Towards Active Cable Reburial Monitoring using Distributed Fiber-Optic Sensing over 40 km of a High Voltage Marine Interconnector

Matthias **ERDMANN**, AP Sensing GmbH, (Germany), matthias.erdmann@apsensing.com

Justin K. **DIX,** Daniel **ELLIS**, George **CALLENDER** and James A. **PILGRIM;** University of Southampton; (United Kingdom), j.k.dix@soton.ac.uk

Rosalie **ROGERS**, Gareth **LEES**, AP Sensing UK, (United Kingdom), rosalie.rogers@apsensing.com

Henrik Roland **HANSEN**, Energinet.dk, (Denmark), hrh@energinet.dk

Tony **LUCIGNANO**, Statnett, (Norway), tony.lucignano@statnett.no

ABSTRACT

Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS) measurements were acquired over a 40 km section of the 137 km long Skagerrak 4 (SK4) subsea cable before and during a retrenching operation. Five sections of the cable between 140 m and 280 m in length had been identified for reburial using conventional geophysical and video techniques. DTS data taken over a three week period prior to the reburial clearly showed cold spots at all of the planned reburial sites. Absolute temperature at these locations fluctuated by over 8°C, which is interpreted as being in response to temporally and spatially varying bottom water temperatures. The reburial process itself was accurately monitored in real-time using DAS. After reburial, consistent DTS temperatures within ±1°C were measured at all reburial sites, comparable to the adjacent buried sections of the cable and thereby confirming reburial was successful.

KEYWORDS

Cable Survey, Cable Reburial, Distributed Temperature Sensing, Distributed Acoustic Sensing, Exposed Cables, Subsea Cable Monitoring

INTRODUCTION

Distributed Temperature Sensing (DTS) technology based on Raman scattering is widely used for measuring high voltage cable temperature for distances up to ~70 km [1], and its ability to detect exposed cable sections is now well established [2]. Distributed Acoustic Sensing (DAS) technology allows continuous real-time measurements of acoustic emissions and strain changes along power cables. DAS has previously been used to locate sources of acoustic disturbances over large distances ~80 km in terrestrial environments [3]. This paper presents the combined use of DTS and DAS to identify and undertake pre-, syn- and post-reburial monitoring of sections of a marine HV interconnector.

The submarine section of the Skagerrak 4 (SK4) high voltage interconnector runs between Bulbjerg, Denmark, and Kristiansand, Norway, covering a distance of 137 km (Fig. 1). The SK4 cable is a Nexans 500 kV HVDC Mass-Impregnated Non Draining (MIND) cable with a typical fluctuating load profile of up to 1432 A. The cable was installed, in the summer of 2013, to a depth of 0.5 – 2 m below seabed, using a Nexans Capjet trencher in fine to medium sands. Along the whole transect water depths range from 0 to -523 meters relative to sea level (mMSL) (Fig. 1). Burial depths were confirmed using a TSS350 cable survey system.

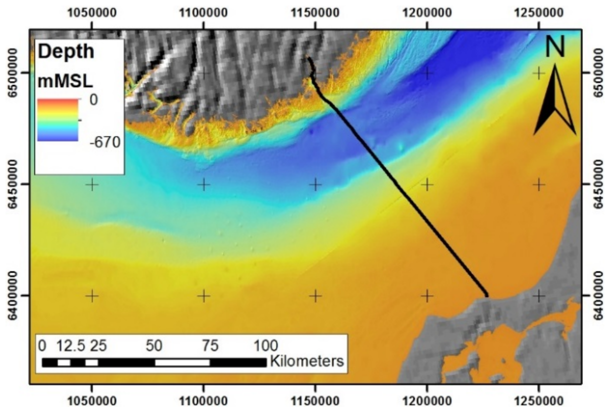

Fig. 1: The location of Skagerrak 4 cable overlaid on the EMODnet Digital Terrain Model [4]

In July 2017 during a scheduled post-installation re-survey (using a combination of high-resolution swath bathymetry, side scan sonar and ROV based video) five cable exposures were identified in the first 35 km of the cable off the Danish coast. Exposure widths ranged from 5 - 60 m and they occurred in water depths between -15.5 and -31 mMSL (Fig. 2). A reburial campaign was subsequently planned for July 2018 and this provided an opportunity to test the potential of combined DTS and DAS study of the reburial process. The bathymetry in Fig. 2 is from July 2018 and shows downstream scour that has developed in the 12 months between the two survey campaigns.

