite images allows to overcome many of the aforementioned difficulties with measurement campaigns. Nevertheless, the ability of SDB to supplement in-situ data also has its limiting factors, as light cannot penetrate the water column infinitely deep due to in-water characteristics like turbidity and algae and atmospheric conditions like cloud cover.

Clean images can be generated from a multitude of satellite images and transformed into heat maps (envelopes), which memorize the historical seabed mobility for various time windows. These heat maps are particularly useful in the subtidal regime, indicating nearshore areas with high seabed mobility in bright colors while stable areas appear dark (see Figure 5). Information derived from satellite derived heat maps can be used to perform first-order qualitative assessments of suitable areas for cable landfalls as well as more detailed quantitative assessments of channel, depression, shoal, and sand wave / bar dynamics in terms of migration speed and direction.

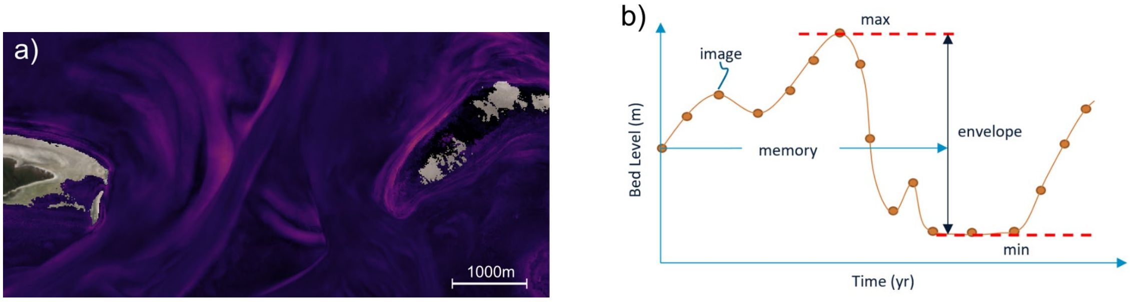


Figure 5: a) Depth Proxy Heat Map of the ‘Friese Zeegat’ (area between Wadden Sea islands Ameland and Schiermonnikoog). Bright (dark) colors indicate dynamic (stable) areas. b) schematizes the derivation of the heat map from clean (composite) optical satellite images.

3.3. Cable route optimization

Dynamics of the seabed can significantly influence cable burial depths. In particular, the migration of sand waves can result in cables either exposed on the seabed or buried under a thick layer of sediment with associated challenges such as cable overheating. Optimization of the cable route design based on seabed dynamics can significantly reduce risks and costs associated with power cable installation, operation, maintenance and failure [4].

Algorithms have been developed to minimize cable length and initial burial depth but also to avoid areas where cables might be exposed or buried too deep. Further advancements in the optimization algorithms have been made by including not only seabed dynamics but also other constraints such as archeological sites, environmental areas and areas with possible unexploded ordnances. The advancements have resulted in a tool capable of optimizing cable routes in such a way that risks of failure due to exposure or overheating can be reduced significantly over the lifetime of the windfarm (see Figure 4b).

3.4. Cable – seabed thermal interaction

The subsea cable temperature dynamics are influenced by several system characteristics, such as cable geometry, operational power signal, the surrounding seabed soil permeability/thermal conductivity or the background sea temperature. Fiber-optic based distributed temperature sensors (DTS) provide in-situ measurements of temperature dynamics in export cables. We explore the use of these signals to derive insights on the cable operating conditions, with a focus on the estimation of the cable's depth of burial (see Figure 6), a critical aspect in cable-life monitoring. In order to capture long-short term temperature dynamics in the cable, a detailed simulator is used. Unfortunately, physically-based thermal models result often in prohibitive simulation times. We have developed routines to accelerate physically-based cable-soil thermal dynamics, such that the relevant space-time scales can be accounted for in computationally intensive applications (e.g. probabilistic design, cable burial depth inversion etc).

