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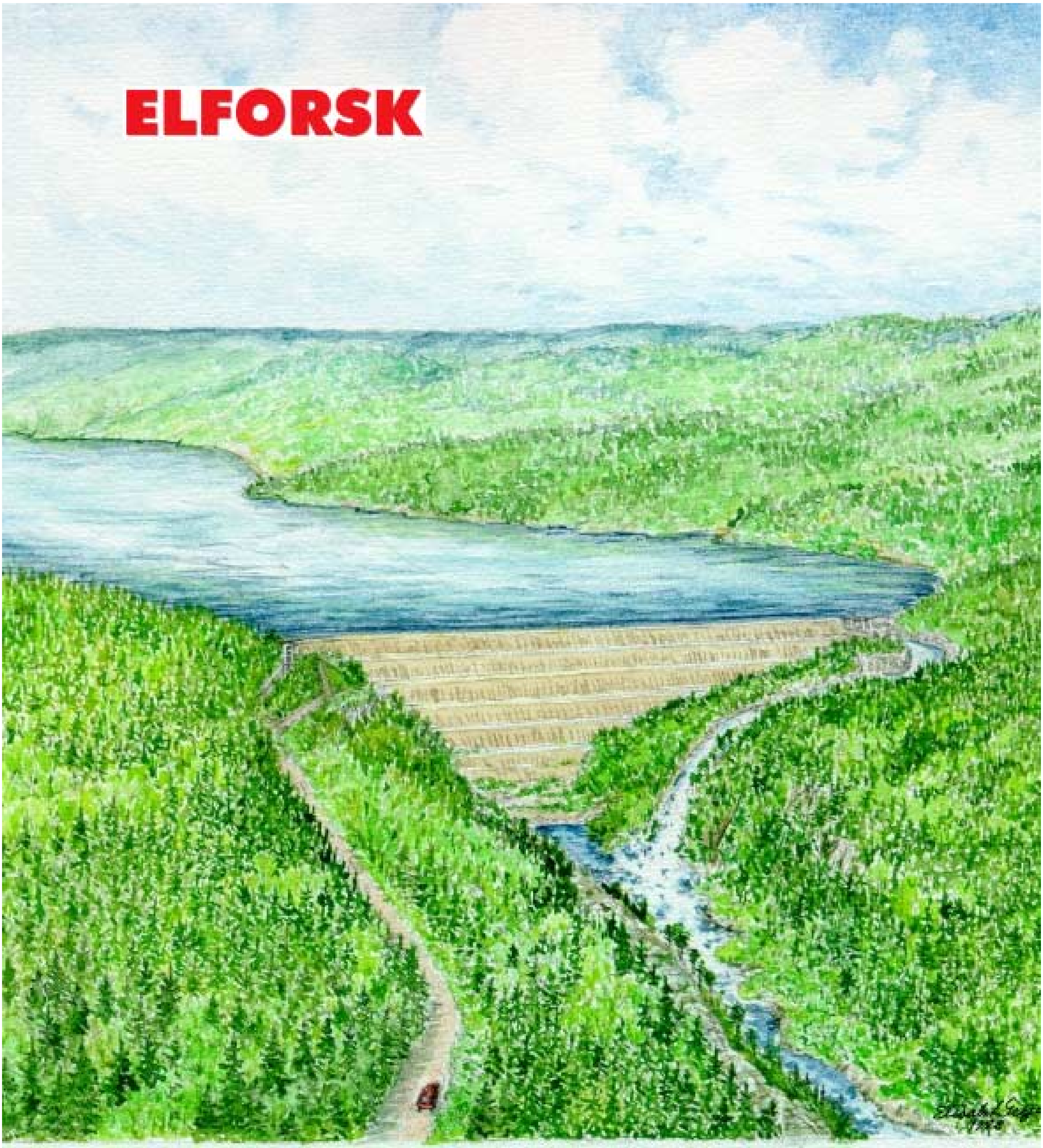

DAM SAFETY

DISTRIBUTED STRAIN MEASUREMENTS FOR EMBANKMENT DAMS – Laboratory Tests, Installation, and Initial Monitoring Experiences

Rapport 03:19

DISTRIBUTED STRAIN MEASUREMENTS FOR EMBANKMENT DAMS – Laboratory Tests, Installation, and Initial Monitoring Experiences

Elforsk rapport 03:19

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Sammanfattning

Rörelsemätningar är en klassisk övervakningsmetod som utförs regelbundet på flertalet dammar. Mätningarna är dock begränsade till ett antal punkter på dammen. Mätningar med fiberoptik däremot ger möjlighet till att på ett enkelt sätt mäta rörelser längs hela dammen. Vilken riktning rörelserna har kan dock inte fastställas eftersom mätningarna endast kan ge besked om var kabeln töjts och hur stor töjningen är.

Ett system för att mäta töjning i optiska fiber ”Distributed Temperature and Strain System”, DTSS, har tagits fram av Sensornet. Inom detta projekt har systemet testats tillsammans med en ny typ av kabel som tagits fram tillsammans med HydroResearch. Kabeln har installerats i Ajauredammen och en liknande kabel finns också installerad i Aitik.

De laboratorieförsök som utförts i detta projekt visar att kabeln förmår att överföra rörelser från dess mantelyta in till fibern där töjningen mäts, samtidigt som kabeln ger skydd mot mekanisk åverkan. Vid tester visar kabeln på en linjär respons upptill en töjning av 4600με, vilket var det högsta värdet som användes i försöken. Någon glidning av fibern inuti kabeln har ej kunnat upptäckas. Dämpningen i fibern är konstant. Laboratorieförsöken visar att kabeln är lämplig för att mäta de rörelser som kan förekomma på dammar och liknande konstruktioner.