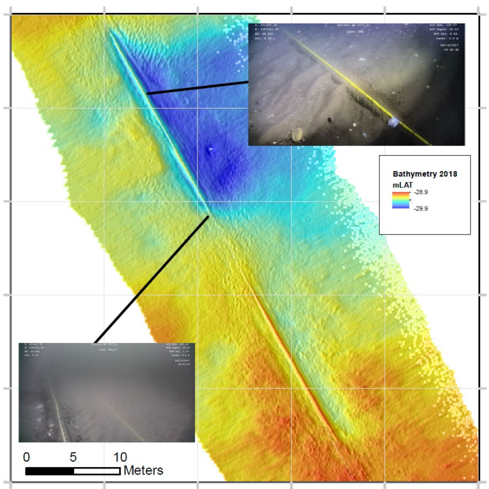

Fig. 2: High resolution swath bathymetry of an exposed section of cable. Insets show video stills of exposure of the cable and external fiber optic cable

For this study, DTS and DAS instruments were installed onshore 3.97 km from the Danish coast and connected to fibers in the same sensor cable strapped to the outside of the SK4 cable. DTS monitoring started seventeen days prior to reburial and for a further two days after reburial, whilst the DAS system recorded for a window of a single day focused around the reburial operations. Reburial was performed using a Helix T750 Jet Trencher. The planned zones of reburial ranged in length from 30 m to 200 m. Pre- and post-reburial depths were determined by a TSS440 cable survey system

METHOD

The DTS device was a single-mode N4525A DTS with maximum reach of 70 km, measurement time of 30 minutes, and spatial resolution of 4 m. The DAS instrument was a N5200A with a range option of 50 km, sampling rate 500 Hz, and spatial sampling interval 1.25 m.

Due to the relatively low load (average load 864 A with a maximum of 1432 A) of the single conductor cable, and due to the exterior position of the sensor cable, the measured DTS temperatures are dominated by ambient temperature fluctuations rather than load induced fluctuations.

This fact has been verified by dynamic modelling of the SK4 cable using Finite Element software, following the approach of Hughes et al. [5, 6]. This approach accounted for conductive heat transfer in the cable and both conductive and convective heat flow within the surrounding burial medium. A thermal conductivity value of 2.1 W/(m*K) and a permeability of 1E-11 m^2 were extracted from the nearest available geotechnical data.

Time-dependent simulation of cable and environment using the time-varying load of SK4 during July 2018 and assuming a burial depth of < 0.1 m resulted in load-driven temperature variations at the fiber optic cable of < 1.5°C, while the amplitude of temperature variations in the conductor was approximately 12°C. This variation in fiber temperature is small in relation to ambient temperature fluctuations over the measurement period of up to 8°C.

RESULTS

Cold Spots in Single-Time Step DTS Profiles

Several single time-step, pre-reburial, DTS records taken on July 10th, 2018 over the range of the planned reburial positions (up to 40 km fiber length) are shown in Fig. 3. The first 4 km of the fiber are recording terrestrially buried sections of the cable and the initial part of the inter-tidal zone and will not be discussed further here. In the immediate sub-tidal zone the temperature drops from c. 11°C to c. 7°C and then at c. 6 km the temperature rises to c. 14°C with low amplitude (up to 3°C) long-range fluctuations for the remainder of the measurement length.

