Downstream Seepage Detection using Temperature Measurements and Visual Inspection – Monitoring Experiences from Røsvatn Field Test Dam and Large Embankment Dams in Sweden.

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SUMMARY

Visual inspection of the downstream toe is a well established method to detect seepage outflow areas. However, visual inspections are time consuming and can not be done continuously. Temperature measurements in the dam using optic fibre or PT-100 sensors can be performed continuously and independent of weather conditions. Systems for long term monitoring using optic fibres have been installed in about ten embankment dams in Sweden. A similar system was also installed at the Røsvatn field test dam in Norway, where several unknown defects were built in. These two methods, and some electrical methods, were compared in a blind test. Temperature and visual inspections agreed well with the real defects.

1 INTRODUCTION

Internal erosion is a major cause of failures of embankment dams. Methods for seepage monitoring and internal erosion detection are therefore essential for the safety of earth embankment dams. Experiences from all over the world indicate that the use of existing methods is not perfect, and that a lot of dams need improved surveillance. New standards, guidelines, and technical improvements are the main driving forces to collect more and more data, both in time, and space mainly using conventional monitoring parameters. Additional methods are sometimes applied, but mostly on research basis. However, visual inspections are still important and can probably not be replaced by any monitoring method.

There are only a few monitoring methods that can be installed after the dam is constructed. One of those is to install an optical fibre along the dam toe, for measuring the temperature along the dam. Other possible methods are resistivity and Self–Potential that are further described in the paper by Dahlin, et al (2004), within this proceeding.

Temperature measurements for seepage detection in dams started in Germany in the late 1950's (Kappelmayer 1957). Extensive research has also been performed especially in Germany and Sweden during the last 20 years (cf. Armbruster 1983, Merkler et al 1989, and 1995, Johansson 1991 and 1994). Based on the experiences obtained in the practical use, the method seems now to be more and more accepted. An example of this was a meeting in Paris arranged by IREX and the EUCOLD, Working Group on Internal Erosion in Embankment Dams, where temperature measurements were the main theme (Symposium IREX/EWG, April 26-27, 2004). The possibility to use the method at the blind test at Røsvatn was thus a good opportunity to verify the performance of the method.

2 VISUAL INSPECTION

2.1 Methodology

Visual inspection is the most common method of dam surveillance. It is based on at least four of the five senses:

- Faculty of vision – seepage outflow can be seen,
- Auditory sense- seepage outflow can be heard
- Sense of smell – the vegetation will be different at wet areas
- Sensitivity – the soil may be soft, wet etc.

Inspections of the upstream slope, the crest and the downstream slope are normally done on weekly basis in Sweden. Special checklists are developed in order to guide the inspector. Important observations on the downstream slope and dam toe may be:

- Wet areas
- Increased drainage flows
- Surface erosion
- Deformations, cracks, sink-holes

The general problem is to document the observations in a systematic way, despite the use of checklists. A large problem is that all observations are more or less relative, i.e. a comparison between actual status with the previous status observed. The main reasons are that inspectors may have different ability, and the weather conditions may influence the observations. Photos are sometimes helpful to verify slow changes. Inspectors with long experience will however be able to observe small changes, but will in general not be able to quantify the defect. Visual inspections will probably also in the future be the most common surveillance method, despite some weaknesses in the methodology.

2.2 Examples of seepage outflow

Wet areas on the downstream slope or toe may be a sign of increased seepage, may be due to different construction material or may be caused by internal erosion. Sometimes the flow will be concentrated and easy to detect both by the eyes, visually, and sometimes also by the ears, audibly. Such an example is shown in Figure 1 where muddy water from the dam could be seen when flowing out into the downstream ditch. A sound could also be heard from the inside of the downstream fill.

Figure 1 Concentrated outflow of muddy water and fines into a downstream ditch parallel to the dam.

Seeping/leaking water can sometimes be detected directly on the surface of the dam toe. Small leakage/seepage outflow may be observed by the occurrence of different types of vegetation (Figure 2). This kind of observation is sensitive and useful, and may point out small seepage that cannot be seen in itself. The soil may also be softer in such areas, and the vegetation will may smell differently.

Figure 2 Light green vegetation indicating a seepage outflow area (within the white line).

A third way of observing outflow weak outflow areas is by observing the effect of the first snow. A seepage outflow will cause a slightly higher temperature on the soil surface. A light snowfall will then melt in seepage outflow areas. This indication is very clear, sensitive and useful (Figure 3), but the occasions when optimal meteorological conditions are favorable are rare. At large seepage/leakage flow the snow layer may be thinner during the entire winter.

Figure 3 Seepage outflow area indicated by areas where the snow has melted.

3 THERMAL PROCESSES IN DAMS

3.1 General

The temperature in an embankment dam depends mainly on the temperature in the air and in the upstream reservoir. These temperatures vary seasonally and create seasonal temperature variation within the dam (see Figure 4) due to advection (caused by seepage flow) and heat conduction.

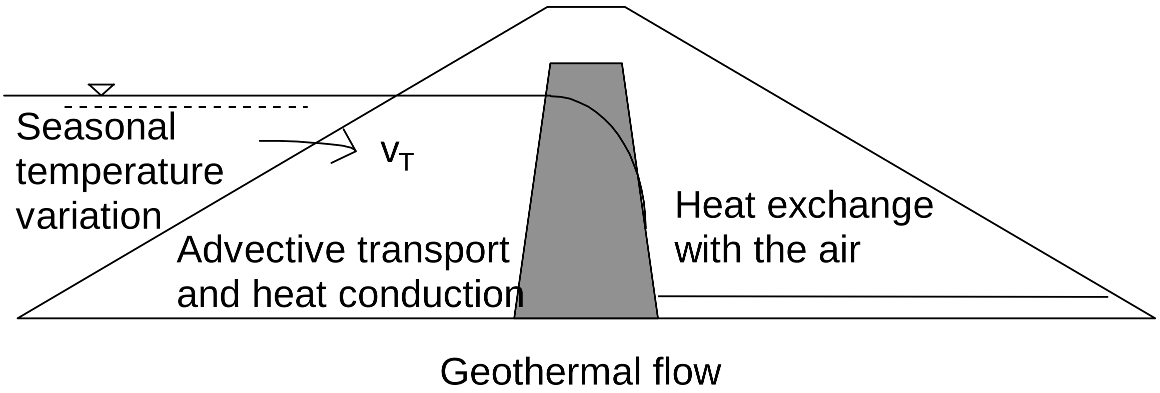


Figure 4 Basic thermal processes in an embankment dam.

The seepage flow is normally small in embankment dams (hydraulic conductivity often less than 10^{-6}m/s) and the seasonal temperature variation in the upper part of the dam depends essentially on the air temperature at the surface. The influence from the air decreases with depth, and is less than 1^{o}C for depths in the dam body that exceed 10m. This process must however be considered in small dams with heights less than about 20m, or if measurements are made at the dam toe at shallow depth. In larger dams with heights above 100m the geothermal flow must be considered, as well as the thermal stratification in the reservoir.

Temperature acts as a tracer with the seasonal temperature variation as source. Low seepage flows will not affect the thermal condition in the dam, and the temperature will remain constant. At increasing seepage flows the temperature in the dam will begin to vary seasonally. The amplitude of the variation is dependent on seepage flow, the seasonal variation at the inflow boundary, and the distance from the boundary to the measuring point.

The thermohydraulic behavior of an embankment dam is complex. It includes such basic thermal processes as heat conduction (from the dam crest and from the foundation due to geothermal flow), advection and radiation. The first two processes are partly coupled to each other because viscosity and density of water are temperature dependent. The problem is further complicated by the variation in material properties in the dam, and the different conditions in the saturated and unsaturated parts of the dam. In order to analyze the problem certain assumptions have generally to be made. The general problem can be studied using coupled transport models (based on FEM or FD). At most dam application with concentrated seepage/leakage a simplified evaluation can be considered. The evaluation method for flow quantification presented below can then be used to evaluate the seepage from temperature measurements in the dam.