Laboratorieförsöken visar att mätsystemet kan mäta töjningar med en noggrannhet mellan 7με och 40με för 1 m upplösning längs kabeln, vid en mättid av 8 minuter. Temperaturen kan mätas med en noggrannhet av 1.6°C. För både töjning och temperatur gäller att högre noggrannhet kan erhållas vid längre mättid eller vid lägre upplösning längs kabeln (>1m).

Inledande fältmätningar har utförts i Ajauredammen. Temperaturmätningar utfördes där för att testa kabelns prestanda och för att kontrollera att installationen var korrekt utförd. Mätningarna visar att kabeln kan användas för mätning av rörelser, vilket därför kan utföras i kommande projekt.

Vid den första installationen för DTSS som gjordes i Sädvadammen 1999 var inte den nu testade kabeln tillgänglig. Därför fästes en tunn fiber (singlemode) på en kabel innehållande fiber för temperaturmätning (multimode). Vid mätningarna konstaterades att den utanpåliggande singlemode-fibern var skadad. Därför kan endast temperaturmätningar utföras på Sädvadammen.

Mätsystemet möjliggör mätning längs dammarnas hela längd och kan därför också användas som dammbrottsvarningssystem. Systemet är för närvarande ganska dyrt och är därför lämpligare för regelbundna mätningar för att upptäcka eventuella rörelser i dammen.

Summary

Sensornet and HydroResearch have been working on demonstrating the application of Distributed Temperature and Strain Sensor (DTSS) developed by Sensornet for monitoring movements in Dams. In anticipation of DTSS prototype being available for field tests, installations at Sädva and Ajuare were made in 1999 and in 2001, respectively.

The first experimental installation was at Sädva in 1999. No dedicated cable for strain measurements was available at this time, so a tiny buffer coated single-mode fibre was strapped together with the multi-mode cable. The field tests in November 2001 showed that the tiny single-mode fibre was damaged. Therefore, only temperature measurements were performed at Sädva dam using the multimode fibre cable.

A robust cable designed was proposed for installation at the crest of Ajuare dam in 2001. The cable is designed to efficiently and reliably transfer strain from the cable jacket to the sensing fibre, while protecting the fibre from the environment and rough handling. Movements on the crest can thus be detected by strain measurements.

The cable contains two single mode fibres and two multimode fibres. The cable integrity was tested in November 2001 by measuring the backscatter traces of all four fibres using a distributed Temperature Sensor (DTS) unit developed by Sensornet. The results indicated that the cable was installed successfully and the temperature profile was also recorded using the multimode fibres within the same cable.

This document reports laboratory characterisation of the cable, and its sensitivity when used with the DTSS. It shows that the cable has approximately the same strain sensitivity as uncabled fibre, and hence that there is no slippage between the cable and fibre. The cable exhibits a linear response with applied strain and no hysteresis up to the maximum strain tested (4600με). The cable loss is the same as that of uncabled fibre and does not change with applied strain.

The DTSS was shown to have an equivalent frequency shift resolution of 7με and an amplitude resolution of 1.6°C for a spatial resolution of 1m and a measurement time of 8min. Therefore, the combined strain and temperature resolution is limited by the amplitude measurement error and the temperature compensated strain resolution would be 40με uder the above conditions. Finer resolutions can be obtained by increasing the spatial resolution or the measurement time.

The experiments show that the cable and DTSS perform as expected and are ideal for strain measurements in applications such as dam monitoring. Field measurement at Ajuare dam using DTSS can therefore be carried out as the next step.

The DTSS allows monitoring movements over the entire length of a dam. The location as well as the strain in the fibre will be detected, while the direction of the movement will be unknown. The system can be used either as an Early-Warning-System with continuous monitoring, or as an investigation tool to measure movements regularly.

Content

1 Introduction

There is an urgent requirement to measure strain in many civil structures such as dams, bridges and tunnels. Optical fibre sensors are increasingly been used to measure both temperature and, more recently, strain in many such constructions. Sensornet have developed a sensing instrument, the Distributed Temperature and Strain Sensor (DTSS), which is uniquely capable of measuring both strain and temperature at 1m intervals over long lengths of optical fibre. The challenge is to design a suitable cable to imbed in the structure to be monitored. The cable must be rugged, to withstand rough handling, yet must efficiently couple strain applied to the cable into strain applied to the fibre – this is an unusual property as most cables are designed to isolate the fibre from any cable strain. In addition, an efficient way to transfer strain from the structure to be monitored (in this case an earth dam) to the cable must be devised.

This project is mainly based on two previously research projects performed by Sensornet and HydroResearch. Also those projects were funded by Elforsk AB (Project No1286 in 1998, and No1356 in 1999).

Sensornet and HydroResearch are collaborating in many areas relating to dam monitoring, one of which is in the development of a cable and installation method for measuring strain in earth dams. The companies have had a cable designed for this application, a section of which has subsequently been installed in Ajuare dam. This has been done during several years in parallel with the development of the monitoring system. Three different cables have been installed in three dams, intended for strain measurements. The third dam is a tailing dam at Aitik that is similar to the cable at Ajaure, but it’s not included in this project.

All field measurements were made in November 2001, while the laboratory tests were concluded in April 2003.

The purpose of this document is to report lab tests made on the final cable (used in Ajaure dam) and, in particular, to assess the suitability of this cable, combined with the DTSS, for the task for which it was designed: the structural monitoring of dams.