At 10.031 km along the fiber (-15.7 mMSL) is the first of five clearly identifiable Cold Spots which records a localised drop in temperature of 5°C (CS-1). An additional four cold spots, at 17.700 km (CS-2: -22.6 mMSL), 24.157 km (CS-3: -25.9 mMSL), 29.793 km (CS-4: -29.1 mMSL) and 38.288 km (CS-5 -30.9 mMSL) respectively, have temperature drops of 2 - 4°C relative to the adjacent ambient levels.

The width of these cold spots ranges from 85 - 180 m. The location and exposure lengths of the cold spots relative to the visually/geophysically identified exposures correlate to within 130 m of the actual cable exposures and are summarised in Table 1. The exposure positions and lengths can be defined from the geophysical data to the decimeter level (depending on the resolution of the swath). However, numerical modelling suggests that, beyond the completely exposed zone of the cable, sections of the cable buried to a depth of c. 0.1 m will still contribute to the cold spot in the DTS data. Consequently, the cold spots will extend beyond the actual exposed zone, and so comparison between the two datasets is only possible at the tens of meters scale.

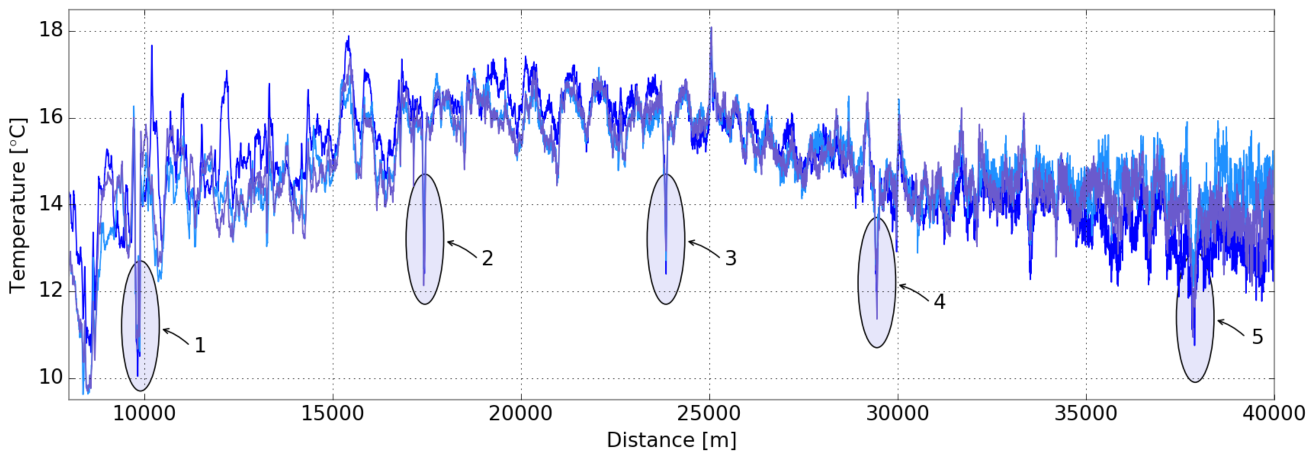

Fig. 3: DTS traces before cable reburial with five identifiable cold spots

Cold Spot	DTS Length [m]	DTS Location [DaC– km]	SI Length [m]	SI Location [DaC– km]
1	210	9.957	10, 59, 27	10.031
2	120	17.583	11	17.700
3	130	24.047	17	24.157
4	160	29.692	21, 23	29.793
5	180	38.153	5, 21	38.288

Table 1: Comparison of exposure lengths and locations of the DTS temperature anomalies and those derived from the original site investigation (SI) data. Distances are from the start of the cable.

DAS Reburial Results

The reburial operation began July 27th, 2018, 19:47 UTC starting at CS-5. The operation of the trencher could be clearly monitored using the DAS instrument both through the raw acoustic signal and the Frequency Band Energy (FBE) signal. The data aligns with the specified positioning data of the trenching machine. Frequency Band Energy plots also show how the reburial activity pauses for five minutes, then continues (Fig. 4).

