Detection of defects in the experimental dam at Älvkarleby using temperature measurements

S. Johansson, P. Sjödahl & S. Berglund
HydroResearch SJ AB, Täby, Sweden

ABSTRACT: Temperature measurements and their ability to detect defects in embankment dams have been studied on an experimental embankment dam. The dam was built as a research dam at the Vattenfall AB laboratory facilities in Älvkarleby, Sweden. It was constructed with six built-in defects. Several monitoring methods were applied on the dam during first filling and the first one-year period of operation. One of the applied methods was temperature measurements in optical fibres installed along the whole length of the dam at several locations and levels. The design and location of the defects were unknown to the researchers applying the measurements. Several methods were applied for evaluation of the temperature data. For instance, sudden temperature changes in time and space were searched for and examined, and the seasonal variation was studied. Numerical modeling was performed to increase understanding of potential defects and to support interpretation. The evaluation identified zones with anomalous temperature that were interpreted as defects. In some cases, the locations corresponded to the real defects, whereas several anomalies could not be associated with known defects. Some of the defects did not result in increased seepage, which made detection with temperature measurements challenging. The study offers a unique opportunity to evaluate the use of temperature measurements and their ability to detect the unknown built-in defects and develop the understanding of seepage processes in embankment dams.

1 INTRODUCTION

Vattenfall has built an experimental embankment dam at their laboratory facilities in Älvkarleby. The dam has six built-in defects, each representing damages that eventually could evolve to a dam break (Lagerlund et al., 2022). These defects are sized to be realistic, while still large enough to be realistically detected in blind-tests by suitable geophysical methods. One of the applied methods is temperature monitoring using cables with optical fibres, which were installed in the dam.

The use of optical fibres for dam monitoring started in 1998 and is widely used in embankment and tailings dams, especially in Sweden. The most common application is seepage flow monitoring based on temperature measurement, but also strain measurements and acoustic measurements are used (Johansson et al., 2023).

The design of the experimental dam was based on experiences of a previous blind test in Norway in 2003 where the potential of resistivity, self-potential and temperature surveying was undertaken on a rockfill embankment dam (Johansson and Nilsson, 2005). That dam, with a height of 5.25 m and a length of 37 m, was built with a central till core with supporting rock fill and with built-in defects. It was known from a desktop sensitivity study based on the material properties of the construction materials that it would not be possible to detect small defects using single campaign surveys. However, geophysicists managed to indicate defect locations by testing a monitoring approach investigating changes over time.

The Norwegian blind-test dam was not built as a conventional earth embankment dam, where there would normally be filters separating the impermeable core from the outer coarse pervious shell (rock fill). To further improve the concept of using experimental dams, the dam at Älvkarleby, was designed in accordance with the Swedish dam safety guidelines (RIDAS, 2017).

2 THE EXPERIMENTAL DAM

2.1 *Design of the dam*

The experimental embankment dam at Älvkarleby has an impermeable core surrounded by upstream and downstream filter zones and support fill (Fig. 1). It is 20 m long, 4 m high, and its base against the foundation perpendicular to the dam line is 15 m. The two sidewalls that the dam connects to are slightly angular (12.5%). The bottom slab is inclined 1% towards the downstream side, where a ditch collects the seepage water through the dam body. This seepage is divided by ribs into eight sections where flow is continuously monitored.

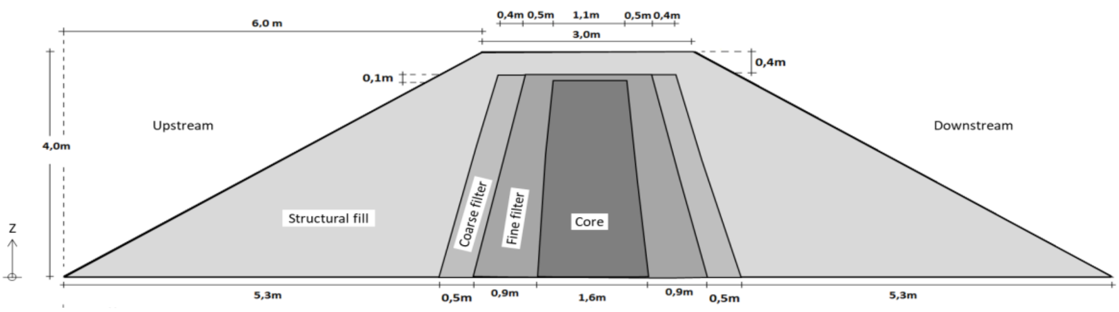

Figure 1. Cross-section of the experimental dam (Lagerlund et al., 2022).

