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Technical Paper

The use of fibre optic distributed sensing technology to detect changes in sediment overburden

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Abstract

Fibre optic cables can be used as sensors to monitor changes in temperature and strain through the analysis of backscattered light. This can be linked to changes in the ambient conditions surrounding the cable. Active distributed temperature sensing relies on an external heat source relative to the fibre optic cable to measure the properties of, and changes in, the surrounding medium. An experiment was conducted using fibre optic sensing technology to monitor changes in sediment overburden. Fibre optic cables were buried in a channel containing saturated sand and water with an external heat source. The depth of overburden sediment above the cables was reduced, while the associated temperature response along the cable was monitored. This paper explains the characteristics of heat transfer from an active heat source to the surrounding soil medium providing a means to translate from the temperature measurement to the associated overburden thickness. The techniques used here are intended to be applicable to measurements of seabed scour above buried power cables.

Keywords: Distributed temperature sensing, buried power cables, seabed scour, optic fibre sensor

1. Introduction

Fibre optic cables are often included in the power cable assembly to transmit telecommunications (Fig 1). When used as an optic fibre sensor (OFS), they can measure the conductors' thermal and structural integrity during operation by monitoring optical signal attenuation, which acts as an early warning system to detect changes along the power cable. This additional application has gained pace over recent years, almost to a point where it can be considered a prerequisite in subsea cable installations for preventive maintenance and asset management strategies. The principle of fibre optic monitoring is based on the detection of backscattered light to quantify changes in temperature and strain from OFS.

Backscattered light is composed of three main spectral components: Rayleigh, Raman and Brillouin, of which Raman and Brillouin are currently used to report temperature and/or strain along the optical fibre. Raman spectra differ from Brillouin spectra by having a fixed frequency but variable intensity. In comparison, Brillouin interaction exhibits a frequency shift through the scattering process. The correlation of the frequency shift is linearly dependant on the refractive properties of the optical fibre, and thus the strain and temperature changes within. Unlike Raman scattering, Brillouin scattering can propagate over long distances without significant attenuation, allowing for analysis of longer cable lengths where necessary.

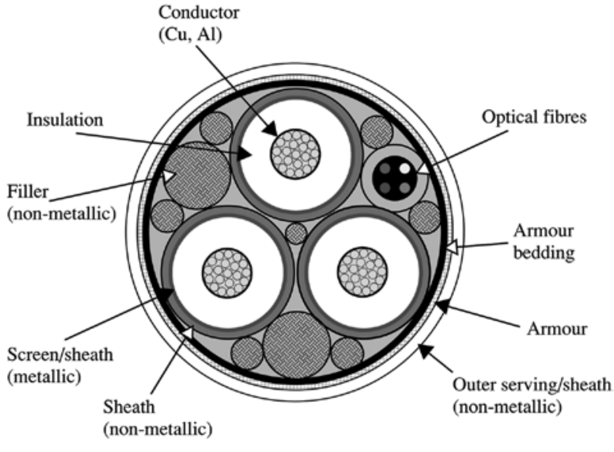

Fig 1: Typical power cable assembly (adapted from DNV GL, 2014)

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Applications of OFS used for cable condition monitoring have been documented by Hara et al. (1999) for monitoring temperature distribution in a 500 kV DC submarine power cable, and by Zhao et al. (2014) for the real-time monitoring of strain in a three-phase 110 kV subsea cable. Svoma et al. (2009) discussed the benefits of integrated fibre optic arrays within power cables to measure thermal runaway created by seabed sediment mobility, which can alter the thermal conductivity of the medium surrounding the cable, leading to hotspots. Continuous and real-time monitoring of temperature can also reveal cold spots caused by removal of sediment that once surrounded the cable, possibly leading to free spans if unchecked. Fractures in the cable from seismic activity or anchor drag can also be detected (Omnisens, 2015). Ultimately, remote monitoring along cable arrays can optimise future power cable design (Fromme et al., 2011) and cable installation procedures by measuring thermal efficiency in known sediment types.

A distributed temperature sensing (DTS) system can be used to measure spatial and temporal variability in the subsurface at a high resolution along cables over tens of kilometres in length. Two forms of measurement are currently recognised: active and passive sensing. Passive sensing can be used to monitor the ambient temperature of the subsurface when an OFS is buried beneath the surface or placed on top of the seabed. Active sensing relies on an external heat source that may vary depending on changes to internal and external properties of the surrounding medium. An example would be power cables where electrical resistance within the conductor gives rise to internal heat. The amount of heat generated by an electrical cable depends on the load being carried as well as its construction and insulation thermal rating. A maximum temperature reaching 90 °C is considered for a subsea cable using polyethylene insulation (Pilgrim et al., 2013) for example.

DTS systems have been successfully demonstrated in various applications, such as monitoring terrestrial pipelines (Inaudi and Glisic, 2010), changes in soil moisture content (Steele-Dunne et al., 2010) and in hydrological temperature-depth profiling (Arnon et al., 2014). This paper, however, focuses on sensing the changes in sediment overburden around a simulated power cable buried in an aquatic environment using Brillouin optical time domain analysis (BOTDA).

Seabed sediment mobility challenges the effectiveness of the subsea cabling industry, especially in shallow water where strong tidal currents are located and where seabed materials are often non-cohesive. Around the UK strong seabed currents, accentuated during tidal surges and storms, are commonplace. Offshore territories with names like 'The Wash' and 'Race Bank' conjure images synonymous with transient shifting seabed bathymetry. Some of these environments have largescale offshore wind farm developments where inter-array and interconnector seabed cables need to be buried to ensure optimum thermal efficiency and to prevent damage caused by third-party activities.

Seabed sediment transport can be prevented by mitigating against scour or infilling scour pits with sandbags and rock fill. Related cold spots in cables can be detected by occasional DTS monitoring, but the gradual thinning of sediment cover above a cable in an area of high sediment transport should be detectable as a gradual reduction in local temperature. Using active DTS, Zhao et al. (2012) experimentally demonstrated how scour can be detected around subsea pipelines. But limitations include the need for the OFS with an active heat source to be installed to the side of the pipeline, which would add to cost as well as create operational issues. Power cables, in comparison, generate heat during operation owing to electrical resistance and can provide the means for active monitoring of changes in thermal gradient.

Extending the work of Zhao et al. (2012), but on a smaller scale and with a power cable rather than a pipeline in mind, the sensitivity of the DTS using Brillouin scatter to measure temperature variation due to changes in sediment thickness is demonstrated in this study. A long channel containing sand with a covering of water forms the basis of the model presented in this paper. A heat tape is embedded in the sand together with an OFS, where the heat tape mimics the power cable in generating heat. Sediment cover is manually reduced and the temperature change monitored showing the sensitivity of the monitoring system to measure real time changes in overburden.

2. Experiment setup

The test setup consisted of ten 1 m long sections of a concrete U-channel (referred to here as 'channel') that had been locked together with a silicone sealant placed between each joint. The dimensions of the channel cross-section are presented in Fig 2(a).

