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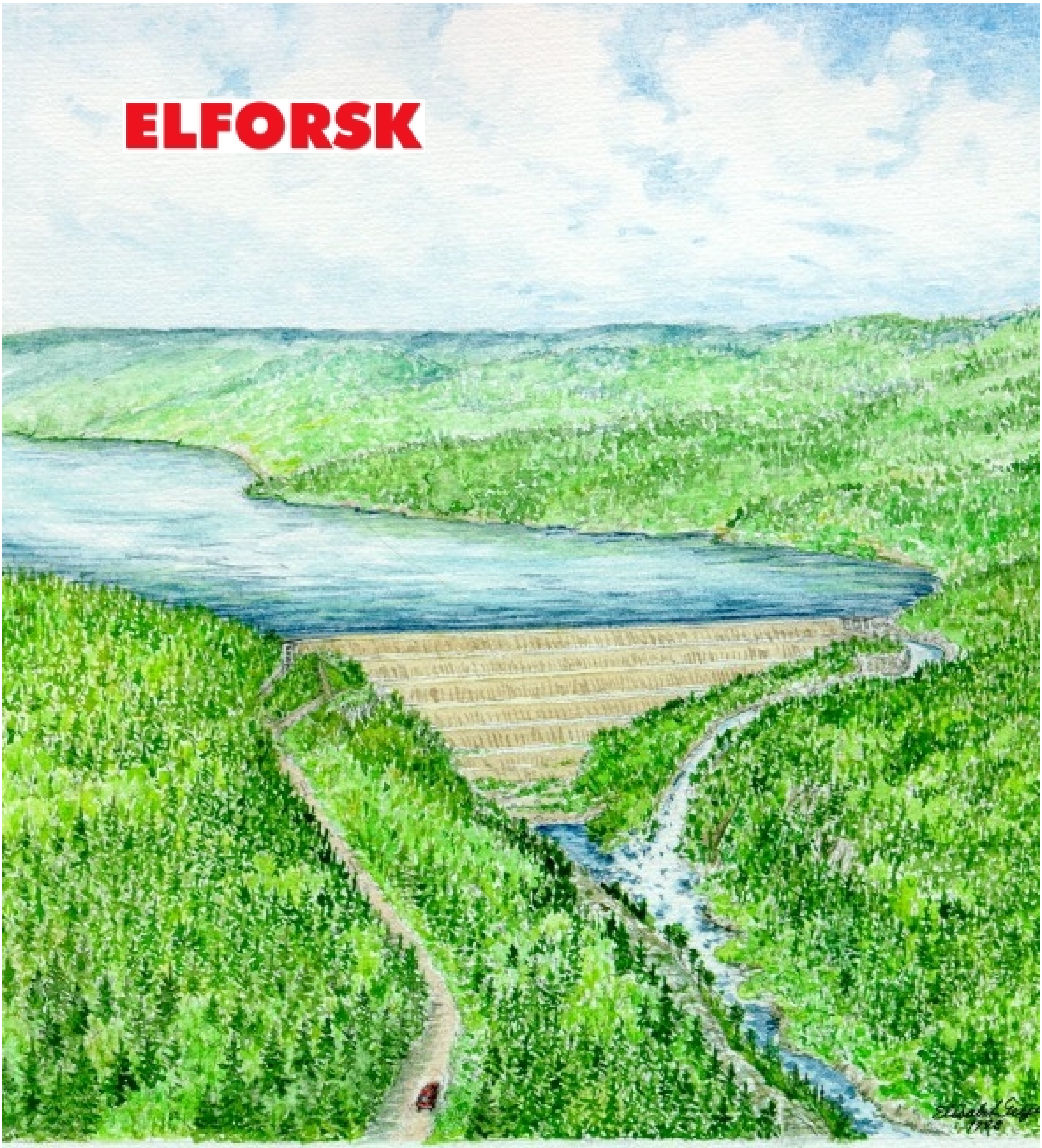

DAMMSÄKERHET

Fibre-Optic System for Temperature Measurements at the Lövön Dam

Rapport 99:36

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Förord

BC Hydros W.A.C. Bennett damm i British Columbia, Kanada, är en 183 m hög och ca 2000 m lång jorddamm som dämmer upp en ca 30 mil lång sjö med en regleringsvolym av 70 miljarder m^3 vatten.

Två sjunkgropar uppstod under juni respektive september 1996 i Bennett-dammen. Man beslöt tillsammans med delstatens dammsäkerhetsmyndighet att magasinsnivån omedelbart skulle avsänkas. Därefter startade omfattande undersökningar av dammen både med mer beprövade metoder samt med nyare metoder som legat i forskningens framkant.

Hösten 1996, i anslutning till det inträffade, beslöts det att ett utvecklingssamarbete skulle starta mellan BC Hydro och svensk kraftindustri med inriktning på dammsäkerhetsfrågor kopplade till inre erosion, sjunkgropar och reparationsmetoder.

Utvecklingssamarbetet har varit mycket givande för båda parter. Det var ett unikt tillfälle att direkt kunna få tillgodogöra sig resultatet av de mycket omfattande utrednings-, undersöknings- och FoU-insatser på högsta internationella nivå. Genom detta utbyte har ett antal rapporter från svensk sida tagits fram, bl.a. den föreliggande. I detta samarbete har Urban Norstedt, Vattenfall Vattenkraft, och Gunnar Sjödin, Vattenregleringsföretagen, utgjort styrgrupp för VASO Dammkommitté och kraftindustrin och finansierande företag har varit alla medlemmar i Svenska Kraftverksföreningen.

Stockholm i december 1999

Elforsk AB

Sammanfattning

Temperaturmätningar i vattenståndsrör har utförts vid Lövöns kraftverk sedan 1993 för att lokalisera områden med avvikande vattenströmning, samt för att följa förändringar av läckaget. Erfarenheterna har varit goda. I samband med ombyggnaden av dammen 1998 installerades optiska kablar avsedda för temperaturmätningar. Tekniken för att mäta temperaturen längs en optisk fiber har utvecklats snabbt under det senaste decenniet. Prestanda har ökat samtidigt som kostnaderna sjunkit. Denna utveckling bedöms kunna fortsätta ytterligare.

Installationen vid Lövöns kraftverk är unik. Fiberoptiska kablar omger tätkärnan på olika nivåer utmed en sträcka av 60-100 m. Sammanlagt finns ca 1750 m kabel i dammen, vilket ger lika många mätpunkter. Dessutom finns tre mätsektioner där konventionella tryck- och temperaturgivare har installerats. Dessa temperaturgivare har en mycket hög noggrannhet, vilket medför att kontroll av det fiberoptiska systemet kan utföras.

Mätningar utfördes under cirka tre månader (mellan 1998-11-11 till 1999-02-15). Systemets driftsäkerhet var hög liksom den relativa mätnoggrannheten, vilket bedöms vara bättre än 0.2°C. Den absoluta mätnoggrannheten var dessvärre sämre (ca 2.5°C). Detta beror förmodligen på en felaktig kalibrering på plats för den aktuella fibern. Tack vare de konventionella temperaturgivarna kunde systemet kalibreras i efterhand. För kommande installationer bör därför konventionella temperaturgivare installeras för detta ändmål.

Mätningarna har gett en god bild över temperaturvariationerna i dammen. Dessa är homogena vilket tyder på att dammens funktion är den avsedda. På grund av den korta mätperioden, samt den lagrade värmen från dammens byggnation, har ej någon utvärdering av flödet gjorts. Detta är dock möjligt vid eventuellt fortsatta mätningar. De något lägre temperaturerna där den nya tätkärnan ansluter till den gamla tätkärnan antyder att vattenströmningen där är högre.

Kostnaden för kabeln och installationen uppgår till cirka 32 kr/m. Denna kostnad är liten i jämförelse med dagens kostnad för mätinstrumentet, som uppgår till cirka 900 000 kr.

Genom att temperaturen kan mätas över hela dammen kan en bättre förståelse erhållas för temperaturförloppet i dammen. Installationen är än så länge unik, varför det finns stort intresse av att följa de resultat som kan fås. Installationen kan användas i flera forskningsprojekt, där temperaturens inverkan har betydelse. Bland dessa kan speciellt nämnas:

- Temperaturmätningar för verifiering av utvärderingsmodeller för vattenströmning, samt,
- Temperaturmätning i dammkrönet för studier av tjälförlopp.

Summary

The rapid development of fibre-optic systems within the last decade has further increased its applicability for dam monitoring. The number of parameters that can be measured has increased, as well as the monitoring performance.

The objective with this project was to test such a system for a new dam, where a complete installation was possible to achieve. This initial short time test could then be followed by long term monitoring both for research purpose and for monitoring the dam performance.

A first test installation for temperature measurements was made at the Lövön embankment dam. Two optical fibres were installed for research purposes in the dam for a Distributed Temperature Sensor (DTS) system. Measurements were made between 11 November 1998 and 15 February 1999. Three monitoring sections were also established for long term monitoring of pressure and temperature. The result between the two temperature monitoring systems could then be compared.