The dam rests on a rigid concrete support structure submerged into a riverbank of 12 m of sand overlying bedrock (drained conditions). The experimental dam thus has its crest in line with the surrounding ground. To the extent possible, the design is made to avoid structural members with negative impact on geophysical measurements. The bottom concrete slab of the containment has therefore been reinforced with fibreglass reinforcement bars. Since there is no electrically conductive reinforcement this resembles a foundation on rock.

2.2 *Built-in defects*

Six built-in defects were designed to represent different types of damages (see Figure 2-3 and Table 1). Numerical simulations were made in the design phase by the researchers in order to provide guidance on size and material properties to be used in the defects. Some defects change the seepage flow rate and seepage path, while others change the material properties. Changes in seepage will affect the temperature, so defects that will change the flow rate are more probable to be detected (Defect #2, #3 and #4). Defect #1 and #5, are only expected to be detected if insufficient compaction around the cubes initiates changes seepage flow. Defect #6 seems not possible to detect using temperature, as its effect on seepage is negligible. Being a blind test, the positions of these defects were not known to the investigators during the first evaluation.

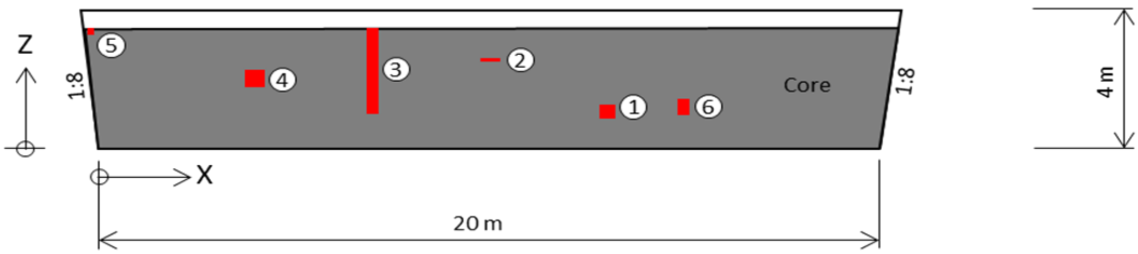

Figure 2. Longitudinal section showing the six defects (Lagerlund et al., 2022).

Table 1. Description of the defects (Lagerlund et al., 2022).

DEFECT					COMMENT
No.	Type	Material	Shape	Size (m)	
1	Cavity	Wood	Cube	0.4 x 0.4 x 0.4	Centrally in core
2	Horizontal permeable zone - centrally	Crushed rock, 4-8 mm	Square	0.5 x 0.1	Through core
3	Vertical loose zone	Crushed rock, 8-64 mm	Circular	0.3 x 2.5	Centrally in core
4	Boulder	Concrete cube	Cube	0.5 x 0.5 x 0.5	Centrally in core
5	Horizontal permeable zone - at abutment	Crushed rock, 4-8 mm	Square	0.2 x 0.2	Through core
6	Fine filter defect on upstream side	Crushed rock, 8-64 mm	Square	0.3 x 0.3	Centrally in core

Figure 3 Description of the defects (Lagerlund et al., 2022).

2.3 *Cable installation*

The cable installation (Fig. 4) is extensive compared to typical installation in large dams, where normally just one or a few cables are installed along the dam. In the experimental dam there is one cable, placed at four levels in the upstream filter, and on the core crest (Johansson and Bernstone 2022). Some parts of this cable are also placed in the reservoir, allowing the water temperature to be measured. A second cable is used to measure at five levels in the downstream filter, and a third cable is placed closed to the dam toe. The fibres in two cables in the centre of the dam are spliced, in order to achieve a loop allowing all fibres in the centre of the dam to be measured in one channel. Measurements in the toe cable were performed in a separate channel.

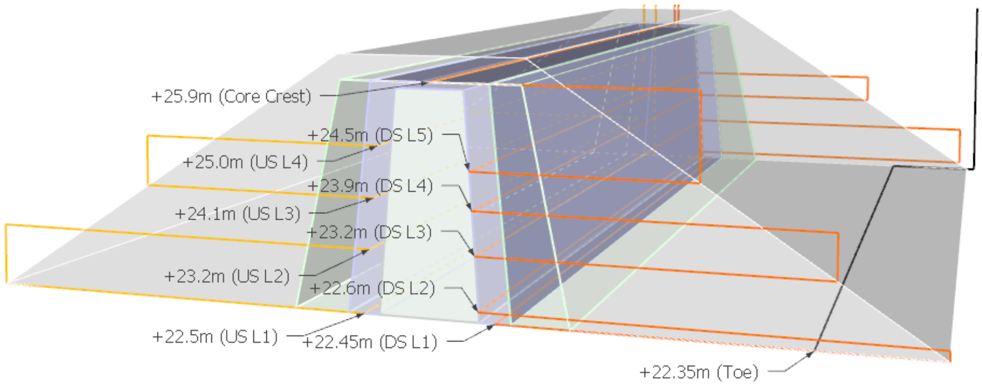

Figure 4 Cable installation in the experimental dam showing upstream cables on different levels (yellow USL1-USL4), core crest cable (orange), downstream cables (orange DSL1-DSL5), and toe cable (black).

