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New solutions for remote monitoring of pre-cast concrete service reservoir and sludge lagoon

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The use of distributed temperature and/or strain measurements for embankment and reservoir monitoring has grown in recent years. The paper elaborates on two different methods applied through two installation examples in the UK. To reduce risk, a leakage monitoring system using distributed fibre optic temperature sensing (DTS) with a spatial resolution of 0.7 m has been installed at the newly constructed 45ML Hanchurch Service Reservoir. The gradient method provides information regarding possible seepage by monitoring absolute temperatures over time. Heat pulse method consists of measuring the temperature changes over time using DTS following heating the hybrid cable with a known electrical power input. Central to the £7 million investment on the century-old Curdworth sludge lagoon is the installation of a novel combined leakage and movement of the early detection system. The system is based on distributed fibre optic sensing methods for measuring strain and temperature, both fully automated with a time resolution of about an hour. Instrumentation can be analysed in real time. Trigger levels are being established during a trial period, linked to an automatic alarm system, which supplements site-based surveillance. This will facilitate the early detection of potential embankment/reservoir integrity issues and, in turn, will enable prompt action to be taken to reduce risk and in an extreme case the implementation of essential repairs in order to prevent a dam failure.

Notation

C_T	temperature coefficient
C_ε	strain coefficient
dT	temperature increase during heat-pulse measurement
T	current temperature condition
T_0	reference temperature condition
ε	current strain condition
ε_0	reference strain condition
v_{B0}	Brillouin frequency peak in the reference temperature and strain condition
v_{Bs}	Brillouin frequency peak in the current temperature and strain condition

1. Introduction

The early detection of any seepage, movement or deformation of embankment(s) is critical to ensure the long-term safety and integrity of reservoirs. Most catastrophic failures can be avoided if continuous monitoring is installed, allowing time for risk-reduction activities and early implementation of essential repairs.

In recent years, the distributed temperature sensing (DTS) and distributed temperature and strain sensing (DTSS) methods have been developed and are increasingly used to assess strain and temperature changes for multiple industrial needs, including embankment monitoring (e.g. Aufleger *et al.*, 2011; Dornstädter and Dutton, 2016; Fabritius *et al.*, 2017).

Two application examples are presented in this paper.

Fibre optic monitoring systems can be installed during the construction of new facilities, such as Hanchurch Service Reservoir, or during the rehabilitation of existing infrastructure, such as Curdworth sludge lagoon.

Hanchurch Service Reservoir retains food-grade water for human consumption and is constructed of pre-cast concrete walls. It therefore incorporates significantly more wall joints than an in situ form of construction, which arguably introduces a higher risk of bacteriological failure in the long term, particularly when backfill is placed against external reservoir walls. The leakage detection is based on two methods: the gradient method and the heat-pulse method (HPM).

An innovative, combined leakage and movement detection system has been installed on the century-old Curdworth sludge lagoon, which forms part of Minworth Sewage Treatment Works in north Birmingham, United Kingdom. The leakage detection system is based on the complementary use of the DTS and the HPM, which provides information on the water

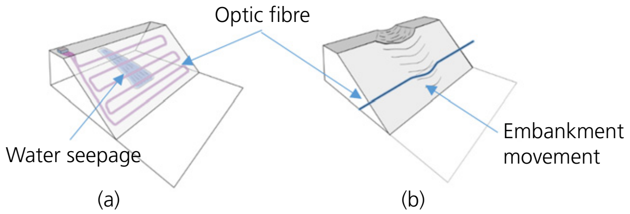

Figure 1. Basic principle of fibre optic sensing for leakage ((a) temperature) and movement ((b) strain) monitoring in embankments

content and water flows in the near field of the cable (e.g. Aufleger *et al.*, 2008; Dornstädter *et al.*, 2014). The accurate monitoring of soil movement, which could be an emerging slip, is ensured by the DTSS method.

2. Fibre optic sensing

For this monitoring set-up, two backscattering processes, namely the Raman scattering (DTS) and Brillouin scattering (DTSS, operating with the Brillouin optical frequency analysis, or BOFDA, technology), were used to probe the physical environment along the optical fibre (Figure 1).

Fibre optic sensing works by sending a short laser pulse down an optical fibre. A small part of the light that propagates through the fibre is backscattered at every single point of it. This process depends on the physical state of the cables, which itself depends on the environment in the neighbourhood of the fibre. Once firmly installed in the ground, the temperature of the ground, as well as the different movements of the embankment (settling, sliding) are automatically transferred to the cables, which act as intrinsic sensors. The location where these changes occur is detected with a high degree of accuracy, so that leakage and ground movement can be monitored and the position determined (0.5 m resolution for the DTSS and 0.7 m for the DTS).