The DTS measurements were successful but not as accurate as expected. The relative accuracy was excellent (below 0.2°C) but the absolute temperature was 2.5°C higher than temperatures measured by the temperature sensors in the piezometers. However, the results provide valuable information about the seepage in the repaired part of the dam and adjacent part of the old dam. The relative accuracy is sufficient, but the absolute accuracy must be improved. Another way may be to install other type of temperature sensors that can be used for calibration. This should be considered in new installations.

The results provide valuable information about the seepage in the repaired part of the dam and adjacent part of the old dam. Similar installations should therefore be valuable in new embankment and tailings dams.

Thanks to the accurate vibrating wire temperature sensors the installation can be used for testing other types distributed temperature monitoring system in field. This will be of importance when new system will be presented.

Outdoor installation cost was 20SEK/m and the cost of the fibre was 12SEK/m. The cost for each installed temperature sensor will then be 32SEK (<4USD). The cost for the monitoring system was about 900000SEK, but was rented for the measuring period. Other systems with lower performance and lower cost were also available. Future development will reduce the cost and improve performance.

The installation is still unique in the word and can be used in several ways in the future research projects, in addition to the basic monitoring of the dam performance. Of special interest are:

- Temperature monitoring to develop seepage evaluation methods; and
- Temperature monitoring to study frost penetration in the core crest.

Content

1 Introduction

Two sinkholes occurred in 1983 and 1986 at the Lövön embankment dam, just about 10km south of Strömsund. Several actions (grouting, stabilizing berm, increased monitoring etc) were taken. It was then conclude that internal erosion was the most reasonable reason. In 1997 it was decided to repair the entire damaged part of the dam, which was done in the summer 1998. The chosen repair method was construction of a new dam combined with a slurry trench. The work allowed installing fibre-optic cables in order to test a new type of temperature monitoring.

Internal erosion is a major cause of failures in embankment dams. The seepage flow increases slowly, closely coupled to the induced material transport that can take place over a long time. The potential to detect local internal erosion at an early stage is limited with traditional seepage measurement because the drainage collecting area is too large. Seepage monitoring systems with higher accuracy and resolution are therefore needed. Of particular importance are methods that are able to register small changes in the seepage rate through a dam, and thus detect internal erosion at an early stage before it starts to affect the safety of the dam.

Regular temperature measurements started in the Lövön dam in 1993. The temperature result has been valuable to detect seepage areas and areas where seepage changes occur.

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. This installation at Lövön is unique and provides excellent possibilities to study both monitoring methods and temperature/seepage phenomena, which are the main objective with this project.

The research project has been funded by Elforsk AB and the installation has been provided by Graningeverkens AB.

2 Fundamentals of distributed fibre optic systems

2.1 Background

The development of fibre optics for distributed temperature measurements was started in the middle of the 1980s (e.g. Dakin et al. (1985)). Since then, commercial systems have been developed and the performance of distributed sensors has steadily improved. More recently, a new approach has allowed optical fibres to measure strain and pressure, e.g. Horiguchi et al. (1989). Early systems based on this new idea could not distinguish between changes in strain (or pressure) from changes in temperature, however a system has recently been demonstrated that can measure these parameters independently (Parker et al – 1997).

2.2 Measurement processes

When light is launched down an optical fibre, 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 so 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 both the amplitude and frequency shift of the Brillouin light can be measured, temperature and strain can be simultaneously determined. Also, as pressure can be converted into strain in the fibre, the Brillouin technique may be used to simultaneously measure temperature and pressure.

2.3 Temperature Sensing

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 weak backscattered light at the Raman wavelengths is recorded against time. Analysis of the Raman light powers 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 1m, temperature resolution of ±0.25°C, measurement time of 60 seconds and a range of a few kilometres are now commercially available.

2.4 Strain and temperature

Raman light can be used to measure temperature, however, the Raman signal is insensitive to the axial strain in the fibre. To measure strain, Brillouin scattering is used. This has the advantage of having a higher signal level than that of Raman scattering, but requires more care in the system design as it is necessary to measure the frequency, as well as power, of the Brillouin signal. The Brillouin frequency depends upon the strain and the temperature of the fibre. For isothermal conditions, it is possible to determine the strain of the fibre by measuring the frequency alone, however, in most cases, it is necessary to have some other means of determining the temperature of the fibre. This can also be achieved using Brillouin scattering since the power of the Brillouin light depends linearly upon the temperature of the fibre (and negligibly upon the strain of the fibre). By measuring the Brillouin power, then, it is possible to determine the temperature and use this to correct for temperature cross-sensitivity in determining the strain from the Brillouin frequency.

2.5 Pressure and temperature

Changing the pressure around a fibre induces a strain in the fibre. In this way, the technique described above can equally be used to determine pressure and temperature. The only difference between the two systems would be in the way the fibre is installed. For strain and temperature measurement, the fibre should be attached to, or placed within, the structure whereas for pressure measurement, the fibre should be loose and immersed in the fluid whose pressure is to be determined.

3 The Lövön Embankment Dam

3.1 General

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.

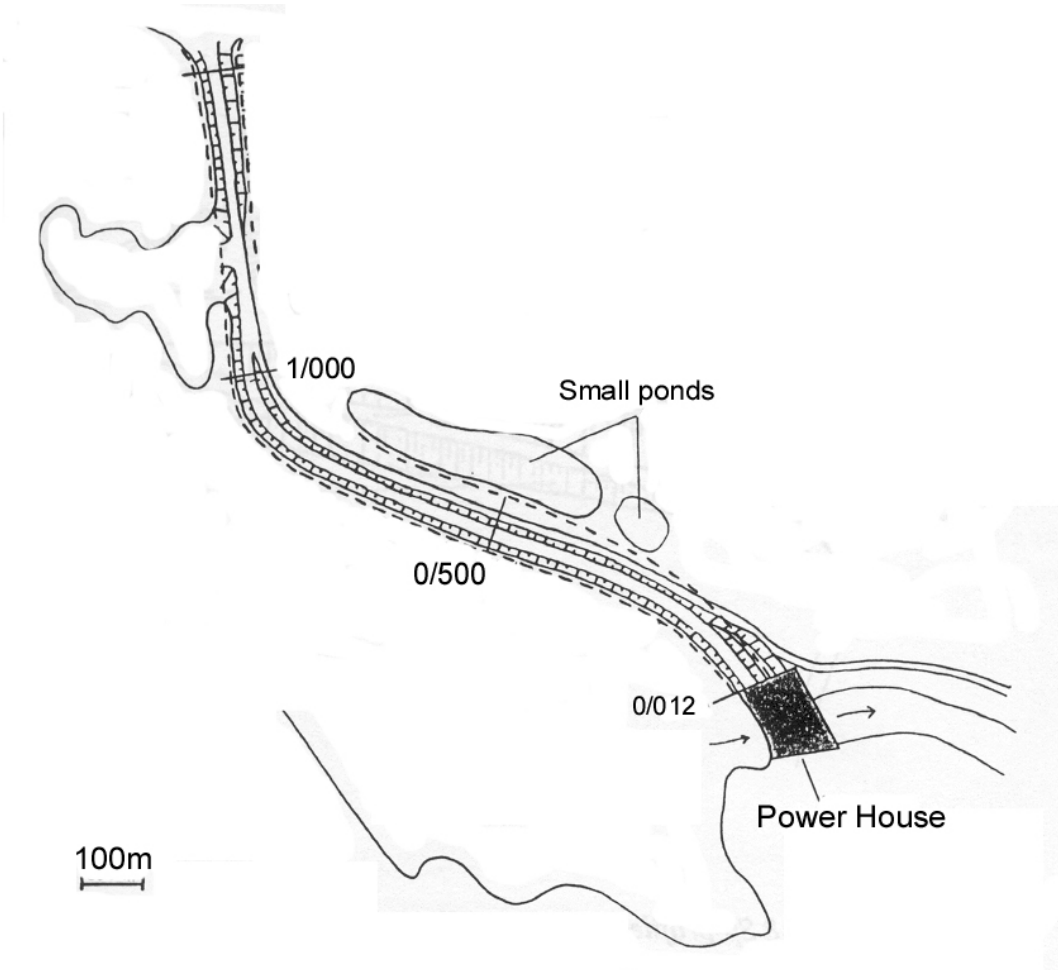


Figure 1 Plan over Lövön embankment dam.

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. The bedrock is between El. 264 and 267. This implies that water leaking through the bedrock and the dam cannot be collected and measured.