A vertical wall comprising 12 mm thick waterproofed plywood was clamped at each end of the channel using corner clamps at the top and a gravity block at the base. Sealant was applied to seal gaps between the channel and the wood panel ends. At the lower corner of the wood ~50 mm above the base of the channel, an 18 mm hole had

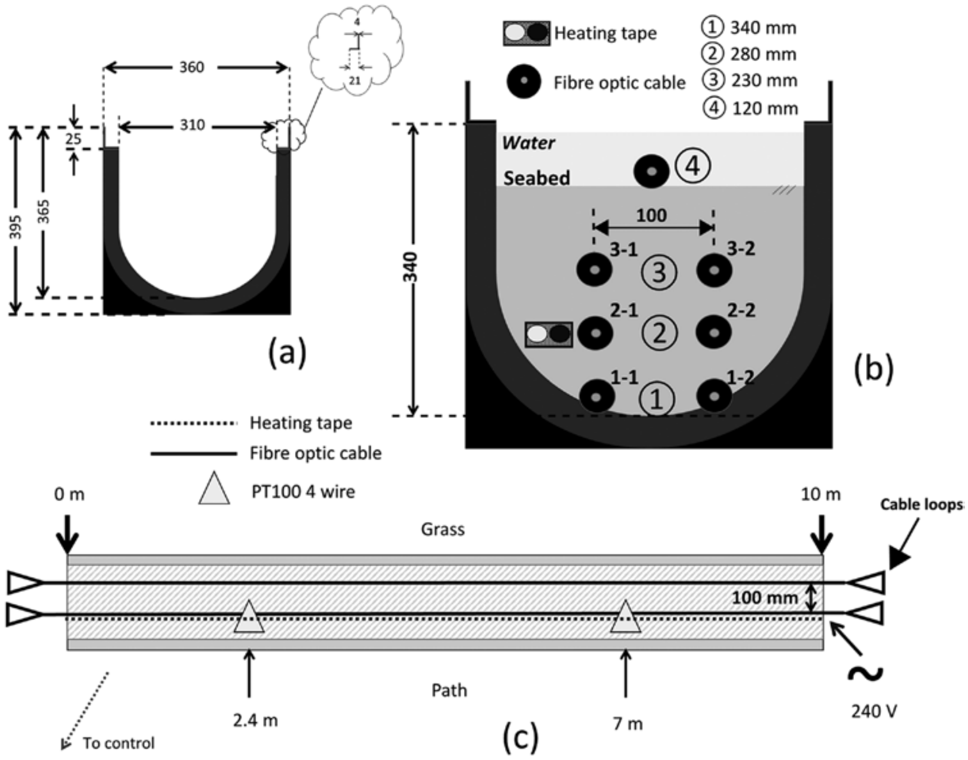

Fig 2: Sketch of the experimental setup: (a) dimensions of the channel; (b) placement of heat tape and fibre optical cables within the sand; and (c) plan view showing position of PT-100 thermometers (all dimensions in millimetres unless stated)

been drilled to accommodate the heating tape. The self-regulating heating tape was 12 mm wide and 10 m long, supplied by Heat Trace^{TM}, UK as 75FSS2-A rated at 75 W per metre (Failsafe Super, 230 V metal sheathed heating cable). Self-regulating heat tapes are cables whose local resistance increases when the temperature in that location rises beyond target, thereby reducing the local heat output while the remainder of the cable generates heat as before. The aim is to supply heat only where it is needed to maintain the source temperature.

The cable was supplied with a termination kit consisting of a silicone shoe and a socket that isolates the 240 V power input cables with an earth cable and bracket that connected to the outer cable. The tape supply wires were connected to a terminal block and then to a 16 A, 14 m long cable. The cable connected to a socket containing a 16 amp type C residual current circuit breaker (RCBO) with a 30 mA trip to protect the heating tape during operation. To protect the exposed connection against surface water, the entire terminal block was immersed in ACC silicone adhesive (RS 448-0286). The cable passed through the wooden end panels on the channel and the annulus was back filled with high temperature resistant sealant. The potting compound for the terminal blocks was also applied on the cable after drying, where it entered and exited the wood panel enclosure and ensured a waterproof seal. The heat tape was supported using wooden blocks during initial setup of cables and sensors in the channel.

Fibre optic cables (Mayflex Excel OS2 4C 9/125), specific to measuring temperature by removing the influence of strain, were laid at the base of the channel directly below the heating cable and 100 mm to the side (Fig 2b). These were fixed to the base of the channel using duct tape. The cable was one continuous 100 m length and was placed in the 10 m long channel with 4 m loops exposed outside the channel at each end. This was so that the cable could be doubled back along the channel at the same elevation or placed at a different elevation. The significant length of these loops was necessary to distinguish and identify these cable sections during analysis.

As a separate and independent point of temperature reference, sheathed, four-wire, ceramic platinum resistance thermometers (PT-100) were placed at two locations along the channel (Fig 2c) and attached to the OFS closest to the heat tape (2-1) using a cable tie. The PT-100 (supplied by Labfacility, UK) were monitored using a Pico® Technology PT-104 data logger connected to a computer. Two loggers were used with eight PT-100 sensors.

After placement of 20 m length of cable with PT-100 sensors at the base of the channel, the channel was flooded with water before placing the brown medium-grained sand. The sand was then gradually added across the channel to remove air and thus achieve uniform density. The particle size distribution of the sand in Fig 3 indicates the distribution of particles as shown by the coefficient of uniformity (C_u) and coefficient of concavity (C_c), which are derived from the particle size (D) passing at 60%, 30% and 10%.

The sand was placed up to the level of the heating cable so that it rested on the sand surface. A length of OFS was then attached to the heating cable with cable ties and a PT-100 sensor was attached to the cable at 2.4 m and 7.0 m along the channel. Two 10 m sections of OFS were then placed at the same depth as the heating tape and at a horizontal separation of 100 mm from it. Sand was then added and another duel cable length placed at a higher elevation above the heating tape, as shown in Fig 2b. A cross-section of the cable arrangement at each elevation is presented in Fig 2c.

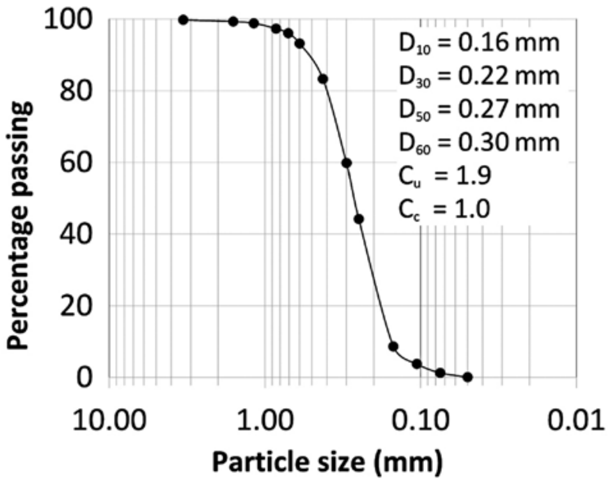

Fig 3: Particle size distribution of sand used in the channel

A single length of cable was then placed above the final layer of sand to measure conditions at the simulated seabed. The cable positions were identified as 1, 2 and 3 representing a reduction in elevation towards the seabed, with '-1' referring to vertical alignment with the heating tape and '-2' as 100 mm offset from it. Thus cable reference 1-1 represents the OFS at the base of the channel directly below the heat tape and '3-2' the OFS located above the heat tape offset by 100 mm separation. The OFS along the heat tape is referenced as '2-1'. The OFS along the seabed is referenced as '4'. The depths of all the OFSs were measured incrementally along their length. Variations in depth up to 20 mm off the intended cable elevation are due to localised variations during manual placement of the sand.