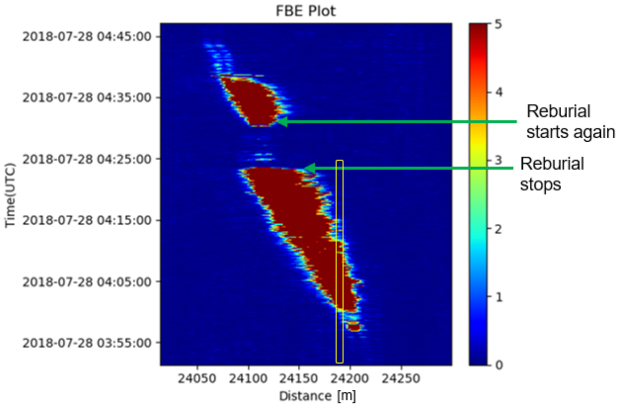

Fig. 4: An example of the Distributed Acoustic Sensor data for Cold Spot 3 (CS-3) during reburial

The reburial operation at all five reburial positions could be successfully monitored by DAS and the locational comparison between the DAS start and end point of trenching locations and the actual trenching activity on the bed gave a spatial comparison of within ±5 m.

Cold Spot	DAS Length [m]	DAS Location [DaC– Km]	SI Trench Length [m]	SI Location [DaC– Km]
1	226	10.013	218	10.022
2	290	17.604	280	17.602
3	135	24.142	143	24.136
4	147	29.802	145	29.801
5	158	38.264	159	38.266

Table 2: Comparison of exposure lengths and locations of the DAS trenching signatures and those derived from the post-reburial swath data.

Cold Spot Temperature Time Series

The full time-series DTS data for the five Cold Spot positions, and for two representative locations of permanently buried cable, named Reference Buried Cable (RBC) sections, have been analysed: RBC-1 at 26 km along the cable offshore (depth of lay 0.97 m) and RBC-2 near shore at 8.46 km along the cable (depth of lay 1.8 m), both are shown in Fig 5.

The temperature time series at RBC-1 was relatively uniform fluctuating between 15°C and 16°C over the first two weeks, increasing to 17°C by the 26/07/18 and stabilising at 15.5 ± 0.5°C until the end of the measurement period. By contrast, RBC-2 which is buried over a meter deeper but much closer to shore, fluctuated by ±1°C about an ambient of 10°C over the first two weeks, rising to 11°C for the final week of the measurement period. The five exposed cable sections (CS-1 to CS-5) have much more varied temperature profiles. For the first four days, temperatures were relatively static for each location, with an overall range between 11°C and 13°C. There is no consistent temperature relationship with either depth or distance offshore.

During the 14/07/18 both CS-1 and CS-2 showed rapid increases in temperature by 5°C and 2°C, respectively. These two temperature profiles continued to fluctuate with an additional significant temperature step-change occuring on the 18/07/18. Just prior to the reburial operation, both recorded a temperature of 17°C, with CS-1 actually having reached the maximum recorded temperature for the whole measurement period of 19.8°C during this time.

CS-3, CS-4 and CS-5 exhibit a more consistent temperature change. All three locations continue to record stable temperature levels (c. 12 ± 0.5°C) until the 18/07/19 when CS-4 and CS-5, located in the same water depth and c. 8.5 km apart, start to increase in temperature at a similar rate rising to c. 15°C just prior to reburial. CS-3 in slightly shallower water and a further 5.5 km closer to shore has a step change in temperature on the 18/07/18 equivalent to that seen at CS-1 and CS-2. Then it follows a similar rate of temperature rise (c. 0.4°C/day) reaching 17°C, equivalent to CS-1 and CS-2 immediately prior to reburial.

Post-reburial, all five cold spot positions and the reference burial section RBC-1 recorded very similar temperatures of 16.25 ± 0.25°C for the remainder of the monitoring period.

