Summary report Joint-Industry-Project CAble Lifetime Monitoring (JIP CALM)

Summary report Joint-Industry-Project CAble Lifetime Monitoring (JIP CALM)

Author(s)
Niek Bruinsma (Deltares)

A collaboration between AgileTek, Aker Offshore Wind, Boskalis, BREM, Deltares, DEME, DNV , ECE Offshore, Eneco , Hellenic Cables, Hengtong Submarine Power Cable, RWE, Jan De Nul, Marlinks, Marsh, MIRDC, National Grid, Ningbo Orient Wires & Cables, ORE Catapult, Omnisens, Orsted, Primo Marine, ScottishPower Renewables, Shell, Silixa, TKF, TNO, Van Oord, Vattenfall, VdHP and Wood.

Summary report Joint-Industry-Project CAble Lifetime Monitoring (JIP CALM)

Client	Rijksdienst voor Ondernemend Nederland
Contact	Niek Bruinsma (niek.bruinsma@deltares.nl)
Reference	TEHE118019 (Project referentie voor RVO) The project was carried out with funding from the Ministry of Economic Affairs and Climate and the Ministry of Agriculture, Nature and Food Quality, National schemes EZK and LNV grants, Top Sector Energy implemented by Rijksdienst voor Ondernemend Nederland.
Keywords	Joint-Industry-Project CALM, offshore wind, cable failure root cause, cable life monitoring, fibre optics, seabed mobility, cable route optimization, detection of cable burial depth

Document control	
Version	0.1
Date	01-12-2022
Project nr.	11204209-000
Document ID	11204209-000-HYE-0002
Pages	53
Classification	Public report
Status	final

Doc. version	**Author/companies**	**Reviewer**	**Approver**
0.1	Niek Bruinsma (Deltares)[1]	Jan-Joost Schouten	Dirk-Jan Walstra

---

[1] A collaboration between AgileTek, Aker Offshore Wind, Boskalis, BREM, Deltares, DEME, DNV , ECE Offshore, Eneco , Hellenic Cables, Hengtong Submarine Power Cable, RWE, Jan De Nul, Marlinks, Marsh, MIRDC, National Grid, Ningbo Orient Wires & Cables, ORE Catapult, Omnisens, Orsted, Primo Marine, ScottishPower Renewables, Shell, Silixa, TKF, TNO, Van Oord, Vattenfall, VdHP and Wood.

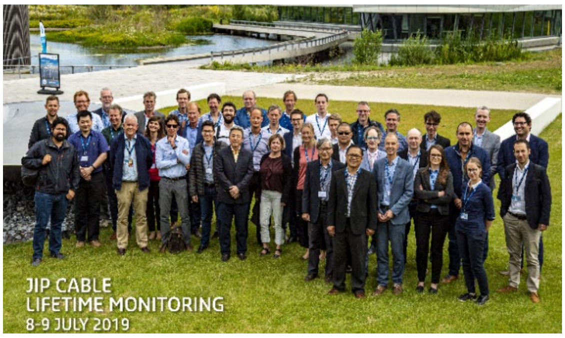
CALM

Deltares
TNO innovation for life
DNV
BREM funderingsexpertise
VANDERHOEKPHOTONICS
AgileTek
AKER OFFSHORE WIND
Boskalis
DEME OFFSHORE
Eneco
ECE offshore
CABLEL HELLENIC CABLES
HTGD 亨通光电 HENGTONG OPTIC-ELECTRIC
Jan De Nul GROUP
MARLINKS
MARSH
MIRDC
nationalgrid
omnisens
CATAPULT Offshore Renewable Energy
ORIENT 东方电缆 ORIENT CABLE
Ørsted
primo marine Independent Marine Infrastructure Expertise
RWE
SCOTTISHPOWER RENEWABLES
Shell
SILIXA
TKF
Van Oord Marine ingenuity
VATTENFALL
wood.

Netherlands Enterprise Agency
TKI WIND OP ZEE Topsector Energy

Summary (*in Dutch*)

Om aan de toenemende vraag naar duurzame elektriciteit te voldoen, zijn en worden op grote schaal offshore windparken gebouwd waarin alle windturbines met elkaar en met het landelijke elektriciteitsnet zijn verbonden door middel van onderzeese stroomkabels. Storingen aan deze stroomkabels leiden meestal tot aanzienlijke kosten als gevolg van lange uitvaltijden en hoge reparatiekosten. Om deze negatieve effecten te verminderen is in juli 2019 het Joint Industry Project CAble Lifetime Monitoring (JIP CALM) gelanceerd. Dit project liep tot december 2022 en hierin werd door 31 internationale, veelal marktpartijen samengewerkt om de betrouwbaarheid van onderzeese stroomkabels over hun volledige levensduur te verbeteren. Het project bestond uit vier hoofdtaken: (1) Oorzaken van kabelstoringen onderzoeken, (2) monitoren tijdens de levensduur van kabels, (3) interactie tussen kabel en zeebodem en tot slot (4) de logistiek en kosten beoordelingen.



JIP CALM project team bij kick-off meeting in 2019.

In de eerste taak werden 135 storingen van onderzeese stroomkabelsystemen, bestaande uit onderzeese kabels, verbindingen en afsluitingen, verzameld bij de partners en opgeslagen in een beveiligde omgeving om de vertrouwelijkheid van de informatie te waarborgen, dit is beschreven in Hoofdstuk 2. De statistische storingsanalyse omvatte het bestuderen van de verdeling van storingen over het type kabelsysteemcomponent, spanningsklasse, kabelsysteemverbindingstype, isolatietype en type onderzeese kabelsysteemtechnologieën. Bovendien werden het type bedrijf dat storingsgegevens aanleverde en geografische storingsdistributiegegevens getraceerd zonder de vertrouwelijkheid in gevaar te brengen. Deze analyse heeft geresulteerd in belangrijke aanbevelingen voor verbeteringen a) van het kabelontwerp, b) tijdens de fabricage, c) tijdens de installatie- en d) gebruiksfase om risico tot storingen te voorkomen. Verder wordt aanbevolen dat er in alle onderzeese kabelprojecten meer aandacht is voor kwaliteitsmanagement, met goed kwaliteitsmanagement kunnen veel van de storingen voorkomen worden. Om te helpen dit tot stand te brengen is binnen dit project een kwaliteitsmanagementfilosofie en -procedure opgesteld. Daarnaast worden ook verschillende kwaliteitsmanagement-, kwaliteitsborgings- en kwaliteitscontroleacties aanbevolen.

Onderzeese stroomkabels zijn voorzien van een geïntegreerde glasvezelkabel om onder andere data te versturen en de temperatuur van de kabel te kunnen meten. De tweede taak van dit project betrof de ontwikkeling van een nieuw glasvezel- (Fibre-Optic, FO) monitoringsysteem dat continu de mechanische belasting van onderzeese stroomkabels gedurende hun levensduur bewaakt, en is beschreven in Hoofdstuk 3. Dit systeem bestaat uit een FO-sensor, geïntegreerd in de stroomkabel, die is aangesloten op een uitleesinstrument voor het meten van gedistribueerde rek. De nauwkeurigheid en reactietijd van commercieel beschikbare FO-uitleestechnologieën zijn onderzocht met behulp van een speciaal ontworpen testframe, waarbij is geverifieerd dat statische en dynamische rek aangebracht over een lengte van 2 meter tot op een afstand van minstens 50 km kan worden geregistreerd, i.e. een typische lengte van een offshore kabel. Van twee FO-sensor concepten zijn prototypes vervaardigd in een continu fabricageproces en vervolgens geïntegreerd in twee soorten 3-aderige onderzeese stroomkabels voor de offshore wind industrie. Door het combineren van meerdere

optische vezels in deze sensor kunnen de buigstraal en rek in de stroomkabel onafhankelijk worden bepaald. De encapsulatie van de optische vezels in de sensor en integratie van de sensor in de stroomkabel is in detail gemodelleerd, om zowel een goede mechanische respons als de integriteit van de sensor te verzekeren. De stroomkabels met geïntegreerde FO-sensoren zijn vervolgens aan een serie mechanische belastingtests onderworpen om het monitoringsysteem te evalueren. De ontwikkeling en tests zijn uitgevoerd in nauwe samenwerking met de betrokken industriële consortium partners. Dit heeft geresulteerd in de bevestiging van het potentieel voor de verdere industrialisatie van het ontwikkelde monitoringsysteem voor het meten van kritieke mechanische belastingen, zoals buiging en torsie, gedurende de levensduur van onderzeese stroomkabels.
Binnen dit tweede onderzoeksthema werden twee aanvullende deeltaken uitgevoerd. Stick-slip is het verschijnsel waarbij soms spontaan een schokkende beweging optreedt bij over elkaar schuivende voorwerpen. Om het begrip in de industrie van het stick-slip gedrag van onderzeese kabelgeleiders te vergroten, is een testprogramma opgesteld om het gedrag van de draden in de geleider onder buiging en spanning te evalueren, dit is beschreven in Hoofdstuk 4. Ten tweede werden de prestaties van gedistribueerde akoestische metingen (DAS) technologie geëvalueerd voor het detecteren van de begraafdiepte van een onderzeese stroomkabel, dit is beschreven in Hoofdstuk 5.

De derde taak heeft betrekking op het vergroten van begrip van de dynamische zeebodem en het belang ervan voor onderzeese stroomkabels, dit is beschreven in Hoofdstuk 6. Dit is momenteel een van de grootste risico’s in het ontwerp van een kabelproject. De dynamiek van zandgolven is van cruciaal belang en er zijn significante vorderingen gemaakt bij het toepassen van een 3D-morfologisch model voor een zandgolfveld. Dit resulteert in een beter begrip van de drijvende krachten achter het veranderen van de zeebodem en daarmee het beter kunnen voorspellen voor toekomstige zeebodemniveaus die relevant zijn voor waar en hoe diep je stroomkabels moet begraven. Met behulp van slimme algoritmen en satellietbeelden zijn er tevens kaarten gegenereerd die de dynamiek van de zeebodem nabij de kust laten zien wat belangrijk is voor de aanlanding van de exportkabels die de stroom van het windpark naar het vaste land brengt. Verder is er een tool voor het plannen van kabel routes ontwikkeld die rekening houdt met de dynamiek van de zeebodem en het uit te baggeren volume zand om de kosten en risico’s bij het begraven van kabels te minimaliseren. Tot slot is er is een thermisch kabel model ontwikkeld om de begraafdiepte van kabels te kunnen meten. Dit is getest tegen gedistribueerde temperatuur metingen (DTS) van een onderzeese stroomkabel, dit is in Hoofdstuk 7 beschreven.

De vierde taak betreft een kost- en impactbeoordeling, dit is beschreven in Hoofdstuk 8. Om de impact van de voorgestelde innovaties van de eerste drie hoofdtaken goed te kunnen beoordelen, is er een gedetailleerd model van het kabelinstallatieproces ontwikkeld en gevalideerd met casestudies van een representatief operationeel offshore windpark. Het model maakt gebruik van een discrete event-benadering voor simulatie van de transport- en installatielogistiek voor de beoordeling van de planning en kosten, waarbij rekening wordt gehouden met de realistische operationele aspecten en de weersomstandigheden. De impact van de innovaties is beoordeeld in vergelijking met een referentie case van een offshore windpark.

Summary (*in English*)

To satisfy the ever-increasing demand for electricity, significant quantities of offshore wind parks have been installed in which all the electricity is transported via submarine power cable systems. Failures of submarine power cable usually lead to significant costs due to long outage times and high repair costs. To reduce these negative effects the Joint Industry Project CAble Lifetime Monitoring (JIP CALM) was initiated in July 2019. The project, which ran until December 2022, was a collaboration between 31 international industry parties to increase the reliability of submarine power cables over their complete lifetime. The project consisted of four main tasks: (1) Cable failure root causes, (2) Cable lifetime monitoring, (3) Cable-seabed interaction and (4) Logistics and cost impact assessments.

JIP CALM project team at kick-off meeting in 2019.

In the first task 135 failures of Submarine Power Cable System consisting of submarine cables, joints and terminations were collected from the partners and stored in a secure environment to ensure the confidentiality of the information, this work is presented in Chapter 2. The failure statistical analysis included studying the distribution of failures over cable system component type, voltage class, cable system connection type, insulation type, and type of submarine cable system technologies. Additionally, the type of company providing failure data and geographical failure distribution data were traced without compromising confidentiality. This analysis resulted in key recommendations for improvement during a) the cable design, b) manufacturing, c) commissioning, d) and operation stages to prevent failures. Also, it is recommended that all submarine cable projects focus on the quality management because it was learned that many failures are preventable with good quality management. To help realize this, a quality management philosophy and procedure is prescribed and various quality management, quality assurance and quality control actions are recommended.

The second task focussed on the development of a new Fibre-Optic (FO) monitoring system that continuously monitors the mechanical loading of submarine power cables over their lifetime, this work is presented in Chapter 3. The developed system consisted of a FO-sensor unit integrated in a power cable and was connected to a distributed strain read-out instrument. Available FO read-out technologies have been investigated and their accuracy and response time for both static and dynamic strain over 2 meters window were practically verified up till at least 50 km distance using a dedicated test frame. Prototypes for two FO-sensor unit concepts were manufactured in a continuous process and integrated in two types of 3-core inter-array submarine power cables for the offshore wind industry. Detailed modelling has been performed to assure good mechanical sensor response as well as sensor integrity. The submarine cables with integrated sensors have been subjected to a series of mechanical pre-qualification tests and successfully passed all these tests. Both the development and testing were performed in close collaboration with the industrial consortium partners. This has resulted in the confirmation of the potential for further industrialization of the developed cable lifetime monitoring system for measuring critical mechanical load conditions of submarine cables, such as bending and torsion.

Within this second research topic two additional subtasks were performed. The stick–slip phenomenon, is the spontaneous jerking motion that can occur while two objects are sliding over each other. In order to advance the industry understanding of subsea cable conductor stick-slip behaviour a test programme is required to evaluate the behaviour of the wires within the conductor under bending and tension, this work is presented in Chapter 4. Secondly the performance of Distributed Acoustic Sensing (DAS) technology was evaluated for detecting burial depth of a subsea power cable, this work is presented in Chapter 5.

The third task relates to the assessment and understanding of the dynamic seabed and its importance for submarine cables, this work is presented in Chapter 6. Sand wave dynamics are of key importance and significant advances have been made in applying a 3D morphological model for a sand wave field. This 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 important for landfall of export cables. A cable routing tool is developed, which considers these seabed dynamics in the design of cable routes to minimise burial efforts and risk of de-burial of the cables. A thermal cable model was developed and tested against DTS measurements from a subsea power cable, this is presented in Chapter 7.

The fourth task deals with the cost and impact assessment, this work is presented in Chapter 8. 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 has been assessed in comparison to a reference offshore wind farm case.

Contents

1 Introduction to JIP CALM

1.1 Background

Submarine power cables are applied in the offshore wind industry to connect individual wind turbines and whole wind farms to the onshore electricity grid. Unfortunately, these power cables show to be less reliable than desired, resulting in revenue losses due to temporary limitation of the energy supply and high repair costs. Given the increasing dependency of society on renewable energy sources, it is important both from a societal and financial point of view to increase the reliability and lower the costs of both existing and new offshore wind farms. As a main bottleneck regarding reliability of offshore wind farms lies in power cable failures, these power cables must become more reliable. Exactly this is the overall high-level goal of the Joint-Industry-Project CAble Lifetime Monitoring (JIP CALM).

In virtually all offshore wind farms, the turbines that generate the renewable electric energy are connected in arrays. Power cables, so-called ‘inter-array cables’, connect the individual turbines in multiple strings and bring the electric energy to a collecting offshore substation. The inter-array cables typically are three-core submarine medium voltage (MV) AC power cables. In the offshore substation, a transformation to high voltage (HV) AC or DC takes place to enable transmission of the harvested energy to shore. All energy harvested by the wind farm then is transported to the electricity grid on land by a so-called ‘export cable’. This cable typically is a single three core submarine high voltage AC (HVAC) power cable system, though also other variants exist such as a double three core submarine HVAC cable system, or a high voltage DC (HVDC) cable system, using two single core cables in a bundled formation. Commonly, the export cables also comprise fibre optics for telecommunication, control and sensing applications.