Measurements at the dam toe can be made in standpipes cc 10-50m, where manual or automated measurements can be performed, preferably on different levels. An optic fibre can also be, buried close to the groundwater level or below, can also be used to measure the temperature all along the dam. Some examples from these different approaches are shown below.

3.2 Evaluation methods

Temperature can directly be evaluated based on temperature changes in space or time for similar located sensors. Such a qualitative evaluation method is in many cases sufficient enough to detect leakage anomalies. A long measurement time will improve the evaluation quality.

DamTemp is a software that provides an evaluation tool for analyzing a common case in embankment dams - increased seepage in a limited zone through the dam core, see Figure 5. The software calculates the thermal field in two dimensions, assuming that the zone has an extension along the dam. DamTemp simulates the combined convective-conducted heat transfer with a few important simplifying assumptions. This must be kept in mind when using the software and interpreting the results.

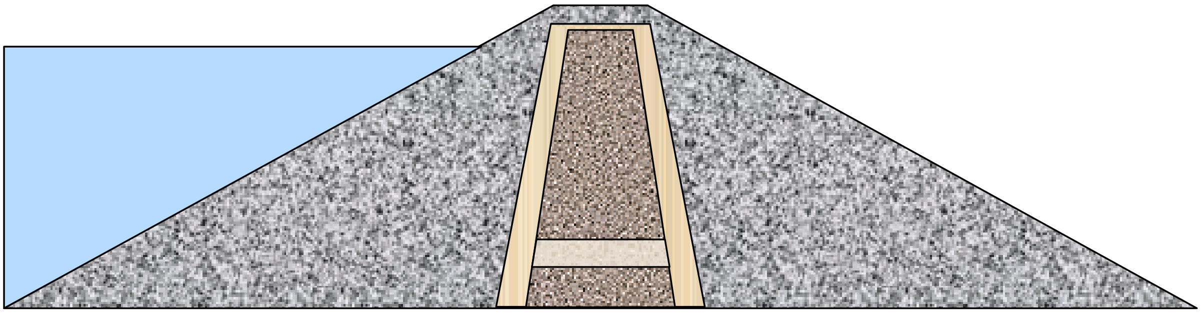


Figure 5 Cross section of an embankment dam with a zone with increased seepage, i.e. the ideal case to study with the software DamTemp.

Experience from temperature monitoring in several dams has shown that concentrated seepage flow is common. The flow can be 10-1000 times higher in such damaged zones than in the undamaged part of the dam, where the seepage flow thus can be ignored. The temperature field in the seepage zone and in the adjacent material is then mainly given by seepage flow (i.e. advection dominates) and the boundary condition. This allows a simplified three layer model (see Figure 6) with;

- an upper zone with heat conduction (in x- and y-direction) and no advection,
- a central seepage zone with advection (in x-direction) and heat conduction in y-direction; and
- a lower zone with heat conduction (in x- and y-direction) and no advection.

One important advantage with DamTemp is the limited amount of input data that have to be assumed. Seepage flow can be evaluated from measured temperatures based on thermal properties only. No data of hydraulic conductivity etc have to be assumed.

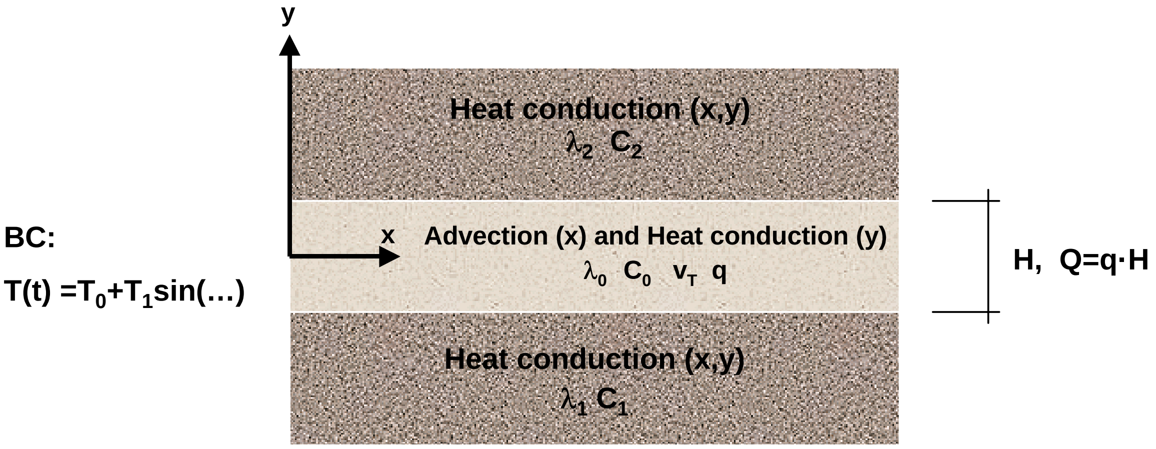


Figure 6 Basic assumptions and input parameters for the model.

4 EXPERIENCES FROM SOME SWEDISH INSTALLATIONS FOR TEMPERATURE MEASUREMENTS

4.1 Measurements in open observation wells (standpipes)

Temperature measurements in embankment are nowadays a common surveillance method in Sweden. Measurements are normally performed manually in open observation wells once a month in order to follow the seasonal variations. This has been done in about 30-40 dams, during longer or shorter periods.

The longest series is at Näs power plant, where monthly measurements have been performed since 1987. The embankment dam at Näs is about 15m high and located in the Dalälven River. The downstream water level is entering into the lower parts of the downstream fill. No traditional leakage measurements are thus possible. Several observation wells are located at the downstream toe.

An instructive example of sudden seepage increase was observed in observation well V08 in year 2000. After 13 years with a constant seasonal temperature variation between 4 and 11ºC, the maximum temperature increased to 17ºC, and the minimum temperature decreased to about 2ºC. The only explanation for this was a seepage increase. A sinkhole was also observed close to this area in 2002. Seepage calculations with DamTemp indicated a seepage increase from about $8\cdot10^{-6}$m^3/(s,m) to about $1.8\cdot10^{-5}$m^3/(s,m) at elevation +59.2m and about $5\cdot10^{-4}$m^3/(s,m) at elevation +60.7m, i.e. a seepage increase of about 2-60 times. For the following three years a decreasing seasonal temperature variation is was observed, indicating a decreasing seepage. The seepage decrease may depend on a self healing process. It may also be a reason for a small sinkhole that was observed in autumn 2003.