A conventional interpretation of this DTS time series data, particularly prior to burial, would be that such rapid changes in temperature data are driven by natural changes in burial depth. However, dynamic numerical modelling of the SK4 cable suggests that in these seabed conditions in excess of two meters increase in burial depth within 1 - 2 days would be needed to achieve just a 4°C temperature rise. As seen in Fig. 2, although bedforms are present at all cold spot locations, they are small in amplitude (<0.2 m). Time-lapse swath bathymetry suggests they are not particularly mobile, with bed level change between 2012 and 2018 at the cold spots being typically < ±0.2 m p.a. There is always the potential of extreme events impacting on the seabed and moving large volumes of sediment, but a contemporaneous wave buoy record from the Väderöarna wave buoy (Eastern Skagerrak) identifies no storms occurred during the monitoring period with an average wave height of only 0.8 m and a maximum of 2.7 m [7].

We propose that prior to reburial the fluctuations in the Cold Spot position temperature records are actually due to changes in ocean bottom temperatures. The temperatures recorded from the buried cables at the reference sections are interpreted as being a combined signature of ocean bottom waters and groundwater, with the ratio of the two controlling the absolute temperature actually recorded.

Direct sea bottom temperature records are not available for the Skagerrak, but daily, calibrated (RMS error 0.43°C – with model temperatures being consistently higher than observations), mean seabed temperature forecasts are available at a grid spacing of 1.5 km from the UK Met Office's FOAM Shelf Seas Atlantic Margin Model (AMM15). The data is grouped over 33 vertical levels spread across full ocean depths (0 - 5000 m) of the full model domain. The July 2018 data were downloaded from the EU Copernicus Marine Service Information, Northwest Shelf Ocean Physics Analysis and Forecast model [8] and daily mean temperatures extracted for each Cold Spot and the two reference locations.