2 The DTSS

The DTSS, or Distributed Temperature and Strain Sensor, is a prototype instrument developed by Sensornet, which measures the entire Brillouin spectrum (the Brillouin shift and power for both the Stokes and anti-Stokes light) at every 1m along the fibre (Parker et al 1997). On-line analysis of this data allows the strain and temperature to be measured simultaneously and independently at all points along the fibre. This independent measurement of strain and temperature (which allows strain to be measured without temperature cross-sensitivity) requires the full Brillouin spectrum to be captured – a feature that is unique to Sensornet's DTSS (Farhadiroushan and Parker 1996).

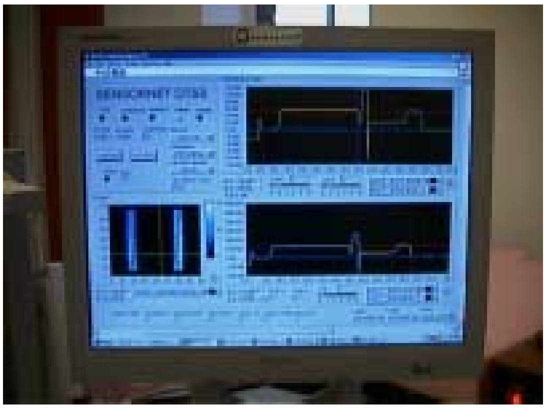

Figure 1 Sensornet DTSS (left) and software interface (right).

The DTSS used in these tests was configured to give a 1°C temperature resolution and a 20$\mu\varepsilon$ strain resolution for a spatial resolution of 1m and a measurement time of around 20mins. Sensornet's DTSS is housed in a single field-transportable 6U rack mountable box with an inbuilt PC (there is no need for a separate control or interface PC). Although these tests only required a short sensing length (a few hundred metres) the DTSS is designed to be able to operate over lengths of up to 10km.

The DTSS saves the following data: raw Brillouin spectra for every 1m in the fibre (which may be post-analysed as necessary to examine any interesting features), OTDR (fibre loss) data, Brillouin shift data, Brillouin power data, temperature data and strain data (all of which are collected at every metre interval in the fibre). Here, we present the strain data for all tests (the purpose of these measurements was to measure strain) but also some temperature and OTDR to illustrate how the system operates and to examine the reliability and repeatability of the cable.

3 The DTSS Cable

The cable tested here (Figure 2), was designed for dam monitoring and has the following product code: **DC-DTSS02S.4MC/3MD-DTS02A3GB/1GC/900**. It contains two single mode fibres for use with the DTSS system, and two multimode fibres for use with the Sensornet DTS system (which measures only temperature along a length of fibre), if the user should wish to use a DTS system at some time. Each system only requires one fibre (they take single-ended measurements) – the second fibre was added for redundancy. The specifications for the cable and the fibres are shown in Table 1 and Table 2.

Figure 2 DTSS cable breakout.

Diameter	5mm
Minimum Bend Radius: Under Installation Tensile Load	15x outside diameter
Under Long-Term Tensile Load	10x outside diameter
Operating Temperature	-40°C to +85°C
Storage Temperature	-55°C to +85°C
Crush Resistance	1,800 N/cm
Impact Resistance	1,500 impacts
Flex Resistance	2,000 cycles

Table 1 DTSS cable specifications.

Colour	Fibre type	Fibre characteristics	Instrument
Orange and blue	9/125 single-mode fibre	attenuation of 0.4dB/km @ 1300nm and 0.3 dB/km @1550nm	DTSS
Green and brown	50/125 graded-index multimode fibre	3.0dB/km+600MHz-km @850nm and 1.0dB/km+600MHz-km @1300nm	DTS

Table 2 Optical fibres' specifications.

The cable should be terminated with angled FC/APC connectors on a single mode fibre, for use with the DTSS, and angled E2000 connectors on a multimode fibre (if required), for use with the DTS.

4 Laboratory tests

4.1 The test arrangement

These tests had two purposes: to characterise the DTSS cable and to determine the DTSS performance with this cable. Both objectives were achieved using a single fibre/cable arrangement as shown in Figure 3. The DTSS was attached to a known, calibrated, fibre which was subjected along its length to known temperature and strains. This allowed us to evaluate the DTSS measurement accuracy and resolution and to demonstrate the DTSS's unique capability of being able to make strain measurements without a temperature cross-sensitivity. The far end of the calibrated fibre was connected to a 313m section of the DTSS cable. This comprised around 50m of cable loosely coiled on the floor of the lab, with the remainder of the cable tightly spooled on a reel, as supplied by the cable manufacturers. Within the loose section, around 4m of cable was subjected to various strains. This was achieved by clamping one end of the cable and then pulling the other end to get the required extension, and hence strain, and than clamping that end.

Due to the nature of the cable, it was difficult to ascertain the zero strain length of the strained section since a certain amount of tension is necessary to straighten the fibre and make it accurately measurable. Hence the strain was calculated by relative changes in the length of the strained section and by looking at the Brillouin shift in the loosely laid part of the cable. This region was assumed to be under zero strain and the average Brillouin frequency in this section taken to be the zero-strain frequency.