Typical scale of offshore wind farms that are developed since 2016 in the Dutch EEZ is about 350 MW, but in the near future, wind farms will be developed at a much larger scale (typically at a 2000 MW) and further offshore. Typical ratings of currently available offshore wind turbines range between 8 and 15 MW, meaning that something like 25 to 45 turbines per 350 MW wind farm. The cost of offshore wind is significantly influenced by the progress of technology, e.g., wind turbine upscaling and advances in installation and O&M and by the wind farm scale and location (e.g. distance to shore, wind climate and water depth). What is interesting is that the percentage of cost (CAPEX) related to the inter-array and export cables required in a wind farm is relatively low with typical values of 3% to 10% of the total cost of an offshore wind farm.

Unfortunately, these power cables form a weak link as they appear to fail rather regularly. When a subsea power cable of an offshore wind farm fails, wind farm energy production is reduced or even fully blocked for several weeks or even months. Both failures in export cables or in inter-array cables lead to significant financial losses, as no energy can be delivered and the repair of submarine cable in offshore conditions is very costly and time consuming. Also, society will be increasingly dependent on this form of renewable energy and it is therefore important that offshore wind energy is a reliable source of energy.

JIP CALM, a research project with 31 industry parties, was initiated in July 2019 with the objective to make offshore wind energy more reliable and to help reducing costs due to cable failure. The research looked at aspects related to subsea power cables, which play a crucial role at getting offshore wind energy to our homes. The remainder of this document explains the work that was performed in the JIP CALM project in the period of 2.5 years; from July 2019 till November 2022. The JIP CALM project is financially supported by the NL Agency RVO under the R&D program TKI Wind op Zee (Reference TEHE118019).

1.2 Project objectives

The main objective of the research is to increase the reliability of supply of renewable energy offshore by reducing the number of power cable failures. A direct consequence will be that a) the risks for offshore wind projects will be further reduced, b) offshore wind energy will be available more reliably, and c) that the levelized cost of energy (LCoE) will be reduced.

The project has mainly focused on four components: 1) root cause analysis of cable failures, 2) cable lifetime monitoring, 3) cable-seabed interaction, 4) cost impact analyses, see also the project structure in Figure 1.1.

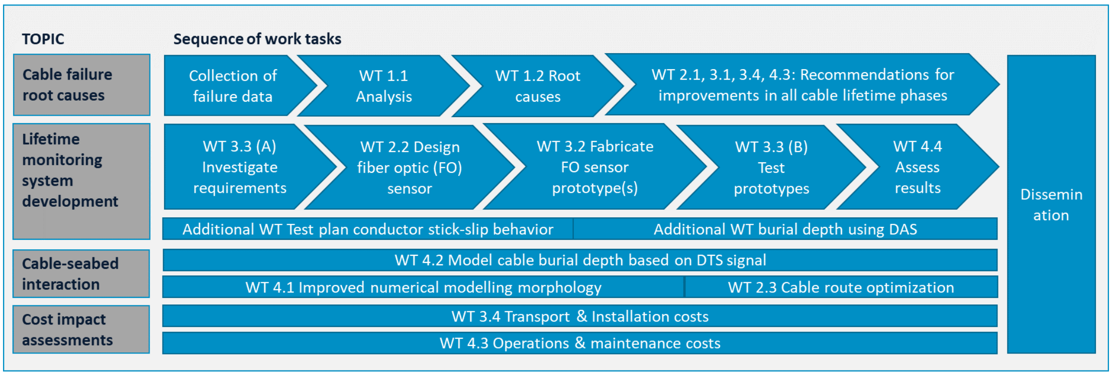


Figure 1.1 Project structure of JIP CALM research project consisting of 4 main topics. The different work tasks (WT) refer to the project proposal.

1.3 JIP CALM consortium

In the JIP CALM consortium, the entire value chain of the offshore wind industry related to subsea power cables is represented: manufacturers, owners, operators, contractors, insurance companies, consultancy firms and research institutes, see Figure 1.2.

Figure 1.2 Project consortium of the JIP CALM research project. The JIP CALM project is financially supported by the NL Agency RVO under the R&D program TKI Wind op Zee (Reference TEHE118019).

Project communication
In order to inform each other and to discuss the scope and the intermediate results progress meetings were organized approximately every half year. Because of the large group size (and the related size of the meeting room facilities) and most meetings were held at Deltares in Delft, note that for part of the project duration there were COVID regulations preventing live meetings, so part of the meetings were held online.

Figure 1.3 Group photo of JIP CALM consortium taken during the 5th progress meeting on June 27th and 28th 2022.

Steering Committee
Every collaborating party was represented in the JIP CALM Steering Committee; each member having one vote. The role of the Steering Committee was to:

- give advice (solicited or unsolicited) to the executing companies;
- vote for decisions on project scope or project organization (within limitations of subsidy rules and awarded project plans);
- respond to questions by email in which the opinion of a participant is asked.

It was decided early in the project that Steering Committee decisions were taken mostly during online meetings, and not wait until next progress meeting, to make them more efficient and prevent travel costs and CO2 emissions.

1.4 Project deliverables

The individual project deliverables are introduced in the different sections of this report. In summary JIP CALM has produced a total of 7 separate reports (all confidential to the JIP CALM consortium) on the various different performed research topics:

List reports:

- DNV (2022). Analysis of submarine cable system failures and their underlying causes. Ref: 22-2971, Rev.3.
- TNO, DNV & VDHP (2022). Fibre-optic monitoring system development for submarine cables - concept development. Ref: TNO 2022 R11865.
- Wood (2022). Development of Test Plan for Assessment of Conductor Stick-Slip Behaviour. Ref: OP215113-REN-REP-001.
- Deltares (2022a). Burial depth detection with Distributed Acoustic Sensing. Ref 11204209-056-HYE-0001:
- Deltares (2022b). Cable-Seabed InteractionWT4.1 - Improved morphology. Ref: 11204209-011-HYE-0001.

- Deltares (2022c). Temperature in submarine cables: numerical modelling approach based on DTS. Ref: 11204209-012-HYE-0003.
- TNO (2022). Guide to Improve Offshore Cable Installation. Ref: TNO 2022 R12182.

Scientific journal and conference papers on the project results are written by the project consortium, some have been published in 2022 and others will follow in 2023, see also Section 1.5.

More information on current and future project deliverables can be obtained from Niek Bruinsma (niek.bruinsma@deltares.nl or CALM@deltares.nl). Please consider the confidentiality period which expires on 30 September 2027. Note that members of the JIP CALM Project Consortium already have immediate access to the deliverables.

1.5 Knowledge dissemination

During the project we communicated about JIP CALM in the following way:

- Article "*Major joint industry project for more reliable offshore cables*", Deltares website.
- Article "*Offshore wind industry joins forces to reduce costs of cable failures*" DNV website.
- Article "*Industry Teams Up to Reduce Offshore Wind Cable Failure Costs*", offshore-energy.biz, 11 April 2018.
- Article "*New JIP Commits to Cable Failure Reduction*", offshorewind.biz, 12 April 2018.
- Presentation "*Open kick-off meeting JIP CALM*", at Deltares on 8&9 July 2019.
- Article "*Improving Cable Reliability*", Offshore industry magazine, vol. 12 issue 5 2019.
- Article "*Keep CALM and Reduce Cable Failures*", Offshorewind.biz, 16 July 2019
- Article "*New JIP to Reduce Subsea Power Cable Failures Launched*", offshore-energy.biz, 17 July 2019.
- Article "*Joint project aims to make cables more reliable and less costly*" Riviera, on 23 July 2019.
- Article "*Digitalizing traditional operations plays a vital role in the energy transition*", DNV annual report 2019.
- Presentation "*Joint Industry Project: CAble Lifetime Monitoring*", Offshore power cable engineering and reliability forum in Prague, 11 February 2020
- Article "*Windparken betrouwbaarder maken door te leren van storingen*" TKI website on 7 july 2020.
- Article "*Innovaties kunnen windparken op zee honderden miljoenen euro's goedkoper maken*", Wind Nieuws, nr. 3 2020.
- Twitter Deltares "*The Cable Lifetime Monitoring Joint Industry Project (JIP CALM) has started. More than 30 international organisations have joined forces to reduce subsea power-cable failures and make offshore wind energy more reliable.*"15 July 2019.
- Presentation "*Joint Industry Project for Subsea 'Cable Lifetime Monitoring' (JIP CALM)*", 2nd Annual Subsea cable installation, asset management and reliability Forum Amsterdam, 30-31 March 2022.
- Presentation "*Advances in Assessing Seabed Mobility*", 2nd Annual Subsea cable installation, asset management and reliability Forum Amsterdam, 30-31 March 2022.
- Conference publication and presentation "*Failure cause analysis and prevention of subsea cable failures in a joint industry project (JIP CALM)*", CIRGE conference Paris, 30 August 2022.
- Presentation "*Experiences from Failure Investigations on Submarine Power Cables*", 2nd Annual Submarine Power Cable and Interconnection Forum, Berlin, 15-16 November 2022.
- Presentation "*Learnings from a joint Industry Project on submarine power Cable Lifetime Monitoring (JIP CALM)*" 6th Subsea Power Cable Installation, Reliability & asset Management Summit, Online, 6-8 December 2022.

- Conference publication and presentation “*Satellite derived bathymetry for monitoring nearshore dynamics*”, International conference on coastal engineering, Sydney 4-9 December 2022.
- Conference publication and presentation “*3D modelling of Sand wave fields*”, International conference on coastal engineering, Sydney 4-9 December 2022.
- Conference publication and presentation “*The design of cable routes considering morphodynamics*”, conference to be decided, 2023.
- Publication scientific journal “*FM modelling (2DV) of sand waves*”, journal to be decided, 2023.
- Publication scientific journal “*Cable burial detection using a temperature model approach*”, journal to be decided, 2023.
- Publication (submission of abstract for publication with option for presentation) “*Failure cause analysis and prevention of subsea cable failures in a joint industry project (JIP CALM)*”, JICABLE’23 Lyon, 18-22 June 2023.

1.6 Spin-off of the project

The 31 project partners apply the new knowledge in new and existing offshore wind farm projects. Next to this, spin-off has been achieved during the JIP CALM project and some interesting R&D projects are under development. Some examples are mentioned here.

1. Industrialization of the FO-Sensor. During the JIP CALM project, a new type of sensor concept was designed, integrated in a power cable, mechanically tested and found suitable for evaluating mechanical load conditions of the cable. This has demonstrated the potential of this technology. One of the manufacturers participating in JIP CALM has announced to industrialize this technology. In future offshore wind projects (and for example also offshore solar energy) it will be possible to use these 'smart cables' to perform measurements during the entire lifespan of the cable (from manufacture, transport, installation to use) in order to possibly detect and prevent failure mechanisms at an early stage. Besides, the generic FO-based sensing concept has found to be applicable for a broad scope of applications, like monitoring the structural integrity.
2. JIP SEACODE (under development, possible start 2023), which focuses on the development of a digital laboratory for predicting offshore sand wave dynamics. The aim of this project is to develop an interactive design tool based on three-dimensional Delft3D-FM predictions and assimilation of data models, and thereby better predict changes in the seabed in an efficient and inclusive way. The output of data model-fused tools can be used by the offshore wind industry to support decision making in implementing sustainable offshore operations.
3. JIP CPS 1.0 (2022-2023), which focuses on the analysis of the stability of cables and cable protection systems (CPS) subjected to waves and currents. During JIP CALM, in 2021, it came to light that there were issues with CPS in offshore wind farms. This research project has been set up with a number of JIP CALM partners to further investigate the problem and better understand this complex system. This is done through literature research, model development and scale experiments.
4. JIP CPS 2.0 (application ongoing, possible start in 2023), the follow-up to the JIP CPS 1 mentioned above. JIP CPS 1 is a small-scale study to map out the biggest knowledge questions. The research performed in JIP CPS 1 is used to setup efficient and targeted (large) scale model experiments and modelling in JIP CPS 2, to further understand the complex hydrodynamic loads on cables in order to refine the design method. In addition, different stabilization methods for cables, such as rock berms or rock bags, will be evaluated to guide the industry in designing measures to prevent damage to current and future cables.

In addition to these very concrete initiatives for further research, exploratory talks are underway to see if we can continue with a joint industry project on burial depth analysis of offshore cables with innovative modelling and measurement methods. The JIP CALM consortium has also shown interest in further developing the cable failure database in order to keep learning more lessons for future projects. Finally, the topic of dynamic cables is an important and challenging research area too which a follow-up research project should be addressed.

1.7 Report structure

This report summarizes all activities that were executed in the framework of JIP CALM. The remainder of the report discusses the cable failure root causes in Chapter 2, Cable lifetime monitoring in Chapter 3, Development of a test for stick-slip in Chapter 4, Burial depth detection using distributed acoustic sensing in Chapter 5, Cable-seabed interaction in Chapter 6, Temperature model for burial depth in Chapter 7 and Logistics and cost impact assessments in Chapter 8. Finally, Chapter 0 lists a summary of the conclusions from the project.

2 Cable failure cause analysis

This section describes the secure collection, storage and in-depth root cause analysis of cable system failure data shared with the JIP CALM consortium (DNV 2022).

2.1 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 established 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 'behind closed doors' while generic, anonymized results could be shared with the consortium in order to take learnings from the failures in submarine power cables. At the end of JIP CALM, all partner data container original information content was deleted from data platform. Some of the learnings are shared below.

2.2 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), see Figure 2.1.

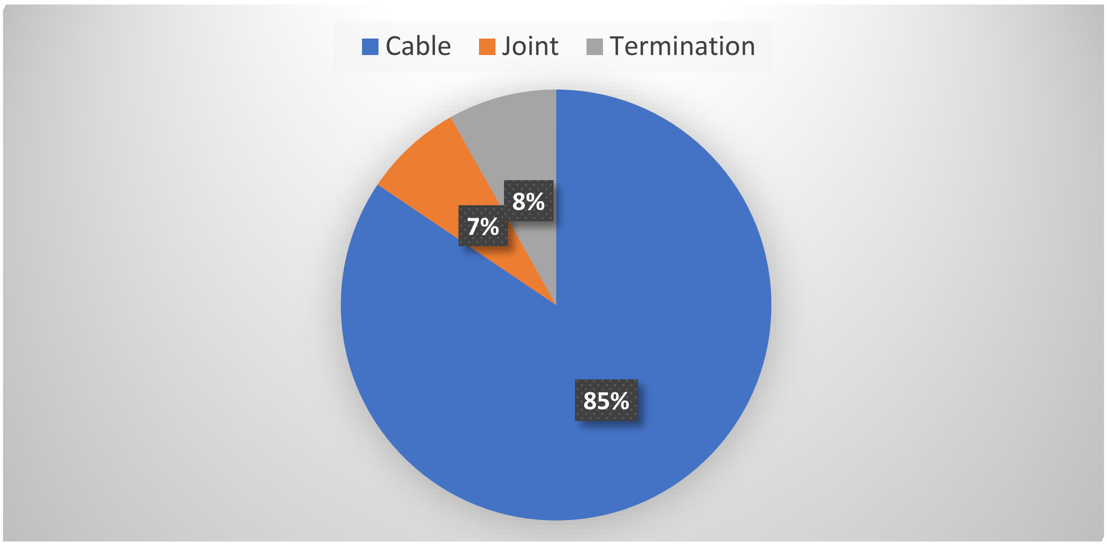


Figure 2.1 Classification of the received dataset in percentage of the cable system component type.

It is worth noticing that the percentages show failures related to the whole dataset, not the percentage of failures 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 kV≤Um≤36 kV- 31% of the cable dataset), the HV(AC) class (36 kV<Um≤170 kV- 25% of the cable dataset), the EHV(AC) class (170 kV<Um- 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, see Figure 2.2.