The temperature is determined with the help of Raman spectroscopy on the backscattered light. The intensity of the anti-stokes signal depends on the local temperature of the fibre, while the intensity of the stokes signal remains unchanged, so that the fibre temperature can be calculated from the stokes to anti-stokes intensity ratio. The exact location of the measurement point is assessed by considering the propagation velocity of the light in the optical fibre and measuring precisely the elapsed time between the emission of the light pulse and the reception of the signal. Temperature data are measured every 2 min along one single MM optical fibre loop – this temporal resolution is fully exploited for the operation of heat-pulse tests. Once averaged, they also allow for the automatic compensation of DTSS data, sensitive to both temperature and strain changes, and isolate the desired information about strain changes.

The Brillouin scattering phenomenon results in a light frequency shift that depends on the local mechanical (strain) and thermal state of the optical cable, with the following relation:

1. $$\nu_{Bs} = \nu_{B0} + C_{\mathrm{T}}(T - T_0) + C_{\varepsilon}(\varepsilon - \varepsilon_0)$$

where C_{T} and C_{ε} are, respectively, the temperature and strain coefficient, ν_{B0} is the Brillouin frequency peak in the reference temperature and strain condition (T_0, ε_0) and ν_{Bs} is the Brillouin frequency peak in the current temperature and strain condition (T, ε). For the DTSS-BOFDA, operating in the frequency domain, a Fourier transform of the return signal must first be calculated to assess the exact location where the changes are taking place.

2.1 Leakage and seepage detection method

There are different approaches to detect seepage using fibre optic temperature sensing. The first approach, called the gradient method, is based on absolute temperature changes within the body of the dam caused by seepage water (Kappelmeyer, 1957). This method is limited to cases with a temperature gradient between the seepage water and the dam material. This method has been proven to be an invaluable seepage indicator. A fibre optic seepage monitoring was installed at the Knezevo dam in Macedonia (Aufleger *et al.*, 2011), Merowe dam in Sudan (Aufleger *et al.*, 2008) and Isarkanal Speichersee in Germany (Aufleger *et al.*, 2008). Examples in the United Kingdom can be seen at the Riding Wood and Digley reservoir dams where a fibre optic seepage monitoring was installed (Dornstädter and Dutton, 2016). This passive method can only be applied when there is a temperature difference between the seepage water and the dam material. To overcome this limitation, a second active approach is used. The HPM, or temperature difference method, involves measuring the temperature changes using the DTS while heating the hybrid cable by sending a known electrical current through the integrated electrical conductor (copper strand). For the gradient method, it is essential that the water temperature T_{W} is clearly different from the ground temperature T_{G} along the optical fibre FO. For HPM, it is not a requirement (Figure 2). The temperature increase in the immediate vicinity of the cable is highly dependent on the heat capacity and heat conductivity of the surrounding material. Taking the heating time and power into account, the normalised temperature difference and the effective thermal conductivity (TC) can be calculated. By analysing the change of the thermal properties over time, information regarding the water content (saturation) and possible water flows is derived.

2.2 Movement monitoring method

The monitoring of the relative strain changes along the fibre (DTSS) allows the detection and localisation of strain events of the magnitude of about 100 μstrain (100 mm/km) to identify dam movements such as settling and sliding. The total strain value obtained with the DTSS method contains a superimposition of information such as a certain inhomogeneity of the optical fibre, the handling conditions of the cable and the backfilling and settlement of trenches resulting from the cable installation. In order to detect current ground motion, strain changes are analysed. Sudden strain variations, even of low amplitude, can indicate rapid ground movement and would be detected. Long-term accumulation of strain changes is also evaluated.

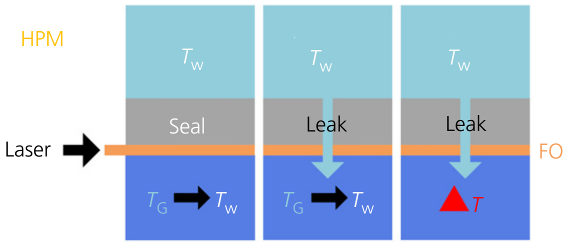

Figure 2. Detection of a leak with an optical fibre (FO) installed behind a thin sealing layer. To the left, a no-leak situation, where the water temperature T_W equals the ground temperature T_G along the optical fibre FO. In the centre, a leaking situation, with T_W equals T_G. To the right, necessity to create an increase of temperature ΔT by using the heat-pulse method

3. Hanchurch service reservoir

The seepage monitoring system installed at Hanchurch reservoir is based on fibre optic temperature measurement. All three approaches mentioned above have been implemented in the seepage detection method. However, as there is no temperature gradient, the HPM has proved more applicable. The sensor is a hybrid fibre optic cable which enables the HPM to be applied to estimate the local distribution of seepage flow and rate. In addition, to enhance the evaluation, the apparent TC is calculated in the final visualisation software using the results of the HPM method.

3.1 Site installation and set-up

The monitoring cables are installed along all the exterior walls of the reservoir. The cables cover all the joints in the walls of the precast concrete wall sections. The vastly increased number of joints inevitably introduces a higher risk of failure in the long term compared to an in situ construction.