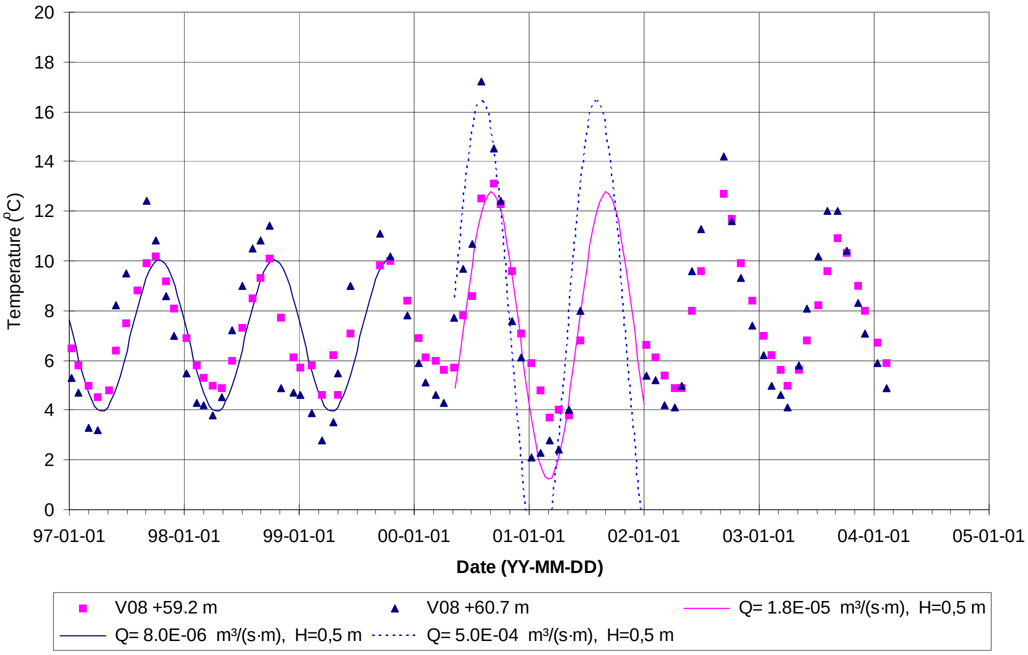
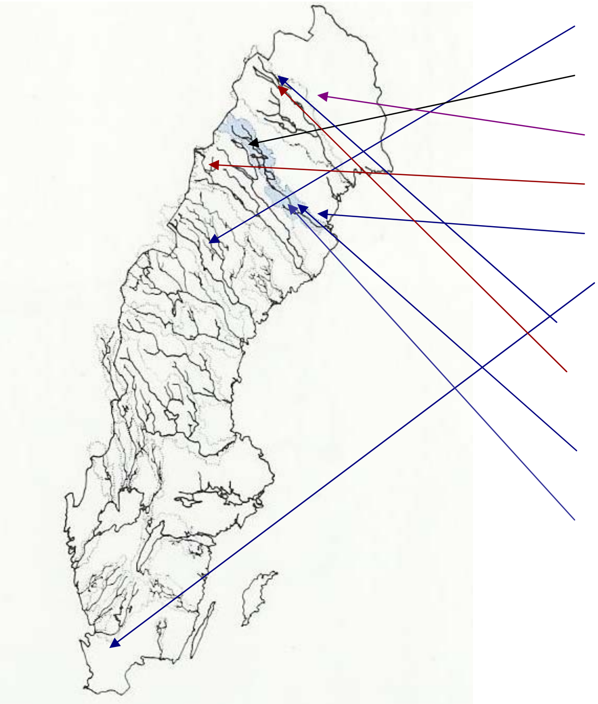


Figure 7 Measured and calculated temperature at observation well V08 at two levels.

4.2 Fibre optics – general

The application of fibre-optic systems for temperature measurements in new dams was studied in Sweden in 1993. The idea was presented in Sweden and France and a first test installation in a dyke was made in France in 1995 by EdF (Albalat and Garnero (1995) and Fry (1997)). Johansson (1997) and Dornstädter (1997) further described the concept. The installation at Lövön was made in 1998 and was the first one in Sweden (Johansson and Farhadioushan 1999).

Distributed Temperature Sensing (DTS) using optical fibres has been developed significantly during the last ten years. The performance has been improved and the cost has been reduced. Commercial systems are now available that meets the demand for dam monitoring, are now available. The capability has also been proved in several research projects (Johansson et al, 1999, 2000a, 2000b). Optical fibres are now installed at 10 dam sites in Sweden (Figure 8), but also in Germany, France, Turkey, China and Canada. Distributed Temperature Sensing (DTS) allows identifying areas with higher seepage or increasing seepage. Information about seepage location can be given by one single temperature measurements in the fibre. If desired, long term or several measurements will also give possibilities to evaluate the seepage flow rate.



1.	Lövön (1998)	Seepage
2.	Sädva (1999)	Movements (Temperature)
3.	Aitik (2000)	Both
4.	Ajaure (2001)	Movements
5.	Vargfors (2001)	Seepage
6.	Hylte dam and dyke (2002)	Seepage
7.	Suorva West (2003)	Seepage
8.	Suorva East and Sågviksdammen (2004)	Movements (Temperature)
9.	Bastusel, 3 dams (2004)	Seepage
10.	Gallejaure 4 dams (2004)	Seepage

Figure 8 Dam sites in Sweden with optical fibres installed for temperature and/or strain measurements.

The fundamental of DTS is the back scattering of light in the fibre. When light is launched down an optical fiber, a small fraction is scattered back towards the source. This light is formed of three principle components, which are separated in wavelength: Rayleigh light, Brillouin light and Raman light. Rayleigh light is not significantly changed by strain and temperature and may be used for referencing and loss measurements. The Raman light power depends upon the temperature at the point at which the light was generated, and thus may be used for temperature measurement. The power of Brillouin light also depends upon temperature, whereas the frequency shift of the Brillouin light depends upon both temperature and strain. Thus, provided that both the amplitude and frequency shift of the Brillouin light can be measured, temperature and strain can be simultaneously determined.

The most established distributed optical fibre sensing technique uses Raman scattering to determine temperature. Here, a pulse of light is sent into the fibre and the power of the backscattered light at the Raman wavelengths is recorded against time. Analysis of the Raman light intensity variation with reflection time gives the temperatures at all points along the fibre. The important parameters defining the performance of such a system are the spatial resolution, the temperature resolution, the measurement time and the sensing length. For example systems with a spatial resolution of less than 1m, temperature resolution of better than ±0.1°C, and a range of a several kilometres are now commercially available.

4.3 Fibre optics – Initial long term and single investigation at Lövön dam

The embankment dam at Lövön is located about 120km north of Östersund. It was built between 1972 and 1973 and has a total length of 1500m. The greatest height of the dam is 25m, close to intake to the power station, where the dam is founded on rock. The rest of the dam is founded on natural moraine. The dam is a zoned earth dam and has a core of moraine. The core is vertical at the highest part but it gradually changes to an inclined core at the lower part of the dam. Gravel filters surround the core and the supporting fill consists of gravel and some rockfill. The upper retention level is at El. 287.0 and the lower retention level is at El.284.0. The downstream water level is at El. 273, and the bedrock is between El. 264 and 267, that is between 8 and 10m below the downstream water level. This implies that water leaking through the bedrock and the dam cannot be collected and measured by conventional leakage systems.

During the summer of 1998 the upper part of the dam was excavated down to elevation +272 along an 80m length from the intake structure (section 0/018) to about section 0/100). The excavation was carefully documented and several examples of internal erosion were found due to improper downstream filter and construction errors. From excavation level and down to the bedrock, a diaphragm wall was constructed in the old core and down to the bedrock. A sheet pile was pushed in the slurry down to the bedrock. Additional drilling and grouting was carried out in the bedrock in order to obtain a proper sealing between the diaphragm wall/sheet pile and the bedrock. The diaphragm wall ends at section 0/058.

A new core of moraine replaced the excavated part of the dam with proper downstream filters. The core, which was placed on a filter layer with a geomembrane on top, that was sealed towards the sheet pile, see Figure 9.