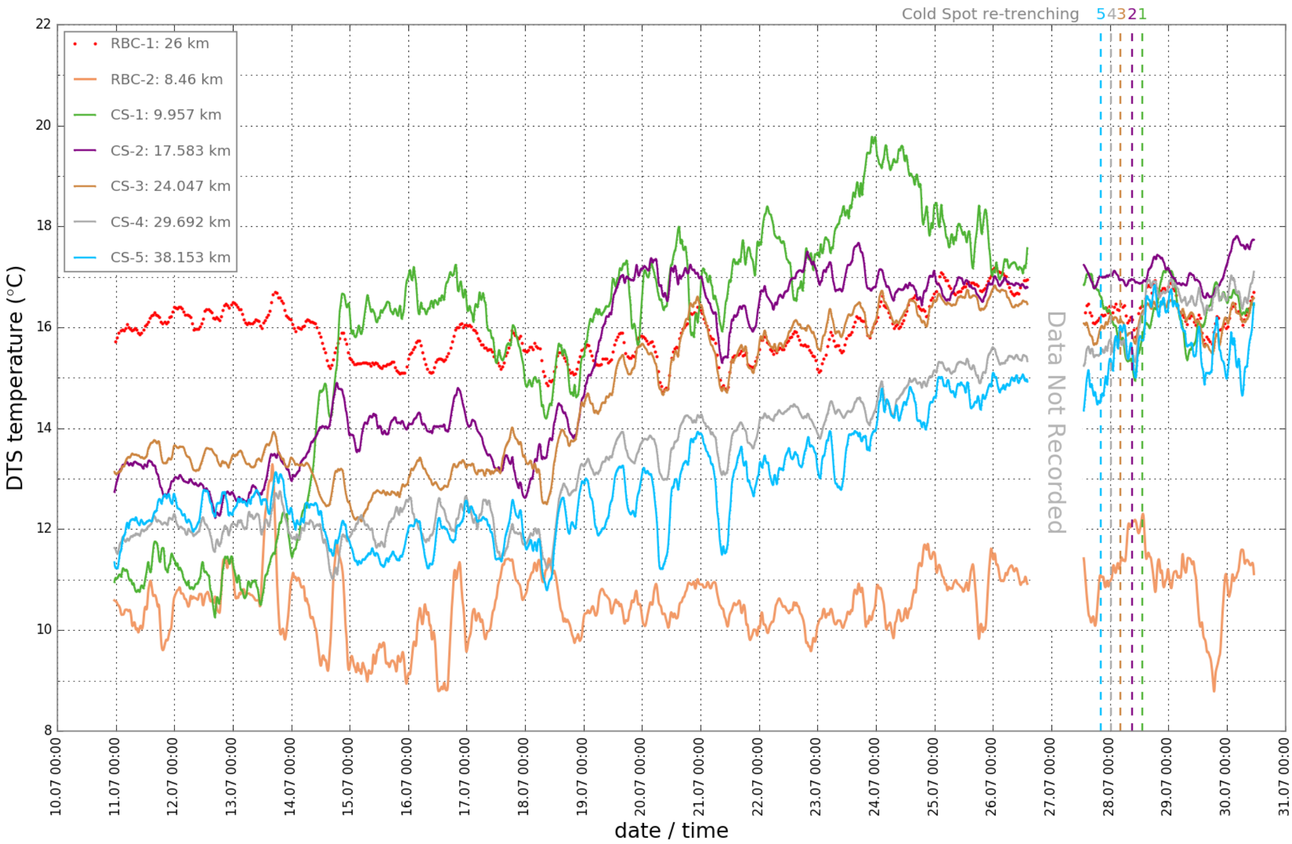

Fig. 5: DTS time series (10-31/07 2018) for Cold Spot positions CS-1 to CS-5 and Reference Buried Cable sections at 8.46 km and 26 km. The timing of the re-trenching operations (starting at CS-5) is also indicated

The modelled sea bottom temperature profiles show a systematic change both in space and time. As per the DTS measurements CS-1 exhibited the highest temperatures (17 - 20.5°C) and CS-5 recorded the lowest temperatures (8.5 - 16°C), with these temperatures steadily increasing through the month. CS-3, CS-4 and CS-5 record temperature differences of < 2°C throughout the pre-reburial period, with the model temperatures consistently exceeding the DTS measurements. This is in-line with the quoted positive temperature bias of the model [8]. However, CS-1 and CS-2 have a differential of up to 6°C and 4°C respectively. The largest discrepancy is between the modelled bottom water temperature of 17.1°C at CS-1 versus a temperature of 11°C recorded by the DTS system in the first four days. The rapid acceleration in temperature of the DTS measurements on the 14/07/18 brings the temperature to within the < 2°C differential typical of the other Cold Spot positions. We propose that these rapid changes are in response to warm Jutland Coastal Waters [9] advecting in to the Skagerrak from the south-west with this coastal plume of warmer water being clearly seen in the modelled output (Fig. 6).

At RBC-1 the seabed water temperature initially fluctuates between 13.5°C and 14.5°C. If propagated to the cable burial depth of c. 1 m, these ambient temperatures would give simulated cable surface temperatures of 15.5°C to 16.5°C, within 0.5°C of the recorded DTS temperatures. The seabed temperatures increase over July, to reach a maximum temperature of 17.6°C, but this is not reflected in an increase in cable temperature. This suggests changes in water temperature are not synchronously propagated to 1 m cable depth.