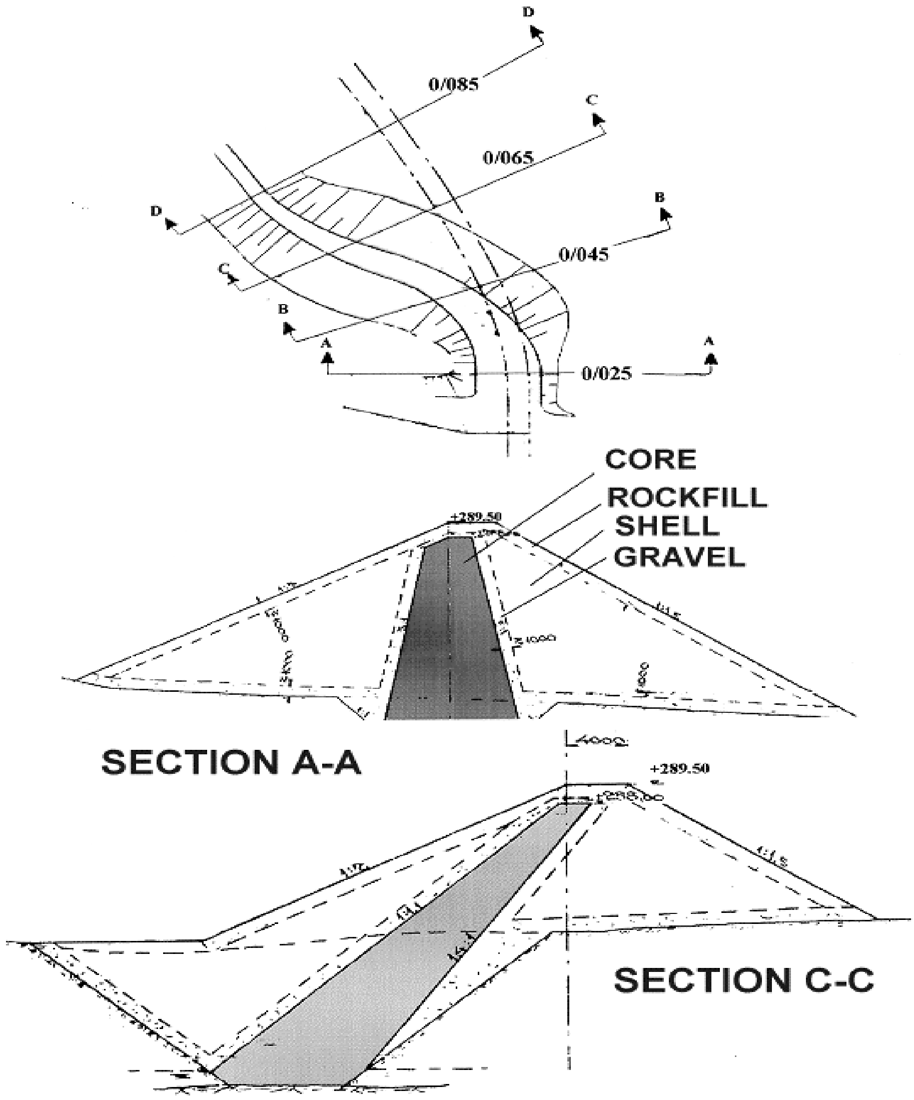


Figure 2 Plan (detail) and two sections over Lövön Embankment dam.

3.2 Operational experiences

A sinkhole occurred in 1983 on the upstream face at 37m from the centre of the intake section (section 0/037). The volume was estimated to be 6-8m^3. The sinkhole was backfilled and investigations started. The monitoring of piezometer levels was also extended in the new standpipes. In 1986 a wider sinkhole was observed at almost the same place (largest depth at section 0/034). This sinkhole had an extension of about 20m^2 and was about 1m deep, see Figure 3. After further investigations in 1986 and 1989 it was concluded that internal erosion was going on in the dam. Grouting was performed in 1992 in the bedrock and in the contact zone between the rock and the core. The total amount of cement grout in the contact zone was about 20 tonnes and about 20 tonnes in the bedrock. A stabilising downstream berm was also constructed in 1994 in order to achieve an acceptable safety margin against a dam break.

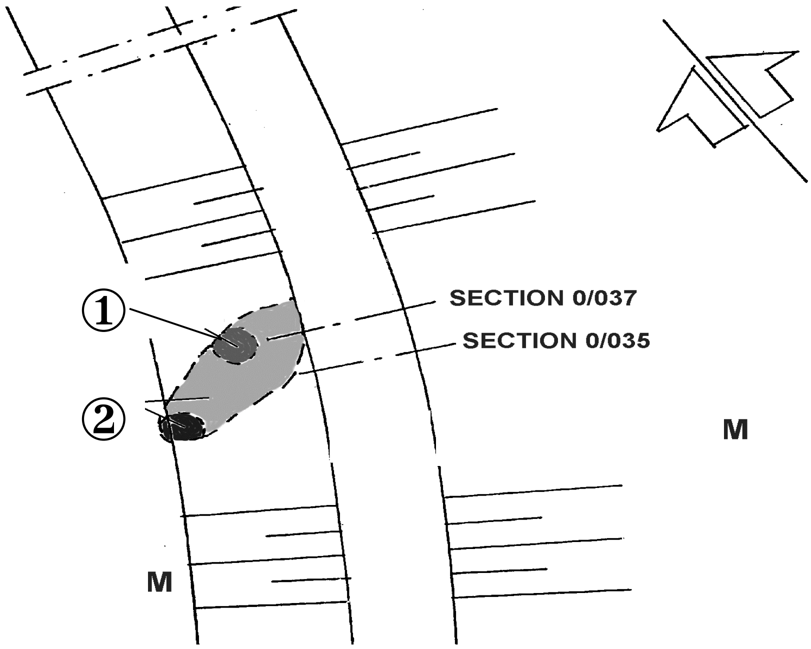


Figure 3 **Location and extension of the sinkholes in 1983 (①) and 1986 (②) on the upstream side.**

Temperature measurements were started in 1993 in order to locate seepage areas and detect seepage changes. A small seepage increase was detected in the lower part of the core at sinkhole area and in the bedrock in outer part of the grouted area.

Water levels in the standpipe increased suddenly in August 1997. After examination of all results the owner Graningeverkens AB decided to repair the dam the following year.

3.3 Rehabilitation in 1998

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, a diaphragm wall was constructed in the old 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 was placed on a filter layer with a geomembrane on top that was sealed towards the sheet pile, see Figure 4.

Figure 4 **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 Graningverken AB)**

3.4 Conventional monitoring installations for pressure and temperature

Three monitoring sections were established (in section 0/035, 0/045 and 0/060) to monitor pressure in the foundation, in the old core, and in the downstream part of the new dam. The locations of the piezometers were chosen such that the function of the diaphragm wall, the rock grouting and the new dam could be studied.

All cables were drawn downstream perpendicular to the dam line out into the downstream filter. Cables from one level were collected together, attached to the concrete wall close to the intake, and then further attached to a multiplex unit. The unit was connected to a data logger that was controlled by a PC. The PC had a modem and could be fully remote controlled. All data was stored in the PC for presentation and analyses. The automatic system started to run on the 14^{th} of January 1999 due to some initial problems with the communication between the multiplex unit/data logger/PC. Manual measurements were carried out until during the construction time.

The pressure was measured by five vibrating wire piezometers (Geokon 4500SX-50) that were installed in each of section 0/035 (denoted as 035:1, 035:2, … 035:5) and 0/045 (denoted as 045:1, 045:2, … 045:5). Two piezometers were also installed in section 0/060 (denoted 060:1 and 060:5). The location of each piezometer was similar for all sections (see Figure 5).

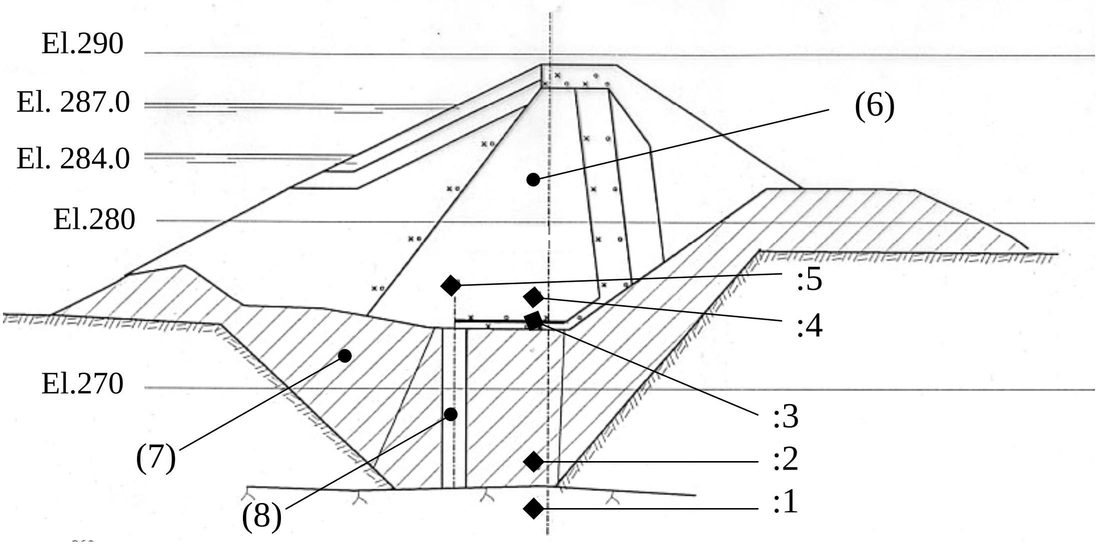


Figure 5 Section through the dam showing the instrumentation installations.