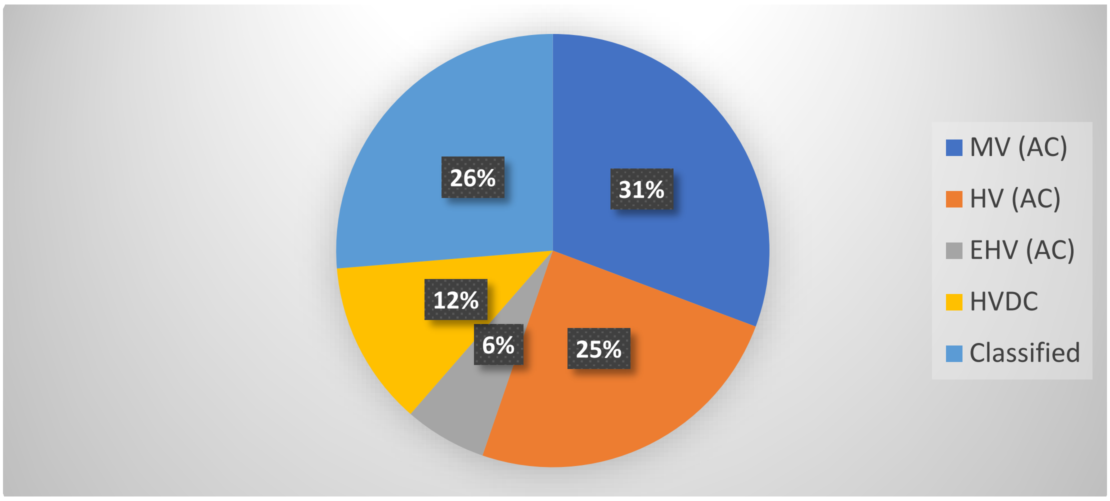


Figure 2.2: Distribution of cable failures with respect to three voltage ranges

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, see Figure 2.3.

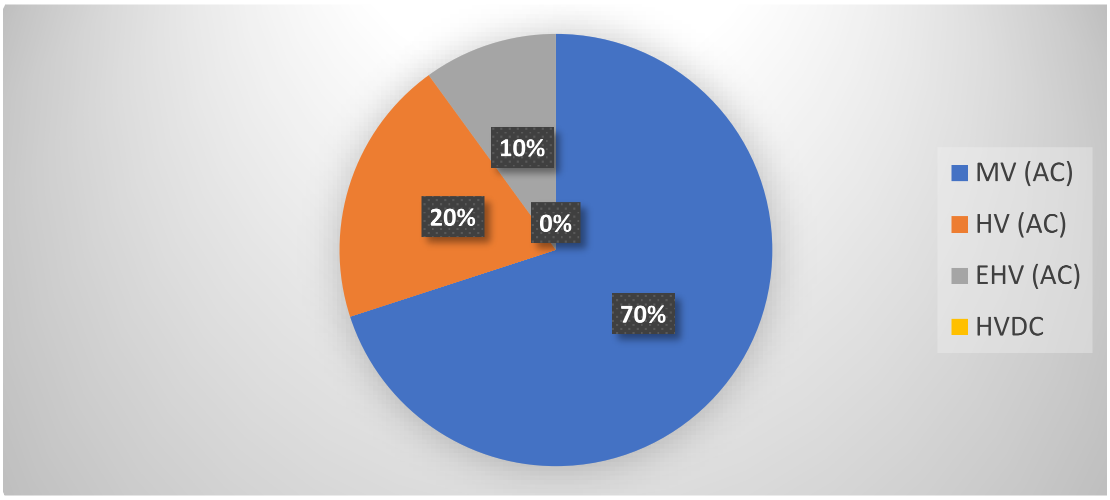


Figure 2.3: Distribution of joint failures per voltage range.

An effort was made to trace the geographical origins of the dataset. As most of the JIP CALM project partners originate from Europe and operate in Europe, almost all failure cases have been experienced in Europe.

The JIP CALM project primarily focused on the North Sea region and, because of that focus, attracted also a majority of partners that are amongst others active in that region. The reason for the JIP CALM project to focus on the North Sea region lies in the type of project and the Dutch government grant that is connected to it. Despite this focus, the project results can be used much more widely in the World, for which reason also partners with interests in other regions in the World have participated in the JIP CALM project.
To demonstrate the effect of this on the JIP CALM failure datasets, a coarse geographical division has been made between 'Zone 1' encompassing the region around the North Sea, Baltic Sea, Irish Sea and the English Channel. Zone 2 then comprises failure records received from all other geographical regions across the world. The results are provided in Figure 2.4 and show that 69% of the failures reported in JIP CALM stem from the Zone 1 geographical area.

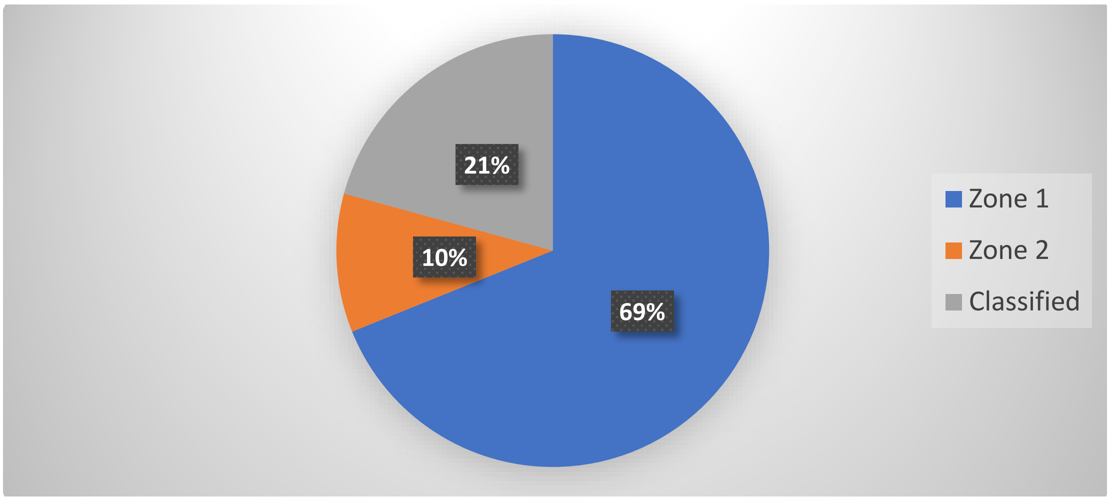


Figure 2.4: Geographical distribution with respect to Zone 1 and Zone 2 arrangement.

The JIP CALM failure datasets reveal an approximate failure rate of 1.24 failures per 100 circuit km-year over the years 2006-2015 (inclusive) in Zone 1. The failure rate comprises all reported failures occurring in all the cable's life phases. It was found that about 40% of this failure rate, thus a failure rate of 0.5 failures per 100 km-year emerges when only failures detected during the operational phase are considered. The actual failure rates in reality may be higher than currently calculated because not all failures will have been reported in the JIP CALM datasets.

2.3 Failure analysis and findings

The failures have been related to dominant failure mechanisms, which initiated 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 was an important reason that led to failure.
  - For HV cable sections, components deviating from type tested components (so no representative design test), and cables not being designed to cope with the appropriate forces or platform vibrations.
  - For EHV cable sections, cables being designed for inappropriate mechanical forces emerged as a key factor.
- Related to the manufacturing phase:
  - For MV cable sections, material or production problems such as extrusion errors, insulation material impurities, -inclusions or -contaminations and incorrect cable assembly were identified.
  - For HV cable sections, contaminations of raw materials and incorrect cable assembly in combination with insufficient Quality Assurance and Quality Control (QA/QC) procedures.

    - For HVDC cable sections, material or production problems such as extrusion errors, insulation material impurities or inclusions were often found.
- 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.

2.4 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 occurs.
- 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.
- Perform adequate geological, geophysical and/or geotechnical studies to identify the risks on soil subsidence and ensure that if these risks exist, the installation design and/or cable design are developed to withstand these situations.
- 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.

3 Cable lifetime monitoring system development

This section describes the development, manufacturing and testing of a Fibre-Optic (FO) based system to continuously monitor the mechanical loading of subsea power cables throughout the cable lifetime (TNO & DNV 2022).

3.1 Problem formulation

The extensive failure root cause analysis, as conducted in this project and reported by DNV (2022), has showed the dominance of mechanical failure mechanisms, and that failures occur and are initiated in all lifetime phases of the cable. Based on these findings, the requirements for the cable monitoring system have been determined and verified in consultation with the industry partners, including cable manufacturers and installation contractors.

By continuously measuring the internal strains in subsea power cables by means of distributed strain sensing, the monitoring system aims at timely detection of critical loading conditions during the full life cycle. This can help to prevent failures, which is key to integrity management and qualification.

One of the key parameters of interest to ensure cable integrity during coiling, load-out and installation is the bending radius (see Figure 3.1). As exceeding the minimum bending radius can lead to premature failures, this has initially been selected as main design driver for the sensor system concept. Other parameters of interest are elongation, compression and torsion.

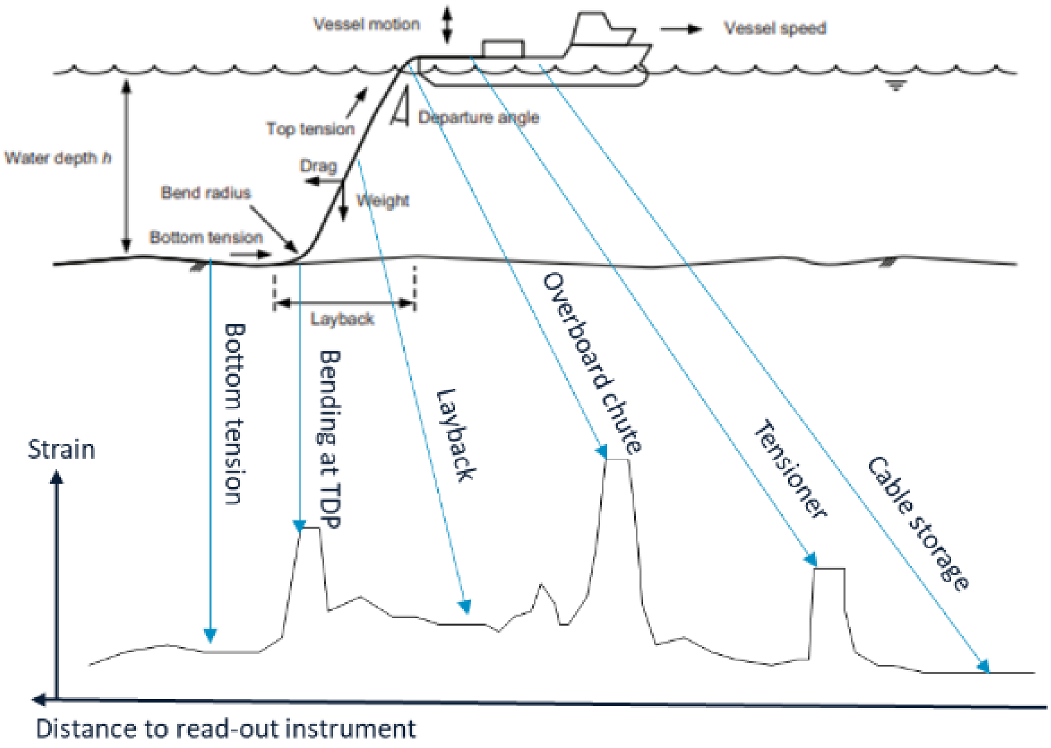


Figure 3.1 Representation of various strain exposures to the power cable during the offshore cable installation. Source: Recommended Practice (RP-0360)- Subsea power cables in shallow water (DNV, 2016).

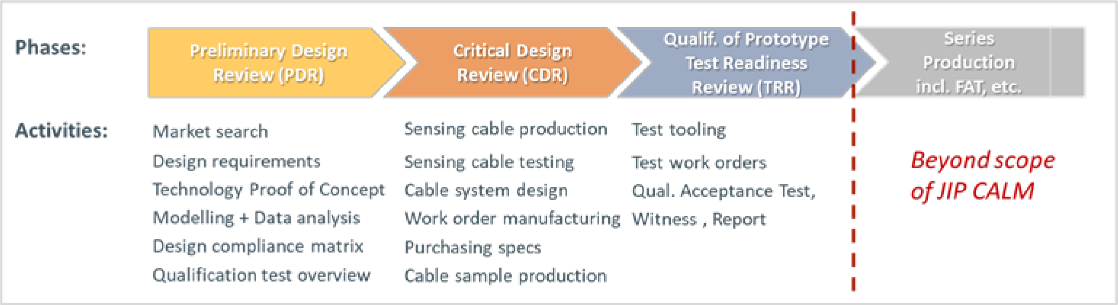
3.2 Monitoring system concept

The developed concept makes use of a cable-integrated sensor unit that contains several optical fibres that are tightly encapsulated in a well-defined geometry. All sensing fibres are connected to a FO-strain readout instrument that measures the strain distribution over the full length of the sensing fibres. For the sensor read-out, several technologies have been considered and tested, including Brillouin Optical Time Domain Reflectometry/Analysis (BOTDR/A) and Distributed Acoustic Sensing (DAS).
The following requirements have been 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 elevated strains in the cable up to 50 km of cable length;
- The monitoring concept shall be applicable to monitor cable integrity over the total lifecycle, spanning from production, transport, deployment to operation;
- The major parameters to monitor for early warning on failure-endangering conditions are, i.e., bending, elongation, torsion, mechanical impact[2];
- The FO sensing unit shall be produced such that it can be integrated into various submarine power cable designs. Technology for the read out of the sensing cable must be accurate in localizing the events, detecting the mechanical loading condition of the cable, while responding typically within seconds to the events in order to prevent overloading.

3.3 Approach for development

The followed approach is illustrated in Figure 3.2, for which a detailed Engineering Work Plan was agreed upon with the directly involved industry partners.



Phases:	Preliminary Design Review (PDR)	Critical Design Review (CDR)	Qualif. of Prototype Test Readiness Review (TRR)	Series Production incl. FAT, etc.
Activities:	Market search Design requirements Technology Proof of Concept Modelling + Data analysis Design compliance matrix Qualification test overview	Sensing cable production Sensing cable testing Cable system design Work order manufacturing Purchasing specs Cable sample production	Test tooling Test work orders Qual. Acceptance Test, Witness , Report	*Beyond scope of JIP CALM*

Figure 3.2 Structure of Engineering Work Plan.

3.3.1 Generic sensor concept

The developed sensor concept consisted of three tight-buffered optical fibres in an isosceles triangle geometry, measuring distributed strain. Analytical modelling showed that parameters of interest could be derived from the measurements, while the differential strain measurement concept compensates well for errors from various origins. The optical fibres are moulded in a polymeric body material using well-known continuous processes, and integrated into a power cable, without metallic enclosure. The outer shape and dimensions can be tailored to the specific cable design and location where the sensor unit is to be integrated.

With three-core AC submarine cables being the largest market share, the chosen concept was developed first for this category. The sensor concept could also be developed for integration into single-core DC cables, although due to the different cable design compared to AC cables, this would require a significant additional development effort.

---

[2] The FO-strain sensor readout enables to monitor cable temperature in parallel, similar as with commercially available Distributed Temperature monitoring Systems.

3.3.2 Sensor modelling, prototyping and testing

Three cable-specific sensor unit designs have been modelled in collaboration with three cable manufacturers. The unambiguous sensor response to critical parameters such as minimum bending radius, axial strain and twisting has been evaluated using both analytical modelling, (see Figure 3.3), Finite-Element Modelling and physical model tests (see Figure 3.4), showing a good match between theory and results. The helical winding is to show the effect of a cable-integrated sensor that follows the lay-up length of the cores in three-core cables.