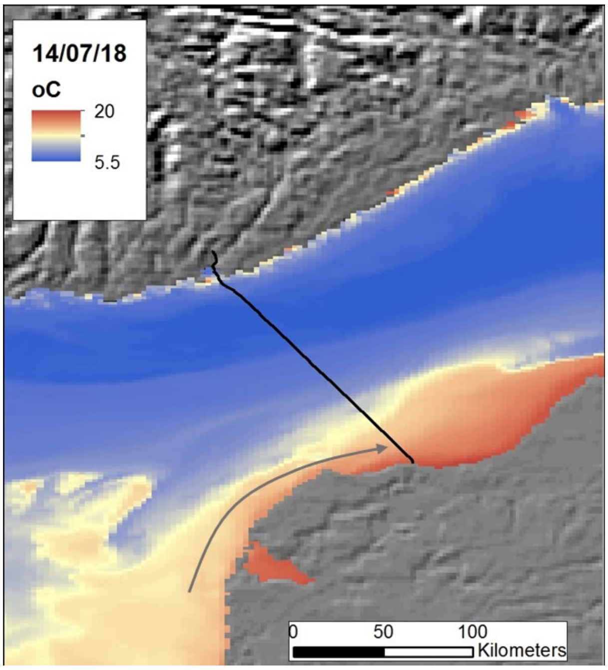

Fig. 6: The 14/07/18 Seabed temperatures from the UK Met Office FOAM AMM15 model. The direction of flow of the warm Jutland Coastal Waters is shown in grey

The second reference cable location (RBC-2) shows a systematic offset of 8 - 9°C between DTS measurements and ambient bottom water temperatures (which fluctuate between 17°C and 19°C). However, measurements of groundwater temperature at an on-shore borehole

(Ellidsbol Waterworks – [10]) only 6 km from RBC-2 gives consistent groundwater temperatures of 8 - 9°C over the summer of 2018 (these values are directly comparable to measured summer groundwater temperatures along the Danish coast [11]). Modelled cable surface temperatures based on this ambient porewater temperature, at 1.8 m burial depth, are within 0.5°C of those recorded by the DTS.

Finally, the post-burial DTS measurements cluster at 16.25 ± 0.25ºC, and in sync with the permanently buried reference cable section RBC-1. This reflects the now consistent nature of the burial depths (between 0.6 – 1 m) at all of these locations and thus the effectiveness of DTS data alone in establishing if reburial has been successful. To get these DTS temperatures from the numerical model requires an ambient porewater temperature of 14°C. With a modelled ambient seabed temperature during this period being 5.5°C higher, it suggests that porewaters are almost certainly mixed with the significantly colder (8°C) groundwater. The process of mixing between groundwater and downward advected ocean bottom waters in a series of continental shelf settings is the focus of extensive current study (e.g. [11], [12] and [13]) and has significant implications for both design and dynamic cable ratings.

DISCUSSION & CONCLUSIONS

The simultaneous acquisition of DTS and DAS data during pre-, syn- and post-reburial of a marine high voltage interconnector provides an excellent opportunity to test the potential of these systems to monitor the long-term life of such cable systems. The HV system configuration and operation is particularly challenging as the relatively low loads and the location of the fiber-optic cable on the exterior of the cable requires a detailed understanding of spatial and temporal variations of both the soil and water column thermal properties to produce a robust interpretation. However, using a combination of specifically acquired and publically available oceanographic and hydrological datasets a coherent interpretation of the monitoring data is possible. This in turn has been calibrated against the actual reburial data to confirm many of these interpretations.

The key conclusions of this work are:

1. The DTS is capable of identifying cable exposures in marine settings. Numerical modelling suggests that, beyond the completely exposed cable sections, zones of burial up to a depth of c. 0.1 m will contribute to the cold spot in the DTS data. This results in the DTS being able to resolve exposure position and length to the tens of meters scale.
2. In the exposed cable sections, temperature fluctuations of over 8°C are recorded, and for cables running at relatively low temperatures they could be easily mis-interpreted as representing rapid over-burial. However, a clear understanding of ambient bed dynamics and oceanographic sea bottom temperature conditions demonstrate that these changes are in fact driven by water-column temperature variations.
3. The temperature profiles of buried sections of the cable demonstrate that ambient porewater temperatures are not just driven by the overlying ocean water column, but can also be affected by the local groundwater temperatures even several tens of kilometers offshore.
4. Consequently, without a proper understanding of these environmental factors, ”cold spots” could be easily missed.
5. The DAS monitoring of the syn-reburial process acts as a very accurate monitor of the trenching process with the DAS-derived distances being within ± 5 m of the actual trencher location on the bed.
6. Post-reburial DTS measurements clearly demonstrate the effectiveness of the re-burial process and through comparison with well constrained numerical models are able to confirm the success of the burial process.