All cables contain both multimode and single mode fibres. This enables measuring using Distributed Temperature Sensing (DTS), Distributed Acoustic Sensing (DAS) and Distributes Strain Sensing (DSS). Furthermore, the cable in the downstream toe contains a copper wire, which can be used for heating in so-called heat pulse tests (often referred to as “active DTS method”). For information about temperature monitoring using optical fibres see Tyler et al. (2009) and Dakin et al. (1985). Measurement using DAS has also been done in this dam (Johansson et al. 2021).

The dam chainage (Section) along the dam starts at the top left at the connection with the sloping concrete wall on the left side (Section 0 m) and ends at the right abutment at Section 20.6 m on the crest. The bottom of the dam starts at Section 0.3 m and ends at Section 20.3 m.

2.4 *Monitoring equipment*

Temperature measurements started in February 2020, i.e., about two months before filling started. Measurements were made using a Silixa XT-DTS. The unit was placed in a monitoring container, where diurnal temperature variations occur. This effect was seen in the temperature data versus time as small variations (<0.1°C). However, no temperature compensation was needed.

One channel was used to measure the temperature in the cables in the centre of the dam, whereas the measurements at the dam toe were made in the second channel. Data were continuously uploaded to a webserver, making it possible to follow the temperature on-line using efficient data presentation. Measurements were taken each 2 hours, with a sampling resolution of 0.25 m and a measuring time of 30 minutes.

2.5 *Water level operation*

Initial filling of the water started in April but had to be aborted. The main first filling of the dam up to the retention water level started on May 4 and was performed slowly during working days. The water level was kept constant during weekends. The retention level was reached on May 28, 2020. It was then kept constant until September 2021 when the water level was decreased stepwise.

3 RESULTS – FIRST FILLING

Temperature measurement during first filling, or during annual reservoir filling, has been found valuable when applied on large dams. The usefulness of such measurements was also demonstrated for the experimental dam, showing significant temperature changes in both space and time during the first filling when also transient effects were observed. Transient effects were expected since the core was not fully saturated.

Waterfall plots (or color maps), created for each line (USL1, USL2, …, DSL5) give general information about the temperature distribution in the dam for a chosen period. One example from the first filling is shown in Figure 5, which also shows the mean temperature and the temperature difference. Areas with early response indicate larger seepage flow rates, and/or seepage flow in the lower part of the dam. In this case we can identify early responses at Section 7 and 12 m, which correspond to Defect #3 and #2, respectively. About one week later a response was found at Section 4 m, and two weeks later at Section 0 m. The latter corresponds to Defect #5.