The deployment of the cables along the precast concrete panels is shown in Figures 3(a) and 3(b). The arrangement comprises two cables, the perimeter cable at the bottom (dashed line) and the sensor cable which follows the joints of the precast panels (solid line). The fibre optic cables are directly mounted onto the

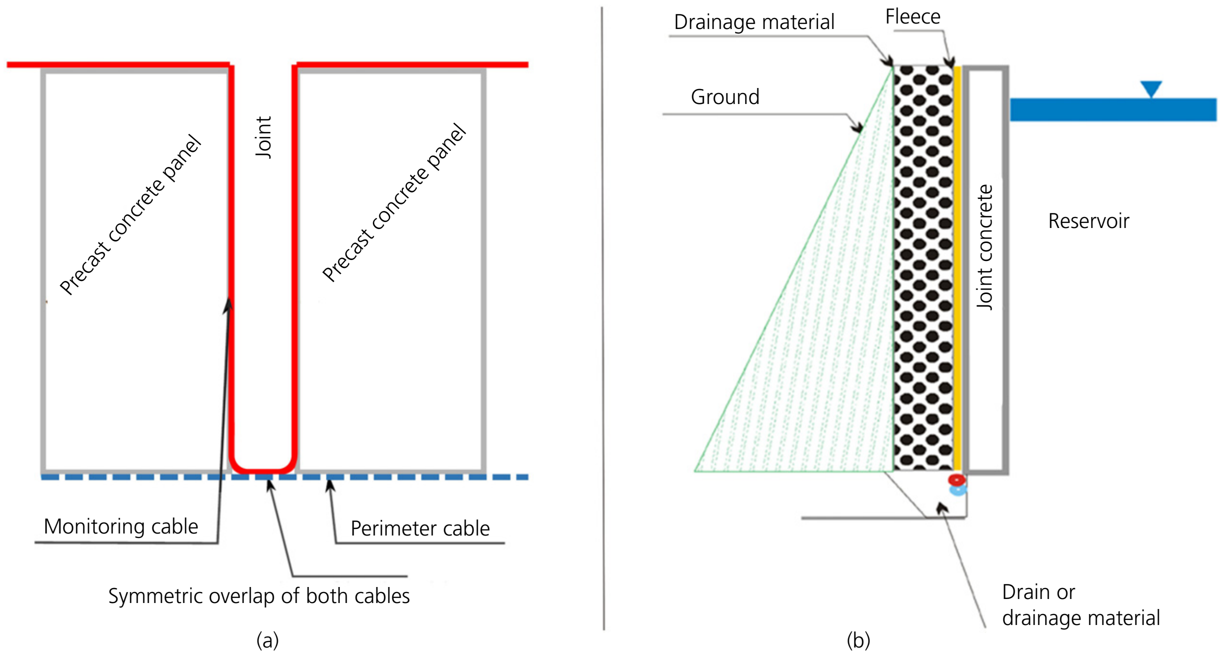

Figure 3. Location of cable placement at the external walls with the monitoring cable: (a) elevation view; (b) cross-section

precast concrete wall. They are placed between the wall and the outer drainage membrane (a fleece-like material was used here), as in Figure 3(b). This layout achieves a high degree of sensitivity in the event of possible leakage. The perimeter and monitoring cable overlap in the bottom of each precast concrete panel for calibrating the exact position of any leakage. This arrangement ensures that the exact position of each precast concrete panel can be identified by performing a heat-pulse measurement of the perimeter cable.

The heat-pulse measurement of the perimeter cable, used for calibrating the system, is shown in Figure 4. The application of the perimeter cable for calibration avoids the need to calibrate each precast concrete panel manually by setting heating marks. The introduction of the perimeter cable for calibrating the monitoring cable considerably decreased the installation time for the monitoring system and provided the ability to perform the calibration even after the backfilling of wall sections (without having direct access to the concrete panels and cables). This simplified the integration of the installation works of the monitoring system while construction works continued on site.

A total of 2500 m of fibre optic cable can be continually measured with a time resolution of 2 min and a spatial resolution of 0.7 m. The entire cable length of 2500 m was divided into three electrical heating circuits (three heat-pulse sections) following a technical feasibility and cost efficiency assessment. A measurement takes about 90 min per heat-pulse section.

3.2 Simulation test

The successful performance of the leakage monitoring system was demonstrated by a leakage simulation test. The soil covering the first half metre of the top of the monitoring cable was removed. Afterwards water was poured continually for about 90 min on the top corner of the monitoring cable to simulate leakage at this position, then the heat-pulse measurement was performed for 60 min. The flow rate was estimated on site to be about 0.3–0.4 l/s.