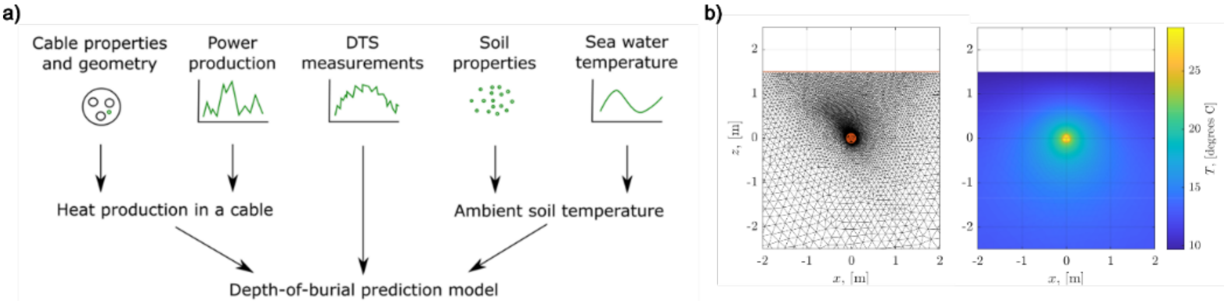


Figure 6: a) Seabed-cable thermal interaction components, b) grid and simulated temperature 2D field for a 1.5 m buried cable section.

4. COST-IMPACT ASSESSMENTS (WP4)

This section provides information regarding the cost and impact assessment of the proposed innovations in this project. For this task, the team developed a detailed model of the power cable installation process and validated it with real wind farm cases.

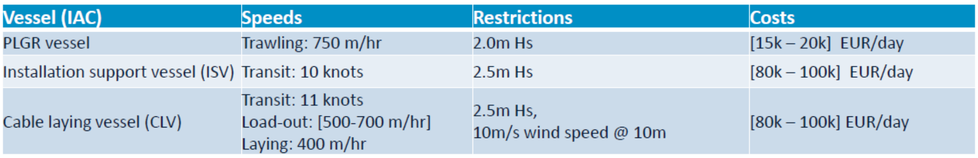
4.1. Methodology

The methodology applied to assess the impact of electric cable innovations is based on discrete event modelling of the logistics processes [7], [8]. This starts with a detailed method statement, containing all the required steps in the process, including the personnel and equipment needed and duration of the activity. Other inputs for the model are wind farm location and layout, environmental conditions, weather limits for vessel, etc. The simulations of the scenarios are performed in a framework [9], that allows uncertainty quantification through stochastic (Monte-Carlo) variation of inputs. This provides a view on the spread in estimated duration and cost of a campaign for different realizations of e.g., the wind and wave conditions. Two specific validation cases, developed with project consortium partners, confirmed the capability of the method. From these cases, a generic method statement has been derived that is used for the reference case and scenario studies.

4.2. Reference case

The offshore wind farm in the baseline scenario is located approximately 18 km from the Dutch coast in the North Sea. The wind farm covers approximately 225 km^2 and consists of 140 wind turbines of 11MW. The pull-in team and the installation support vessel are based at a port which is 30 km from the wind farm. The standard shift duration of offshore technicians is 12 hours. Two vessel types are modelled in the process of inter array cable installation. The Installation Support Vessel (ISV) is mobilised to transfer and accommodate technicians. The Cable Laying Vessel (CLV) is mobilised to load and lay the inter array cables. Table 1 shows the vessel data used for the reference case.

Table 1: Vessel data for the reference case



Vessel (IAC)	Speeds	Restrictions	Costs
PLGR vessel	Trawling: 750 m/hr	2.0m Hs	[15k – 20k] EUR/day
Installation support vessel (ISV)	Transit: 10 knots	2.5m Hs	[80k – 100k] EUR/day
Cable laying vessel (CLV)	Transit: 11 knots Load-out: [500-700 m/hr] Laying: 400 m/hr	2.5m Hs, 10m/s wind speed @ 10m	[80k – 100k] EUR/day

A dataset that includes 10 years of simulated data (2008-2018) of the wind and wave at the given site is run to simulate the weather workability window. Sensitivity analysis on the reference case indicates a clear dependency on the different realizations of the wind and wave conditions.

Figure 7 shows the duration of the installation campaign in number of days, when considering no weather effect (‘perfect weather’) and the different realizations of the wind and wave conditions. On average, including weather effects, this results in an approximately 30% increase in duration. The spread around the average weather conditions is estimated to be about 10% of the installation duration.