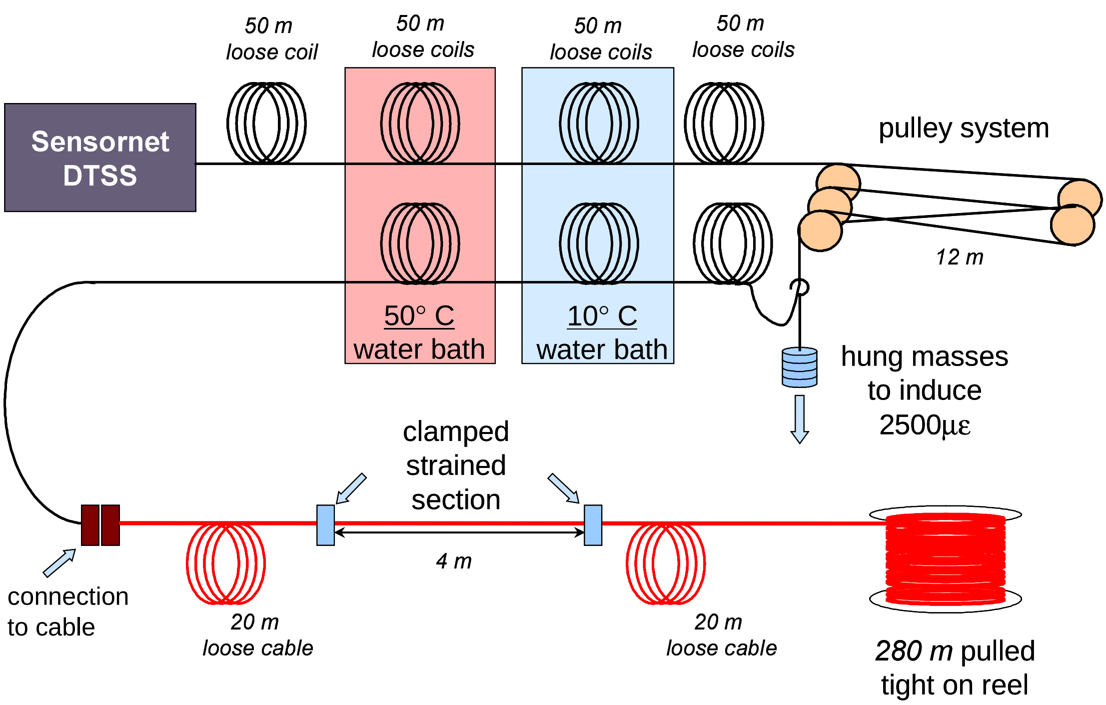

Figure 3 **Test arrangement: black: calibrated test fibre, red: DTSS cable**

The calibrated fibre and cable were connected together using FC/APC connectors, with an FC/APC connector also used to connect the test fibre to the DTSS.

4.2 Tests conducted

Throughout the measurements, the calibrated test fibre was subjected to constant temperatures and strains as described in Table 3. The 4m section of DTSS cable was strained from 2608με to 4614με and then back down to 3110με. Approximately even step sizes were used as showed in Table 4. The cable was tested while subjected to first increasing and then decreasing strain to check for any hysteresis. Each measurement took around 8mins.

Fibre or cable	Section start (m)	Section end (m)	Strain (με)	Temperature (°C)
Fibre	0	54	0	Room
Fibre	54	112	0	50
Fibre	112	164	0	10
Fibre	164	223	0	Room
Fibre	223	238	2500	Room
Fibre	238	299	0	Room
Fibre	299	354	0	10
Fibre	354	394	0	50
Cable	394	412	loose	Room
Cable	412	416	various	Room
Cable	416	446	loose	Room
Cable	446	708	spooled	Room

Table 3 Fibre and cable arrangement (note distances are approximate)

Applied Strain (με)	Measurement
2608	1
3110	9
3486	8
3611	7
3861	6
4113	2
4364	5
4489	3
4614	4

Table 4 Strains applied to 4m cable section

4.3 Data

The DTSS collects Brillouin spectra and loss data at 1m intervals along the length of the fibre. The instrument then uses this data to calculate the temperature and strain along the fibre. When calculating the strain, the user has two options: to either use or not use temperature correction. Using temperature correction gives more accurate results (lower systematic errors) but a lower resolution (higher random errors), as the temperature correction operation adds noise the strain data. On the other hand, not using temperature correction gives lower noise but the strain data suffers from temperature cross-sensitivity. Generally, temperature correction is recommended for sensing applications as the temperature along the fibre is not controlled. The finer resolution provided by not using temperature correction is generally only useful in laboratory tests where the temperature can be controlled. Here we present results from both processing techniques.

Figure 4 shows the calculated strain along the fibre without temperature correction. The figure incorrectly shows the changes in temperature between the water baths as changes in strain.