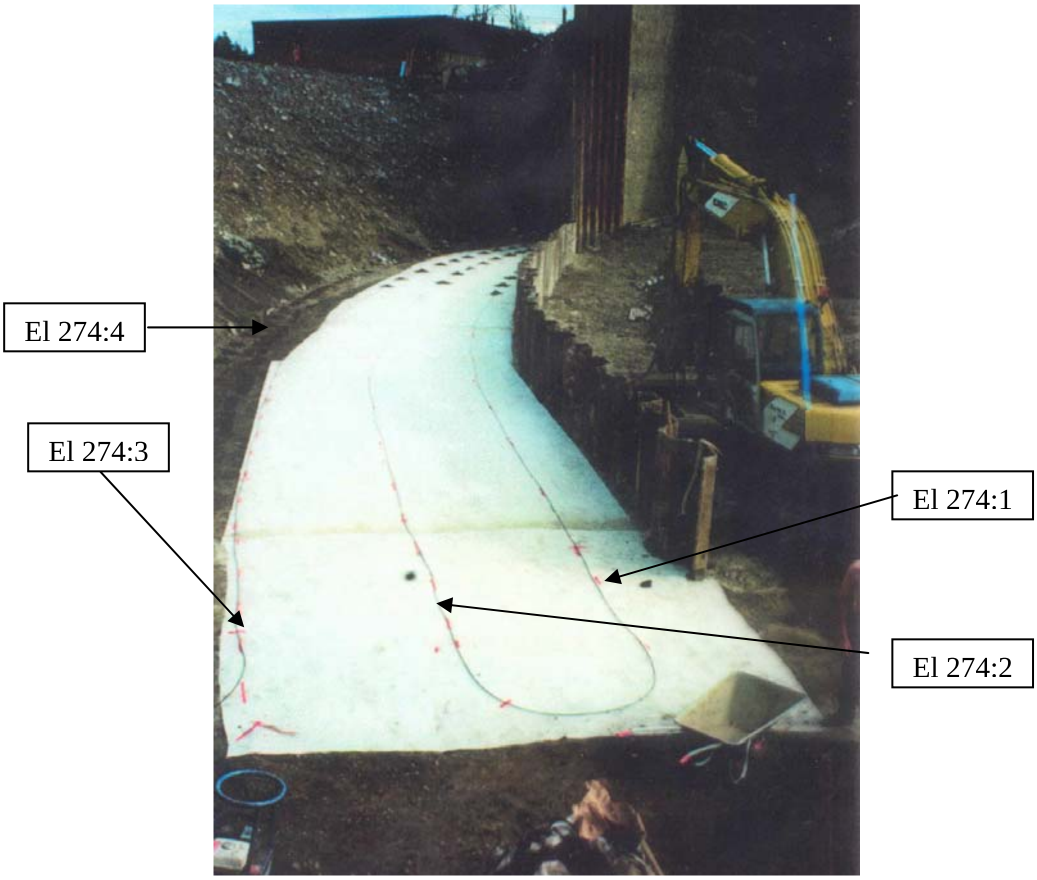


Figure 9 Geomembrane connected to the sheet pile at El +274.0. Two fibre-optic cable loops can also be seen on the top of the geomembrane and on the downstream filter. (Photography by Graninge AB).

Two optical fibre loops were installed to measure the temperature upstream, above and downstream from the core. The totally installed and measured length was 2477m. The position of the fibre was documented at every five metres during the installation. The optical fibres are located on eight levels starting at El. +273.8. The fibre starts at about section 0/010 and goes along to the dam to section about 0/060 or more and then it returns back on the same elevation, see Figure 10. The vertical rise is done along the concrete wall close to the intake. Onward and backward cables on the upstream side were installed close together in order to measure the repeatability with the system.

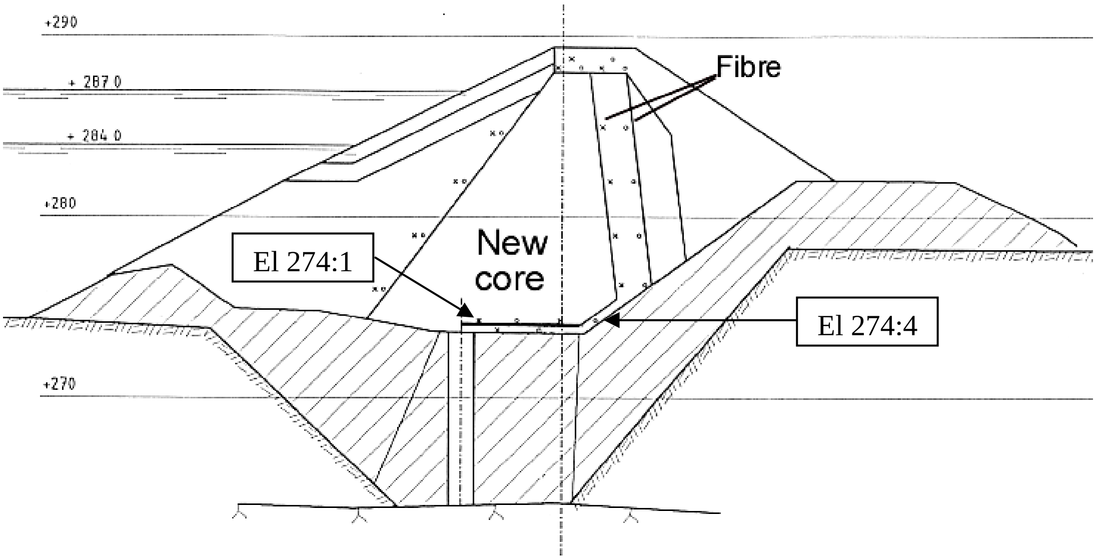


Figure 10 Location of the fibre-optic cables at the Lövön dam.

The first measurements were carried out in from mid November 1998 to mid February 1999. Distributed temperature data were obtained using a DTS 800 manufactured by York Sensors. The spatial resolution of this system was about 1m giving about 1750 temperature values along the length of the optical fibre cable installed in the dam. The absolute accuracy for measuring in a loop is ±0.5°C (with a length of 4km and 40s measurement time), according to the supplier. This performance was however not achieved, as concluded in the report, where all details can be found. (Johansson, Farhadioushan, 1999).

A second measurement was made in 2004, using a Sensornet DTS. It has about ten times higher accuracy and is also much more stable and reliable than the system used in 1998. Measurements were made during six days, and compared with temperature measured by the very accurate vibrating wire temperature sensors.

The temperature at all elevations below El. 276m shows a lower temperature around section 0/028m and at the end of the monitored part of the dam (from section 0/050 to 0/062m). All these locations are surely in the saturated part, except El. 276 that may be slightly above the water table. The lowest temperature is at the most downstream cable at El 274 (cf. El 274:4 in Figure 11) in both these areas. No signs of concentrated seepage is seen at the core (constant temperature along cable El. 274:1-3, El. 276), which indicates that the main seepage passes through the foundation.

The seepage flow cannot be estimated directly from these data. However, the temperature at section 0/028m is similar to that at section 0/060, and the seepage at those sections may therefore also be similar. Seepage evaluations from the temperatures measured in the sensors are regularly made on by Graninge/Sydkraft. Evaluations of the temperature in the vibrating sensor 60:1 indicate a seepage flow about 20-30 ml/(s,m). The length of seepage flow area can be estimated to about 2m, giving a total flow about 0.05 l/s. This seepage flow is harmless for the dam. The total flow at section 0/060 may have an extension of 15-20m, which gives a total seepage flow of 0.5l/s, which also is a harmless flow.

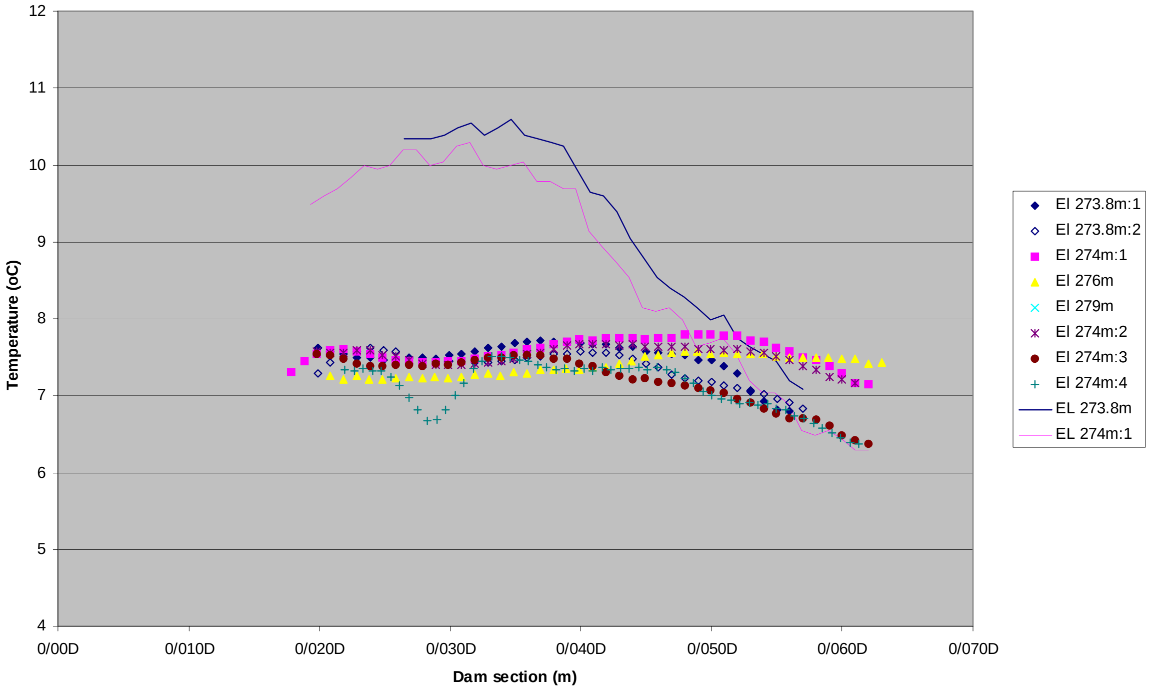


Figure 11 Temperature in the estimated saturated part of the dam at El 273.8m to 276m in 1999 (solid lines) and in 2004 (point markers). Measurements indicate concentrated seepage at 0/028, and between 07045 and 0/060m.