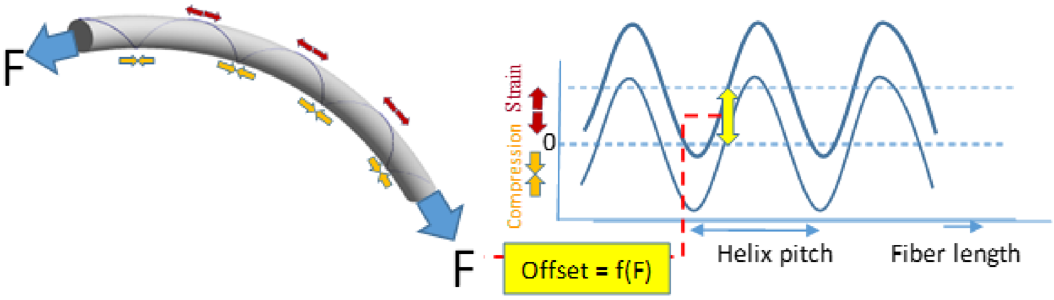
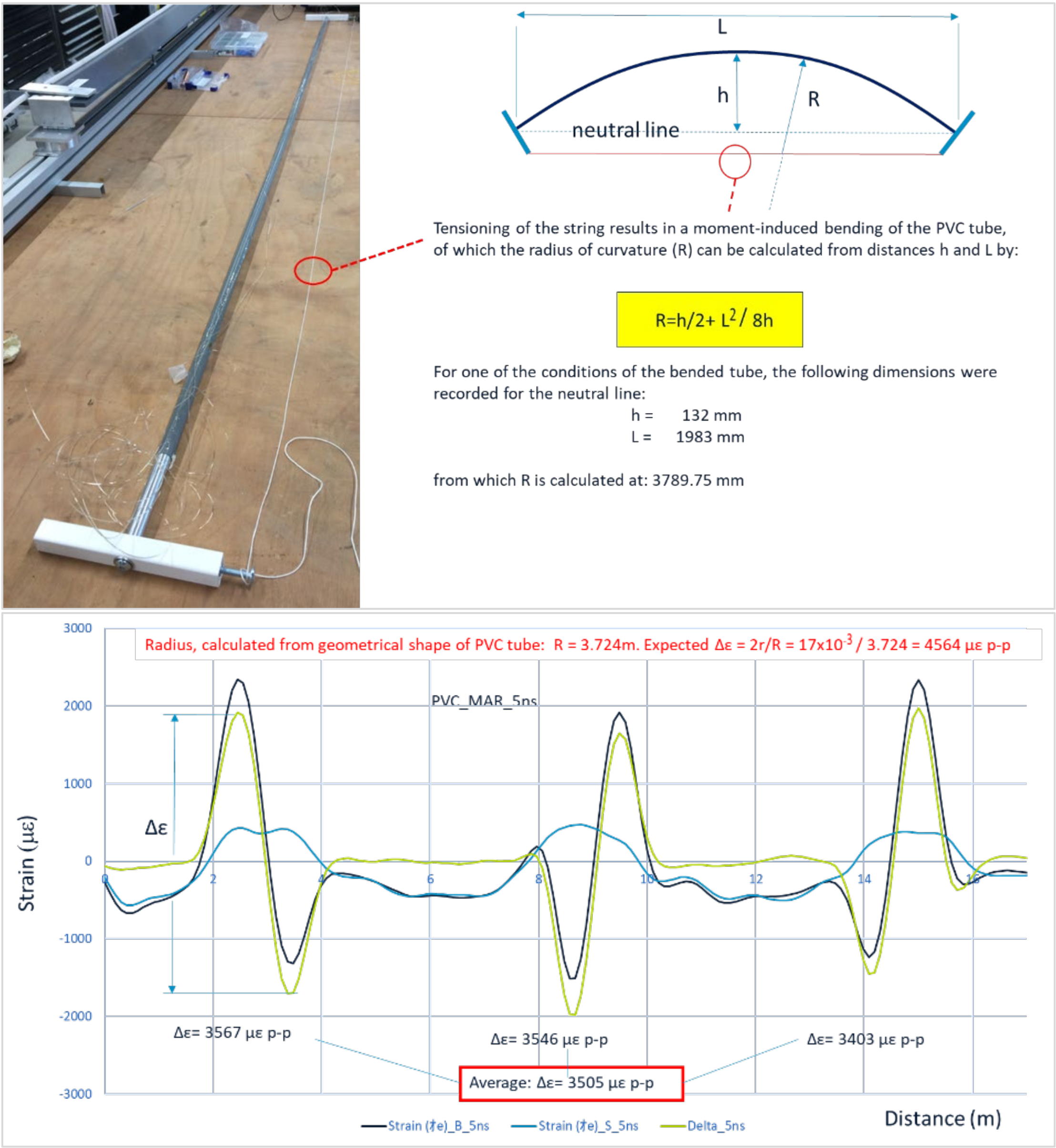


Figure 3.3 Impression of the strain in a single fibre wound in a helix attached to the outside of a bent and stretched flexible component.

Extensive modelling of the design of the sensor unit (being three optical fibres in the encapsulation) and its integration in a power cable has been performed. This showed the importance of the sensor unit geometry and the interaction with the cable to ensure sensor accuracy, while maintaining the integrity of the optical fibres.

All read-out instruments utilize a certain optical pulse length. In combination with helical structure of the power cable, this results in a certain averaging effect of the strain measurements. A correction factor for this effect has been derived and experimentally verified.

Based on the verified sensing concept and sensor unit models, a test plan has been conducted to verify the performance of the monitoring system components: (tight-buffered FO-sensors and read-out instruments) and the whole system for proof of concept. For two fibre optic sensing unit designs, prototypes were produced in long continuous lengths, using standard industry processes.



Tensioning of the string results in a moment-induced bending of the PVC tube, of which the radius of curvature (R) can be calculated from distances h and L by:

$R = h/2 + L^2/8h$

For one of the conditions of the bended tube, the following dimensions were recorded for the neutral line:

h = 132 mm
L = 1983 mm

from which R is calculated at: 3789.75 mm

Radius, calculated from geometrical shape of PVC tube: R = 3.724m. Expected $\Delta\varepsilon = 2r/R = 17\times10^{-3} / 3.724 = 4564$ με p-p

$\Delta\varepsilon$= 3567 με p-p

$\Delta\varepsilon$= 3546 με p-p

$\Delta\varepsilon$= 3403 με p-p

Average: $\Delta\varepsilon$= 3505 με p-p

Figure 3.4 Measured strains of three helically wound fibres attached to the outside of a bent flexible tube, with the three fibres looped in series, for unidirectional readout.

3.4 Test program and results

The test program included the following phases, starting at small-scale at component level up to full scale tests:

- Evaluation of read out technologies;
- Testing optical and mechanical properties of tight-buffered optical fibres;
- Small-scale testing of FO-sensor units;
- Full-scale pre-qualification testing of FO-sensor units integrated in a power cable.

These tests have been performed for different sensor concepts and read-out technologies from several manufacturers.

3.4.1 Evaluation of read out technologies

Figure 3.5 shows a static test frame (STF), especially designed for JIP CALM to perform dedicated tests in a controlled setup. With the STF, calibrated uniform strain levels have been applied to a single optical fibre over a window length of 2, 4, 6 or 8 m. By inserting long fibre spools, the measurement distance was varied up to over 50 km. The effect of dynamic strain variations, e.g., simulating the movements of a ship during cable installation, or cable vibrations during the operational phase, was tested by an electronically controlled piezo actuator.

Four equipment manufacturers have been involved in these tests. In total three Brillouin DSS instruments and four DAS instruments have been tested. The test results showed that both static and dynamic strains over a 2 m window length could be measured up till 50 km distance.

Although the characteristics of the tested technologies (DSS, DAS) are to some extent complementary, in principle both technologies are candidates to be applied in a monitoring system throughout the cable lifetime.

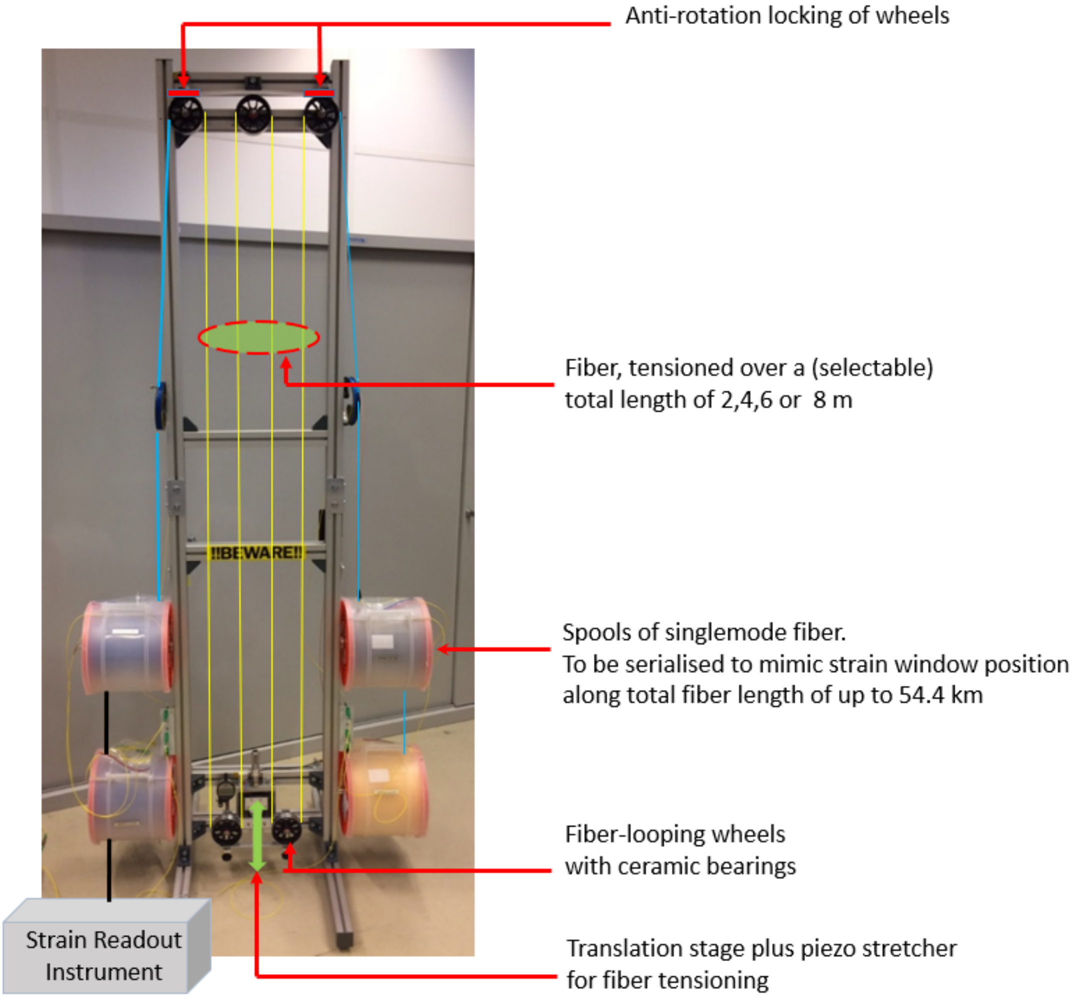


Figure 3.5 Static Test Frame (STF) that used for validating the strain reading performance of various read-out technologies, as developed by VanderHoekPhotonics.

3.4.2 Testing optical and mechanical properties of tight-buffered optical fibres

For testing tight-buffered and reinforced fibres, a similar setup was applied in which a well-defined strain was applied over a 12 m window. This has supported the choice for a proper fibre type and fibre encapsulation.

3.4.3 Small-scale testing of FO-sensor units

The FO-sensor unit prototypes have been tested on their optical and mechanical properties. Figure 3.6 shows a test bench that has been applied for measuring the sensor unit response to pure bending and to bending plus elongation for a well-defined radius of curvature. The test results showed sufficiently low optical attenuation (as required for long distance measurements). Also, the applied bending radii could be retrieved from the measurements with sufficient accuracy.

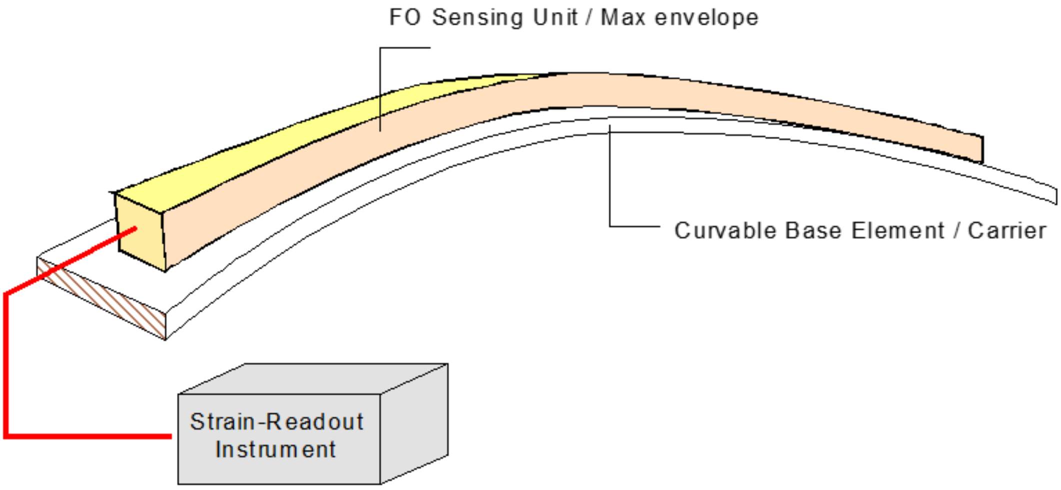


Figure 3.6 Test bench adjustable for different radius of curvature, showing only the maximum envelope of a possible sensor unit geometry (Actual test bench was developed by VanderHoekPhotonics).

3.4.4 Full-scale testing of cable-integrated FO-sensor units

Two different sensor unit prototypes have been produced by two cable manufacturers of the JIP CALM consortium and integrated in their 3-core submarine power cable.
These were integrated in a power cable with relatively short lengths, being sufficient to conduct the mechanical pre-qualification tests.
These tests included:

- Tensile test
- Tensile bending test
- Torsion test
- Crush test

In these tests different read-out instruments, based on Brillouin DSS and DAS technology, have been used. These test results showed that the cable bending radius as well as cable elongation (or axial compression) can be measured independently and with sufficient accuracy with the integrated FO-sensor unit. The FO-sensor also showed to respond to cable torsion (although this cannot be distinguished from cable elongation or axial compression) and to crushing, with the FO-sensor unit remaining intact after the tests. Figure 3.7 shows the test set up for the tensile bending test and 3-point bend test, respectively, at two power cable manufacturers in the consortium. Figure 3.8 shows the measured strains for a bent cable section for different pulse lengths of the read-out instrument.

Figure 3.7 (left) Tensile bending test on a 3-core power cable with integrated FO-sensing unit. The sheave wheel diameter is 6 meters. (right) 3-point bend testing on another 3-core power cable with integrated FO-sensing unit.