During activation of the heat tape, the surrounding soil temperature would increase and begin to affect the temperature of the water above. It was therefore necessary to recirculate the water using small submersible pumps located at each end of the channel. The water at the surface was also cooled by adding blocks of ice to closer simulate typical water temperatures around the UK at seabed depth. In Fig 4, (a) shows the setup of the

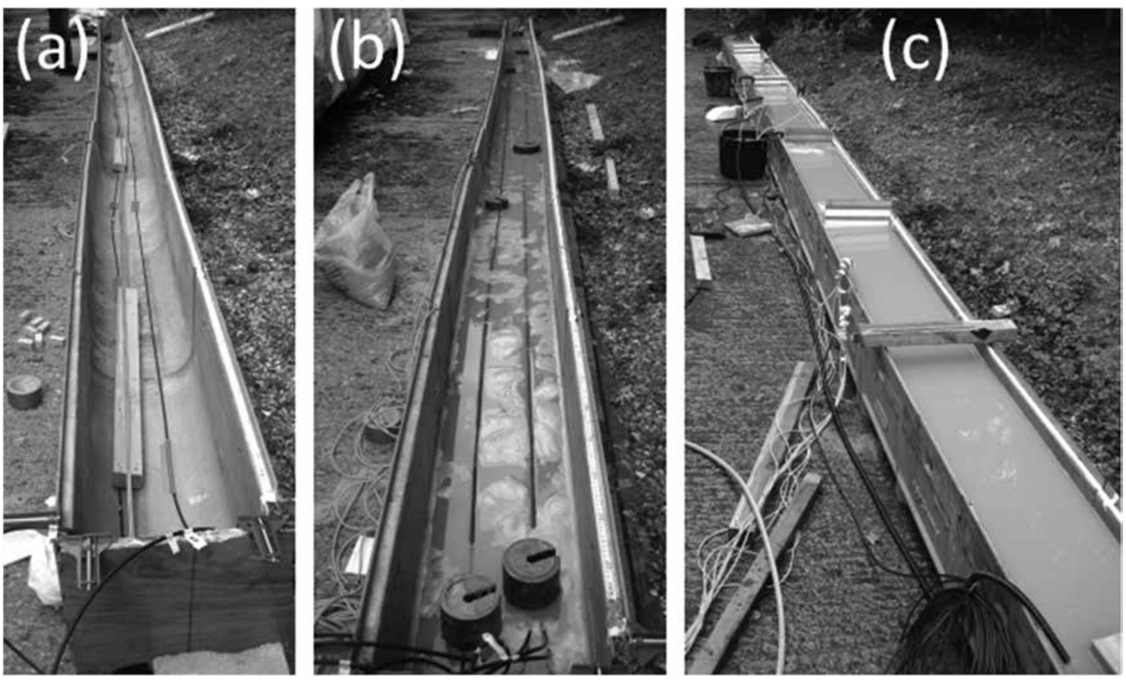

Fig 4: View from the start of the channel (0 m) towards the opposite end (at 10 m): (a) during initial setup; (b) during placement of sand around cables; and (c) final setup with retaining partitions where sediment removal later takes place

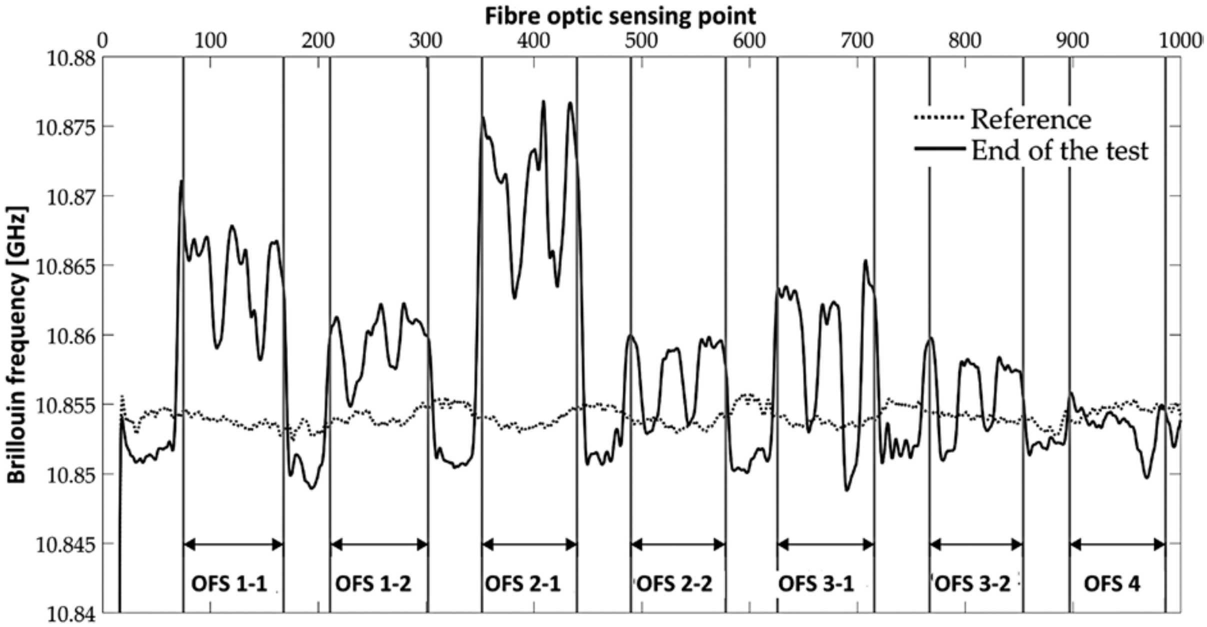

Fig 5: Measurement reported by DITEST STA-R at the beginning and the end of the test period

experiment prior to introduction of sand, (b) at a midpoint during laying the OFSs, and (c) the final setup with vertical partitions marking intended sediment removal.