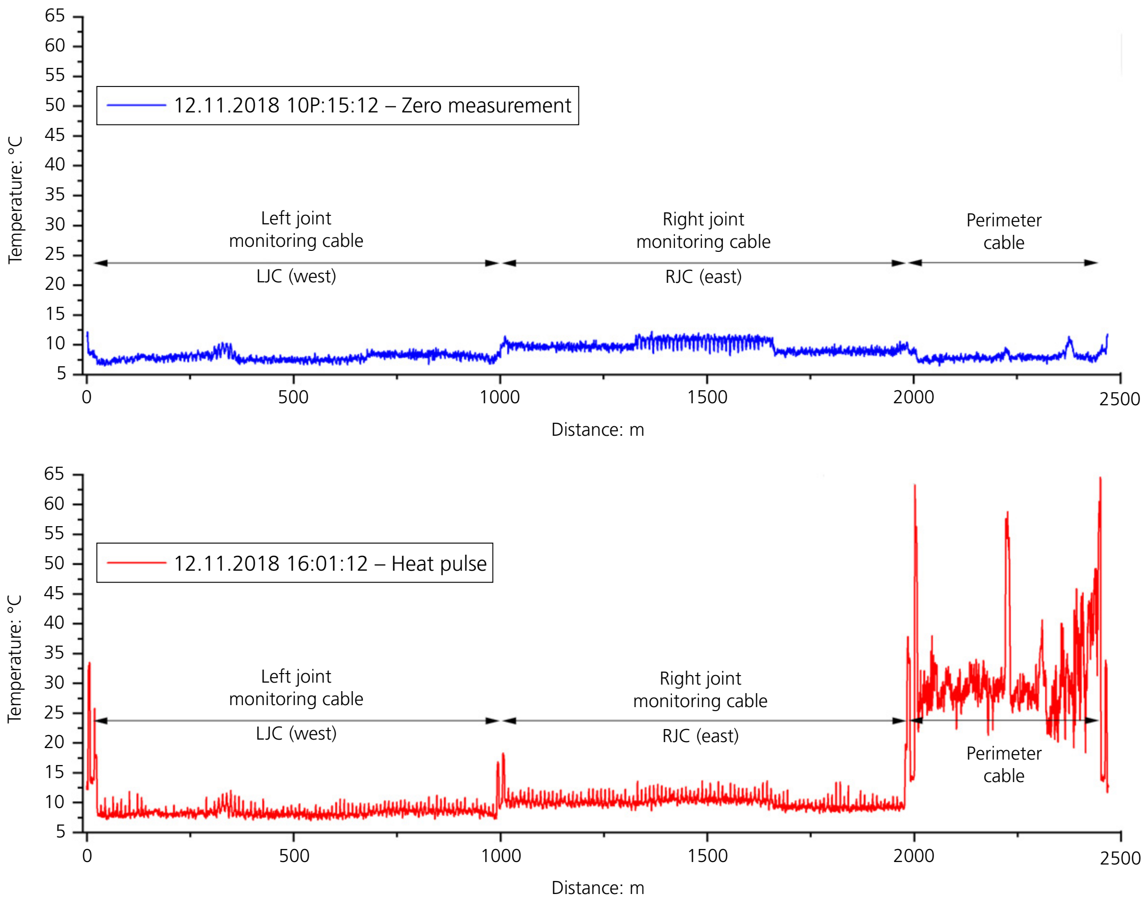

Figure 4. Temperature spikes (0–2000 m) caused by the heat-pulse measurement of the perimeter cable were used for the calibration of the position of the monitoring cable

The results of the heat-pulse measurement were compared with the reference measurement performed the day before (Figure 5). A significantly lower temperature difference can be observed during the simulation test for the affected concrete panel. About 10 m of cable was affected by the leakage simulation test, which approximately corresponds to the length of cable deployed along the joints of the precast wall panels. As the water distributes through the drainage fleece directly next to the monitoring cable, it is reasonable to assume that an entire precast concrete panel was affected by the simulated leakage. This test demonstrated the functionality and high sensitivity of the system, proving both the location of the leak and leakage flow rate.

3.3 Visualisation and alarm triggers

The leakage detection system has been combined with visualisation software which provides the capability to perform fully automated measurements and evaluation of the data. Current measurements together with historical heat-pulse measurements are displayed on the web-based visualisation. This provides a fast and clear overview of the performance of the structure. In the event of seepage, an automated alarm is generated based on the automatic evaluation of the data and the corresponding trigger levels defined. The alarm is displayed on the visualisation software highlighting the defective joint between the concrete walls using different colour codes (green, yellow, red). On-demand alarm system tests can be automatically triggered by way of email or SMS (short message service). The heat-pulse-based alarm system is evaluated every time a heat-pulse measurement is performed – that is, once per week, as part of the regular monitoring of the site. Additional tests can be carried out on demand, for example after an intense period of rainfall, or after other sensors show an abnormal behaviour.