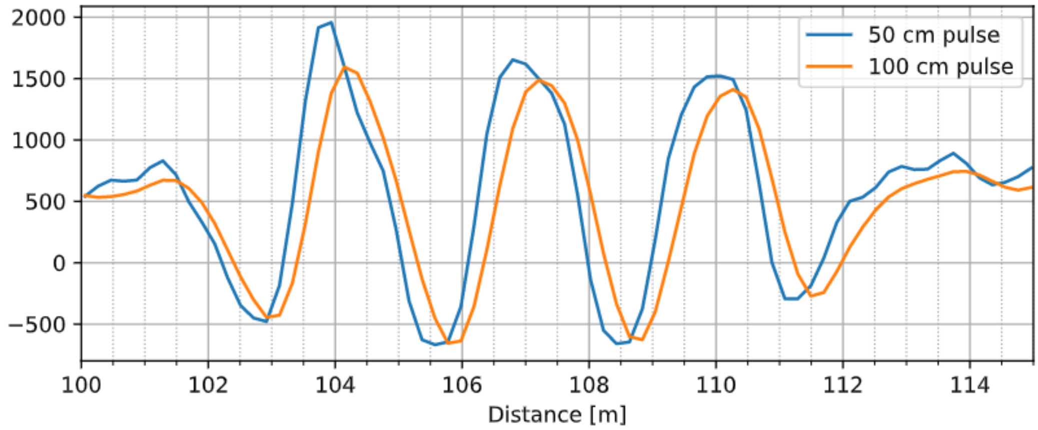


Figure 3.8 Measured strain (µ-strain) vs distance (m) on a 3-core power cable with integrated FO-sensing unit over a sheave wheel of diameter is 6 meters. The measured sinewave is in accordance to the expected theoretical response of the integrated FO-sensing unit.

3.5 Conclusions and future work

Based on the full-scale test results of the integrated sensor units, the developed cable lifetime monitoring system has potential for further industrialization. Envisioned applications are measuring critical mechanical load conditions of submarine cables, such as bending, axial loading and torsion, starting from cable fabrication, load-out, deployment and the operational phase.

Further, the generic sensor concept showed to be applicable for different cable designs, which opens possibilities to develop monitoring systems for HVDC cables and dynamic cables in floating applications.

Regarding the read-out technologies, there is room for further improvement by tailoring equipment settings to the specific requirements in different cable lifetime phases. For instance, during cable deployment, expected strain levels are high and timely detection of critical extreme loads is important, while during the operational phase much lower strains (e.g. fatigue related) are expected as well as incidental high-impact events.

As part of the project several dedicated test set-ups have been developed, as well as tooling for sensor manufacturing and test methodologies, which were essential for the successful monitoring system development and will be useful for further industrialization. As one of the future developments, the Static Test Frame can be extended to enable testing the strain response over a moving window, thereby mimicking the movement of the cable during load out or deployment.

4 Development of a test plan for assessment of conductor stick-slip behaviour

This section describes the development of a test plan for the assessment of conductor stick-slip behaviour in subsea power cables (Wood 2022).

4.1 Background

While there are some accepted practices relating to modelling of conductor stick-slip behaviour, an improvement in the industry understanding of this topic will allow for more accurate relationship of cable curvature ranges to conductor fatigue. The level of stick assumed has a significant effect on the conductor fatigue life and depending on the level of stick assumed, the conductor can be a fatigue-critical component. In order to advance the industry understanding of subsea cable conductor stick-slip behaviour a test programme is required to evaluate the behaviour of the wires within the conductor under bending and tension.

4.2 Test Samples

The test samples for this test programme will include a range of cable conductors of varied construction. To align with construction methods used and to avoid requiring specialised processes for the construction of test samples, the full conductor core (including conductor, screen, insulation and core sheath) can be used for these tests.

Table 4.1 Example List of Conductor Type Variations

Variation	Conductor Size	Conductor Construction	Water Blocking Compound	Conductor Material
V1: Base	Size 1	Stranded	WBC 1	Copper
V2: Conductor Size	Size 2	Stranded	WBC 1	Copper
V3: Conductor Construction	Size 1	Compacted	WBC 1	Copper
V4: Water Blocking Compound	Size 1	Stranded	WBC 2	Copper
V5: Conductor Material	Size 1	Stranded	WBC 1	Aluminium

4.3 Wire Pull Test

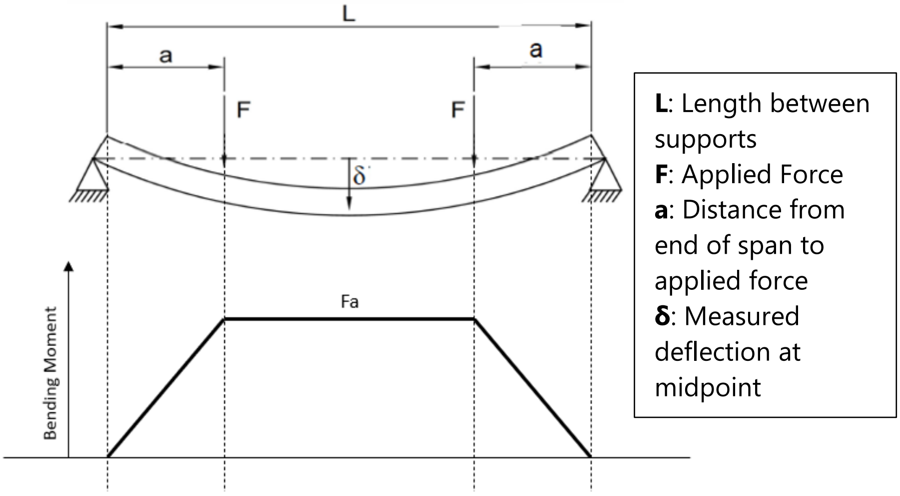
The first test method proposed is a wire pull test, which will help to quantify the effect of friction between the conductor wires.

In this test, a conductor wire is pulled using a known force, in the direction of the conductor wire lay angle. The extension of the pulled wire is measured. The relationship between the pulling force and wire extension can then be related to the resistance provided by friction between the wires. The test is repeated for a minimum of one wire per layer.

4.4 Conductor Bend Test

The second proposed test method is a conductor bend test. The test proposed here is a four-point bend test of the conductor core alone. This allows for focus on the stick-slip behaviour of the conductor wires without influence of the other cable components, such as the armour wires, which tend to dominate the stick-slip behaviour of the full cable.

The four-point bend test is preferable over the three-point bend test for this application as the bending moment and bending radius are constant between the two load application points for a simple beam structure. A schematic of a the four-point bend test set-up is provided in Figure 4.1 and a schematic of the proposed test set up can be seen in Figure 4.2. The tested length of cable is supported at the two ends of the test rig and at two intermediate points such that it may not move vertically or laterally, but axial motion and rotation are permitted as the cable begins to bend.



L: Length between supports
F: Applied Force
a: Distance from end of span to applied force
δ: Measured deflection at midpoint

Figure 4.1: Four-point Bend Test Schematic and Bending Moment Diagram.

The applied load (F) is monitored by a load cell throughout testing, while the vertical displacement (δ) is measured. A moment-curvature plot can then be generated, where the moment is calculated as $M = F \cdot a$, and the radius of curvature can be calculated as $R = \left(\frac{\delta}{2} + \frac{L^2}{8\delta}\right)$. The point at which slip occurs can be identified from this moment-curvature plot as a change in slope. It is anticipated that slip of each layer of conductor wires will happen sequentially from the outer layer inward due to the construction methods used in the stranding of the conductor which result in each layer of conductor wires having a slightly different pitch length and increasing contact pressure.

Additionally, it is proposed to include a means of varying contact pressure on the conductor specimen, to represent the contact pressure that would occur on the exterior of the conductor core due to the presence of the other cores, cable armouring, outer serving etc. in a complete cable. Other variations of interest for this test include variation in the load applied and variation of the sample temperature (for example, to assess the impact of temperature on the materials used in the conductor, such as the water blocking compound found in the interstices).

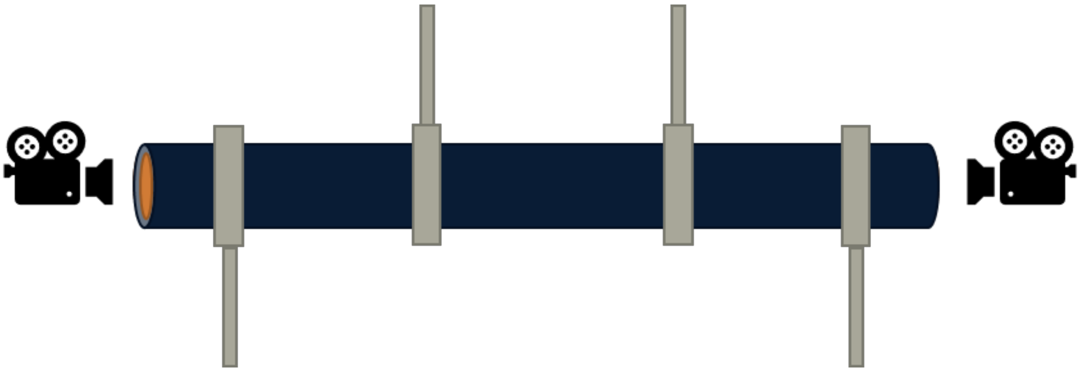


Figure 4.2: Proposed Bend Test Set-Up.

4.5 Test Facility Requirements

The tests proposed require test rigs of a modest size (not expected to exceed a space requirement of 10 m long × 10 m wide × 5 m high). This size of test rig should be easily accommodated in most full-scale laboratories and testing facilities. Testing can be carried out with the conductor oriented horizontally, therefore there is no requirement for large amounts of vertical space that may require a specialist indoor, or outdoor facility.

There is no requirement to perform electrical continuity testing as part of this test programme, however, electrical current is often used to achieve increases in temperature. If other means of achieving the temperature variations required in the test specimen are proposed (and deemed satisfactory by the contracting entity) specialist high voltage laboratory facilities may not be required.

There is no requirement to have the specimen in-water during testing. It would be beneficial to have means of controlling/altering the specimen temperature to allow for the effects of temperature-dependence in materials to be assessed.

Bend tests and pull tests are carried out routinely for cables, therefore the key components of the test rigs are relatively readily available.

The test facility will require adequate standard power and data connections to facilitate the running of the two tests proposed, including power to the test rigs, instrumentation and additional equipment such as cameras, and the capability to transfer and process the test data.

5 Burial depth detection with distributed acoustic sensing

This section describes the development and execution of a physical model experiment to use distributed acoustic sensing for the evaluation of burial depth of subsea power cables (Deltares 2022a).

5.1 Background

Fibre optic cables encapsulated in a subsea power cable buried in the seafloor can be used to records surrounding vibrations and soundwaves using Distributed Acoustic Sensing (DAS) technology. The thickness and the composition of the sediments above the power cable will affect the frequency content and amplitudes of the measured signals. In this project the performance of DAS technology for determining the depth of burial of a subsea power cable was assessed in a scaled laboratory experiment.

5.2 Theory

Fibre optic cable integrated in subsea cables can be used as a sensing device with the Distributed Acoustic Sensing (DAS) technology. When a subsea cable lies on the seabed or is buried under sediment, it can also act as a seismic receiver.
When pressure waves or vibrations are transmitted into soil, they induce different types of seismic waves, namely pressure waves (P-waves) and Scholte Waves. P-waves can be used to estimate p-wave velocity, which provides information on the covering soil and can also be used for travel time analysis to estimate the depth of burial. Scholte waves are a type of interface waves that travel on the boundary between the seawater and the seabed. Scholte waves are more suited to determine soil type than p-wave velocity.

Sources can be categorized into 2 groups: passive and active sources. Passive sources include any type of ambient sound that is present in the area, it can be man-made or natural. Active sources are specifically deployed for the purpose of detection by the sensing cable.
In order to get insight in the feasibility of the sources, the responses were modelled. For that buried or exposed parts of fibre optic cable, different types of seismic waves and sources and realistic values for the acoustic properties of the typical sediments are needed.

5.3 Results and conclusions

Buried fibre-optic cables were proven to be sensitive to incoming acoustic and elastic waves of both low and high frequencies. In this work, active sources were used to generate acoustic and elastic waves. Passive sources could provide an inexpensive alternative, though the resolution of the data is expected to be lower due to high frequency filtering over distance. This study does not include passive sources in either the modelling or the lab setup. Ambient noise modelling would require an elaborate 3-D setup which was beyond the scope of this study. Moreover, the results would not have been verifiable with the lab experiment due to scaling problems and the required acoustic insulation of the flume to avoid side-wall reflections.

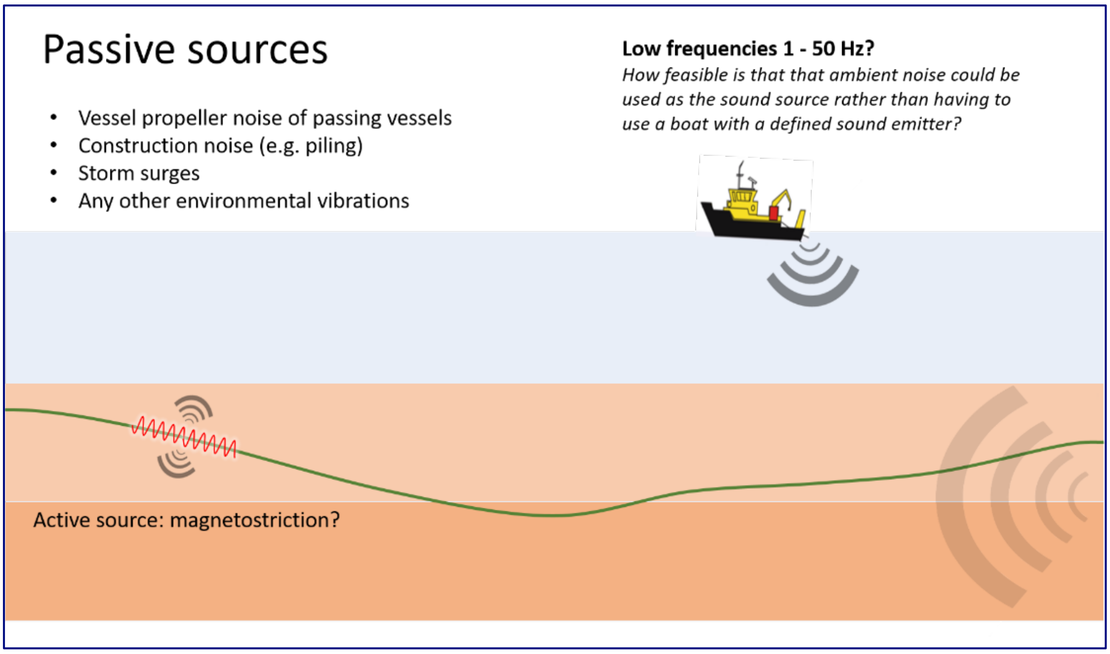
A high frequency p-wave source can help to detect shallow burial with high resolution. The recorded drop in amplitudes as the filtering of the higher frequencies by the covering layers shows the potential of the DAS technology to get insight in the thickness of the overlaying sediment. Due to the shallow depth of the lab scale setup (1) the strongest amplitudes in the data were clipped (2) there were numerous multiple artefacts caused by energy bouncing in the shallow water column and (3) no signal could be retrieved at large offsets. For these reasons, a detailed travel-time analysis and velocity analysis was not possible which would have resulted in a first order depth of burial. Field scale analysis are more suitable for this, see recommendations.

Lower frequency Scholte waves were shown to indicate changes to sediment composition covering the fibre. Changes in sediment type between sand and clay could clearly be detected. Further research is required to investigate if Scholte waves can only detect changes in sediment type or can also be used to specify the sediment type itself. More research is also required to figure out the achievable resolution. The clear detection of Scholte waves provides the possibility of determining S-wave velocity layering below the buried cable.

5.4 Recommendations

Future works should involve the following:

- Investigate the effect of the acoustic structure of a power cable on signal strength and frequency content.
- Scaling to field scale with an active source while also analysing passive noise (sources of opportunity) to determine burial depth through the combination of travel time and velocity analysis (see Figure 5.1).
- Further research is required to determine how the analysis of P-waves and Scholte waves can complement each other.
- A fibre optic based real time burial depth of cable monitoring system. Using data fusion of different fibre optic techniques: Temperature (DTS), Acoustic (DAS) and Strain sensing (e.g. DSS).



Passive sources

- Vessel propeller noise of passing vessels
- Construction noise (e.g. piling)
- Storm surges
- Any other environmental vibrations

Low frequencies 1 - 50 Hz?

How feasible is that that ambient noise could be used as the sound source rather than having to use a boat with a defined sound emitter?

Active source: magnetostriction?