3. The setup of fibre optic sensing system

Following the cable laying and subsequent burial, OFS was connected to a Brillouin-based fibre optic distributed temperature and strain analyser known as DITEST STA-R (manufactured by Omnisens™ Ltd, Switzerland). The measurements reported by the DITEST analyser can achieve a minimum spatial resolution of 0.5 m, with temperature accuracy of 0.2 °C, and the system setup requires access to both ends of the OFS cable. The analyser sends two counter-propagating waves that can be coupled through a non-parametric non-linear process, where the energy transfer from one wave (referred to as 'pump') feeds into the other (called a 'probe'). The sensing process is highly accurate and efficient in identifying the position-dependent frequency information, by pulsing one of the optical waves and observing the local coupling on the counter-propagated wave. It allows each measurement to be completed within 7 mins with the finest setting mode. The measurements collected by DITEST STA-R report data in terms of Brillouin frequency shift which has a linear relationship with temperature, such that 1 MHz = 1 °C increase. Each cable section shown in Fig 2b is highlighted in Fig 5, including 4 m OFS 'loops' that occur at each end of the channel. The largest and smallest shifts in frequency are associated with the cable 2-1 and cable 4, respectively.

4. Baseline checks to establish boundary conditions

The initial reference temperature conditions had to be established first, so that later removal of sediment above the cable at specific locations could be correctly interpreted based on the changes in temperature. To understand the temperature distribution generated by the heat tape when it is activated, the change in temperature (ΔT) can be obtained by taking the difference between two measurements collected by the BOTDA, as shown in Fig 5.

Fig 6 shows the temperature development throughout the testing period based on the initial temperature around 18 °C reported by PT-100 sensor. The temperature changes rapidly when the heating tape is switched on, where 50% of temperature is generated within the first 30 mins and the temperature then increases slowly towards eventual stabilisation. The heat tape was switched off at 320 mins and shows the rapid initial loss of temperature followed by a gradual temperature reduction leading to eventual ambient temperature condition.

Two heating phases were conducted over the course of two separate days and are shown in Fig 7

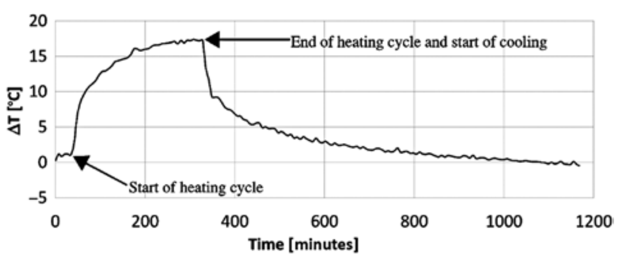

Fig 6: Change in temperature over a full heating cycle as recorded by BOTDA

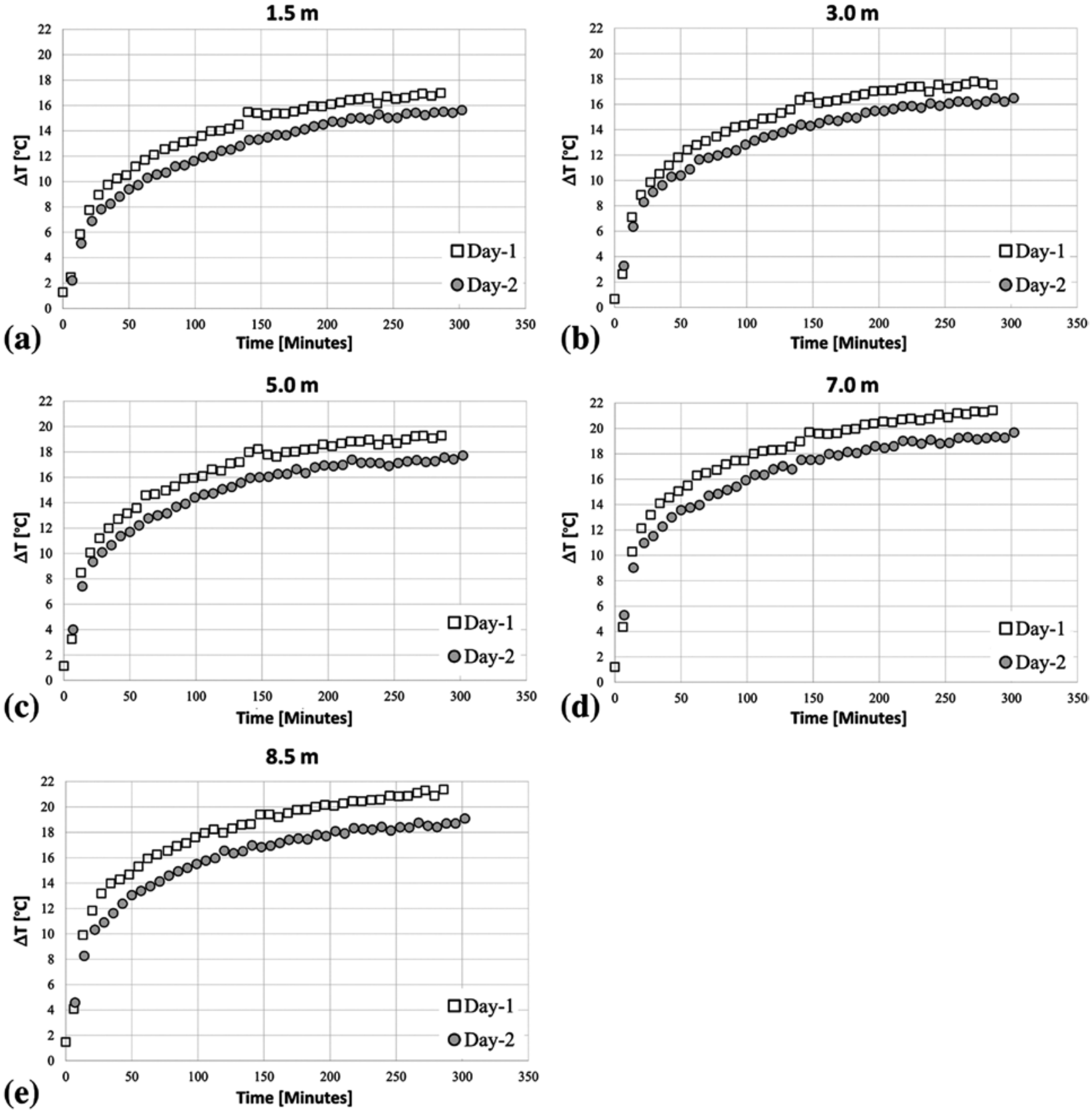

Fig 7: Temperature comparison between two heating phases on day 1 and day 2 at selected points along the channel adjacent to the heating tape

for specific locations along the channel. This comparison serves to demonstrate the reliability of the heating tape system to generate a consistent self-regulating heat source, which potentially highlights any major temperature changes in the experiment between the two days. The results in Fig 7 show that the change in temperature in day 2 was slightly less than day 1. This would be consistent with less temperature variability because of an improved soil packing around the cable (Woodside and Messmer, 1961). Some sediment consolidation would be expected over a 24 hr period. Similarly shaped plots indicate that the cable is generating the same temperature output over the same time step.

The OFS 4 section was laid on the simulated seabed at the interface between the sand and the water to measure water temperature. Water temperature recorded by OFS 4 varied because of partial embedment of the cable in some areas, which detected conduction heat flux from the sand as well as water temperature (Meininger and Selker, 2015). As a result, the readings from cable 4 were not used, and point reference readings were monitored instead using the PT-100 sensors. The water temperature through the heating phases was 17 °C with no appreciable increase caused by heat convection from the sand. This value is comparable with average summer values for the mid-North Sea water temperature (ignoring depth related variability).