Measurements in 2004 showed also that the fibre installation still is working well. Temperature measurements can be made with a relative accuracy better than ±0.1°C, which is very good. Calculated temperature trends (in the order of 0.01°C/day) agree well with those obtained from the very accurate vibrating wire sensors.

4.4 Fibre optics – Single investigation at Vargfors

The embankment dam at Vargfors is about 700m long parallel to the river Skellefteälven. In 2001 a support toe berm was constructed as well as new drainage ditch. In connection to this work an optical fibre cable was installed at the dam toe of the dam. The objective with the fibre installation was to be a complement to the seepage monitoring (that is performed in three conventional weirs) with temperature measurements.

The first measurement was performed in 9-10 December 2003 in order to check the status of the installation and obtain initial temperature data. The DTS measurements were carried out by James Hampson, Sensornet Ltd, and Sam Johansson, HydroResearch, who also was responsible of the evaluation. The work was done on behalf of Åke Nilsson, SwedPower AB.

A new drainage ditch was constructed just downstream the dam toe. The fibre optic cable was placed in the bottom of the ditch, just upstream two drainage pipes **(**Figure 12**)** in order to allow temperature measurements of the water that seeps through the dam and out into the drainage ditch.

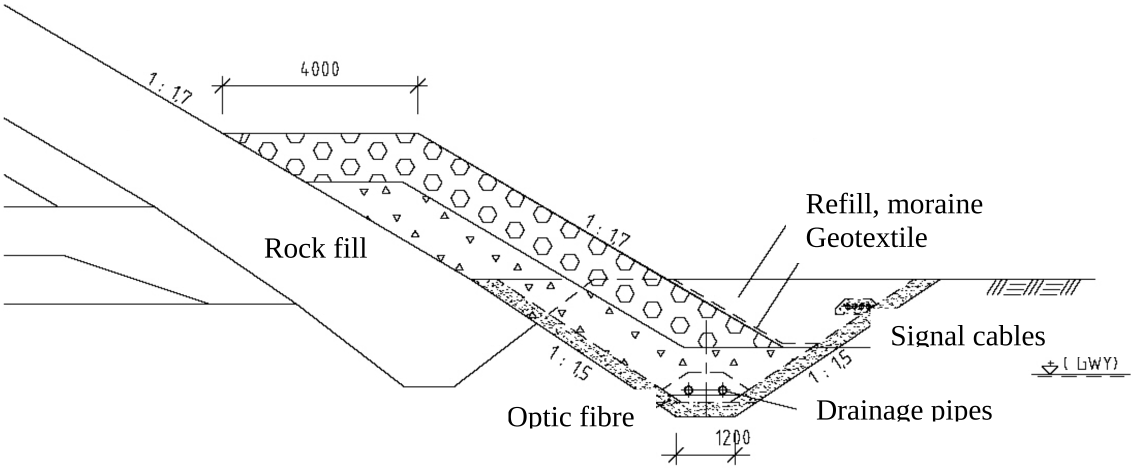


Figure 12 Cross section of the installation

Drainage pipes parallel to the dam toe are connected regularly to wells (called TB1- TB19), where the directional changes are made or additional drainage pipes are added. These additional drainage pipes are directed more or less upstream into the dam in order to reduce the pressure in the downstream part of the dam. At such situations the fibre follows the upstream ditch upstream and downstream before continuing along the dam toe.

Measurements show a temperature in the dam between 4 and 6°C. The temperature change during the measurement time is small. Daily trends have been calculated showing values between 0.0 and -0.1°C/day. These values are less than the monitoring accuracy, which was determined using a vibrating wire temperature sensor installed within a loop of the fibre.

The temperature is given for each meter along the dam, but in the presentation below the result has been transformed to correspond to the dam chainage, using the measured coordinates of the cable. This is cannot be done exactly due to the curvature of the cable between the measured points (with 5m equidistance), difference in vertical level etc. Corrections of internal/external length must also been be done. This transformation will reduce the accuracy of to be in the order of some metres.

The temperature along the dam is showed in section Figure 13). The result shows generally normal seepage conditions with a few possible seepage concentrations. The most significant ones are at section 1615-1620 (D1), and at section 1/120-1/140 (D3). The other ones are smaller and more uncertain, based on this first short measurement. Further measurements are needed to verify and evaluated those anomalies.

The temperature dips that coincide with the TBs are not caused by seepage. The reason is that the upstream drain gives a shorter travel length for the seepage water, compared to its travel length to the dam toe. Therefore, a faster temperature response of the decreasing temperature in the river is seen.

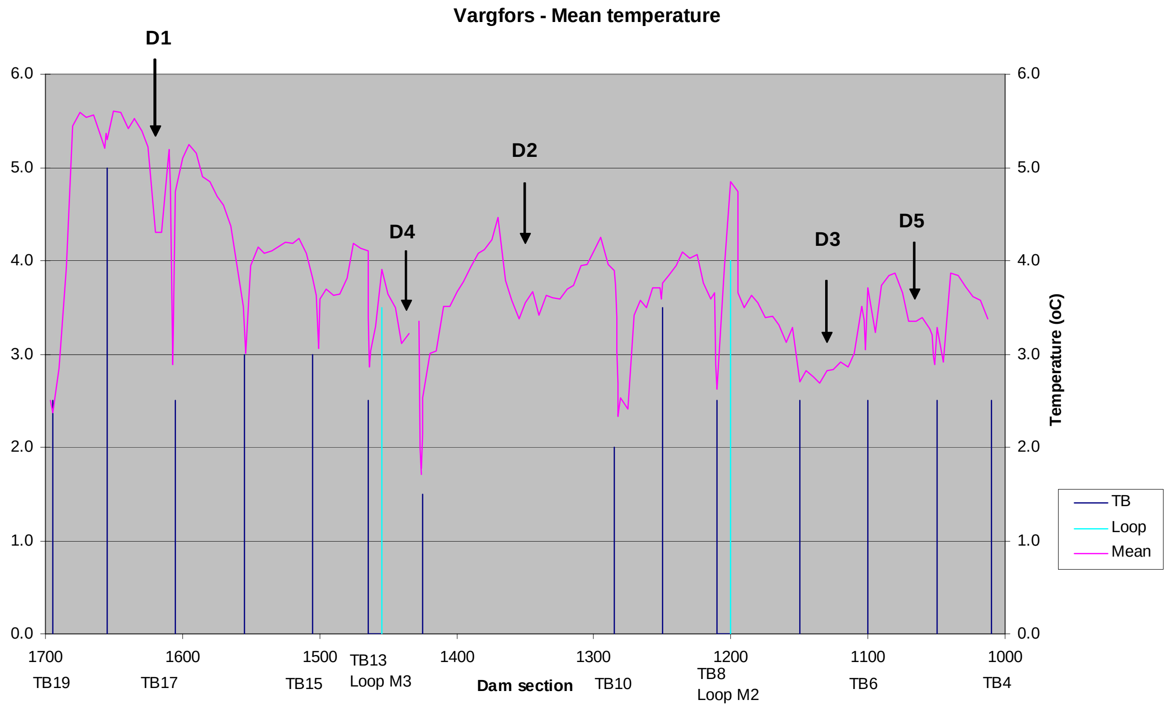


Figure 13 Temperature on each 5m along the dam section.