(:1) piezometer in the bedrock
(:2) piezometer in the old core
(:3) piezometer in the downstream filter
(:4) and (:5) piezometer in the new core
(6) New part of the dam
(7) Old part of the dam
(8) Diaphragm wall and sheet pile

The piezometer type Geokon 4500SX-50 has also a vibrating wire sensor for temperature measurement. The temperature accuracy is better than 0.05^{o}C. Temperature will then be measured in the same points as the pressure that is showed in Figure 5. Two of the piezometers (35:3 and 45:3) are located close to the fibre-optic cables and can therefore be used for calibration.

4 Installations for fibre-optic measurements

4.1 Distributed Optical Fibre Temperature Sensor

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 dam to section about 0/060 or more and is then returned back on the same elevation, see Figure 6.

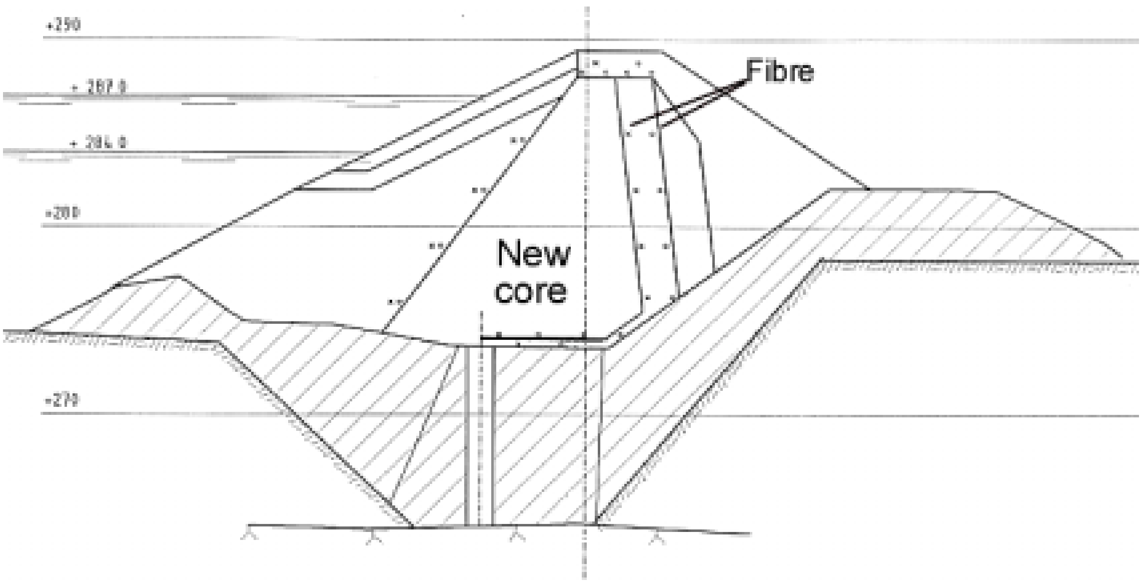


Figure 6 Location of the fibre-optic cables at the Lövön dam.

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. The cable was marked on each metre and the fibre location of the fibre was measured on each 5m. The location of the measuring sections in fibre can thus be determined. All elevations as well as the endpoints for each elevation are shown in Table 1.

The optical fibre cable is a gel filled polyester unitube design containing four individually coated (250µm) fibres. The central tube is surrounded by aramid yarn strength members with an inner polyethylene sheath and an outer nylon sheath. The cable is water, oil, chemical and insect resistant.

The fibre was buried carefully in the filter material. Special attention was taken at the vertical rise along the concrete wall. To reduce effects of eventual settlements a cable loop was made before the rise, see Figure 7.

Outdoor installation cost was 20SEK/m, giving a total cost of about 40000SEK. The cost of the fibre was 12SEK/m. Total installation cost was thus 120000SEK. The cost for each temperature sensor will then be about 32SEK. Indoor installation cost was about 50000SEK.

Table 1 Location of the optical fibres.

Fibre 1	**Upstream and above the new core**	**Fibre 2**	**Downstream side, below and above the new core**	
Elevation	Endpoint Section	Elevation	Endpoint Section	Remark
+276.0m	0/062	+273.75m	0/057	Filter below core
+279.0m	0/079	+274.0m	0/062	Filter and core
+282.0m	0/081	+274.0m	0/062	Filter
+285.0m	0/094	+276.0m	0/063	Filter
+288.0m	0/098	+279.0m	0/070	Filter
+288.3m	0/098	+282.0m	0/080	Filter
		+285.0m	0/093	Filter
		+288.0m	0/099	Filter, above core

Figure 7 Installation of the upstream fibre, with an extra loop close to the vertical rise along the concrete wall.

4.2 Temperature monitoring device

The Distributed Temperature data were obtained using a DTS 800 manufactured by York Sensors. The spatial resolution of this system is about 1 m 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). A spatial resolution better than 1.3m will be obtained (data from York Sensors).

The monitoring unit was installed in the powerhouse. It was controlled by the same PC that was used to store the data from the vibrating wire sensors. The measurement time for each cable was about 10 minutes. Data was stored once a day from November 11 until January 11. From January 21 to the end of the period (February 15) each measurement set were stored, giving a time resolution of about 20 min.

Figure 8 DTS-monitoring system and PC with modem.

The cost for this system was about 900000SEK (1999), but was rented for the measuring period. Other system with lower performance and lower cost was also available. Future development will reduce the cost and improve performance.

5 Result

5.1 Temperatures measured by the vibrating wire sensors

All temperatures measured by the piezometers exhibited very stable values. Data from each two minutes during 12 hours showed a maximal difference of less than 0.001°C, corresponding to the general trend. The standard deviation was less than 0.0002°C. Measured temperature by the vibrating wire sensors seems therefor reliable.

A general decreasing temperature trend in the core was observed for the first months, see Figure 9 until summer 1999, when the temperature increased. The linear decreasing temperature in the beginning was probably a consequence of the heat built-in during the summer, which slowly adjusts to the mean annual air temperature. Another reason for the decreasing temperature may be the drainage of the water from the precipitation from the construction time that also causes an advective energy transport.

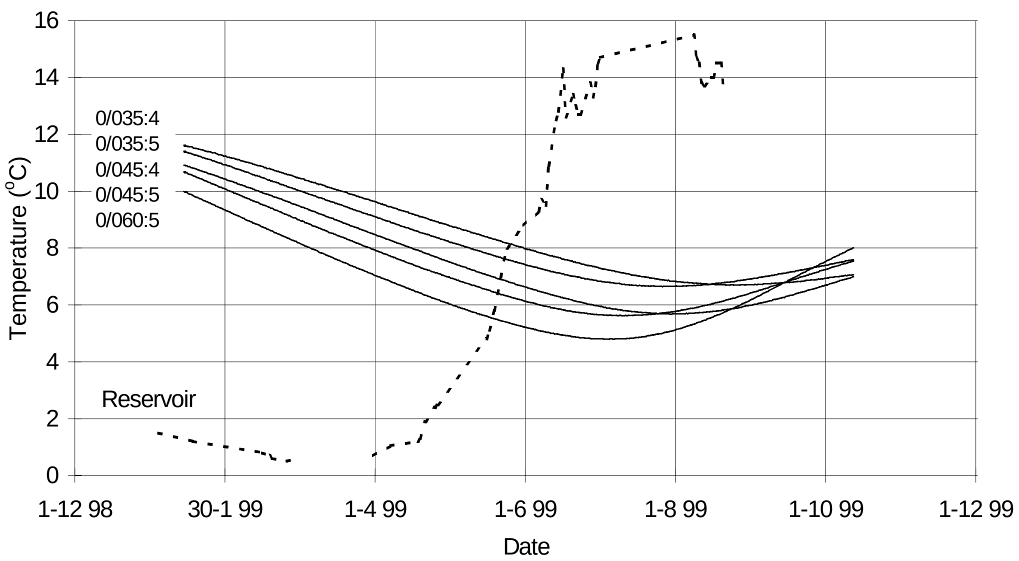


Figure 9 **Temperature in the core in five sensors and in the reservoir. The location of the sensors (sec:1-3) is shown in Figure 5.**

Measurements in the bedrock indicate a significantly lower temperature in section 0/060 than in the other sections. The temperature was about 3°C in the beginning of January and reached its lowest value (about 1.9°C) in March. Some weeks after the temperature started to increase in the reservoir, a temperature increase followed in the bedrock. The low minimum temperature and the rapid thermal response indicate seepage through the bedrock.