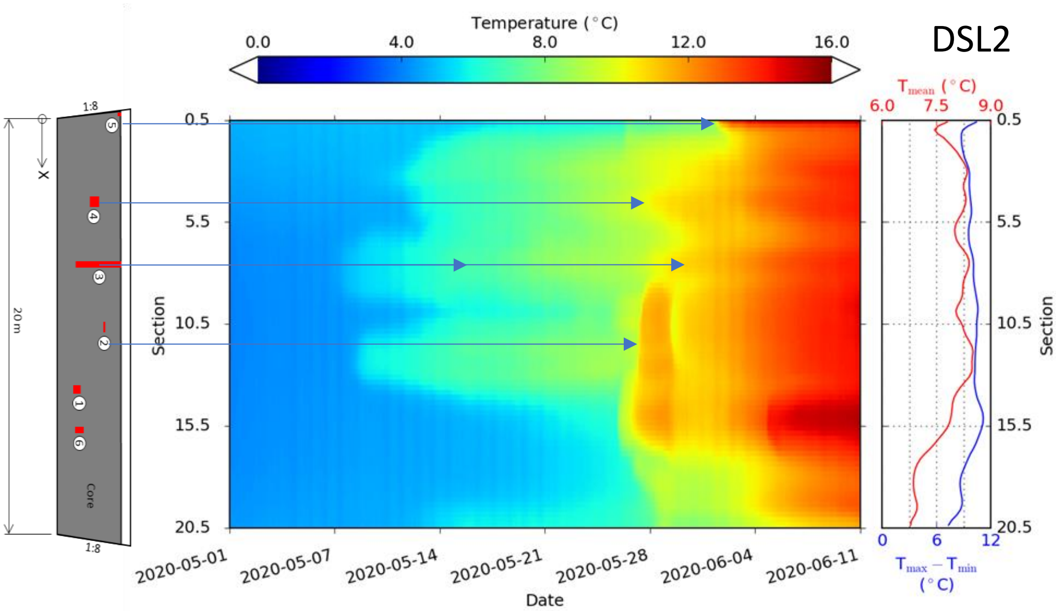

Figure 5. Waterfall plot for location DSL2 showing temperature in colours versus time (x-axis) during first filling over the entire dam width (y-axis). The location of the defects is shown in the figure on the left side and calculated mean temperature (red line) and temperature difference (blue line) for the period in the figure to the right.

Since the cable are placed at multiple levels it is possible to create images of the temperature distributions in the upstream and downstream filters as shown in Figure 6. This is useful for interpretation of the large amounts of data. However, the most detailed information is obtained when plotting the temperature in given points with time and along the dam at a given time. This is especially valuable for calibration of numerical simulations (Johansson and Bernstone, 2022).

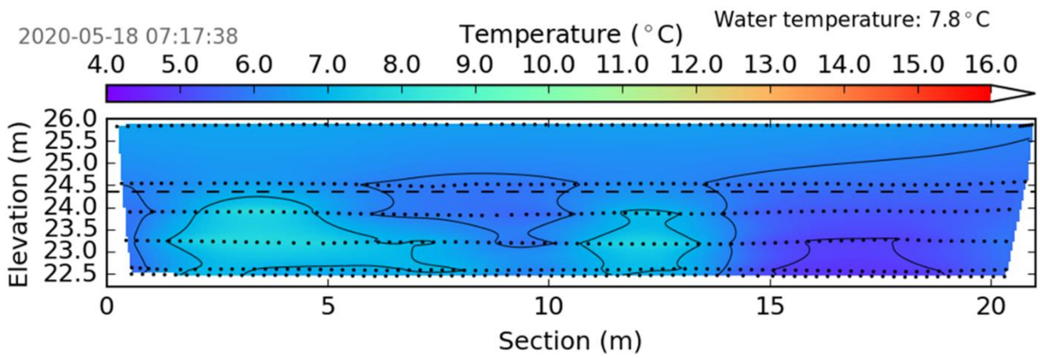

Figure 6. Downstream temperature measured in DSL1-DSL5 on May 18, 2020.

All these types of data presentations are useful for seepage flow interpretation and were all used and presented in the blind-test report. The result from the first filling indicated more anomalies than the six known defects. Some of the anomalies seemed to be of more transient nature, so the final results of the interpretations of data from the first filling were presented in two figures. These figures are shown here (Fig. 7-8), also adding the real locations of the defects. The agreement is within a meter or so for five of the six defects. All transient anomalies are in the lowest part of the dam, and at the abutments close to the concrete walls.

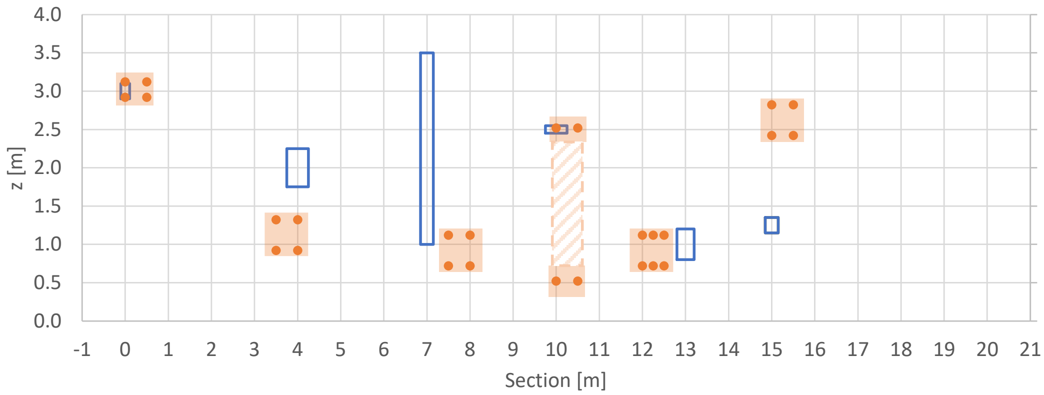

Figure 7. Defect location (orange dots) based on interpretation of data from first filling during the blind-test. The location of the defects is shown with blue lines.