Variations in temperature between days 1 and 2 were also compared to understand the correlation in temperature from heat source with its adjacent cables.

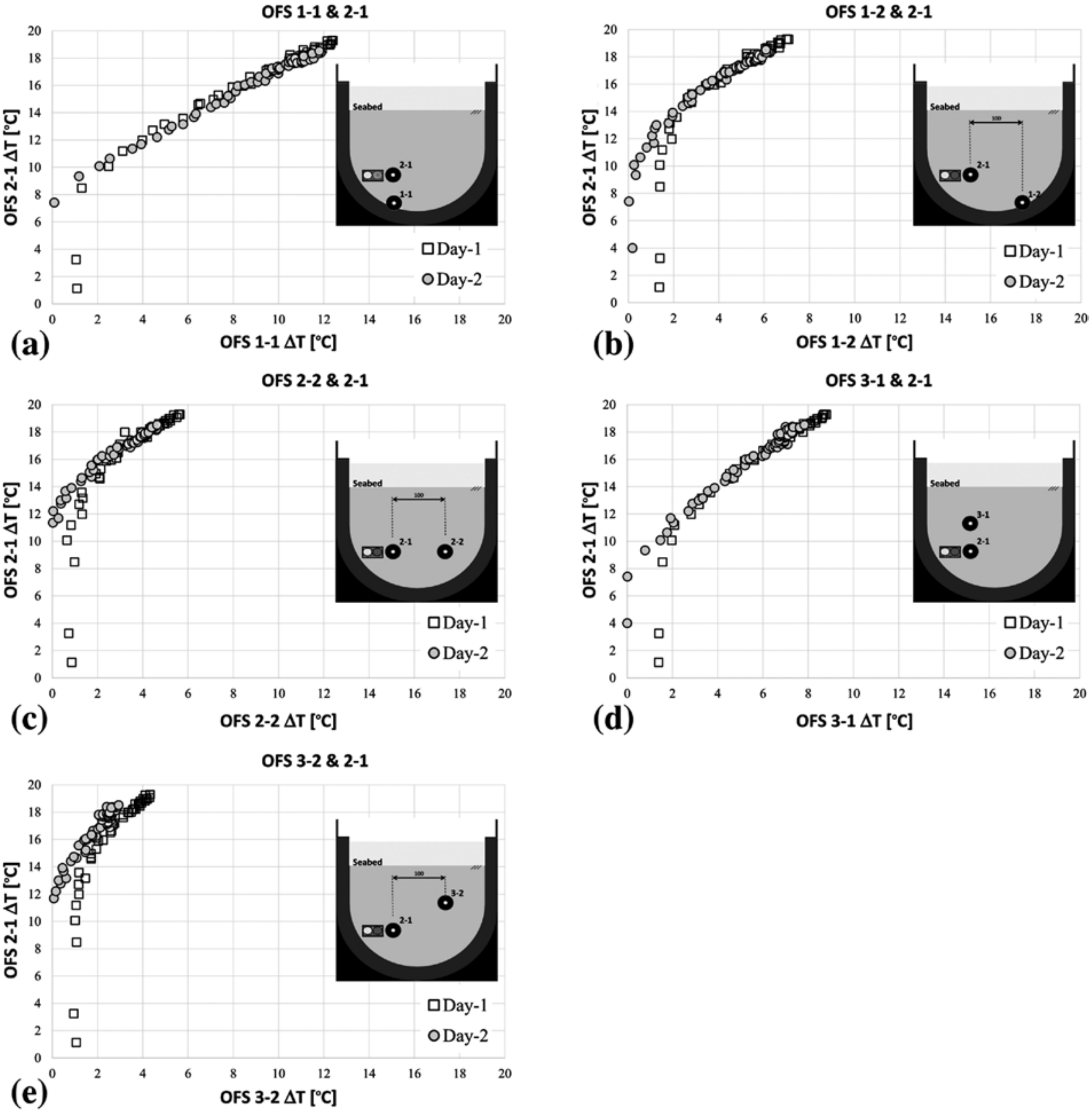

Fig 8: Temperature comparison between the heating tape at OFS 2-1 and adjacent OFSs 1-1(a), 1-2(b), 2-2(c), 3-1(d) and 3-2(e) at position 1.5 m in the channel

Fig 8 shows the temperature comparison between the cables at the heating tape (2-1) and an adjacent cable, both at a point 1.5 m along the channel. Although the data show some variations during early stages of heating, there is similar temperature distribution from the heat tape across the channel on both days. Soil consolidation as identified in Fig 8 at 1.5 m along the channel may be regarded as insignificant.

5. Simulation of sediment removal

The excavation of sediment was undertaken at two zones along the channel once an optimum temperature was established along the heat tape of ~24 °C. The water temperature was cooled using ice to an average temperature of 12 °C. One excavation zone was located between 3 m and 4.5 m (zone 1) and the other between 6.5 m and 8.5 m (zone 2). Each zone comprised three stages of reduction in overburden sediment thickness above the cables. Sediment was retained using vertical partitions and then removed by hand to avoid damaging the fibre optic cables. A cross-section along the channel in Fig 9 shows sediment depth at each stage together with the position of OFSs.

The excavation at the base was undulating owing to slumping of the sand beneath the vertical retaining partitions. No cables were exposed in excavation stages 1 and 2. In the final excavation (stage 3), cables were exposed (3-1 and 3-2) in both zones. The change recorded by 1-1 and 1-2 OFS