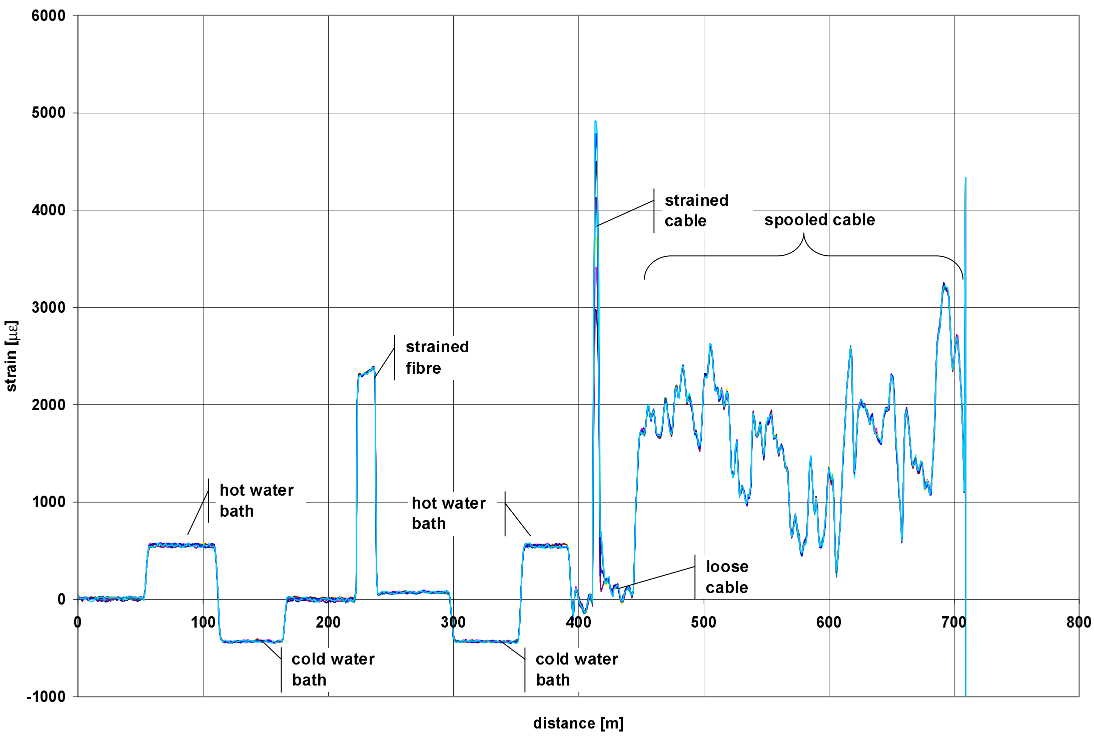

Figure 4 **Strain distribution for all measurements without temperature correction.**

Figure 5 shows the temperature corrected strain data. This correctly shows the fibre in the water baths as having zero strain. The figures show a relatively large amount of strain in the cable spooled on the reel. This strain varies along the cable length with values between 300με and 3200με. The loose cable also shows a small strain variation – between -30με (compression) and +210με. At each point, this cable-strain was constant for the duration of the measurements. Sensornet have seen built-in strains before in other cables and installations. Generally, any applied strain has been found to act in addition to this built-in strain such that a reference measurement (taken at the beginning of the installation for example) can be used to correct for the built-in strain.

Figure 6 shows a close up of the 4m section of fibre to which strain was applied, for all the strains shown in Table 4.

Comparing the applied strain to the measured Brillouin shift (which the DTSS uses to determine strain) gives the strain coefficient for the cable. This is the single most important calibration coefficient for the cable as it determines the strain resolution of the DTSS when used with the cable. The calibration plot (Figure 7) shows the strain sensitivity of the cable is 41.0 ± 1.3 kHz/με.

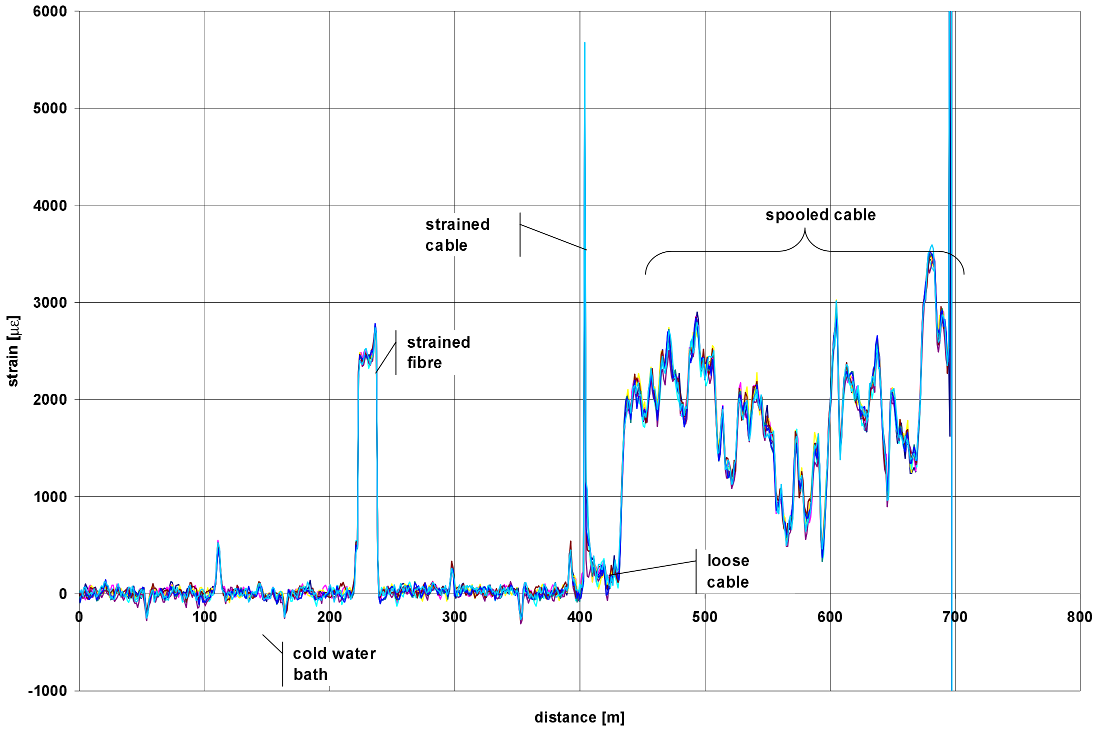

Figure 5 **Strain distribution with temperature correction for all measurements.**

Within experimental errors, this is very similar to the strain sensitivity of our calibrated, non-cabled fibre: 43.3kHz/με. This is a very important finding as it shows there is no appreciable slippage between the cable jacket and the fibre and hence that strain is efficiently coupled from the cable to the fibre. The plot also shows there is no measurable hysteresis in the cable and that the strain transfer to the fibre is linear.