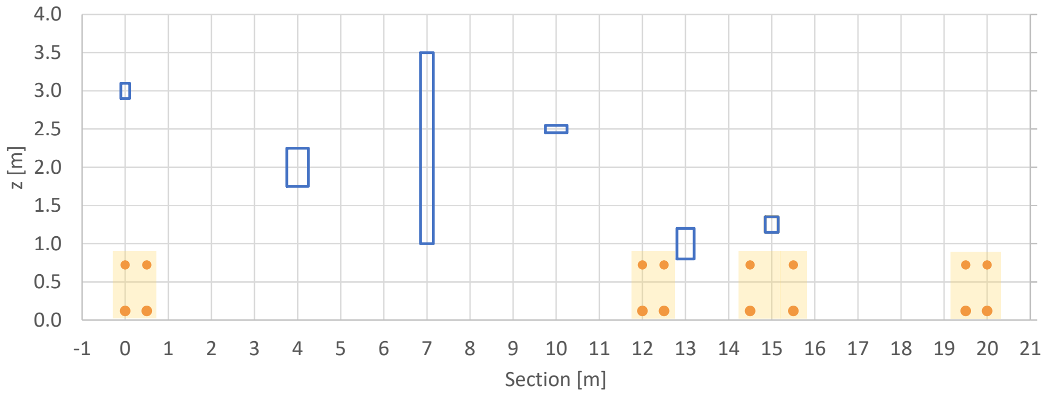

Figure 8. Location of anomalies of transient nature during first filling (yellow areas) interpreted during the blind test. The location of the defects is shown with blue lines.

4 RESULTS – LONG TERM MEASUREMENT

Long term measurements make it possible to study responses to seasonal temperature variations and to identify potentially leakage-related trends developing over periods of several years. Such measurements are usually the preferred option when temperature measurements are utilized for dam surveillance, where they have been extensively and successfully applied. Data interpretations are focused on the identification and quantification of leakage flow by analyzing how incoming temperature pulses change as they are transported through the dam. However, simplified evaluations based on direct comparisons of data from different periods/years are also very useful.

This section presents temperature measurements in the experimental dam during the one-year period September 1, 2020 – September 1, 2021. The aim of this part of the study is to investigate whether the temperature variations observed during this measurement period could provide useful information for the localization of the built-in defects in the dam. Unlike during first filling, the upstream water level was constant (3.15 m) during the whole long term measurement period. The temperature in the upstream water displayed a seasonal variation of c. 20°C, with a minimum in early February and a maximum in mid-July. The air temperature showed a similar seasonal pattern, with a somewhat larger variation (c. 30°C).

The temperature variations during the one-year period can be separated into two distinct periods, one period of decreasing temperatures during autumn and winter 2020, and one of rising temperatures during spring and early summer 2021. Both periods start at more or less homogeneous temperature conditions in the dam, with increasing temperature differences developing in response the changing temperatures in the water and air surrounding the dam. It turns out that the thermal responses and the resulting temperature variations during the two periods are very similar.

Figure 9 presents measured temperatures on the downstream side of the dam after about two months of decreasing temperatures in the autumn. The temperature distribution shows an overall pattern with a central part where temperature is low surrounded by relatively large warmer areas. This could be taken as an indication that leakage flow is larger in the central part of the dam, whereas leakage is smaller on the left and right sides where warmer water remains (except perhaps close to the left wall). However, it should be noted that the internal temperature differences are relatively small, and that the most significant change compared to the conditions at the beginning of the period is a general decrease in temperature in the whole dam.

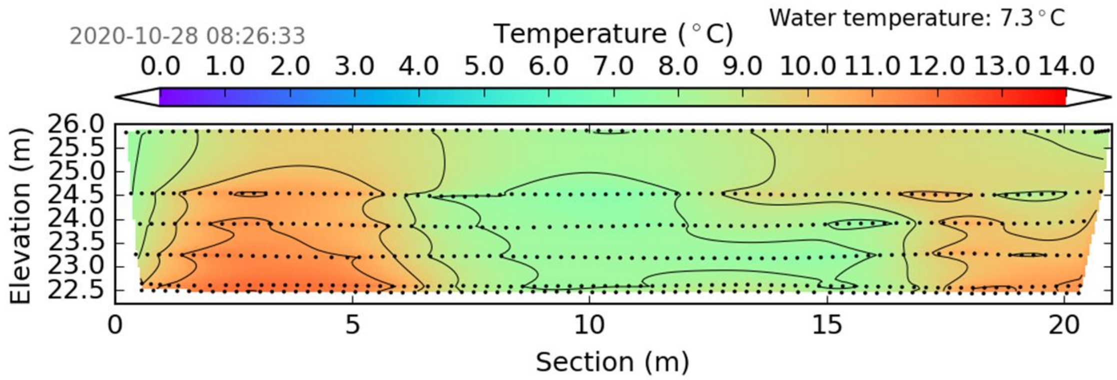

Figure 9. Downstream temperature measured in DSL1-DSL5 on October 28, 2020.