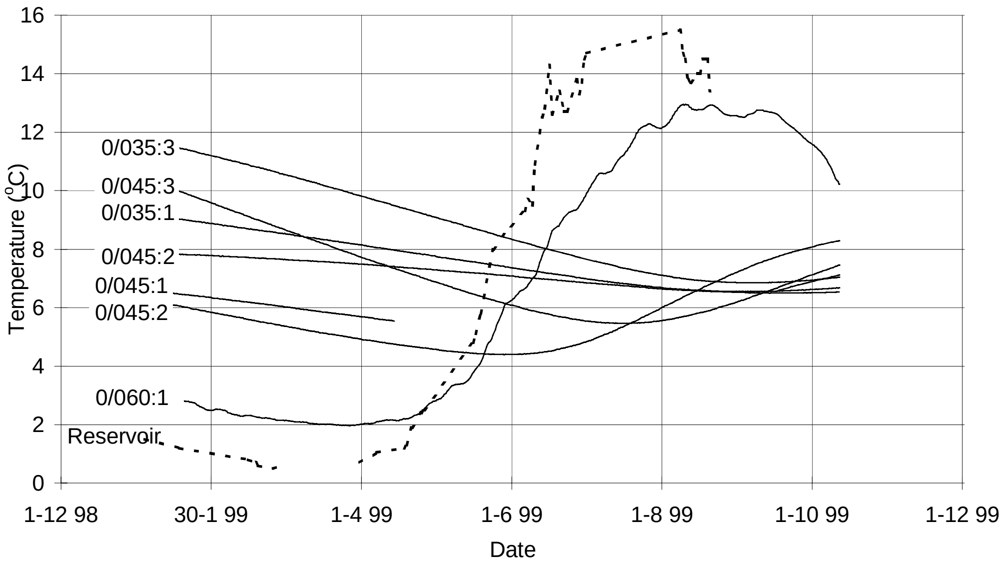


Figure 10 **Temperature in the bedrock and the downstream part of the dam. The location of the sensors (sec:1-3) is shown in Figure 5.**

5.2 Accuracy of the DTS-System

The DTS system showed a high reliability and was in continuous operation during the measurement period. Data storage, however, was interrupted due to a computer stop in January.

The general behaviour of the temperature obtained by the DTS-system exhibits larger variations than the temperature measured by the temperature sensors in the piezometers. A variation of ±0.5°C was common and even larger peaks or drops can be found along the entire fibre length. Those peaks or drops were probably caused by errors in DTS-system itself, because such temperature changes all over the dam are not probable. No such changes have either been found by the vibrating wire temperature sensors, which showed a very stable temperature with slow long-term changes.

Basic output from the system is the temperature along the entire cable, as in Figure 11. The data clearly shows how the cable is installed. First it's an internal reference loop within the instrument, followed by some 10m inside the powerhouse. The fibre is then attached to an outdoor cable stage and comes to the dam after about 130m. Then the measurements start at the different levels in the dam. The return point can easily be seen because the temperature is lower at the end. A mirror image can also be seen on each elevation. After 1020m the fibre returns the same way to the instrument in the powerhouse. The temperature variation during the measuring period is 0.9°C in the reference coil, some degrees in the dam, and about 28°C in the outdoor part.

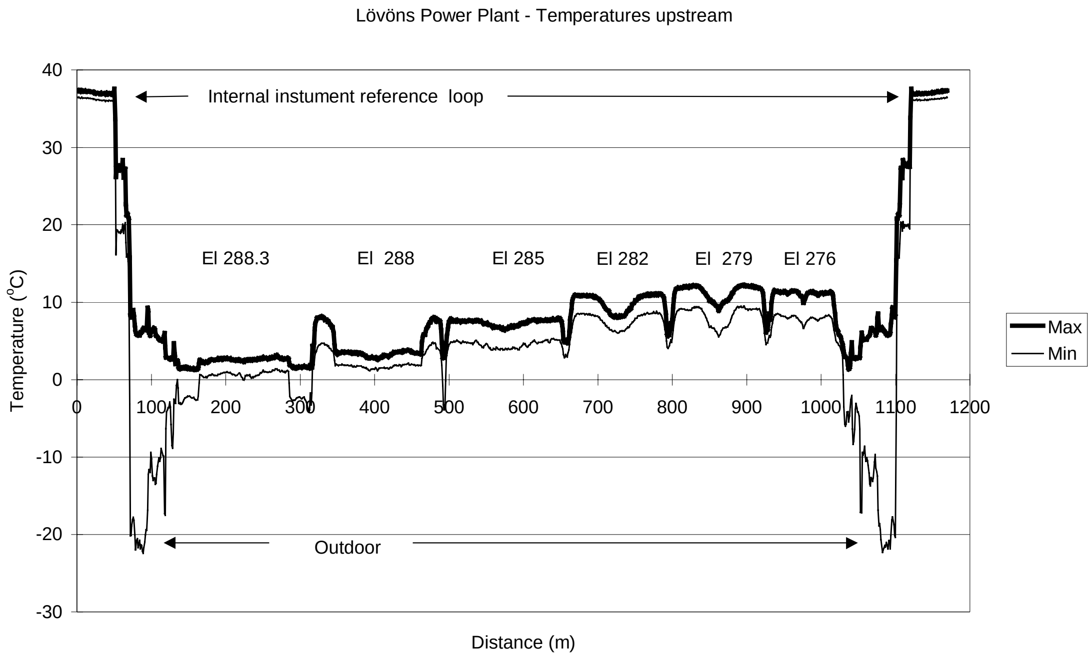


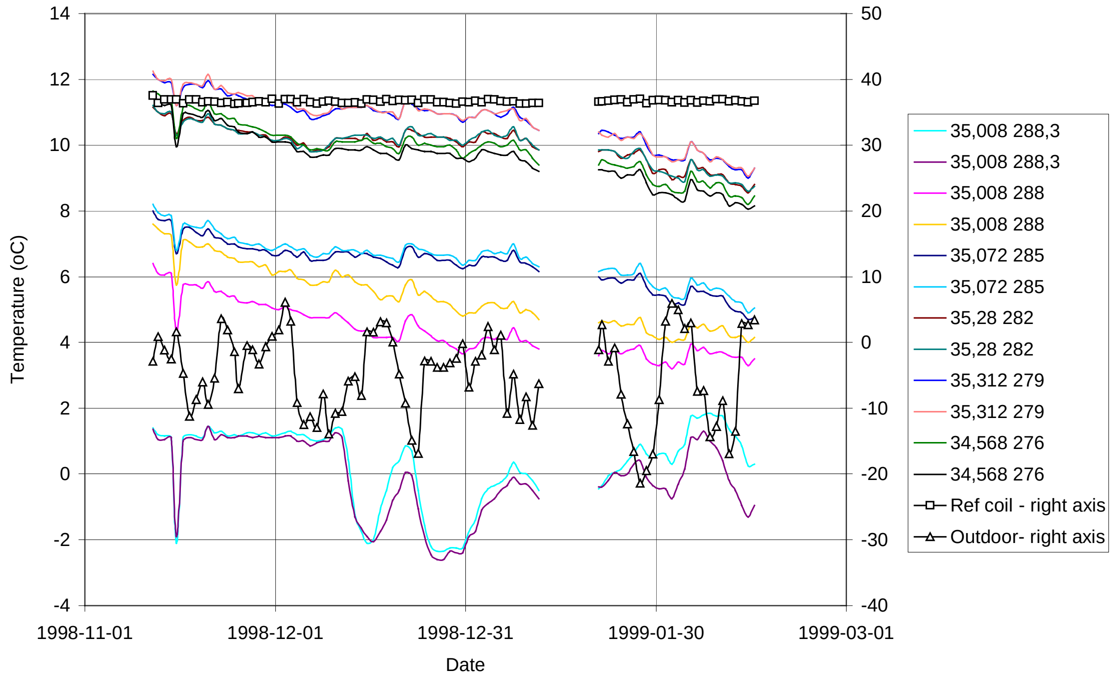
Figure 11 **Maximum and minimum temperature in the upstream fibre during the measuring period.**

Some examples of data in section 0/035 in the upstream fibre illustrate the accuracy and repeatability of the system, see Figure 12. The forward and backward fibres are located very close to each other in the upstream face up to El 285m. The measured temperatures at El 285m and below can therefore be compared with each other. The system shows in this case a good agreement (a deviation <0.2°C) that might be a representative value for the relative accuracy.

However, several sudden dips and peaks all over the both fibres indicate some errors in the monitoring system, because any similar pattern cannot be observed for the vibrating wire temperature sensors. These errors are sometimes short, as in November 1998 with a dip of two degrees for one day. Errors occur also at several days as the one-degree dip around January/February 1999.