The first dip (D1) at section 1/615-1/620, is distinct and exhibits about 1°C lower temperature than adjacent parts. This might be a sign of some higher seepage than in the other parts of the dam. The general temperature in the dam (between 3-4°C) indicates normal seepage conditions, and the small deviation at D1 will not affect the safety of the dam.

The second dip (D2) is wider. In this part of the dam the fibre is placed at a longer distance from the toe. The distance to the surface may also be different. Seepage may be a reason for this dip, but it cannot be concluded from just one measurement.

Dip D3 (section 1/120-1/140) is also wide and in that aspect similar to D2. The fibre is however located in the dam toe all over this area, so the temperature is expected to be constant. A seepage outflow cannot be excluded, but no sure conclusions can be drawn so far.

The two last dips (D4 and D5) are concentrated but smaller and more uncertain. Also some other areas could be mentioned as possible seepage areas.

The result from this short test (half day) should preferably be followed up by further measurements in order to improve the evaluation, if needed. One single measurement of a seasonal variation will never give the full answer.

5 LEAKAGE MONITORING TEST AT RØSVATN

5.1 The site

The unique Norwegian test dam at Røsvatn, about 60km south of Mo i Rana was used in a project with the objective to test some geophysical methods for leakage measurements.

The seasonal temperature variation that is used for seepage detection in several dams was not initially intended to be used in this field test. However, the pre-study made within the project showed that the expected temperature difference between the soil in the dam and the seeping water would cause a significant change of the resistivity in the dam during the measurements.

In order to estimate the temperature change within the core it was decided to measure the temperature of the leakage water at the dam toe. By the same way the information could be used to detect seepage outflow.

The dam is an embankment dam, about 6m high and 40m long, with a core of moraine with similar material and geometry as a normal dam. The detailed design of the dam, bedrock level etc. was not known at the measurements or at the evaluation. The reservoir can be drained using four outlet pipes. Two pipes are operated by valves, while the other are equipped with inflatable rubber packers. The outflow capacity is about 0.05-0.1m3/s for each pipe at high pool. Those valves were used in order to keep the water level constant for some hours during the measurements. Measurements were made at six levels, called Filling#1- Filling #6 (Figure 2). Unfortunately, Filling#1 was interrupted.

Figure 14 Downstream view of the dam at low reservoir level.

All leakage water is intended to be caught in a weir at the left abutment. The weir was built in into a concrete bar located downstream the dam toe. Manual measurements were made regularly during the tests. The visual inspections showed that water was passing under the bar on the left side. The leakage flow showed in Figure 2 is thus not the total flow through the dam.

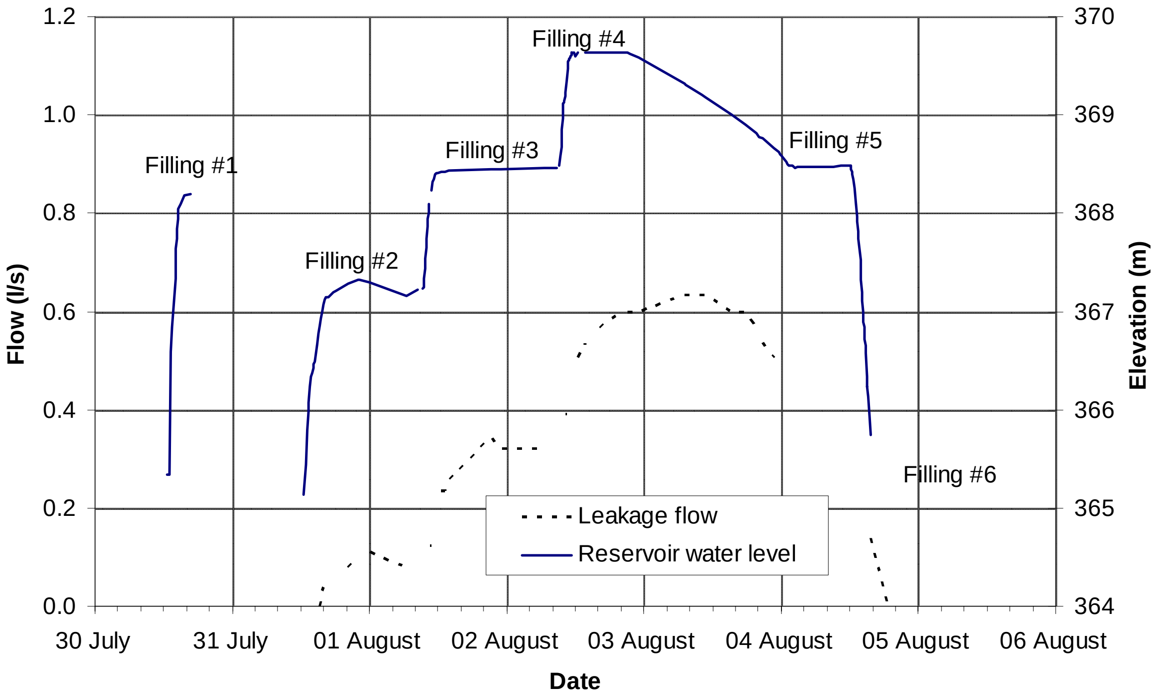


Figure 15 Leakage flow (l/s) in the weir (left axis) at different water levels (right axis).

5.2 Defects

Three defects were constructed in the dam as shown in Figure 16. Information of their size, location and material properties was released long after the final report was given. The material in the all defects was sand. The sizes of the defects were: Defect A - 0.4x0.4m, Defect B - 0.15x1.1m, and Defect C - 0.4x0.4m.

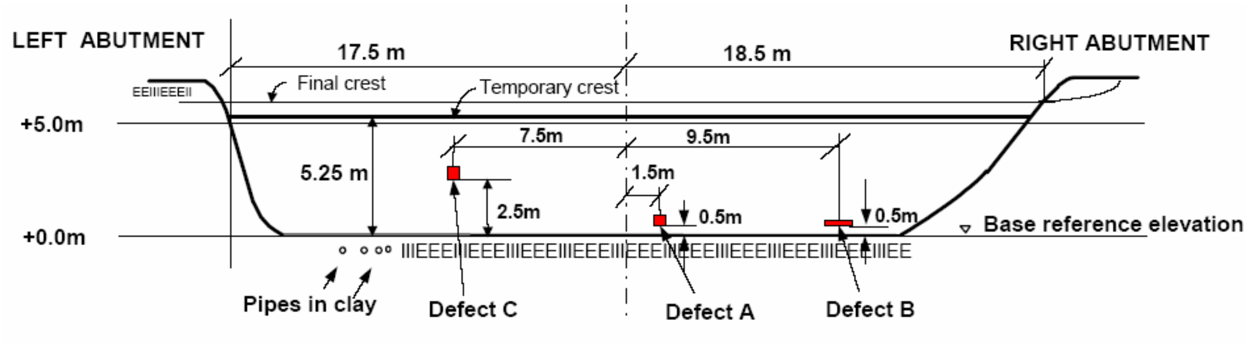


Figure 16 Location of the defects; Defect A at chainage 19m, Defect B at chainage 27m, and Defect C at chainage 10m.

The result presented below (section 6.1- section 6.3, for temperature measurements, and section 7.1-7.5 for visual inspection) is taken directly from the report written by the "Monitoring Group" to the "Defect Design Group". The evaluations presented in section 6.4, and section 7.6 are written after the real locations of the defects were presented, as well as the conclusions.