An alternative and more probable interpretation of the observed temperature changes in the dam is that they primarily are caused by heat conduction from water and air on the dam boundaries. The experimental dam is small compared to the dams where long term measurements usually are performed, and this most likely means that any flow-related temperature signals quickly are levelled out by heat conduction. This implies that observed temperature variations primarily represent differences in heat conduction properties, boundary conditions (air and water temperatures) and distances to boundaries. This is in agreement with results of numerical simulations performed in the design phase of the experimental dam project, and also with simulations performed later (Johansson and Bernstone, 2022).

Most important given the purposes of the present study is that the long term measurements appear to provide only limited useful information for analyses of built-in defects. Extensive data evaluations similar to those of the first filling stage were performed, but the results show very little evidence of localized temperature anomalies that could indicate defects. Possibly, the somewhat more irregular temperature distribution to the right (Sections 16 to 20) could be related to defects (Fig. 9).

In dam surveillance, data evaluations usually rely heavily on analyses of time series data describing the timing and amplitude variations of temperature responses in different parts of the dam. Data of this type from the experimental dam show variations that potentially could be further analyzed in this way. However, this would require support from detailed modelling, since the variations generally are too small to be evaluated by the simplified methods commonly applied elsewhere. This further substantiates the conclusion that long term measurements, as widely applied in dam surveillance, cannot provide adequate information for detection of defects in the present experimental dam.

5 RESULTS – HEAT PULSE TESTS

Temperature measurements using heat as a hydrogeological tracer is referred to as active method or heat-pulse method. The method is based on adding heat and analysing the thermal response, thus making it possible to make both qualitative and quantitative interpretations of groundwater flow. It can be used on embankment dams (Aufleger et al., 2000, 2005) or in fractured rock (Coleman et al., 2015, Maldaner et al., 2019).

On the experimental dam measurements were made in a cable that was installed at foundation level below the d/s support fill (Fig. 4). Two copper wires in the cable were connected in the far end to make a loop. Heat was generated by electrical resistance in the wire when sending a current through the loop. Distribution of power was set by a special monitoring unit (Silixa Heat Pulse System) controlled by an external PC, while the temperature in the cable was measured in optical fibres with the DTS unit. Different combinations of power and length of heating cycles were tested optimising the heating without exceeding the allowed temperature of the fibre optic cable.

The measurements were taken at two separate occasions with high water level (+25.63 m) and low water level (+24.23 m) respectively. The measurements at high water level were taken on the 20th of August 2021 using power of 5 W/m for 60 minutes (Fig. 10). Temperature at the start was rather constant around 18°C along the dam. During the period of active heating temperatures rose between 7 and 11°C. Similar results were obtained with other combinations of power and heating period length.

Qualitative analysis was made by comparing the temperature response along the dam. Assuming the placement of the cable and local soil conditions around the cable is the same would lead to the same heating effect along the dam. In areas with higher seepage heat will be transported away with the seepage water resulting in a lower temperature difference (right part of Figure 10). The seepage is then highest close to the abutments in Sections 1.3-2.2 m and 14.8-19.5 m with the peak in Section 18.4 m. This gives an indication of defect locations. However, as the seepage was divided in sections and the measurements were taken downstream of the dam, the exact location of the defects could not be determined.