In conclusion, DTS and DAS systems have shown to be an effective monitoring tool of active marine HV cable systems. For best results they need to be combined with a good understanding of the ambient environmental conditions.

REFERENCES

[1] T. Lauber, G. Cedilnik, G. Lees, 2018, "Physical Limits of Raman Distributed Temperature Sensing – Are We There Yet?", Proc. 26th Int. Conf. Optical Fiber Sensors, OSA Technical Digest, Paper WF30.

[2] CIGRE WG B1.45, 2019, “Thermal monitoring of cable circuits and grid operators’ use of dynamic rating systems”, 2019, Technical Brochure 756, France, ISBN: 978-2-85873-458-0.

[3] G. Cedilnik, R. Hunt, G. Lees, 2018, "Advances in Train and Rail Monitoring with DAS", Proc. 26th Int. Conf. Optical Fiber Sensors, OSA Technical Digest, Paper ThE35.

[4] EMODnet Bathymetry Consortium, 2018, http://doi.org/10.12770/18ff0d48-b203-4a65-94a9-5fd8b0ec35f6

[5] T.J. Hughes, T.J. Henstock, J.A. Pilgrim, J.K. Dix, T.M. Gernon, C.E. Thompson, 2015, “Effect of Sediment Properties on the Thermal Performance of Submarine HV Cables”, IEEE Transactions on Power Delivery, 30(6), 2443-2450.

[6] T.J. Hughes, T.J. Henstock, J.A. Pilgrim, J.K. Dix, T.M. Gernon, C.E. Thompson, 2015, “Thermal Ratings of Submarine HV Cables Informed by Environmental Considerations”, 9th International Conference on Insulated Power Cables.

[7] Swedish Meteorological and Hydrological Institute: https://www.smhi.se/en/weather/sweden-weather/sea-levels-waves#ws=wpt-a,proxy=wpt-a,lang=en,station=vaderoarna_wr_boj

[8] M. Tonani, C. Pequignet, R. King, P. Sykes, N. McConnell, J. Siddorn, 2018, North West European Shelf Production Centre, NORTHWESTSHELF_ANALYSIS_FORECAST_PHYS_004_013, Quality Information Document, Copernicus Marine Environmental Monitoring Service.

[9] D.S. Danielssen, L. Edler, S. Fonselius, L. Hernroth, M. Ostrowski, E. Svendsen, L. Talpsepp, 1997, “Oceanographic variability in the Skagerrak and northern Kattegat”, 1990, ICES Journal of Marine Science, 54(5), 753-773.

[10] De Nationale Geologiske Undersøgelser for Danmark og Grønland - Water analyses:

http://data.geus.dk/JupiterWWW/vandanalyse.jsp?anlaegid=61288)

[11] C. Duque, S. Müller, E. Sebok, K. Haider, P. Engesgaard, 2016, “Estimating groundwater discharge to surface waters using heat as a tracer in low flux environments: the role of thermal conductivity”, Hydrological Processes, 30(3), 383-395.

[12] A.M. Wilson, G.L. Woodward, W. B. Savidge, 2016, “Using heat as a tracer to estimate the depth of rapid porewater advection below the sediment–water interface”, Journal of Hydrology, 538, 743-753.

[13] J.K. Dix, J. Pilgrim, D. Ellis, H. Porter & G. Callendar, 2019, “Seabed controls on the design and lifetime performance of marine HV cables”. This volume.

GLOSSARY

CS: Cold Spot
DaC: Distance along Cable
DTS: Distributed Temperature Sensing
DAS: Distributed Acoustic Sensing
mMSL: meters Mean Sea Level
RBC: Reference Buried Cable
SI: Site Investigation