Figure 5.1 Recorded signals from passive sources have much lower frequencies resulting in lower resolution data. However, measuring passive sources comes at a much lower cost.

6 Cable-seabed interaction

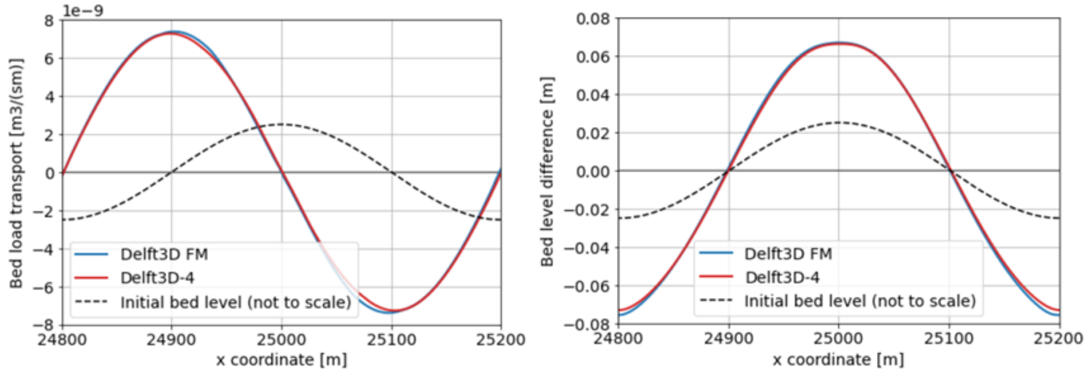
This section describes the work performed on sand wave modelling, satellite derived bathymetry, cable route optimization (Deltares 2022b).

6.1 Sand wave modelling

The assessment of seabed and sand wave dynamics can be of key importance for both the inter-array and export cables (Nemeth et al, 2003) (Roetert et al, 2017). 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 per year (Morelissen et al, 2003). 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.

Various offshore infrastructural projects, like offshore wind farms, thus 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. The use of process-based numerical models could improve the accuracy of these predictions and help quantifying uncertainties over time. Additionally, these models give insight into the effects of extreme events and human interventions, and provide a solution for data-scarce areas.

Not many attempts have been made to accurately predict sand wave dynamics in real-life situations using a process-based model. Due to the need for small grid sizes and large domains, computation times can quickly become unacceptable. The newly developed Delft3D Flexible Mesh (FM) model is able to overcome some of these problems. Through the use of unstructured grids, the desired level of detail can be reached easily in sand wave areas. In combination with the possibility to run simulations in parallel, on multiple cores, computation times can be reduced significantly.



(a) Tide-averaged bed load transport, first tidal cycle *(b) Bed level change in 10 morphological years*

Figure 6.1 Average bed load transport and resulting bed level change for a symmetrical S2 tide (L = 400 m).

First a model-model comparison is carried out between the Delft3D FM and the Delft3D-4 model. Delft3D-4, being the predecessor of Delft3D FM and established in the field of sand wave modelling, provides a benchmark upon which confidence in the Delft3D FM model can be built. This comparison is based on a widely used simplified sand wave model set-up. From this analysis it is concluded that the Delft3D FM model is capable of reproducing the key processes leading to sand wave growth and migration (see Figure 6.1).

Subsequently the model is adapted to include several real cases in the North Sea. First a 2DV transect model has been set up using bathymetry surveys and local current conditions induced by tides, wind and storms (Overes, 2021). Through these case studies the influence of various combinations of tidal forcing was analysed for real-life situations, see Figure 6.2. 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.

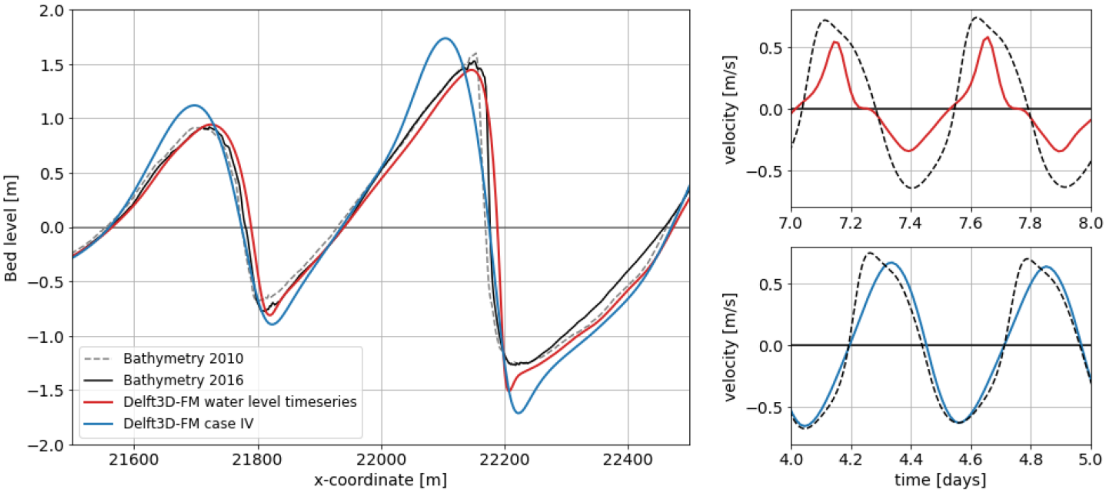


Figure 6.2 Measured and computed bed levels after 6 years with water level timeseries and Case IV forcing (combination of M2, S2, M4 and residual current).

A sensitivity analysis showed a large dependency of the morphological results on both the bed slope parameter and the Chézy roughness. An increase of the Chézy roughness (indicating a less rough bed) or an increase of the bed slope parameter lead to a reduced growth rate, but increased slope flattening. The opposite happens for a decrease of either parameter.

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 (Overes, 2021). At the location of steep sand wave slopes the direction of sediment transport is significantly influenced by bed load 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. Especially in these 3D cases, the upscaling that the Delft3D FM model offers is essential for reaching significant modelling periods.

In these 3D models also human interventions, such as trench dredging prior to cable installation can be included. To test the ability of the model to predict sand wave recovery after such an intervention, a new case was created including such a cable trench. The model showed the ability to simulate the recovery of the sand waves over the years. In these cases also infilling from the sides of the trench occurs, which was clearly visible in the model results (see Figure 6.3).

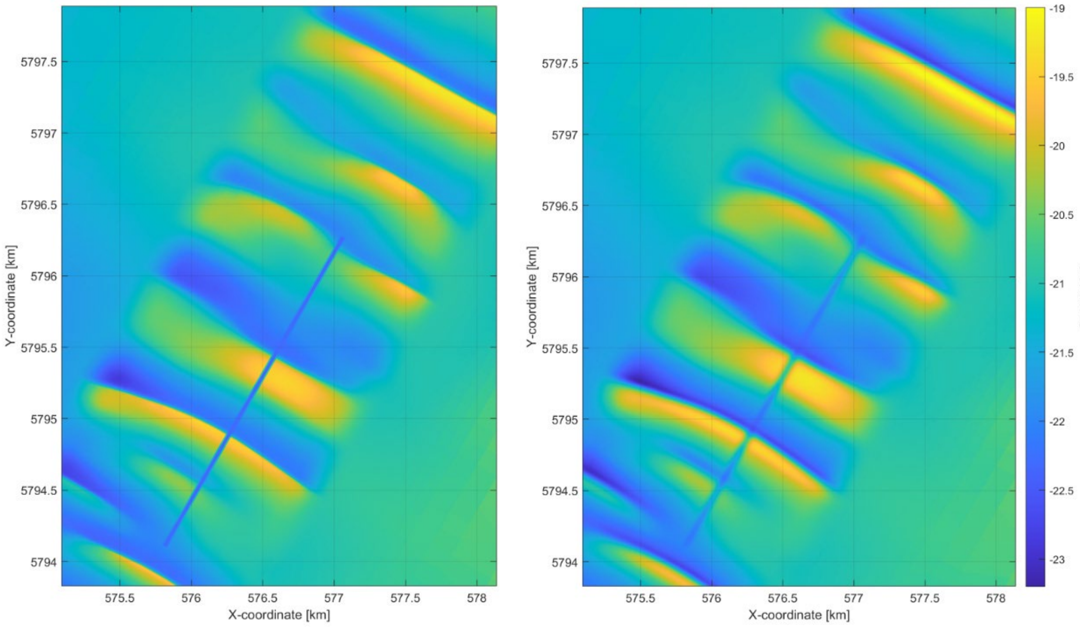


Figure 6.3 Predicted migration of a 3D sand wave area including a dredged trench: initial bed levels (left) and computed bed levels after 5 years (right).

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.

6.2 Satellite derived bathymetry 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 satellite derived bathymetry (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.

Deltares has developed an algorithm that allows to compute SDB from Top of Atmosphere (TOA) images from the Landsat-8 (NASA) and Sentinel-2 (ESA) missions. First, the multi-petabyte data catalogue of the GEE is used to access freely and openly pre-processed (georeferenced) satellite images for the area of interest. These images are filtered (on cloudiness) and stacked together in a so-called composite (combined, clean and average) image to reduce local and high-frequent noise like tidal water levels, boats, clouds (shadows), wave breaking, turbidity and algae (Donchyts et al., 2016). Hereafter, the water depth (D) can be computed as the log-scaled weighted average of the inverse-depth relation, where the weights are derived from the spatiotemporal variability of reflectance (see Eq. 2 and 3).

$$D = E[d] = \sum d * w(f_{clouds}, x, y, t) \tag{2}$$
$$d = log\ (\rho - \rho_{deep}) \tag{3}$$

By calibrating the (water) depth with in-situ data following the work of Pacheco et al. (2015), this technique can generate high resolution SDBs under conditions where light penetration is sufficient and sediment concentrations are relatively low. For environments such as the Dutch Wadden Sea, the depth at which bathymetrical features can be monitored by using a calibrated SDB is roughly estimated to be 4 to 5 m (Burgers, 2020). In clear water this potentially reaches up to 20 m (Zandbergen, 2020). In the Wadden Sea the RMSE of the calibrated SDB compared to in-situ data is found to be in the order of one meter while for clear water this might be reduced to values smaller than 0.5 m. Under less favourable conditions or in cases where the vertical accuracy is not sufficient, the uncalibrated SDB (or depth proxy) can be used to identify coastal features (channels, shoals and ebb-tidal deltas) and gradients in the bed level. Besides, changes of those features can be detected and included in the conceptual understanding.

Within the JIP CALM project, computing bathymetries (using satellite imagery) with vertical accuracies of order one meter are deemed insufficient to monitor cables over their lifetime. Hence, waterborne sonar (MBES) and airborne LiDAR are still required to obtain detailed insight in cable-seabed interactions. However, even in less favourable conditions, assessing horizontal morphodynamics using satellite imagery (depth proxies) can significantly reduce the frequency of these measurement campaigns as well as enhance understanding of the system behaviour in between the surveys (interpolation) and beyond (extrapolation). This is visualized in Figure 6.4. Moreover, assessing historic depth proxies can assist in establishing the most favourable cable trajectory (in terms of cable-seabed interactions) at an early stage of the project proceedings.

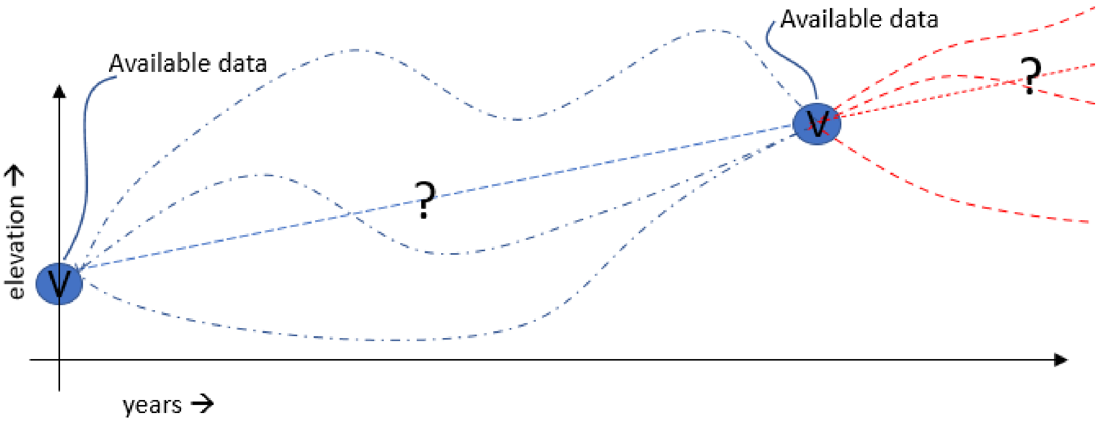


Figure 6.4 Visualization of the temporal interpolant on the added value (?-marks) of using (horizontal) satellite imagery assessments in between and beyond available in-situ data.

Clean images can be generated from a multitude of satellite (composite) 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 colours while stable areas appear dark, see left image in Figure 6.5. Information derived from satellite derived heat maps (as in Figure 6.5) 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 (as in Figure 6.6).

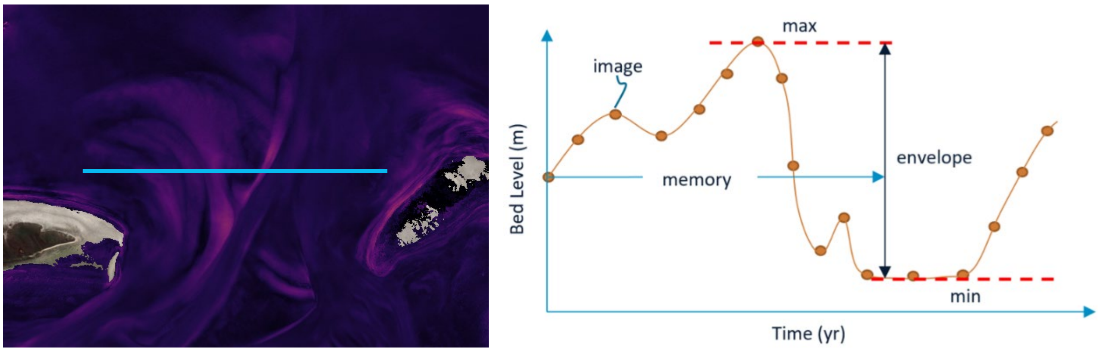


Figure 6.5 (Left) Depth Proxy Heat Map of the 'Friese Zeegat' (area between Wadden Sea islands Ameland and Schiermonnikoog). Bright purple colours indicate dynamic areas, whereas the dark colours indicate stable seabed area. (Right) schematizes the derivation of the heat map from clean (composite) optical satellite images.