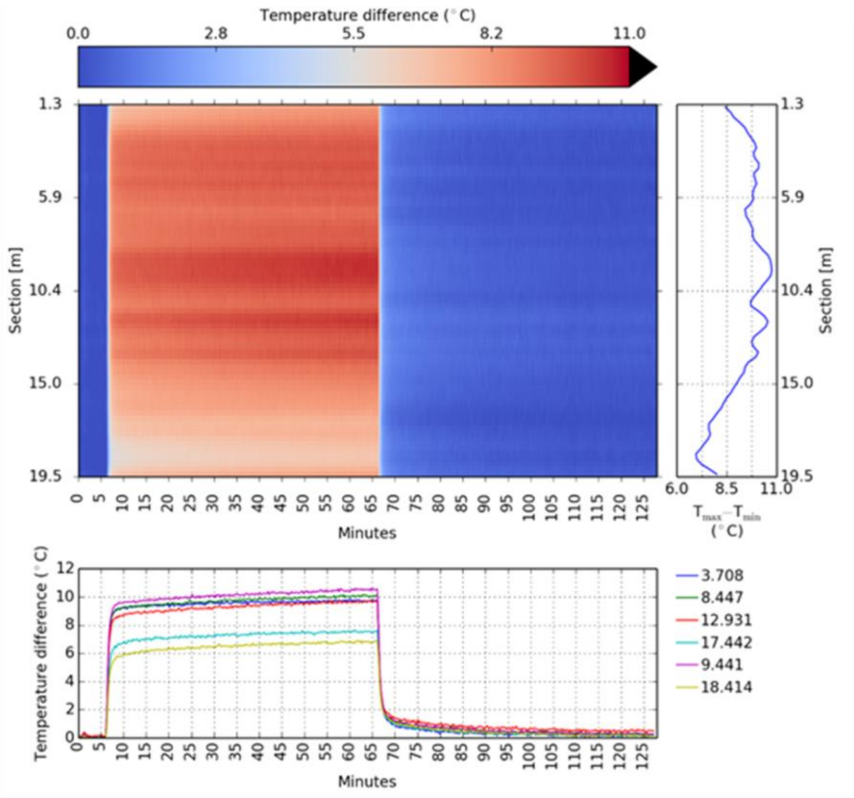

Figure 10. Measured temperature change from measurements taken at high water level applying 5 W/m for 60 minutes. Colour map shows temperature difference from the start ($T-T_0$). Maximum temperature difference ($T_{max}-T_{min}$) is shown in the right diagram. Temperature difference over time for six selected sections are shown in the lower diagram.

Measurement at low water level was made approximately one month later with the reservoir level 1.4 m lower. The results were very similar when it comes to the distribution of the measured temperature difference along the dam. However, a much smaller temperature difference was expected (since lower seepage would give less cooling), but the measured temperature difference was only marginally smaller. This could be explained by differences in water saturation close to the cable. The cable was installed in a thin sand layer just above the concrete foundation and very small variations in the groundwater level would result in changes in saturation and thermal properties of the sand. In fact, the method is very sensitive to small changes in the vicinity of the cable as the radius of influence around the cable is rather small.

Due to anisotropic conditions around the cable, standard evaluation could not be used. Numerical modelling was therefore used to quantify the seepage to approximately 0.5-1.2 l/s having to use assumptions about local geometry that could not be fully verified. The calculations indicated that the seepage flow rates varied ±30% from an average along the dam.

It is recommended that for future use of the active method placement of the cable and installation procedures should be carefully thought through. Placing the cable in the seepage path with homogeneous conditions in the vicinity of the cable give optimal conditions for both qualitative and quantitative evaluation of the seepage.

6 CONCLUSIONS

Temperature distributions in embankment and tailings dams depend on the seepage regime. Distributed temperature measurements using fibre optics are widely used in Sweden for detection of seepage flow changes and internal erosion in dams. Fibre optic cables were installed in the experimental dam built by Vattenfall at Älvkarleby, to test the method and further increase the understanding of seepage processes and how they are related to temperature variations.

The experimental dam has six built-in defects, with locations unknown to the teams attempting to find and characterize the defects by means of a variety of geophysical methods. The temperature measurements were evaluated based on results from first filling, when temperatures were measured as the upstream water level was rising, long term measurements during a one-year period of constant water level, and relatively short tests involving the heat pulse method. Of these temperature-based studies, the measurements during first filling, where temperature signals were enhanced by the rising water level, provided the most useful information.

Evaluation based on measurement from the first filling indicated ten anomalies, of which four seemed to have a more transient nature. After the real locations of the defects had been revealed to the evaluation teams, it was concluded that the observed anomalies agreed with the real ones within a meter or so for five of the six defects. For some of the defects, the locations appeared better constrained in their positions along the dam than in terms of elevation, which is consistent with the differences in measurement resolutions. All transient anomalies were found in areas where construction could be expected to be more problematic than elsewhere in the dam, such as the lowest parts of the dam and at the abutments close to the concrete walls.

The observed temperature changes during the long-term measurements were primarily caused by heat conduction from water and air on the dam boundaries. The experimental dam is small compared to dams where long term measurements usually are performed, and this most likely means that any flow-related temperature signals quickly are levelled out by heat conduction, especially at the present small seepage flow rates. This implies that long-term measurements in the experimental dam provide limited input to analyses of built-in defects, which all can be expected to cause minor seepage flow increases.