6 TEMPERATURE MEASUREMENTS AT RØSVATN

6.1 Field installations and measurements

Temperature measurements were carried out along the dam toe using 23 temperature sensors, in order to estimate the temperature change within the dam, and to detect seepage outflow at the dam toe. For measuring the temperature within the dam, sensors placed in the core should have been preferred.

Sensors with high accuracy (Greisinger PT100) were installed at the toe at 5cm depth, starting at section 1.1m and ending at section 34.3m with separation of about 1.5m. Some sensors were exposed to sunshine while other was placed in the shadow between large boulders, depending on the installation possibilities. The conditions were also changed during the filling, and some sensors were finally covered by water.

6.2 Evaluation and results

Temperatures measured at the dam toe are neither able to determine exactly where a leakage will be located in the core, nor able to define the extent of the leakage because: a single leak through the dam may give several outflows at the toe, a large concentrated leakage flow may be wider at the toe, while a smaller leakage will have a more constant width, and; the distance between the sensors (1.5m) will be the smallest resolution. The several fillings in this case will, however, give some indications of the elevation of the leakage as well of the flow. Evaluation can also be done based on: how quick the temperature response will be at a changed filling level, length of the transient temperature pulse, and; temperature difference between the reservoir water and the outflow water.

Some results are presented in Figure 3. At section 23.7m diurnal variations occur during the entire test period. This indicates that the heat conduction dominates, i.e. a low seepage. The effect of a significant seepage is shown at section 28.4m. The diurnal variation is seen both at Filling #1 and #2, until the temperature rise is interrupted, due to the outflow of seepage water. The temperature is then slowly approaching the temperature in the reservoir. The same is seen in section 20.7m at the Filling#3. Significant seepage outflow areas were found in four areas from the temperatures showed in Figure 17 and Figure 18.

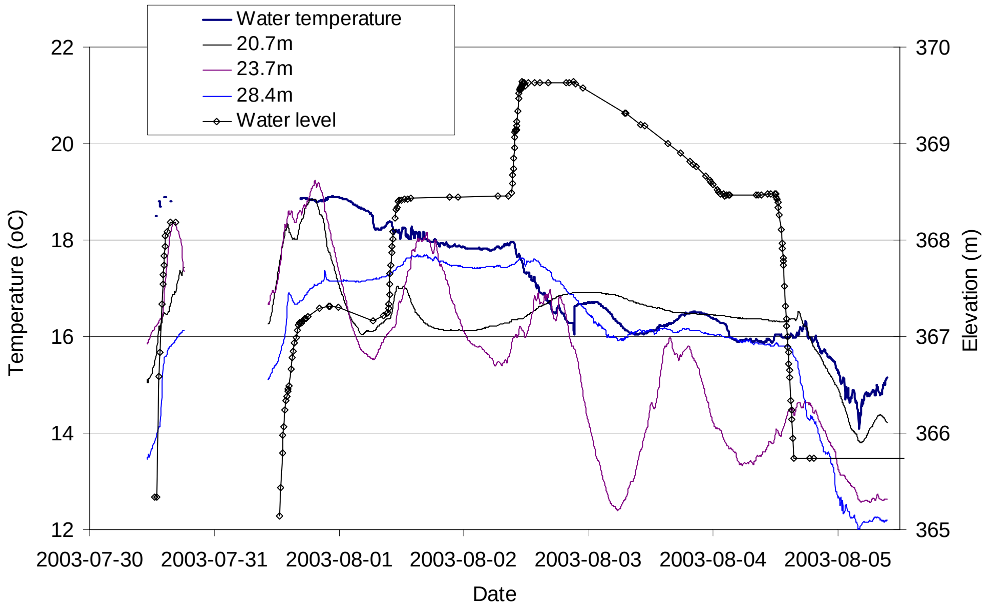


Figure 17 Selected temperature measurements between section 20m and 30m (left axis), and reservoir water level (right axis).

The data were analysed further to estimate the transient temperature change due to the advective energy transport by the seepage flow. Some seepage flow estimations were also made at Filling #1-#3, indicating flows exceeding 0.6l/(s,m^2) at section 27, about 0.2l/(s,m^2) at section 20.7m, about 0.4l/(s,m^2) at section 5.7m, and about 0.3l/s,m^2 at section 10.2/11.6m. The total area of the defect cannot be determined from the temperature data, so the total flow cannot be estimated.

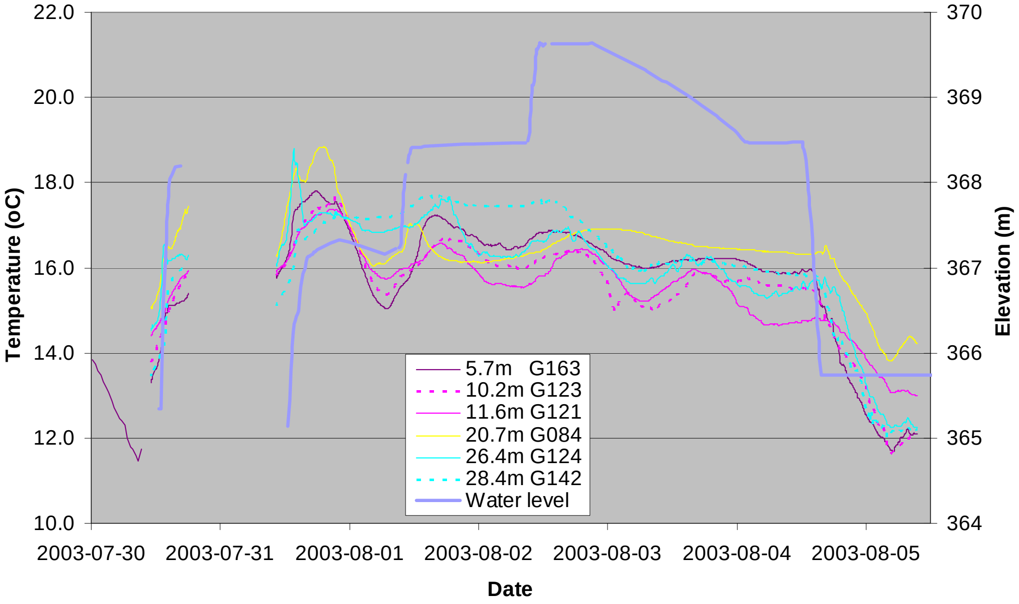


Figure 18 Selected temperature measurements between section 20m and 30m (left axis), and reservoir water level (right axis)

6.3 Detected defects

Four significant leakage paths were detected as summarised in Table 1. The locations at the dam toe may not correspond to the location in the core, but will probably be close. Information about the level and area are interpreted data based on the information from the different fillings. Only the inflow level can be used to estimate the level of the defect. The thermal response is clear at large flows, but at small flow the response may be delayed. It may then be seen after further fillings, which could be misleading when estimating the level of the defect.

Table 1 Summarised result from temperature measurements.

Dam section	Detected at	Estimated inflow level	Final width at the dam toe
5.7m	Filling #1 and #2	365.5m	1.5m
10.2 – 11.6m	Filling #3 or #2	368	2- 3m
20.7m	May be already at Filling#1, but definitively at filling #3	366	1.5m
26.4 – 28.4m	Filling #1 and #2	365.5m	2 - 3m

6.4 Comparison with real defects

These detected leakages areas agrees well with the real ones (Figure 19). Another leakage area was also detected close to the drainage pipes. The elevation in the figure is set to the inflow level ±0.5m. Temperature measurements at the dam toe can normally not exactly determine the level of a defect, just the location along the dam. In this case, however, information from the different fillings could be used to estimate also the level.