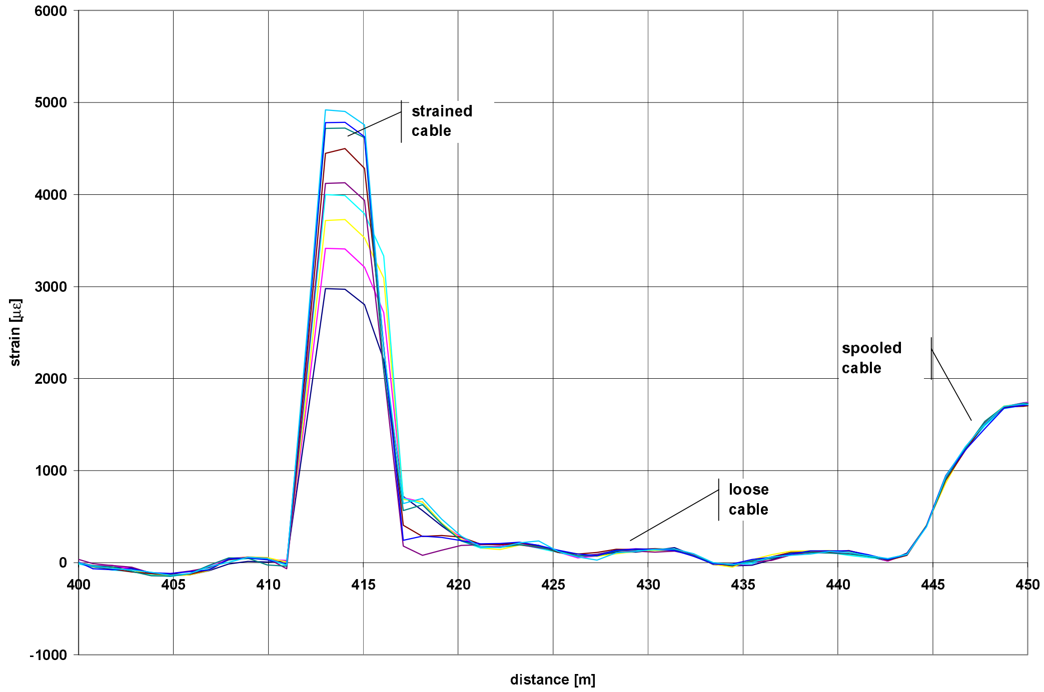

Figure 6 Close-up of strain distribution over 4m strained section for all measurements.

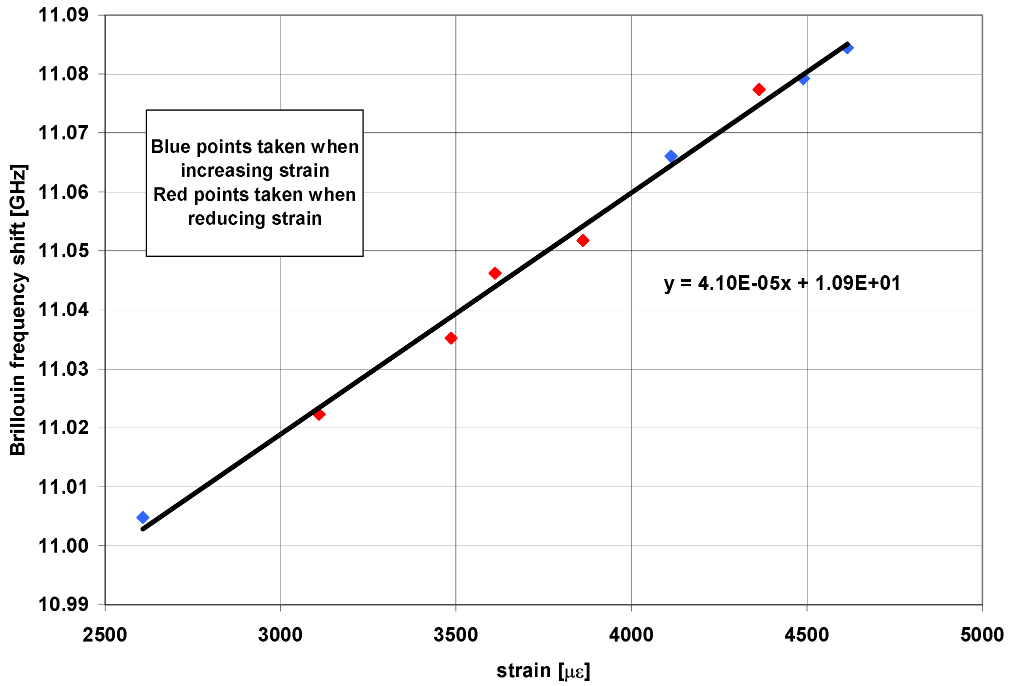

Figure 7 Cable calibration plot.

Figure 8 shows the temperature measured by the DTSS. It shows that the DTSS accurately measures the temperatures in the temperature-controlled water baths and that it correctly measures an approximately constant temperature in the spooled fibre, as expected.