Data evaluations for dam surveillance usually depend on analyses of time series data describing the timing and amplitude variations of temperature responses in different parts of the dam. Data of this type from the experimental dam showed variations that potentially could be useful for analyses of this type. However, the variations generally were too small to be evaluated by the simplified methods commonly applied for such purposes. This further supports the conclusion that long term measurements cannot provide adequate information for detection of defects under the conditions characterizing the processes in the experimental dam.

The application of the heat pulse method demonstrated differences between different parts of the dam that broadly agreed with results obtained from other temperature measurements. The result clearly showed the importance of a proper location of the cable. In this case the water level around the cable changes at high and low reservoir level. This caused different thermal properties around the cable, which changed the thermal response at heating. Numerical modelling was therefore used to quantify the seepage to approximately 0.5-1.2 l/s. Placing the cable in the seepage path with homogeneous conditions in the vicinity of the cable give optimal conditions for both qualitative and quantitative evaluation of the seepage.

Analysis of temperature changes or annual variations performed at typical embankment dams provide excellent possibilities to detect small seepage flow changes and low flow rates. This agrees with the result from these tests, where most of the defects could be detected. This was mainly evaluated from measurements during first filling, while the long-term measurement gave less information in this case due to the influence of heat conduction from the boundaries that was dominating the heat transfer.

7 ACKNOWLEDGEMENTS

The research presented here was funded by Vattenfall R&D and Swedish Energy Agency (project 48411-1). We wish to express our gratitude for valuable support from the project team, Christian Bernstone, Johan Lagerlund, Erik Nordström, and Peter Viklander.

REFERENCES

RIDAS (2017). Kraftföretagens riktlinjer för dammsäkerhet, Swedenergy AB.

Aufleger M, Strobl T & Dornstädter J (2000). Fibre optic temperature measurements in dam monitoring – Four years of experience. ICOLD Congress Q78, R.1, Beijing 2000.

Aufleger M, Conrad M, Perzlmaier S. & Porras P (2005). Improving a Fiber Optics Tool for Monitoring Leakage. HRW, September 2005, Vol. 13, Number 4, p. 18-23.

Coleman T I, Parker B L, Maldaner C H, Mondanos M J, 2015. Groundwater flow characterization in a fractured bedrock aquifer using active DTS tests in sealed boreholes. Journal of Hydrology 528, 449–462. https://doi.org/10.1016/j.jhydrol.2015.06.061.

Dakin, J.P., Pratt, D.J., Bibby, G.W., and Ross, J.N. (1985), "Distributed optical fiber Raman temperature sensor using a semiconductor light source and detector", Electron. Lett., vol. 21, no. 13, pp. 569-570, June 1985.

Johansson, S. & Nilsson, Å. (2005). Internal Erosion Detection at the Røsvatn Test Site - Experiences from blind test using Resistivity, Self-Potential, Temperature, and Visual inspection. Part A – Assessment report. Elforsk rapport 05:42, Stockholm.

Johansson, S., Beaupretre, S., Boue, A., Stork, A. 2021. Distributed Acoustic Sensing for detection of seepage and internal erosion in the Test Dam at Älvkarleby. Energiforsk REPORT 2021:732, ISBN 978-91-7673-732-3.

Johansson S. & Bernstone C. (2022) Temperature Modelling and Distributed Temperature Sensing Using Optical Fibres in a Test Dam, ICOLD 25 Congress, Marseille 2022. DOI: 10.1201/9781003211808-120.

Johansson S., Sjödahl P., Stork A.L., Mondanos M., Persson M. & Wolfsborg R. (in press 2023). Application of Distributed Fibre Optic Sensing Technologies in Embankment Dams. Symposium "Management for Safe Dams" - 91st Annual ICOLD Meeting – Gothenburg 13-14 June 2023.

Lagerlund J., Bernstone C., Viklander, P., Nordström, E, (2022). Embankment Test Dam of Älvkarleby - Description of installed defects and their position., Mendeley Data, V3, doi: 10.17632/k7zrrbxxnb.3.

Maldaner C H, Munn J D, Coleman T I, Molson J W, Parker B L, 2019. Groundwater flow quantification in fractured rock boreholes using active distributed temperature sensing under natural gradient conditions. Water Resources Research 55, 3285-3306. https://doi.org/10.1029/2018WR024319.

Tyler S.W., Selker J.S., Hausner M.B., Hatch C.E., Torgersen T., Thodal C.E. & Schladow, S. G. 2009. Environmental temperature sensing using Raman spectra DTS fiber-optic methods. Water Resources Research, Vol. 45, W00D23, 11 pages.