These errors are though to be resulted from the temperature variations of the internal reference oven. The reference oven houses a 50m section of optical fibre that is used to evaluate the coefficients of the backscattered light and to calculate the temperature profile along the entire length of the sensing fibre. The temperature of the reference oven is controlled and assumed to be constant but it is not measured. However, if the temperature of the reference section changes, say due to sudden temperature change of the control room, then this will appear as a temperature change through the whole length of the sensing fibre. On solution to avoid this possible error is to measure the actual temperature of the reference oven and use this rather than the assumed value.

a)



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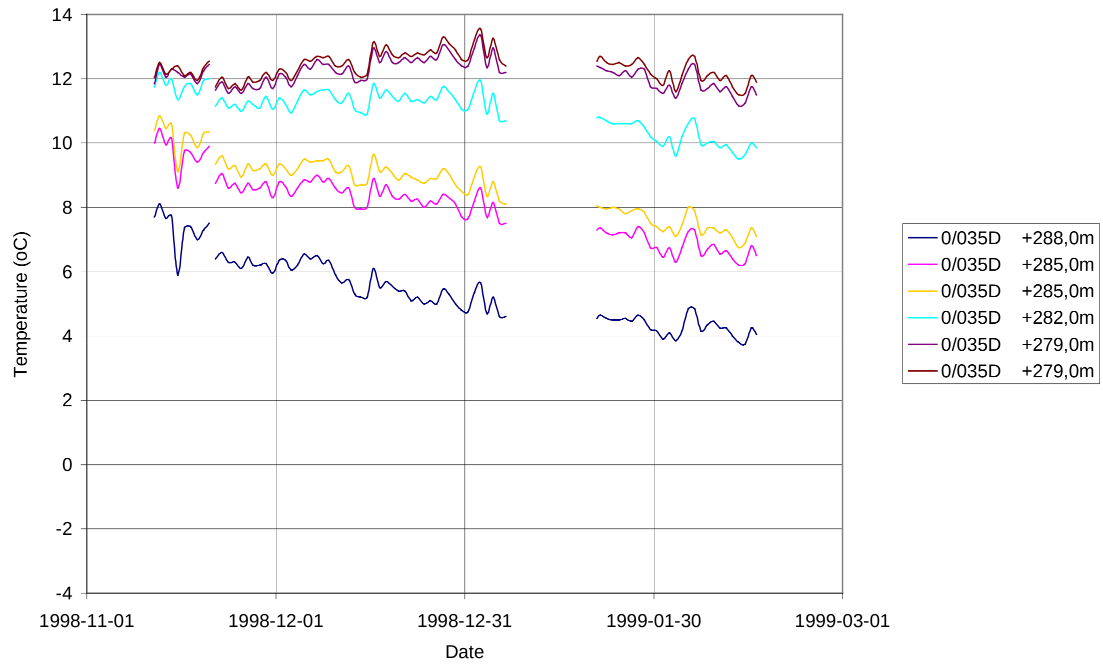

Figure 12 **Measured temperatures in the onward and backward fibre in section 0/035 at different elevations upstream (fig a) and downstream (fig b).**

All data presented above are daily data stored at noon. However, the result from the last period with measurements each 20 minutes gives similar result, see Figure 13. Shorter peaks and dips can also be found on this time-scale. These are larger than the normal noise that is about ±0.2°C. If those large dips and peaks could be eliminated the accuracy should be improved.

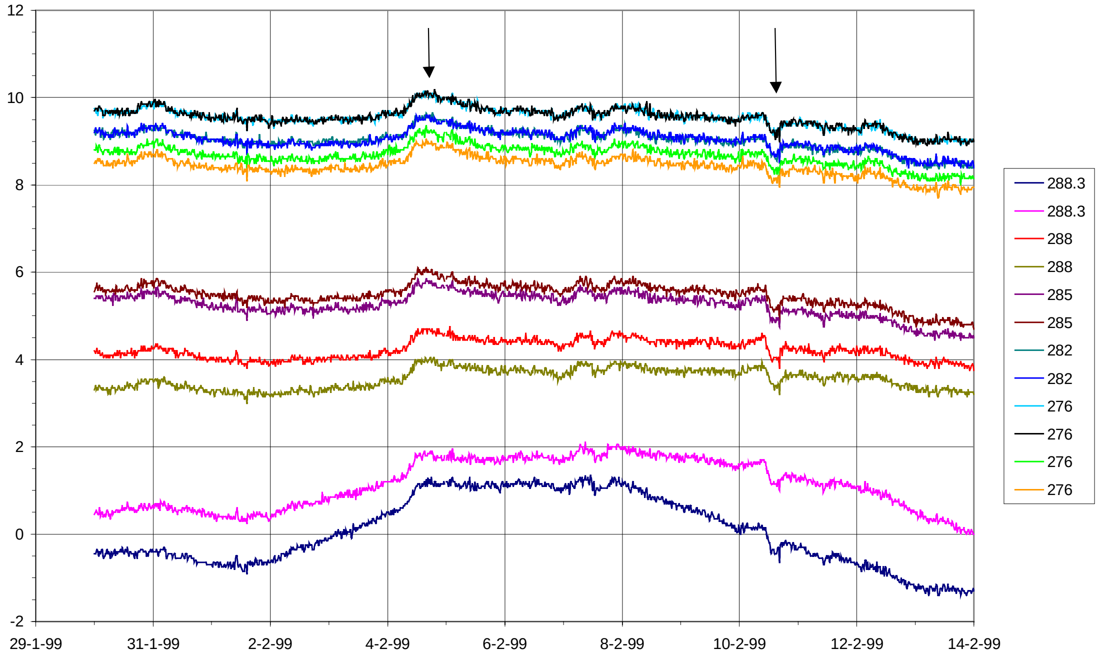

Figure 13 **Measured temperatures each 20minutes in sec 0/035 at different locations on the upstream side. The arrows indicate a short-time peak and a dip.**

5.3 Calibration of the DTS-System

The two piezometers 35:3 and 45:3 are located in the downstream filter under the new core where the optical fibre is also located. The results from the two temperature monitoring systems can therefore be compared. The difference, about 2.5°C, is much larger than expected (accuracy better than 0.5^{o}C), see Figure 14. Comparison was done at two locations (section 0/035 and 0/045) were the temperature was measured both inside (with the DTS-system) and outside the optical fibre (with the vibrating wire temperature sensor). Based on those data an adjustment of about 2.41°C was obtained, based on best-fit linear approximation for both calibration points.

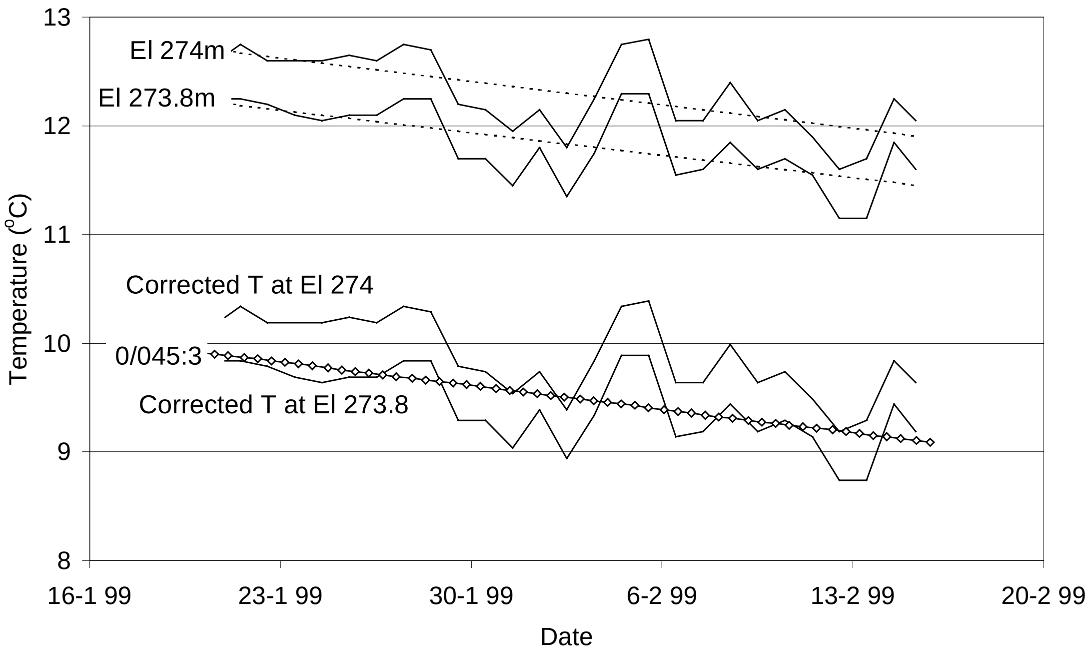

Figure 14 **Measured temperature in piezometer 0/045:3 (El. +273.65m) and in the optical fibre at El. 273.8 and 274m in section 0/045. The piezometer is located between and below the optical fibres. The dotted lines show the best-fit linear approximation to the measured temperatures.**

5.4 Temperatures in the dam measured by the DTS-System

5.4.1 General

The limited monitoring period allows not to obtain a full annual cycle complicates the evaluation of the result. The transient thermal process caused by the construction of the dam implies further problem to evaluate the result. The main objective with this project was however to test and demonstrated the monitoring method. However, some attempt to interpretation has been done below.