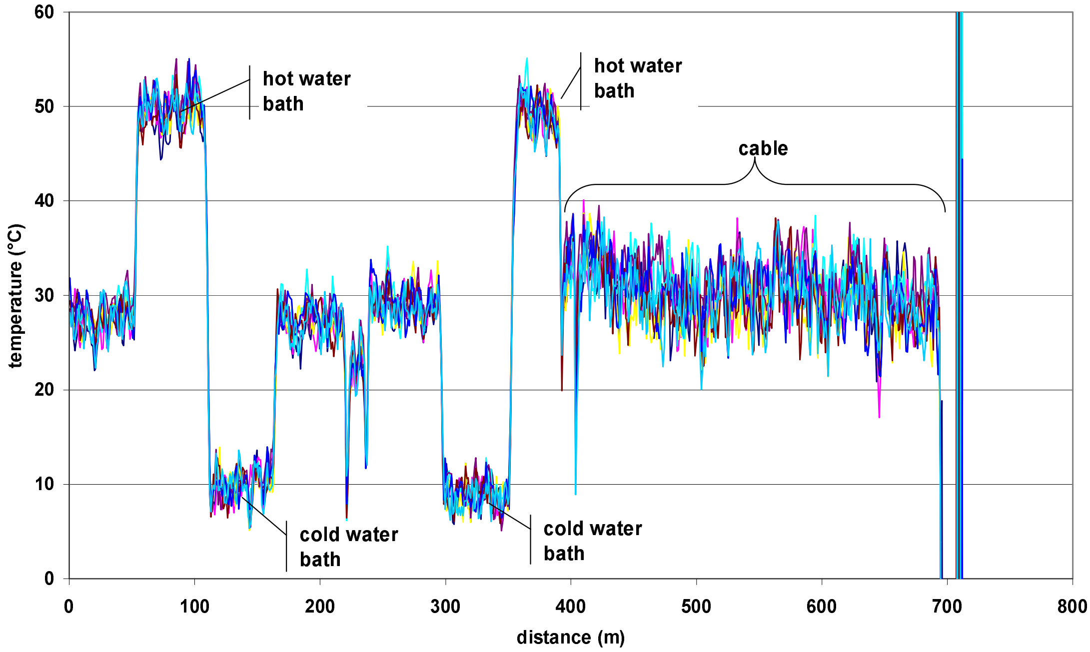

Figure 8 **Temperature distribution for all measurements.**

Figure 9 shows the measured loss profiles of the test fibre and cable. It shows a large loss (2.4dB both ways) in the connector between the test fibre and the cable. However, the previous results show that this loss did not appreciably affect the performance of the DTSS measurements in the cable. The cable shows the approximately the same loss and uncabled fibre (around 0.2dB/km in each direction). Significantly, it shows no change in the loss in the cable as the strain was applied.

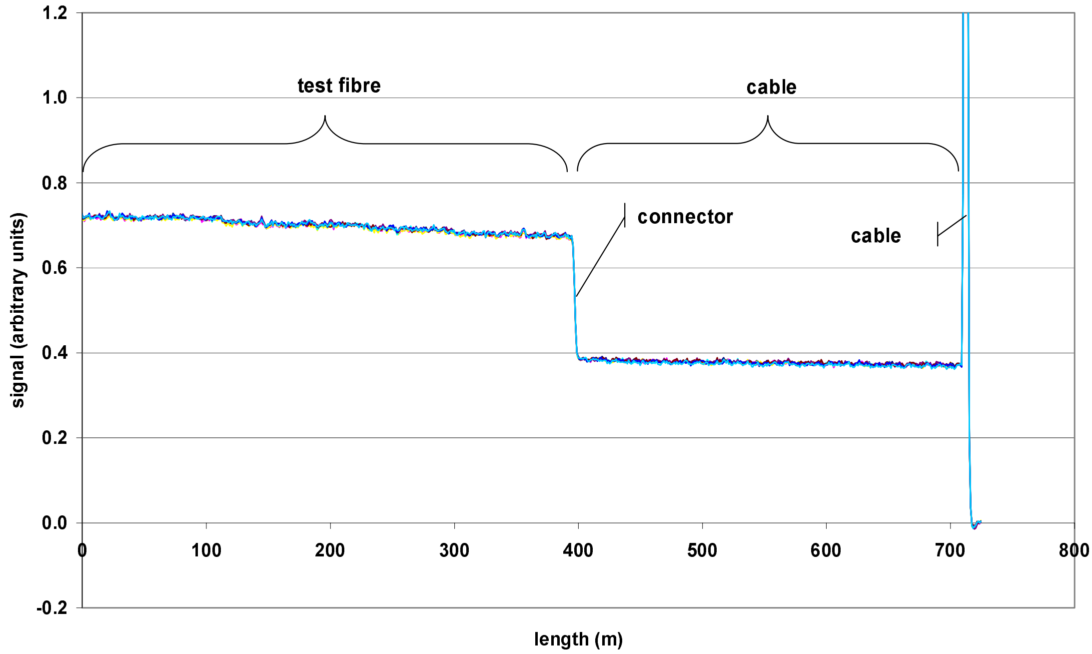

Figure 9 Loss (OTDR) data for all measurements.

4.4 Analysis

The DTSS took reliable distributed measurements of temperature and strain over the course of the tests. It collected temperature measurements with a resolution of 1.6°C and strain with a resolution of 40με with temperature correction, or 7με without temperature correction. The temperature correction was shown to accurately remove the temperature cross-sensitivity in the strain measurements (a major improvement in accuracy which is a necessity in most sensing applications) but at the cost of increasing the random noise and so lowering the resolution. These results were collected with a 1m spatial resolution and an 8 minutes measurement time. The resolutions could readily be improved by increasing the measurement time and/or the spatial resolution. For example, the strain resolution with temperature correction would be around 20με if the measurement time were increased to 20minutes.