4. Curdworth sludge lagoon

4.1 Site description and instrumentation

The Curdworth sewage sludge lagoon dates back to the beginning of the last century. It is located next to the River Tame and

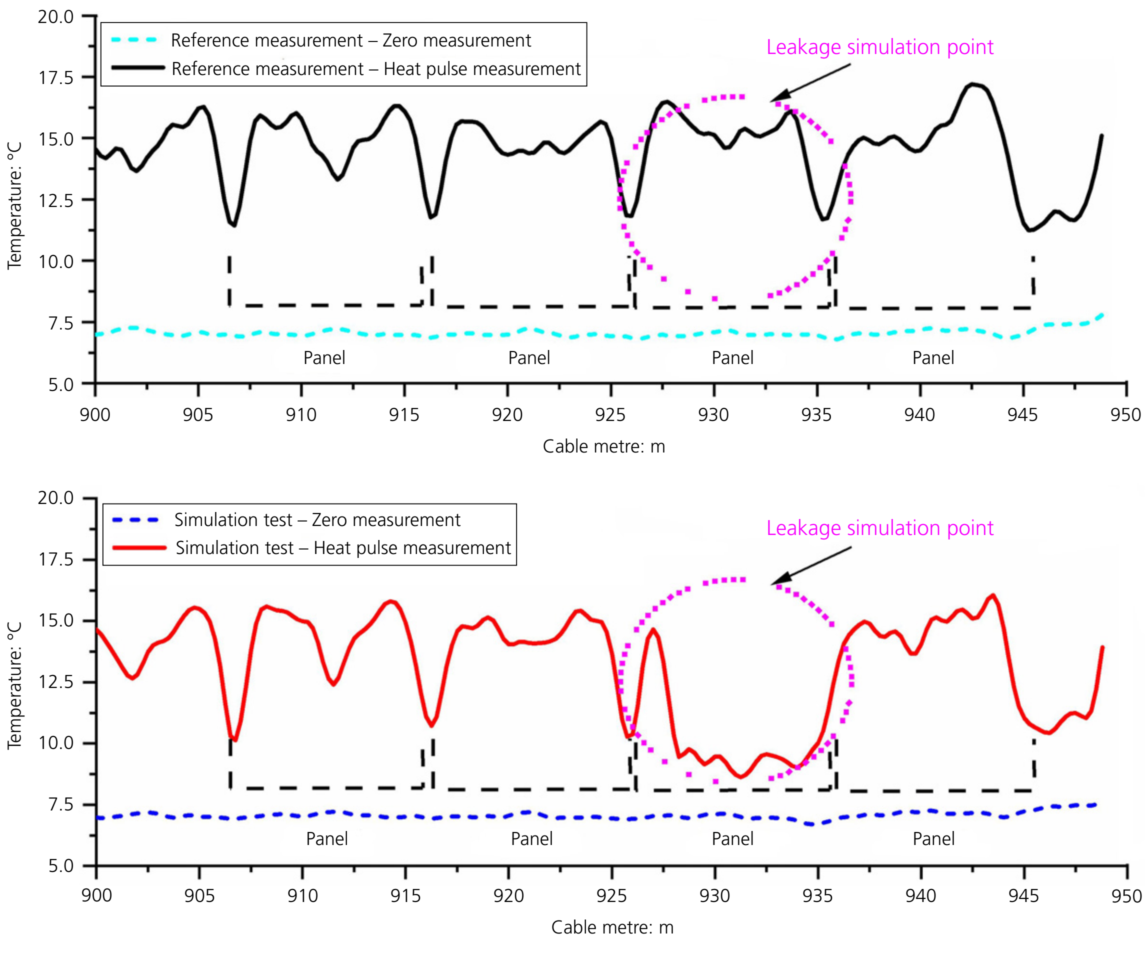

Figure 5. Comparison of the heat pulse of the reference measurement and the simulation test. A significant lower temperature change can be observed for the cable metres 926–936 m

has a height of 8–10 m and capacity of 1 100 000 m^3. While no longer in use, it forms part of the Minworth sewage treatment works, which serves an equivalent population of 2.5 million customers. Extensive risk-reduction works have been implemented (Murfin-Snook and Bowmer, 2019; Severn Trent, 2018).

On the Eastern lagoon, adjoining the final effluent channel, analysis established that the embankment risks needed to be proportionately lower than the southern embankment. A combined leakage and movement early detection system, based on distributed fibre optic sensing methods for measuring strain (DTSS) and temperature (DTS) was therefore installed. This monitors potential seepage water flows and deformations/movements of the ground. A hybrid cable (including multimode (MM) and single mode (SM) optical fibres as well as six copper strands) and a strain cable have been installed in 500 mm deep trenches. In total four different sections with a total length of about 5000 m, comprising strain and hybrid cables, have been installed. Cable loop 1 (green) and cable loop 2 (blue) monitor designated parts of the dam of the Eastern Lagoon (Figure 6). A transmission cable connects loop 1 and loop 2 to an instrumentation kiosk and for monitoring parts of the western lagoon. Cable loop 3 (orange) and cable loop 4 (pink) monitor parts of the dam of the western lagoon. A transmission cable is used for connecting loop 3 and loop 4 to the kiosk and for monitoring parts of the western lagoon.