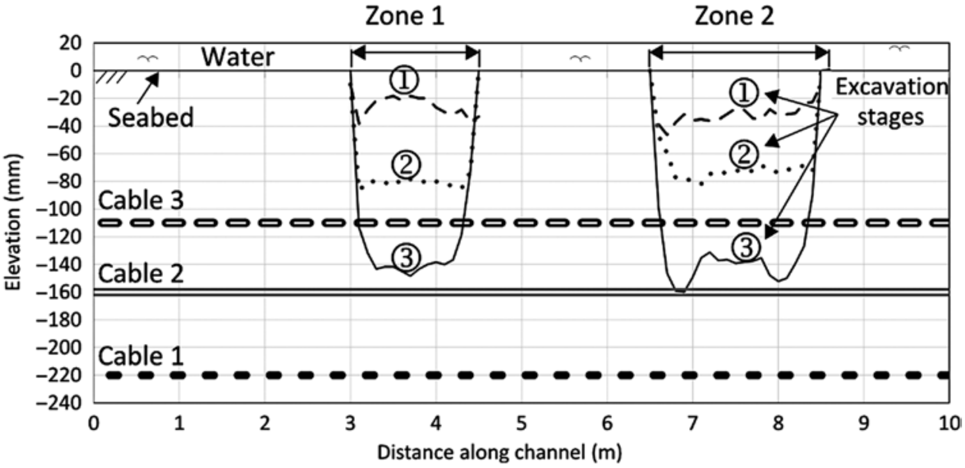

Fig 9: Position and excavation stage of sediment along channel

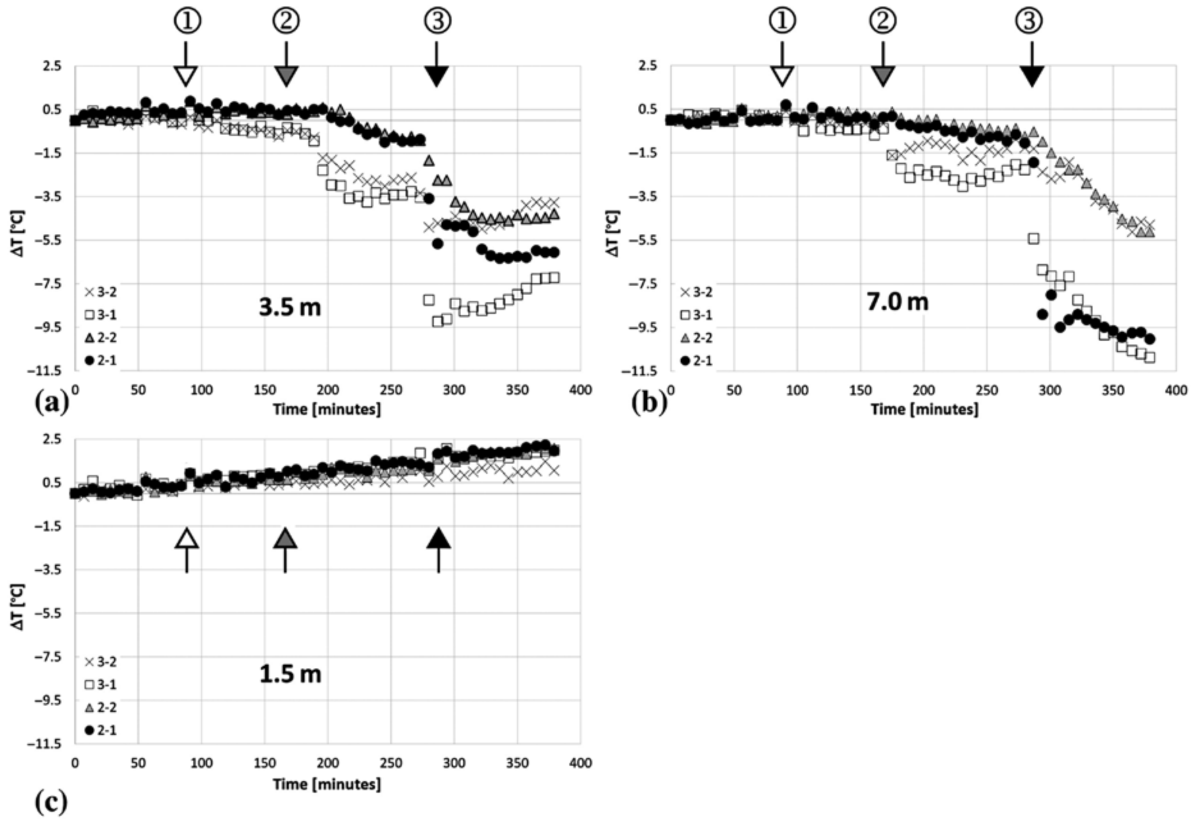

Fig 10: Change in temperature at specific points along the channel in response to sediment overburden excavation at (a) 3.5 m and (b) 7.0 m, with reference to (c) undisturbed sediment at 1.5 m. Arrows and numbers refer to commencement and stage of excavation, respectively

located beneath the heating tape are not discussed further in this paper as they form part of a wider investigation into changes in thermal gradient.

Fig 10 presents the change in soil temperature at three separate positions on the OFS within the channel 300 mins after the start of the test with three stages of sediment removal. The temperature changes are shown by cable positions 2-1, 2-2, 3-1 and 3-2. Figs 10a,b refer to the positions where sediment removal took place. Fig 10c shows the temperature change where no sediment was removed, though arrows show the time when sediment was removed at the two excavation zones. The changes shown after excavation of sediment are discussed in the following paragraphs.

Excavation stage 1: there is a small negative change at 3.5 m and 7 m associated with cable locations 3-1 and 3-2; otherwise a small increase in temperature was detected between 0.3 °C and 0.5 °C. In the undisturbed soil, there is an increase in temperature at 1.5 m between excavation stages 1 and 2 of 0.8 °C.

The removal of up to 40 mm of sediment allows an ingress of water, which cools the cables closest to the surface. The small reduction in temperature due to removal of overburden also effects the cables at 2-1 and 2-2, though the overall reduction is masked by the continual increase generated by the heat tape. This linear increase in temperature from the heat tape is shown at 1.5 m where no sediment disturbance takes place.

Excavation stage 2: change in temperature in zone 1 occurs after 21 mins and in zone 2 after 7 mins. The change affects all cable locations but especially at 3-1 and 3-2, where the temperature reduction is about 3.4 °C. At 1.5 m along the OFSs in the channel, there is an overall increase in temperature of 0.4 °C.

As the overburden further reduces (Fig 9), there is 20 mm cover above the cable 3-1 and cable 3-2. The delay in temperature response between zones 1 and 2 was detected and is due to the excavations not being performed simultaneously, as zone 1 was excavated first. Excavation of the sediment also took longer to perform in zone 2 because the zone is wider. The reduction in temperature in cables 2-1 and 2-2 is of the order of 1.4 °C before the start of excavation stage 3.

Excavation stage 3: there is an immediate change in temperature in zones 1 and 2 affecting all cables but especially cable 2-1, which reduces by 6 °C (at 3.5 m) and 10 °C (at 7 m). At 1.5 m, there is an overall increase in temperature of 0.4 °C.

The exposure of cables 3-1 and 3-2 to the surface water results in an immediate change in temperature. This drop in temperature is larger in cable 3-1 because it is closer to the heat tape and had a higher temperature before exposure. Cables 3-2 and 2-2 show similar temperature change magnitudes during excavation stage 3. However, the exposure of cable sections from cable 2-1 and 3-1 demonstrates the sensitivity of the fibre optic sensor by instantly detecting the change in soil/water environment. The change in temperature at 2-1 in zone 1 was 5 °C, whereas in zone 2 the change was 9 °C due to exposure to the surface water.