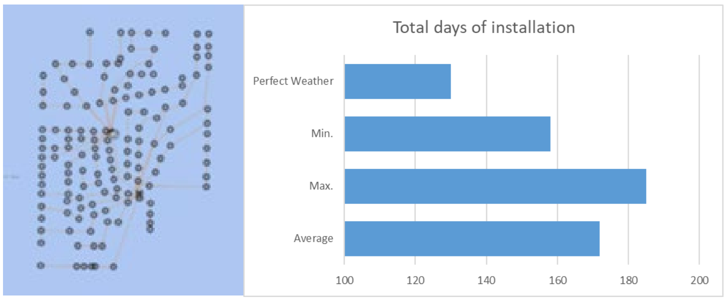


Figure 7: Reference layout (left) and effect of weather conditions on duration of the installation campaign (right)

5. Conclusions and outlook

The results generated from the failure cause analysis indicate a need for greater quality management protocols spanning across all the major lifecycle phases of the cable system. Some of the observations are presented here, with accompanying recommendations to mitigate them:

- Proper component design and production, with the right choice of material, according to operational needs imposed upon the cable system, proves to be very important, along with the requirement of adequate type testing and project specific testing that reflects installation conditions
- It was also observed that the design and transport/installation phases are very critical ones, to ensure that the cable system does not experience mechanical stress beyond permissible levels.

Current laboratory test results confirm:

- Feasibility of FO sensing and strain measurement quantitively
- Satisfying sensitivity and stability of distributed strain sensing under the chosen conditions
- The read-out technology to be capable of capturing the strain in a few meters long section of a fibre up to 50 kilometers, with the required readout response time
- Interesting perspectives for power cable lifetime monitoring

A good transfer of the FO sensing concept into a full-scale test program on a cable integrated sensor system, to be executed and documented in the coming period.

At this project, we are working with methods to accelerate the thermal model evaluation, so that the relevant space-time scales are accounted for, while the simulator can be integrated in probabilistic schemes to derive surrounding soil characteristics. Insights from this research aim at finding recommendations for better design of DTS cable measurement systems and characterize methods for cable exposure event detection.

- By using satellite-derived bathymetry estimates, we could identify near-shore (typically around 20 m depth) zones where large change rates have occurred historically (1985-onwards), and thus inform cable routing tools
- Thermal models for the cable-sea bed interaction need to cover a wide range of temporal scales (high frequency power-driven heating vs. long-term sea-bed background temperature). There is a need for physically based models that can cope with these scales at operational running times
- Cable routing tools should account for predictive seabed morphology dynamics to reduce installation costs and risks

The method for logistics modelling consists of a discrete event process description, simulated using Monte-Carlo variation analysis. The method has been validated on two specific cable installation cases, which gives confidence to use this for the impact assessment of the innovations. The representative reference case for cable installation, a typical offshore wind farm of 140x11MW wind turbines, is defined. Future work in the coming period is the schedule and cost impact assessment of different innovations, such as the FO-based monitoring system. This will be performed by modification of the operational process description in the simulation framework, followed by detailed analysis of the results.

BIBLIOGRAPHY

[1] "Recomended Practice (RP-0360)- Subsea power cables in shallow water," DNV, 2016.

[2] A. H. Hartog, An introduction to Distributed Optical Fibre Sensors, CRC Press, ISBN 978-138-08269-4, 2018.

[3] A. A. Nemeth, S. M. Hulscher and H. J. de Vriend, "Offshore sand dynamics, engineering problems and future solutions," *Pipeline and Gas Journal,* vol. 230, no. 4, pp. 67-69, 2003.

[4] T. J. Roetert, T. C. Raaijmakers and B. W. Borsje, "Cable route optimization for offshore wind farms in morphodynamic areas. Proceedings of the Twente-seventh," in *International Ocean and Polar Engineering Conference*, San Francisco, CA, USA,, June 25-30 2017.

[5] R. Morelissen, S. M. Hulscher, M. A. Knaapen, A. Németh and R. Bijker, "Mathematical modelling of sand wave migration and the interaction with pipelines. Coastal Engineering," vol. 48, no. 3, p. 197–209, 2003.

[6] P. Overes, "Modeling Sand Wave Field Dynamics in the North Sea using Delft3D Flexible Mesh," MSc thesis, TU Delft, 2021.

[7] A. Dewan, M. Asgarpour and R. Savenije, "Commercial proof of Innovative Offshore Wind Installation Concepts using ECN Install Tool," Technical report ECN-E—015-007, Petten, The Netherlands, 2015.

[8] G. Venkitachalam, "Modelling the installation of offshore wind farms," Thesis report, TU Delft, Delft, The Netherlands, 2020.

[9] "software for offshore energy operations," [Online]. Available: https://uwise.tno.nl/. [Accessed 22 12 2021].