4.2 Reference measurement and first results

The acquisition of temperature data started on 17 September 2019 and the first set of heat-pulse measurements was performed on 17 and 18 September. The duration of each heat-pulse measurement was 1 h and the heating power per metre between 11 and 16 W/m. The temperature increase (dT) observed between the end of the heating phases and the initial state was about 4–10 K, which is sufficient for a proper operation of the system. Heat-pulse data, measured on a weekly basis since November 2019, did not show any evolution of the thermal properties of the soil. The results are repeatable, and correlate with the environment in which the fibre is implanted (earth vs. road, embankment ridge, slope or foot), confirming that the environment around the fibre can be characterised by this method. The data appear more stable where the saturation is low, as the dT obtained is larger.

Strain data acquisition started on 20 September, once a reference measurement had been performed. They have since been measured on an hourly basis. As an example, the measurements for a section of loop 1 (Figure 7) are shown. For the monitoring, as the absolute strain values (baseline) strongly vary along the cable, all strain changes are compared to the reference measurement. The absolute strain value itself is not visualised, but is still saved as it provides some information regarding the physical integrity of the installation (the maximum recommended strain for the cable being 10 000 µstrain, or 1% elongation).

Figure 8 illustrates the strain changes observed since the reference measurement for several locations along loop 2. Most areas (e.g. 374.75 m) are characterised by very small strain variations with time (±20 µstrain). In active zones, a distinction is made between short-term and longer-term variations.

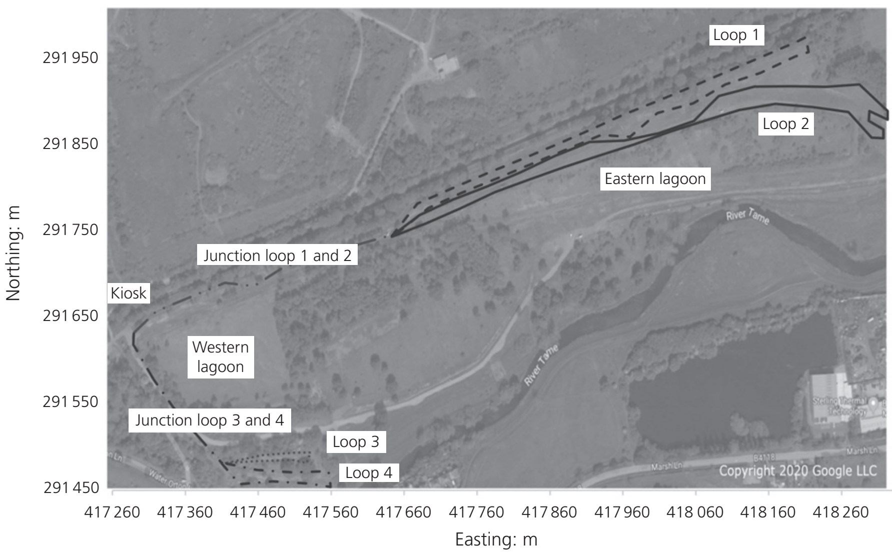

Figure 6. Curdworth sludge lagoon: site description and fibre optic cable layout

Small-term strain variations appear correlated (472.75 m) or anti-correlated (330, 485, 797.5 m) with rainfall occurrences. These variations are spread over large areas of the site, in places several hundred metres apart. The measured strain increases or decreases from week to week, but there is not always a long-term accumulation of strain variation. Locations 472.75 (slope) and 485 m (foot of slope) are characterised by perfectly mirrored variations, as if a movement parallel to the optical fibre leads to successive compression and extension along the cable (Figure 8). This behaviour is observed at several locations on the site, in the same terrain configuration.

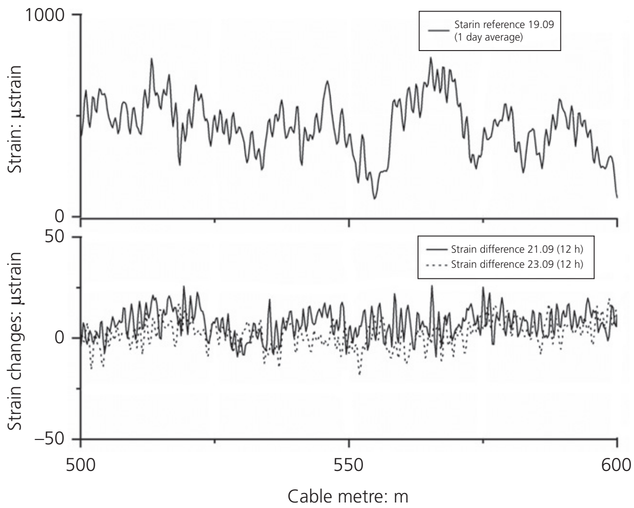

Figure 7. Strain absolute values and strain changes for one 100 m long section of loop 1 on 19 September 2019

Long-term variations, in some places positive (e.g. cable loop extremity at 797.5 m), in other places negative (e.g. ponding area at 330 m), are sometimes added to the short-term fluctuations. This long-term variation was most significant during September to November 2019. This was probably due to heavy rainfall after a dry Spring and Summer in 2019. Since December 2019, the strain variations do not seem to accumulate anymore despite the prolonged rainy weather of February 2020. As appraisal continues, this is thought most likely due to the reducing ground settlement effects following the cable installation.