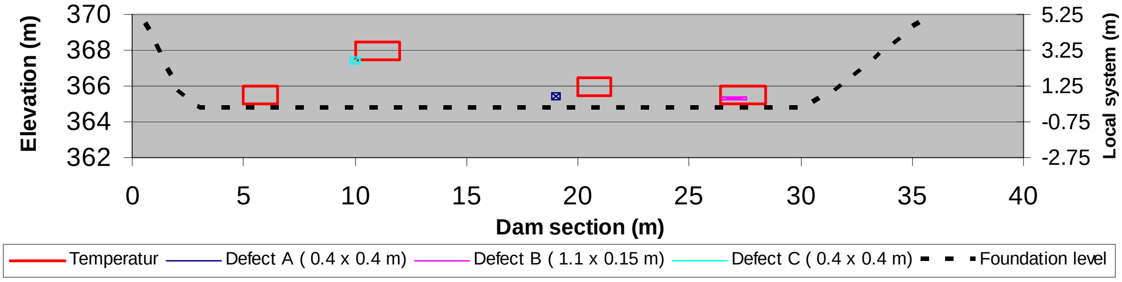


Figure 19 Defect location and defect areas evaluated from temperature measurements. Note that the level is estimated only from the water level in the reservoir.

From the knowledge given after information about the defects were revealed, the flow can be calculated in each defect using the known area (0.16 m^2) of the defects and flux estimation made from the temperature data analysis above. The flow at section 27 (defect B) will thus be about 0.6*0.16=0.1l/s, and about 0.2*0.16=0.3l/s at section 20.7m (defect A). Total flow measured in the weir is about 0.35l/s, at Filling #3. Those values agree well.

7 VISUAL INSPECTION AT RØSVATN

7.1 Dam toe observations at filling #1

No routine observations were made during filling #1, on July 30. A leakage at section 27m was detected around 14:00, just after the filling started. Water started also to overflow the weir at the same time.

7.2 Dam toe observations at filling #2

On July 31, the entire dam toe was dry until 13:43 (at water level about 366m) when a water outflow was found at section 27m, about 1.5m above the dam toe. The outflow area was about 0.5m wide and about 0.3m high, but the seepage was concentrated to two small outflow leakage areas. The rest of the dam toe was dry until the water started to fill up the area upstream the weir. No other wet areas could be observed during the afternoon.

A heavy rain during the evening saturated the dam toe that was still wet the following morning. Inundating water caused by the weir was observed from section 23m to the end of the dam with depths up to about 5cm. A leakage was observed at the left abutment concentrated to connection to the rock, causing standing water up to section 2m.

7.3 Dam toe observations at filling #3

Filling #3 caused slowly increasing flow at both of the previously observed leakage areas. After some ours, standing water was also found between section 4 and 5m. Around 14:00 some outflow was found from the rock on the left side. A very moist area was observed around section 18m. Water was also flowing under the concrete bar. All seepage from the dam was not measured by the seepage weir. Water was also flowing along the drainage pipes (section 8.5m), embedded in clay below the dam.

Generally, the same situation was found in the afternoon (around 16:30). Affected areas were increasing, and the soil also became more or fully saturated. Standing water was found at section 21 and 23m.

At about 21:00 very moist/wet areas was found between section 12 and 19m, and almost saturated around section 22-23.5m. The leakage flows at the old leakage areas were stable.

7.4 Dam toe observations at filling #4

Due to the rain the entire dam toe was wet before filling #4 started. An increasing flow with clear water was observed at the left abutment. Muddy water was found at section 2-4m at 11:30. The entire area between section 12-19m was saturated, and water was standing from section 22m to the end of the dam, and between section 6 and 11.5m. This may also be sign of a small leakage in this area.

7.5 Detected leakages

In summary, several areas with larger outflow were found by visual inspection. Due to the various water levels, some indications were achieved about the inflow level of the defects. These indicated levels are more distinct at high leakage than at low leakage due to the time for the water to pass the dam. Small and diffuse water outflow is further more difficult to detect and estimate, especially at rainy weather. Note also that we can’t be sure that the outflow and defect are located in the same section.

Six areas were detected (Table 2). The first one (section 0-2 m) is probably seepage coming out from the left abutment, and thus not caused by a built in defect. The third one (section 8.5m) has an outflow where the drainage pipes is located, below the foundation level of the dam. This outflow is neither caused by a built in defect. The remaining three may however be caused by the built in defects.

Table 2 Summarised result from visual observations.

Dam section	Observed at	Outflow level (m)	Inflow level (m)	Extension	Estimated Seepage flow (l/s)
Sec 0-2m	Filling #1 and #2 (Morning after lowering the reservoir)	Dam toe +0.5m (Seepage face in silty clay)	367		
Sec 4-6m	Filling #3	Dam toe	368.5	1-2m wide	
Sec 6-11.5m	Filling #4	Dam toe	369.5	3-5 m wide	
Sec 8.5m	Filling #3	Dam toe – 1m	368	Around the pipe	0.2
Sec 18, 21-23m	Filling #3	Dam toe	368	2-3m wide	
Sec 27m	Filling #1 and #2	Dam toe +1.5m	366.5	0.5x0.3m	0.1-0.3

7.6 Comparison with real defects

The result can be compared with the real locations as done in Figure 20. It is difficult to define the level from the water level information, so the inflow level is chosen as the highest possible level. The lowest level is chosen constant, equal to the lowest observed outflow level. Visual inspections will in this case detect all three defects. The seepage outflow areas are much wider than the defect, but will still give some indications where the defects are located.

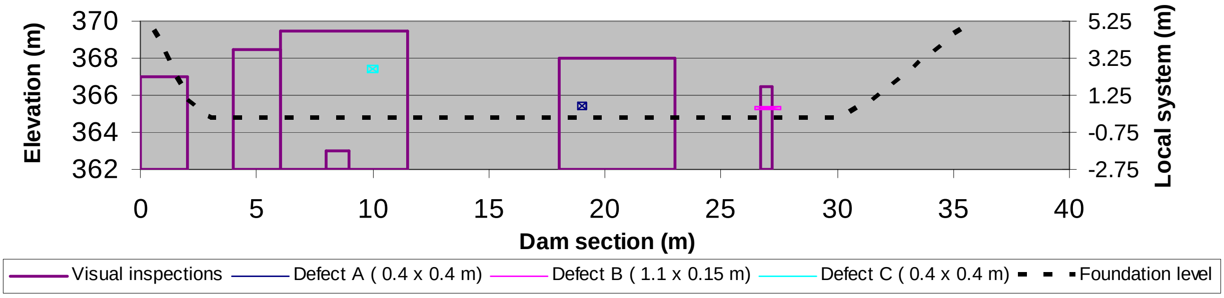


Figure 20 Defect location and defect areas evaluated from visual inspection of the dam toe. Note that the upper level of the defects is estimated only from the water level in the reservoir, and the lowest level is shown as the lowest level of the observed outflow at the dam toe.

8 CONCLUSIONS

The dam toe is probably the most sensitive part of the dam for detection of seepage flow changes. The flow, at least at the Røsvatn test site, seems to pass almost perpendicular to the dam, but with some spreading out. The centre of the outflow area may however indicate defects in the core, although the distance may be significant between the core and the dam toe.

Visual inspection of the dam toe is a well known and a well established method for dam surveillance, and will probably never be replaced by another method. The performance showed at the blind test at Røsvatn was also successful. However, visual inspection is clearly dependent on the weather conditions, and the ability to detect low seepage flow during rainfall is significantly reduced.

Temperature measurement is a sensitive method to detect seepage outflow, which was verified in the blind test at Røsvatn. The best application of the method is long term monitoring, where slow and small seepage flow changes can be detected. The sensibility is in the order of some $10^{-5}m^3/(s,m)$ for normal dams, but depends on where the temperature is measured. If the measurements are taken at a depth of 5-10m from the soil surface a higher sensitivity may be possible, since the influence of the seasonal air temperature variation can be ignored. Measurements taken close the soil surface will be clearly affected of the seasonal variation, which will reduce the sensitivity.

If optical fibres are installed along a dam toe they will provide possibilities to both locate anomalous seepage areas and estimate the seepage flow after short time investigations (normally some days). Longer measurements or repeated measurements will improve the detection capability and the accuracy of the seepage flow evaluations.

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