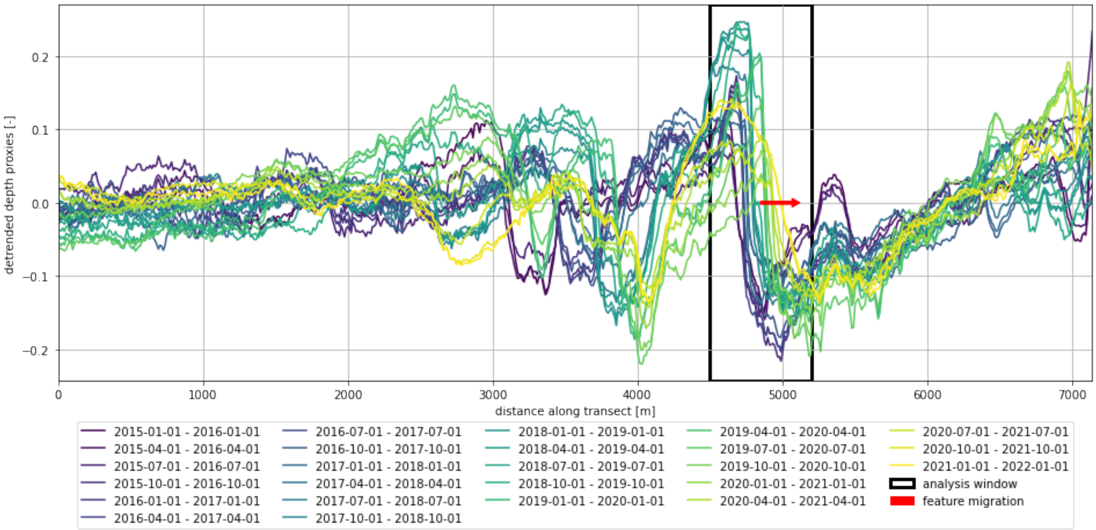
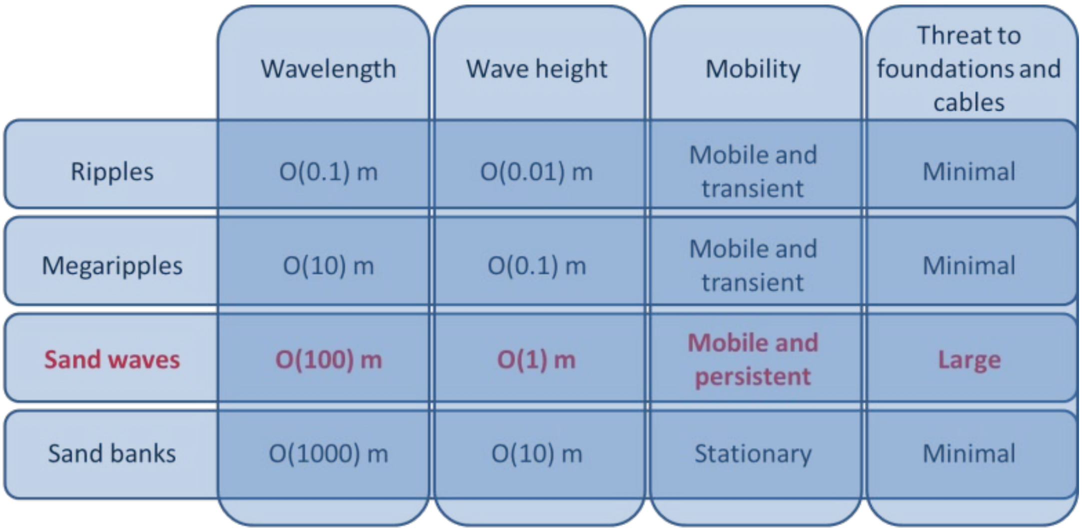


Figure 6.6: Quantitative assessment of morphodynamics along the transect of Figure 6.5 (left). Darker (brighter) lines represent the historic (recent) depth proxies. The analysis window is defined as the black rectangle and the derived feature migration and direction are visualized by means of the red arrow.

6.3 Cable route optimization

Dynamics of the seabed can significantly influence cable burial depths. Typical parameters of geometry and dynamics that distinguish different types of bedforms (wavelength, wave height and mobility) are presented in Figure 6.7. 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 (Roetert et al, 2017).



	Wavelength	Wave height	Mobility	Threat to foundations and cables
Ripples	O(0.1) m	O(0.01) m	Mobile and transient	Minimal
Megaripples	O(10) m	O(0.1) m	Mobile and transient	Minimal
Sand waves	**O(100) m**	**O(1) m**	**Mobile and persistent**	**Large**
Sand banks	O(1000) m	O(10) m	Stationary	Minimal

Figure 6.7 Morphodynamic seabed features and some typical characteristics. Capital “O(.)” indicates “In the order of” (Deltares, 2020, 2022c). Cable failure as a result of exposure is one of the risks in power cable installation. Due to the high associated costs of a cable failure (lost energy revenues and high repair costs), the insurance costs for cable-related claims amount up to 80 % of the total costs.

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 archaeological 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 6.8).

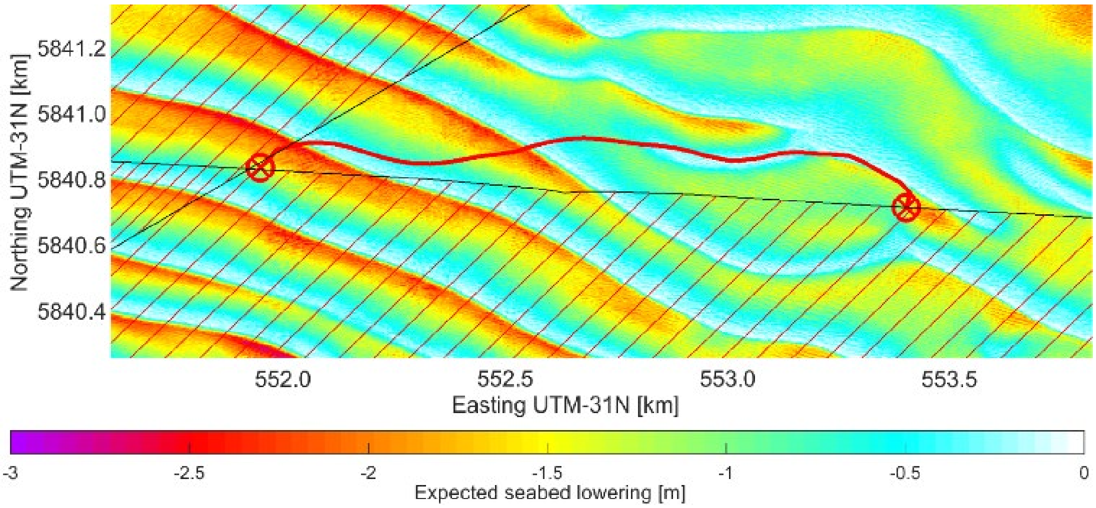


Figure 6.8 Cable route between two turbine locations avoiding areas of significant seabed mobility & constraints (red hatched areas).

To highlight the importance of including morphodynamics in the cable routes a case study was set up focussing on Hollandse Kust West. The fictive layout for HKW without optimized cable routes showed that the effect of sand wave migration can be significant. Examples showed that the required initial cable burial depth could increase to over 3 metres. Parts with limited required burial depths are located in the current sand wave troughs and are mostly subject to seabed level rise. Although this seems beneficial, the risk of overburial, possibly leading to cable overheating, is present.

To mitigate the risks of cable exposure and overburial, the fictive layout for HKW is combined with the design criteria and the optimization algorithms. Results presented on HKW highlighted that the optimized cable route highly depends on the design criteria. For example, shorter cables often imply more dredging (i.e. less ideal route in terms of seabed dynamics) and vice versa. Main conclusion of the case study is that the cable route optimization in these areas has significant gains. Especially, the ability to include morphodynamics in the design and maintenance of cable routes in a wind farm can reduce risks and costs associated.

To test the generic applicability the optimization taking into account seabed morphodynamics was also applied on a number of other locations around the world. One location with very high sand wave dynamics was chosen and one location where morphodynamic activity is very limited (Ten Noorden van de Waddeneilanden Wind Farm Zone, TNW). In the area with high mobility, with cable routes following sand wave troughs, the added benefit of cable route optimization is deemed less compared to HKW. Crossings of sand wave crests are advised to be avoided as much as possible to minimise dredging volumes. In TNW the limited seabed mobility highlighted only marginal gains in cable route optimization. No areas with increased seabed mobility needed to be avoided, resulting in optimized routes following a straight line between WTG locations, minimising both dredging volumes and cable lengths.

7 Temperature in submarine cables and depth of burial inversion

This section describes the work performed on cable burial detection based on a thermal model (Deltares 2022d).

7.1 Background

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. Fibre-optic based distributed temperature sensors (DTS) provide in-situ measurements of temperature dynamics in export cables. We explored 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 7.1), a critical aspect in cable-life monitoring.

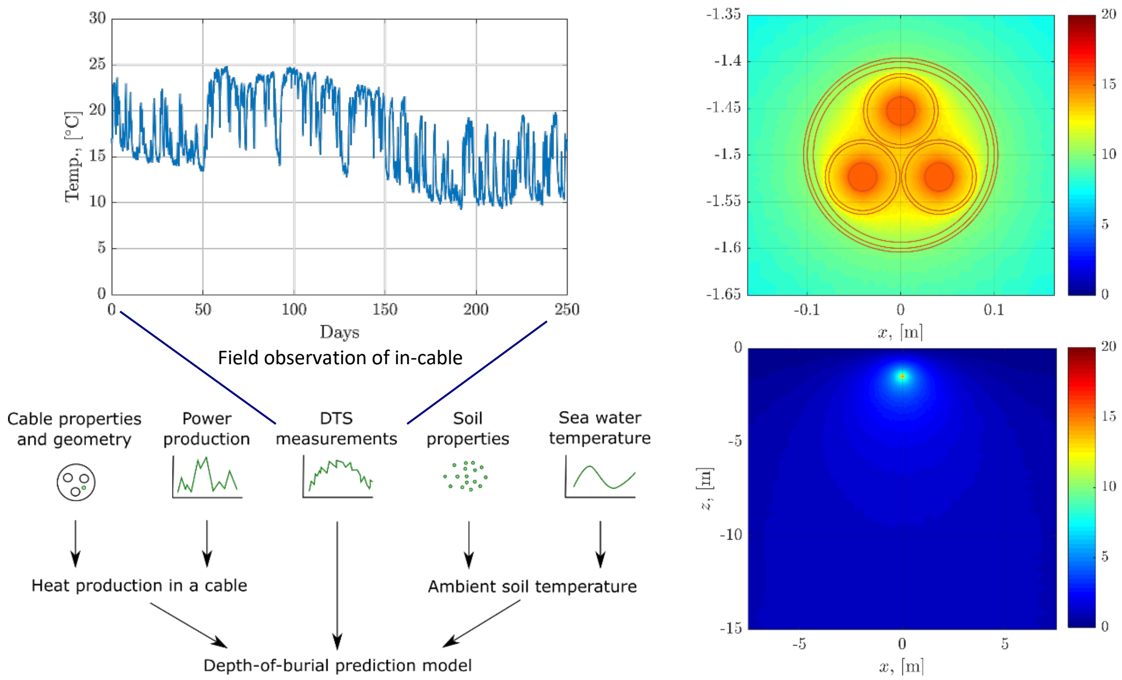


Figure 7.1 (Left) Seabed-cable thermal interaction components, (Right) grid and simulated temperature 2D field for a 1.5 m buried cable section.

Cable-soil thermal modelling is often done based on conceptual model structures (RC-ladder type models) that are calibrated with in-situ observations. However, these models may not reproduce the real processes to the desired detail. On the other hand, detailed (FEM, FV) physically based thermal models, often result in prohibitive simulation times when evaluating long-term processes.

7.2 Modelling approach

We developed a physically-based simulator regarding the advection-diffusion heat equation (finite differences time-marching). This included a description of the fully saturated soil-cross section (thermal properties), seasonal fluctuations of the seabed water temperatures, cable geometry, and a non-linear heat dissipation model accounting for distributed heated surfaces in the cable. This model was used to understand the heating-cooling dynamics and the interaction of the seasonal temperature fluctuation of the seabed with the cable-soil system. However, due to computational limitations, this type of models cannot be used in sampling intensive applications (e.g. calibration of parameters, or probabilistic approaches).

To circumvent this, we proposed two distinctive approaches that accelerated the model computation and thus could assist in the inversion of depth of burial. First, we proposed a hybrid modelling approach that approximates the conduction of heat in the cable-soil section by decomposing the diffusion equation in its harmonics. This approach accelerates 20-fold the evaluation of arbitrary input signals and can represent a direct substitute to the physically based model when conduction is the dominant process in heat transport in the system (i.e. low-permeability soils and mild-thermal gradients). Secondly, we proposed a data-driven model emulator that would learn from a database of model evaluations. This could replicate successfully long-short term thermal processes under changes of system parameters (i.e. soil properties, or depth of burial), however would only be representative of the input time-series in which it was trained.

7.3 Conclusions and recommendations

The physically-based thermal cable-soil model and the two strategies to accelerate its computation were evaluated against literature derived experimental data and through an anonymized real DTS dataset from a real export cable. Additionally, a synthetic cable system was created (based on real cable geometries and power production) to assess the feasibility of extracting information on the cable depth of burial based on DTS observations. The main findings are summarized below:

- The physically-based model was shown to be capable of capturing both conduction and convection when compared to laboratory measurements of a cable-soil interaction reported in scientific literature.
- The angular orientation of the cable (rotations with respect to the centre of the cable) does not generate significant influence in the DTS signal in buried cables (>0.5 m). However, the relative location of the sensor within the cable section does generate strong variations on the measured signal, especially for the high-frequency temperature fluctuations (< 1-10 days). Which means that manufacturing tolerances should be carefully considered when designing DTS cable sensing systems for depth of burial monitoring.
- The DTS signal is mostly insensitive to burial of depth changes for thermal oscillations with frequencies higher than 1/10 days^{-1} (for depths of burial deeper than 50 cm). This suggests the need to account for long-term temperature dynamics when performing depth of burial estimations based on DTS measurements.
- Variations of depth of burial are observed mostly during long-term heating and cooling processes, dominated mainly by the underlying seasonal seabed thermal dynamics (Figure 7.2). Having accurate knowledge on the temperature of the seabed is very relevant for modelling the soil-cable thermal interaction.
- Depth of burial estimates accuracy were seen to be dependent on the absolute depth level. Detectability increases at low burial levels (<0.5 meters) and will likely allow for the identification of de-burial or near de-burial events, yet quantitative estimates might remain uncertain. There is a strong effect of forcing data uncertainty, where low quality

inputs for power to heat dissipation and seabed water temperature might result in large errors in depth of burial estimates.

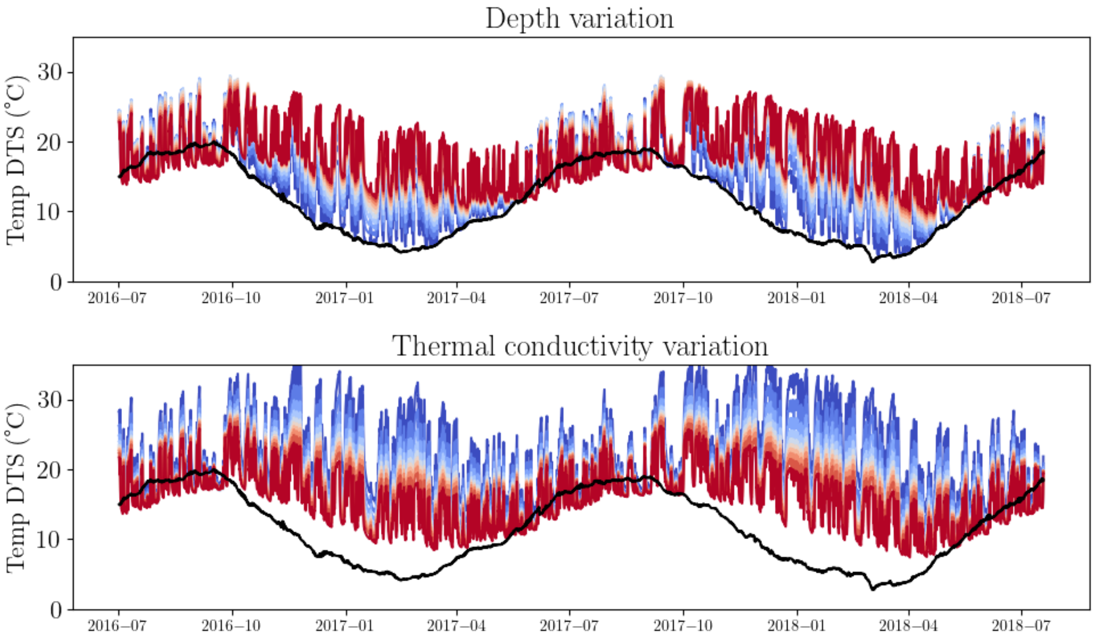


Figure 7.2 Examples of variations of depth of burial (0.15 – 1.95 m) (above) and soil thermal conductivity (1-3 W/mK) (below) for two years of simulated DTS observations (red-blue indicates high to low values) and seabed water temperature (black) for a synthetic power export cable under a realistic dynamic loading.