4.3 Visualisation and alarm triggers

The alarm systems with trigger thresholds are under evaluation as required by Severn Trent; the first one was based on strain measurements, the second on heat-pulse measurement results and the last one on absolute temperatures. The strain-based alarm system is evaluated every 3 h. Both short-term strain variations (changes over 24 h) and long-term variations (change over one week) are controlled. The length of fibre over which the changes are observed must

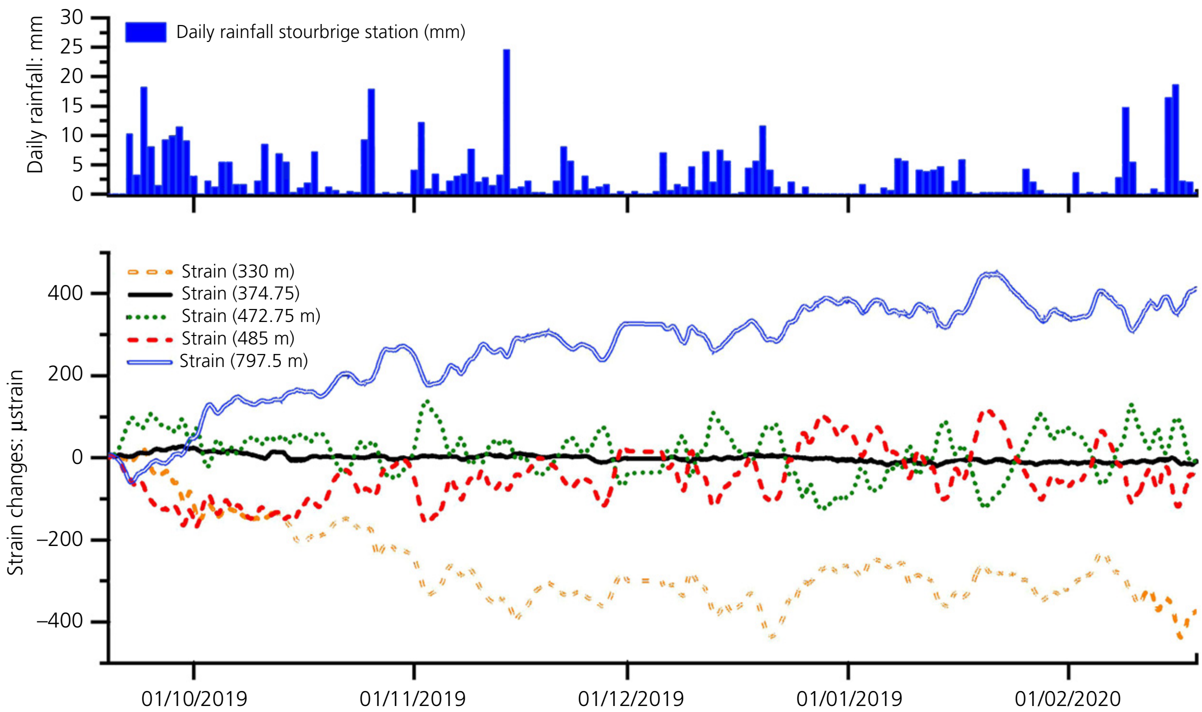

Figure 8. Strain variation at five selected locations along loop 2, and comparison with rainfall data. Location given in Figure 9

also be taken into account, as it influences the total potential movement observed in the embankment. The triggering of a heat-pulse-based alarm differs slightly from the previous example. It is subject to the evaluation of two different parameters in order to avoid false-positive results: the temperature increase reached at the end of the heat-pulse test and the TC of the soil calculated from the soil temperature decay curve after the heat-pulse test. Absolute values or relative changes can be used as thresholds. An alarm based on absolute temperature is used for fire detection, as the embankments are known to spontaneously combust approximately every decade.

5. Outlook and conclusion

Both monitoring systems have already demonstrated a high degree of sensitivity, both when carrying out a leakage test, or by observing minor events (meteorological) during the observation period necessary to establish the thresholds for triggering the alarms. These will take the form of alerts by way of emails and SMS. Alarm status can be checked online at any time. As an example, the illustration of an HPM-based alarm on the site of Curdworth sludge lagoon is shown in Figure 9.

The Hanchurch service reservoir, composed of pre-cast concrete wall panels, presents an increased risk of joint failure that could compromise the integrity of the reservoir. Backfilling to service reservoirs should be avoided wherever practical (Hope, 2016). Where the need for backfill arises the inclusion of a suitable leakage detection system is a significant intervention towards risk reduction. The fibre optic leakage detection system installed at Hanchurch satisfies these requirements, operates as a standalone system and can be remotely accessed.