5.4.2 Upstream section

Longitudinal sections over the temperature field have been made with about one week interval. Two of those are shown in Figure 15. The pictures indicate clearly the location of the isolation that was installed up to about section 0/030. The temperature was still above the freezing point in the dam, but the cold will continue to penetrate into the dam until April/May at those depths. Another observation is that the area above the slurry trench was warmer than outside section 0/058. The colder temperature was probably caused by a higher seepage in this part of the dam, may be below the excavation/lowest measuring level.

The largest temperature difference during the measuring period is in the lowest part in the dam at El. 276m and close to intake (at the left side of the Figure 16). The low temperature as well as the larger temperature difference close to the intake section can be explained by heat conduction from water and air. The large temperature difference at El. +276m cannot currently be explained.

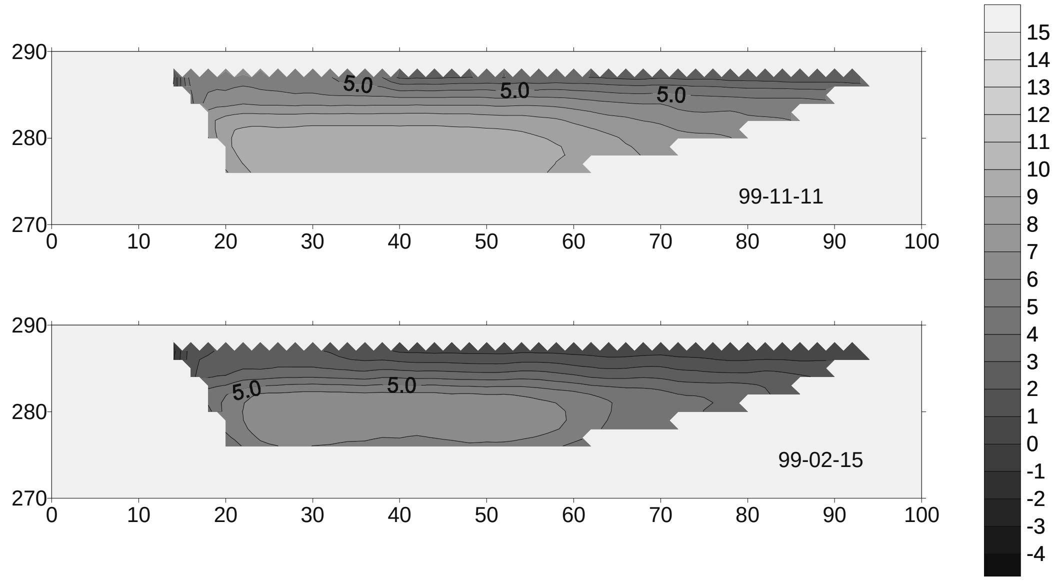

Figure 15 **Temperature in the upstream filter at the beginning and at the end of measuring period (longitudinal section).**

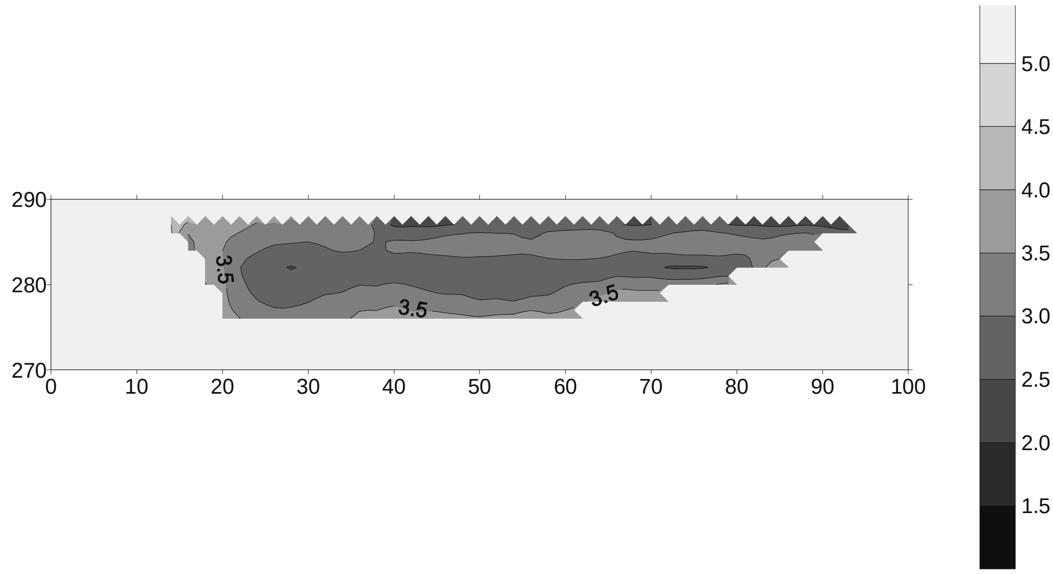

Figure 16 **Temperature difference in the upstream filter between 1998-11-20 and 1999-11-15 (longitudinal section).**

The temperature variation in the outer parts the repaired area where it connects to the old core gives some indications of the seepage. As discussed above (see Figure 11) all temperatures are lower at the turning point of the fibres. This depends probably on a slightly higher seepage in the old core, which gives a more rapid temperature decrease. The temporal temperature variation in the endpoints (see Figure 17) is although similar to the other sections (as shown in Figure 12).

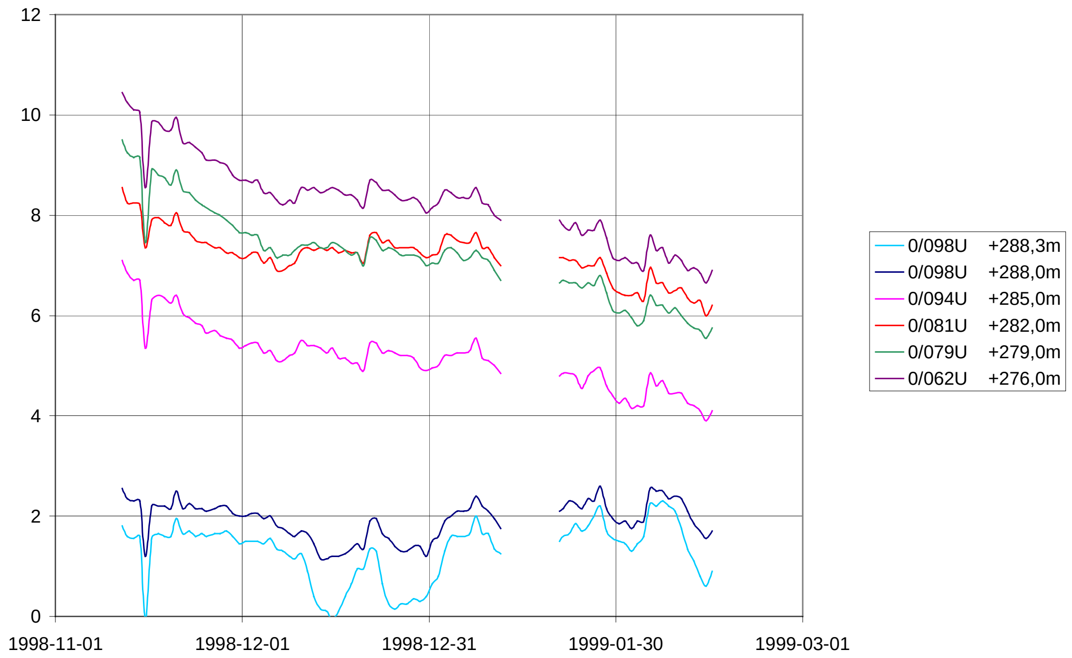

Figure 17 **Measured temperature at different elevations in the upstream cable at the end of the monitoring section.**

5.4.3 Downstream filter

The measured temperature in the downstream filter was similar to that in the upstream part. The influence of the isolation is clearly seen, see Figure 18. The extent of the warmer area is however larger and is extended almost over the entire repaired region. The exception is in the lower part from about section 0/045 were a lower temperature occurs, especially in the last part of the measuring period. The temperature difference in this part is however not remarkable, see Figure 19.