The temperature distribution because of sediment removal can also be shown as a function of channel length. Fig 11 shows the change in temperature

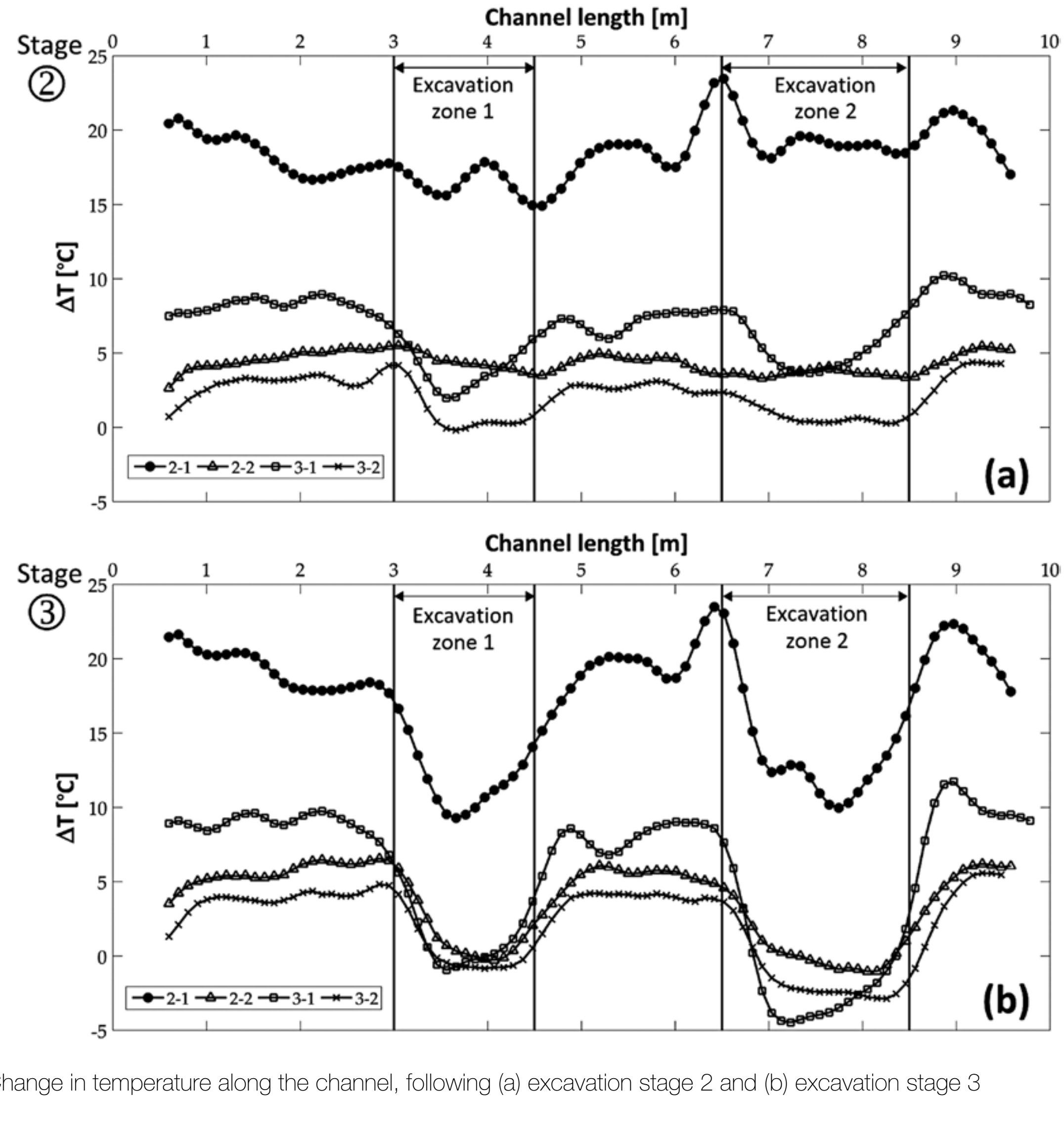

Fig 11: Change in temperature along the channel, following (a) excavation stage 2 and (b) excavation stage 3

along the channel at the end of excavation stages 2 and 3. The most significant changes in temperature are associated with the cable attached to the heat tape, whereas OFS 3-2 and 2-2 shows noticeable changes with smaller magnitude due to their physical positions being further away from the heat source. As expected, the change in temperature is more accentuated after the third excavation (shown in Fig 11b) than after the second excavation (shown in Fig 11a). In the undisturbed sections between the excavations zones, temperature fluctuations also occur. This is likely related to the disturbance of the water column and creation of some vortex during sediment excavation, which will cause some sediment erosion. In addition, behind the retained sections some slumping of the sand occurred. The disturbances illustrate the sensitivity of the DTS system for measuring temperature change.

The change in temperature along the fibre optic sensor is presented as a heat map in Figs 12 and 13. The contour map represents horizontal slices at four cable locations along OFSs 2-1, 2-2, 3-1 and 3-2, and shows the temperature development in the channel throughout the entire testing period. The temperature scale has been adjusted between plots because of the magnitude of temperature proximal to the heat tape. The time when each excavation commences is shown on the left side of each map as arrows. There are several elongate hot spots shown in the contour plots, notably in cable 2-1 at 6.5 m and around cable 3-1 at 8.7 m. This is likely to be associated with higher density soil around the cable or the relative installation position of fibre optic sensor to the heating tape. The OFS at position 2-1 was only directly attached to the heating tape at the cable tie positions leading to thermal discrepancies along the channel. The fibre optic sensing system has detected very subtle changes in temperature variation to the order of 0.3 °C. The positions of sediment removal are clearly shown as reductions in temperature or cold spots.

6. Discussion

With the heat generated from the heat tape increasing linearly during the experiment, the change in