Further testing of de-burial detection strategies in real-field conditions is still pending. A current limitation is the lack of publicly available datasets of observed de-burial events that allow to transparently communicate detectability levels without disclosing business sensitive information. Additionally, a formal uncertainty analysis that takes into consideration real error distributions of DTS, seabed water temperature and heating model inputs should still be performed to more accurately assess the performance of depth-of-burial estimations from DTS observations.

8 Cost-impact assessments

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 guide, method statement and simulation model of the power cable installation process, validated it with real wind farm cases and evaluated the proposed innovations (TNO 2022).

8.1 Methodology

The methodology applied to assess the impact of electric cable innovations is based on discrete event modelling of the logistics processes (Dewan et al, 2015) (Venkitachalam, 2020). 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 the UWiSE framework (TNO, 2021), 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.

The method statement includes a detailed plan (activities with duration and required crew, vessels and equipment) for the main steps of subsea cable installation:

- Spooling on the cable installation vessel
- Preparation of offshore operations
- First end installation
- Cable laying
- Second end installation
- As laid survey

In addition, the steps for cable burying and export cable installation are discussed.

8.2 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 8.1 shows the vessel data used for the reference case.

Table 8.1 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 used 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 8.1 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.

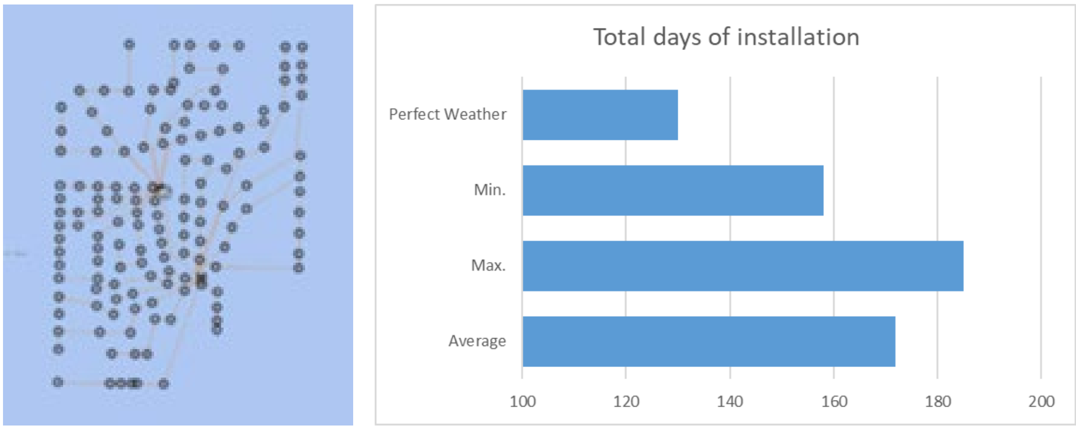


Figure 8.1 Reference layout (left) and effect of weather conditions on duration of the installation campaign (right).

8.3 Impact assessment of the innovations

Four recommendations have been proposed in the project on further precautionary measures that can be brought to the current operations in order to avoid subsea cables being damaged during and after the installation phase:

1. synchronisation tests on the equipment before cable mobilisation;
2. tensioner test before cable mobilisation;
3. function and verification tests on the pull-in equipment, and real time ROV streaming to the topside team during cable pull-ins;
4. continuous monitoring with optical fibre sensors embedded in the cables.

The impact on duration and cost of the installation campaign has been assessed by adding the required steps (activities with duration and required crew, vessels and equipment) to the method statement and model. Figure 8.2 shows the modification for including the tensioner test to the model.

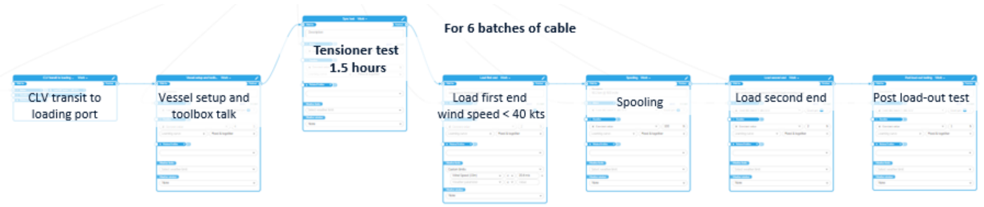


Figure 8.2 Tensioner test added to the simulation model for impact assessment

The simulations show that with these precautionary measures, significant losses and even danger to the personnel can be avoided, at only a small (less than 1%) impact on the duration and cost of the installation campaign.

9 Conclusions

Cable failure cause analysis

135 failures of Submarine Power Cable System consisting of submarine cables, joints and terminations were collected from the JIP CALM partners and a failure cause analysis was performed. The results indicate a need for greater quality management protocols spanning across all the major lifecycle phases of the cable system. Some of the main observations are presented here, with accompanying recommendations to mitigate them:

- Data collection and analysis: The industry can learn more from failures when the root cause of each failure is analysed in detail, and when this information is shared and evaluated by a single body which gathers and analysis all detailed failure data. The JIP CALM showed the willingness of many in the industry to share failure information, but also showed that not all industry partners have shared all detailed failure data. This is required to enhance the learning experience, but often requires companies to provide sensitive information.
- It can be concluded that in order to learn more from failures, creating transparency and willingness to share sensitive information to at least a single independent body as e.g., DNV which can ensure the confidentiality of sensitive information while analysing the technical causes, is crucial. Fragmenting the data between companies and bodies will only reduce the learning potential.
- Many failures that were analysed appear to be preventable. This means that with appropriate attention during all project stages as design, manufacturing and installation, and with an adequate set of quality management measures, the number of failures can be strongly reduced. As this is not appearing to happen by itself, DNV has recommended emphasizing on a clear and strong set of quality management, quality assurance and quality control measures for submarine power cable projects.
- Most subsea cable failure data came from two types of companies: installation contractors and network owners. This also means that whenever failure detection moments are presented, they will tend to show up in the two lifecycle phases for which most reports were received. This does not diminish the quality of the analysis in any manner since care was taken to adopt a holistic view across all lifecycle phases, building upon experience and expertise, but did lead to a certain focus in the failure cases.

Cable lifetime monitoring system development

A Fibre-Optic (FO) based system was developed to continuously monitor the mechanical loading of subsea power cables throughout the cable lifetime. The main results from the development, manufacturing and testing are:

- A generic sensing concept for cable lifetime monitoring was developed and tested in combination with different read out technologies, i.e. Brillouin Distributed Strain Sensing and Distributed Acoustic Sensing), showing that elevated strain levels over a 2 m window can be measured up to a 50 km distance.
- The development has resulted in two fibre-optic sensor prototypes that have been integrated in a submarine power cable and successfully tested on various mechanical loading conditions in a full-scale test rig. Based on the test results of the integrated sensor units, the developed cable lifetime monitoring system has potential for further industrialization.
- Envisioned applications are measuring critical mechanical load conditions of submarine cables, such as bending, axial loading and torsion, starting from cable fabrication, load-out, deployment and the operational phase.

- The generic sensor concept showed to be applicable for different cable designs, which opens possibilities to develop monitoring systems for HVDC-cables and dynamic cables in floating applications.
- Regarding the read-out technologies, there is room for further improvement by tailoring equipment settings to the specific requirements in different cable lifetime phases. For instance, during cable deployment, expected strain levels are high and timely detection of critical extreme loads is important, while during the operational phase much lower strains (e.g. fatigue related) are expected as well as incidental high-impact events.
- As part of the project several dedicated test set-ups have been developed, as well as tooling for sensor manufacturing and test methodologies, which were essential for the successful monitoring system development and will be useful for the further industrialization. As one of the future developments, the Static Test Frame can be extended to enable testing the strain response over a moving window, thereby mimicking the movement of the cable during load out or deployment.

Development of a test plan for assessment of conductor stick-slip behaviour

A test plan was developed for the assessment of conductor stick-slip behaviour in subsea power cables. Because, although there are some accepted practices relating to modelling of conductor stick-slip behaviour, an improvement in the industry understanding of this topic will allow for more accurate relationship of cable curvature ranges to conductor fatigue. Two tests are proposed to determine the stick-slip behaviour:

- A wire pull test to determine the friction coefficient between adjacent strands.
- A conductor bend test to establish the relationship between curvature and slip of each layer of the conductor.

Burial depth detection with distributed acoustic sensing

The performance of DAS technology for determining the depth of burial of a subsea power cable was assessed in a scaled laboratory experiment. From these tests the following main observations were made:

- Buried fibre-optic cables were proven to be sensitive to incoming acoustic and elastic seismic waves of both low and high frequencies. The effect of the acoustic structure of a power cable was not considered and should still be investigated starting with a future modelling study.
- High frequency P-wave sources can help to detect shallow burial with high resolution. The recorded drop in amplitudes as the filtering of the higher frequencies by the covering layers shows the potential of the DAS technology to provide changes in thickness of the overlaying sediment.
- The limitations of the scaled lab setup did not allow a proper travel-time analysis which could be used to quantify depth of burial. A field scale modelling study and an actual field test should be conducted to determine the feasibility and accuracy of finding burial depth of power cables when using (a) an active source and (b) passive noise (or ‘sources of opportunity’).
- Lower frequency Scholte waves were shown to track lateral changes in sediment type between sand and clay covering the fibre optic cable. The clear detection of Scholte waves also provides the possibility of determining S-wave velocity layering below the buried cable.

Cable-seabed interaction

The seabed is dynamic and an of key importance to submarine power cables. Various tools are developed and improved for the modelling of sand waves and morphodynamics in general, which enables the understanding of potential changes in the burial depth of and soil stresses on cables as well as its forces during the wind farm lifetime. This results in a reduced uncertainty, cost-efficient cable routes and minimized risks and O&M costs. The developed tools can be used separately but also in conjunction with one another. The main developments and findings are:

- Sand wave dynamics are of key importance and significant advances have been made in applying a 3D morphological model for a sand wave field. This 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, satellite derived bathymetry (SBD) estimates in the form of heat maps are generated, which show nearshore (typically around 20 m depth) seabed dynamics, which are important for landfall of export cables. This information can be used to supplement available bathymetric data in data sparse environments and help in cable routing assessments at an early stage in the project proceedings.
- A cable routing tool is further advanced in this project. The tool considers the seabed dynamics but also other constraints such as archaeological sites, environmental areas and areas with possible unexploded ordnances in the design of cable routes and can be used to minimise burial efforts and risk of de-burial of the cables.

Temperature in submarine cables and depth of burial inversion

A physically-based thermal cable-soil model and two strategies to accelerate the computation were developed. The model was evaluated against literature derived experimental data and through an anonymized real DTS dataset from a real export cable. Additionally, a synthetic cable system was created (based on real cable geometries and power production) to assess the feasibility of extracting information on the cable depth of burial based on DTS observations. The main findings are summarized below:

- The physically-based model was shown to be capable of capturing both conduction and convection when compared to laboratory measurements of a cable-soil interaction reported in scientific literature.
- The DTS signal is mostly insensitive to burial of depth changes for thermal oscillations with frequencies higher than 1/10 days-1 (for depths of burial deeper than 50 cm). The variations of depth of burial are observed mostly during long-term heating and cooling processes, dominated mainly by the underlying seasonal seabed thermal dynamics. Having accurate knowledge on the temperature of the seabed is very relevant for modelling the soil-cable thermal interaction.
- The accuracy of depth of burial estimates were seen to be dependent on the absolute depth level. Detectability increases at low burial levels (<0.5 meters) and will likely allow for the identification of de-burial or near de-burial events, yet quantitative estimates might remain uncertain. There is a strong effect of forcing data uncertainty, where low quality inputs for power to heat dissipation and seabed water temperature might result in large errors in depth of burial estimates.

Cost-impact assessments

To evaluate the impact of weather conditions and innovations on duration and cost of a cable installation campaign, the team developed a detailed guide, method statement and simulation model of the power cable installation process.

- A cable installation guide has been developed and consolidated together with the project partners. The derived method statement includes a detailed plan (activities with duration and required crew, vessels and equipment) for the main steps of cable installation.
- 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.

- A representative reference case for cable installation, a typical offshore wind farm of 140x11MW wind turbines, has been defined. Simulation of the cable installation process for this reference wind farm clearly shows the large dependency on weather conditions.
- Using the reference case, different innovations have been assessed for impact on schedule and cost: 1. synchronisation tests on the equipment before cable mobilisation; 2. tensioner test before cable mobilisation; 3. function and verification tests on the pull-in equipment, and real time ROV streaming to the topside team during cable pull-ins; 4. continuous monitoring with optical fibre sensors embedded in the cables. The simulations show that with these precautionary measures, significant losses and even danger to the personnel can be avoided, at only a small (less than 1%) impact on the duration and cost of the installation campaign.

10 References

Burgers, F. (2020). *Satellite derived bathymetry for times of absent in situ data.* (Master), Delft University of Technology.

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

Deltares - (2020). Morphodynamics for Hollandse Kust (west) Wind Farm Zone. Ref: 11204811-002-HYE-0001; final report, dated 6 July 2020. Retrieved from https://offshorewind.rvo.nl/file/view/55040638/Report+-+Morphodynamical+Investigation+-+Deltares

Deltares (2022a). Burial depth detection with Distributed Acoustic Sensing. Ref 11204209-056-HYE-0001:

Deltares (2022b). Cable-Seabed InteractionWT4.1 - Improved morphology. Ref: 11204209-011-HYE-0001.

Deltares (2022c). Morphodynamics for Ten noorden van de Waddeneilanden Wind Farm Zone. WOZ2210243. Ref: 11206714-002-HYE-0001; final report, dated 14 February 2022. Retrieved from https://offshorewind.rvo.nl/file/download/4985a940-cf31-4070-aa69-d33ff78c677c/tnw_20220224_deltares_morpho_report-f.pdf

Deltares (2022d). Temperature in submarine cables: numerical modelling approach based on DTS. Ref: 11204209-012-HYE-0003.

DNV, (2016), "Recommended Practice (RP-0360)- Subsea power cables in shallow water".

DNV (2022). Analysis of submarine cable system failures and their underlying causes. Ref: 22-2971, Rev.3.

Donchyts, G., Baart, F., Winsemius, H., Gorelick, N., Kwadijk, J., & Van De Giesen, N. (2016). Earth's surface water change over the past 30 years. *Nature Climate Change, 6*(9), 810-813.

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

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

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

Overes, P. (2021), "Modelling Sand Wave Field Dynamics in the North Sea using Delft3D Flexible Mesh," MSc thesis, TU Delft.

Pacheco, A., Horta, J., Loureiro, C., & Ferreira, Ó. (2015). Retrieval of nearshore bathymetry from Landsat 8 images: a tool for coastal monitoring in shallow waters. *Remote Sensing of Environment, 159*, 102-116. doi: 10.1016/j.rse.2014.12.004

Roetert, T. J., Raaijmakers, T. C. and Borsje, B. W. (2017), "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.

TNO, (2021), "uwise: software for offshore energy operations," [Online]. Available: https://uwise.tno.nl/. [Accessed 2022/12/20].

TNO (2022). Guide to Improve Offshore Cable Installation. Ref: TNO 2022 R12182.

TNO, DNV & VDHP (2022). Fibre-optic monitoring system development for submarine cables - concept development. Ref: TNO 2022 R11865.

Venkitachalam, G. (2020), "Modelling the installation of offshore wind farms," Thesis report, TU Delft, Delft, The Netherlands.

Wood (2022). Development of Test Plan for Assessment of Conductor Stick-Slip Behaviour. Ref: OP215113-REN-REP-001.

Zandbergen, S. (2020). *Multi-case Evaluation of Empirical Methods for Satellite-Derived Bathymetry.* (Master), Delft University of Technology.

Deltares is an independent institute for applied research in the field of water and subsurface. Throughout the world, we work on smart solutions for people, environment and society.

Deltares

www.deltares.nl