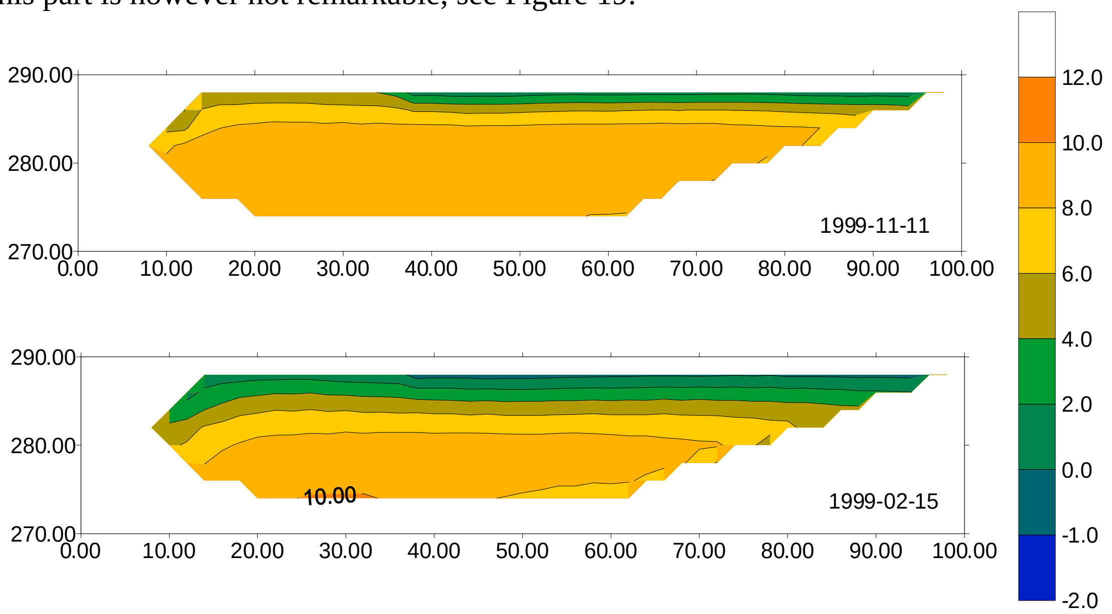

Figure 18 **Temperature in the downstream filter just outside the core at the beginning and at the end of measuring period (longitudinal section).**

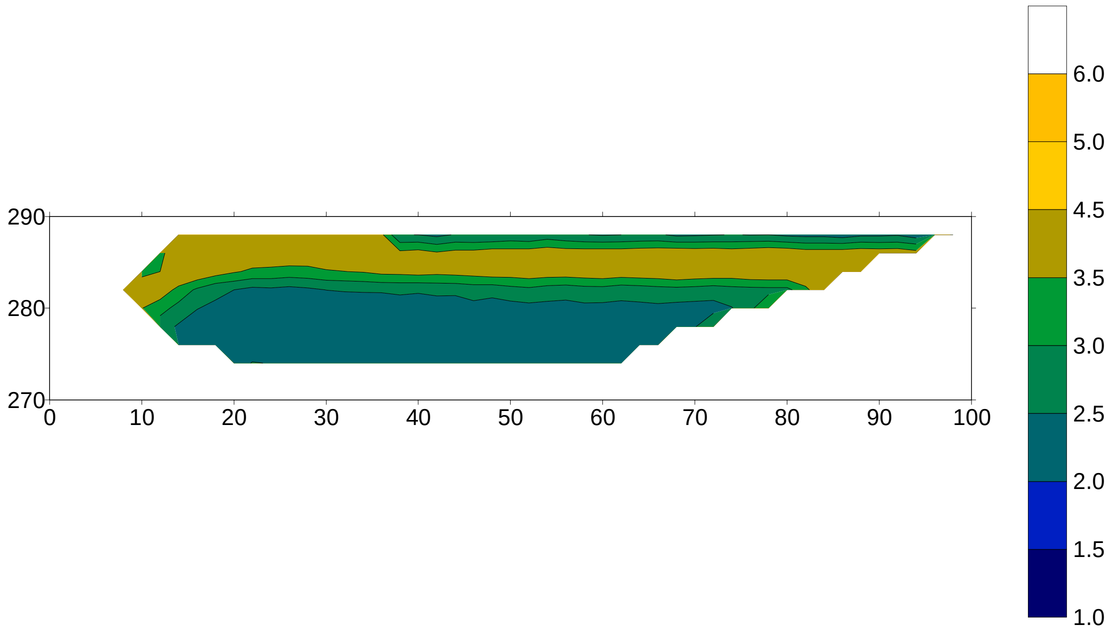

Figure 19 **Temperature difference in the downstream filter between 1998-11-20 and 1999-11-15 (longitudinal section).**

Temperature variation with time exhibits a similar pattern as showed in the upstream fibre. Peaks and drops occur over the entire fibre at same time. This further indicates that they must be caused by the monitoring system. The general trend in the downstream cable in the end of monitoring section shows however a temperature maximum in December/January. This can be compared with the upstream fibre, where a constant temperature decrease was found.

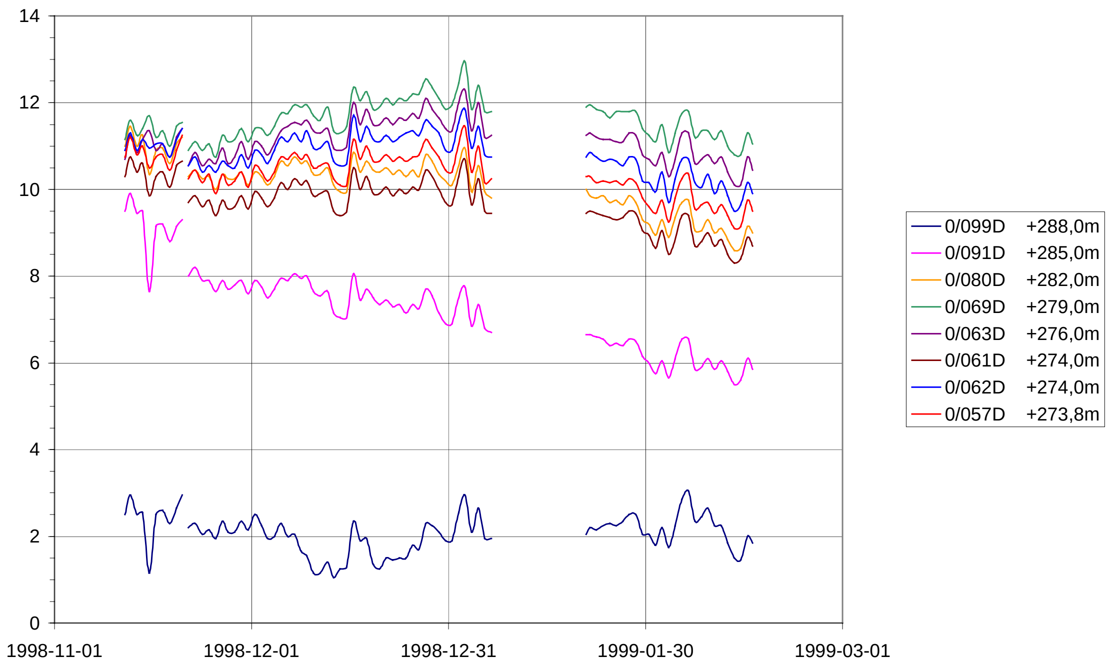

Figure 20 **Measured temperature at different elevations in the downstream cable at the end of the monitoring section.**

6 Conclusions

Temperature measurements have been successfully used at the Lövön embankment dam for evaluation of the seepage flow in the dam. The new installation of fibre optic cables improves the possibility to monitor seepage based on thermal analysis.

This first installation has shown that the method and available monitoring systems can be used. The DTS measurements were successful but not as accurate as expected. The relative accuracy was excellent (below 0.2°C) but the absolute temperature was 2.5°C higher than temperatures, measured by the temperature sensors in the piezometers. This was probably due to using a short length of the sensing fibre and keeping its temperature uniform during the calibration procedure. However, after allowing for this temperature offset value a good agreement is obtained with the trend measured with piezometers.

The unexpected temperature peaks and dips are thought to be due to the temperature variations of the internal reference oven. This error can be eliminated by measuring the actual temperature of the oven. In addition, using a section of the sensing fibre at a known temperature, we could eliminate any common errors caused by the instrument.

The relative accuracy is sufficient, but the absolute accuracy must be improved. Another way may be to install other type of temperature sensors that can be used for calibration. This should be considered in new installations.

The results provide valuable information about the seepage in the repaired part of the dam and adjacent part of the old dam. Similar installations should therefore be valuable in new embankment and tailings dams.

Thanks to the accurate vibrating wire temperature sensors the installation can be used for testing other types distributed temperature monitoring system in field. This will be of importance when new systems will be presented.

Outdoor installation cost was 20SEK/m and the cost of the fibre was 12SEK/m. The cost for each temperature sensor will then be 32SEK, excluding the cost of indoor installation.

The installation is still unique in the word and can be used in several ways in the future research projects, in addition to the basic monitoring of the dam performance. Of special interest are:

- Temperature monitoring to develop seepage evaluation methods; and
- Temperature monitoring to study frost penetration in the core crest.

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