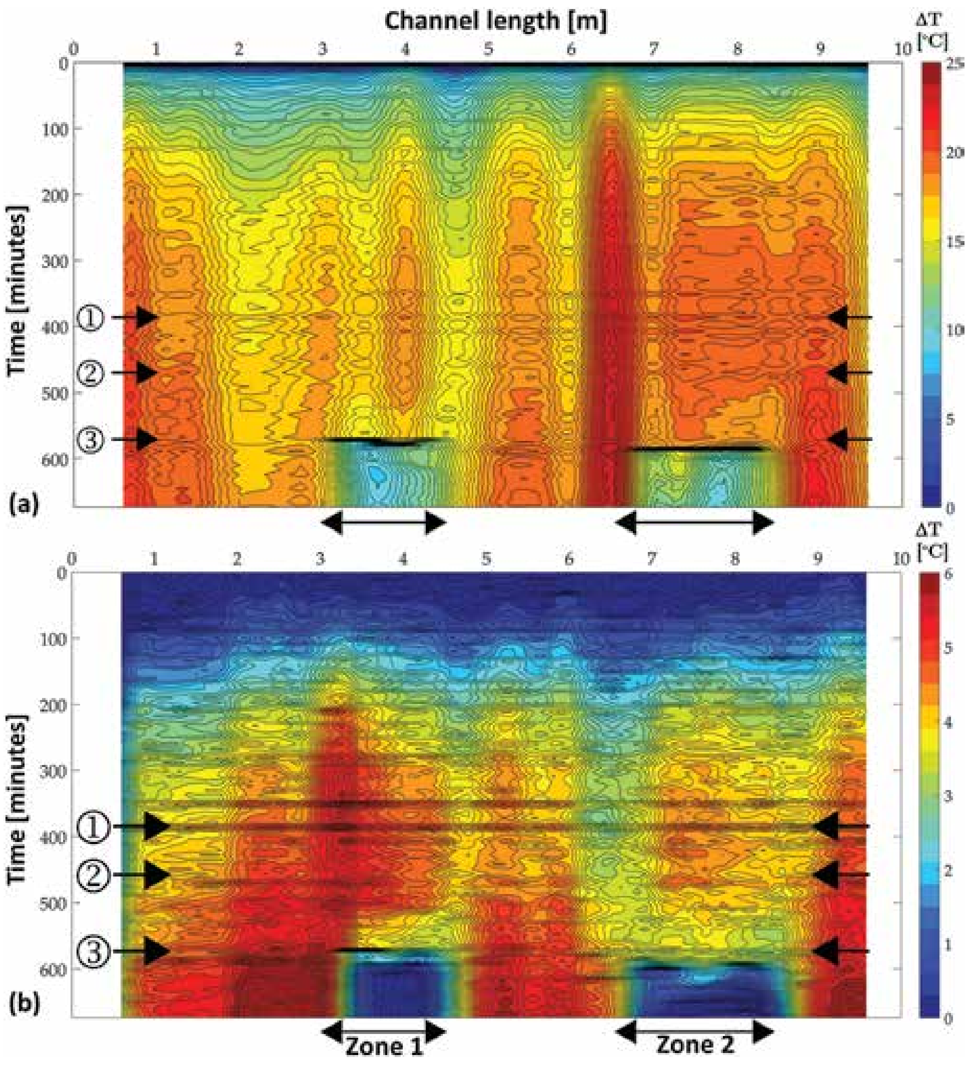

Fig 12: Temperature contour map showing horizontal slices at cable positions: (a) OFS 2-1; and (b) OFS 2-2

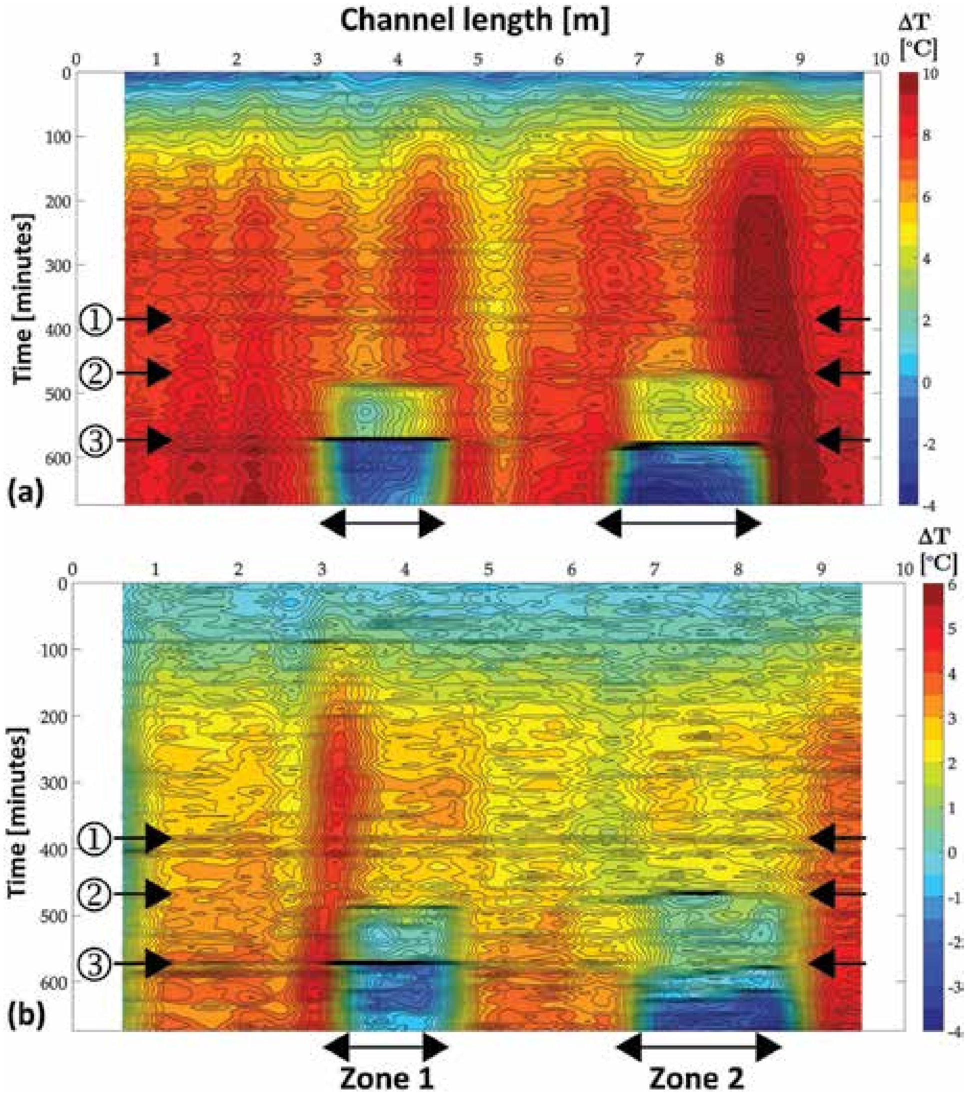

Fig 13: Temperature contour map showing horizontal slices at cable positions: (a) OFS 3-1; and (b) OFS 3-2

sediment thickness can be observed as both a stabilisation and/or reduction in temperature by OFSs. Despite a difference in temperature between heat tape and surface water, a minimum of 10 mm sediment removal could be detected from the temperature in the soil medium. The effective detection of sediment disturbance between excavation zones also demonstrates the sensitivity of DTS system to capture temperature change throughout the test.

The thermal capacity of the soil depends on the grainsize and density, as well as grain type of the material. Sand was used in this experiment for ease of setup and elimination of air during placement above the fibre optic and heat tape. The use of a fine sand/silt mix would change the thermal conductivity and may show a significantly higher temperature difference between cable and seabed. The sensitivity of the DTS to monitor changes in sediment thickness would therefore increase. Changes in the sand packing density and consolidation along the channel would also occur during burial of the power cable beneath the seabed. In granular sediments, changes in consolidation will be rapid. However, as shown in the rapid placement of sand around cables in this experiment, the variation and incremental increase in density around the cable over time can be determined by indirect measurement of thermal changes.

The use of self-regulating heat tape as a source of heat at roughly constant temperature was convenient in the context of the experiment aimed at showing the capability of the optical fibre to detect local changes of soil cover via changes of temperature. In a field application with a real power cable, it will be necessary to calibrate the OFS within the cable after burial and prior to use, as well as at intervals during minimum and maximum current load, in order to offset the corresponding changes in heat generated by electrical resistance. Such further research and development can now be justified.

As shown in this experiment, active DTS has the capacity to act as a monitoring system to measure changes in the sediment thickness. Brillouin backscattered distributed sensing has the potential to monitor cables up to at least 60 km from one commercially available analyser channel. Such techniques could reduce the reliance on, or enhance the interpretation of data from, routine seabed surveys to locate scour pits. This would be especially beneficial during months when treacherous sea-state conditions limit the deployment of geophysical arrays and when storm surges may amplify seabed erosion due to strong currents or even bed liquefaction. Active fibre optic monitoring could also aid in monitoring scour mitigation during rock dumping activities to ensure successful remediation.

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