While no major movement or saturation changes have been recorded on the Curdworth sludge lagoon since the installation

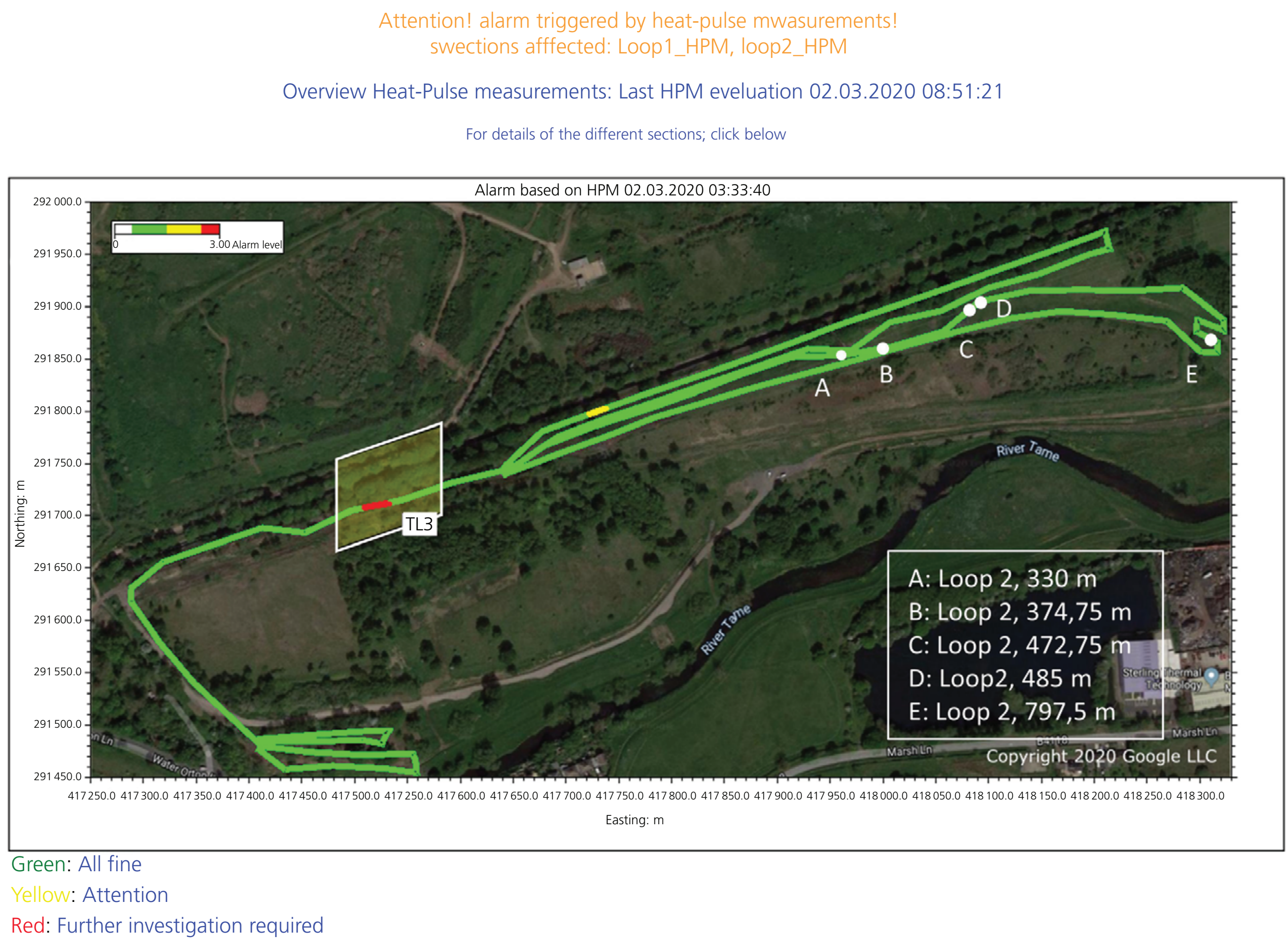

Figure 9. Rapid identification and location of an alarm trigger on site as available to the customer (alarms are not real, for illustration purpose only)

of the alarm system, the first strain results have detected small changes after heavy rainfall events. The system is already proving to be sensitive to environmental changes and will certainly detect possible larger-scale events. The team are keenly awaiting the monitoring of events of greater magnitude to enable these to be interpreted, together with the monitoring of the accumulation of small changes over a very long term (3 months, 6 months, one year). These results will be compared with other data available on the site (inclinometers, topography). The fibre optic monitoring system installed will inform the Emergency Action Plan, established to link both on and off-site emergency responses, ensuring the long-term safety and integrity of the sludge lagoon, which is a registered reservoir under the Reservoirs Act 1975.

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