The cable was found to efficiently transfer strain to the fibre with no loss in strain sensitivity caused by the cabling process. The measured sensitivity was 41kHz/με. There was no evidence of hysteresis, and the transfer of strain to the fibre was shown to be linear with applied strain. The loss in the cable was no more than in uncabled fibre and the loss was shown to be constant up to the maximum strain applied (~4600με).

Tightly spooling the cable is shown to transfer large, and widely varying, strains to the fibre (from 300με to3200 με). Once unwound and relaxed, the strain on the fibre reduces to between -30με and +210με (in the relatively short section of fibre unwound here). This built-in strain will add systematic errors of these magnitudes in measurements made on this cable. It is believed, from previous work, that these errors can be removed by taking a zero-level strain measurement following installation. This reference strain measurement should then be subtracted from later measurements to yield the strain applied to the cable. Although we have seen this process successfully employed on other cables we have tested, this process has not been tried on this cable.

5 Installation and field tests at Ajaure dam

5.1 Introduction

The same cable as was used in the laboratory test was installed in Ajaure dame in July 2001. The field test was made in November 2001. The tests that are reported here were to examine the state of the cable installation in preparation for future measurements. Another reason was to determine the consequence of a damage section on the cable at marking 1/012.3m that was detected in September 2001.

5.2 Installation and fibre cable design

The cable was installed at two levels along the dam as a loop (Figure 10). Both ends of the optical cable are terminated in the monitoring room. We completed the indoor installation with a junction box. The cable is marked at every metre interval. After cutting the cable to length, the markings on the cable were from 165m (minus a 0.5m tail) to 1287m. The total cable length is 1122.5m.

The location of the cable in the dam is measured at each five meter according to the markings on the fibre. The cable around the damage at marking 1/012.3m was drawn into a monitoring well. There is a total of 8m length of the cable, starting at marking 1/000m to 1/018m, wrapped around together in the well.

Figure 10 **Location of the cables on the membrane. (The picture was taken during construction of the dam).**

5.3 Fibre cable continuity test results

All the fibres were tested using one of Sensornet's Distributed Temperature Sensor (DTS) systems. Figure 11 shows the backscatter traces measured for different fibres. The results indicate that the cable installation was successful.

A significant loss is also found in all fibres at a length of 960m due to either a sharp bending of the fibre or to slight damage to the outer jacket of the cable. Therefore most of the measurements were made from the 165m marking end to avoid the effect of this loss for most of the length preceding it. No further damages are seen in the remaining part of the fibre.

According to the markings on the cable, the total cable length is about 1122.5m. However, the total length of the fibres as measured by the DTS system was about 1138.85m (16.4m longer than the cable length). This additional length is due to over-stuffing of the fibre inside the cable. Thus to convert DTS length readings to cable markings, a correction factor of 0.9856 (-1.44%) should be used. A user-specified length correction factor is now included in the latest version of Sensornet's DTS control software so that the user can choose to save the temperature data versus cable length rather than fibre length.

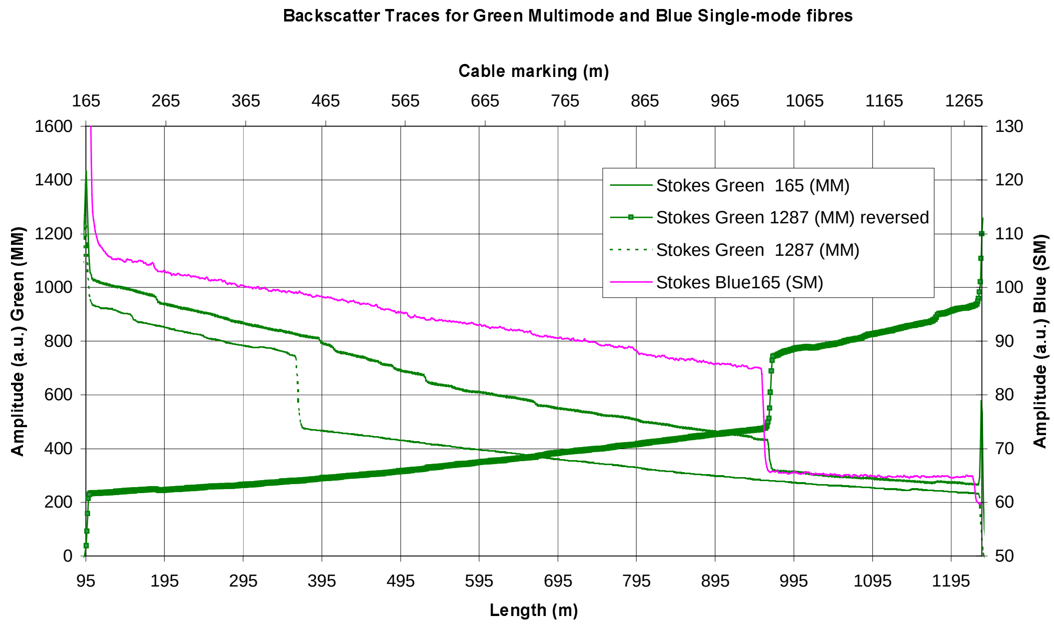

Figure 11 **The backscatter traces for the Blue single-mode from 165m marking end, the Green multimode fibres from 165m marking end and the Green multimode fibre from 1287 marking end. The trace shows a loss due to bending loss or damage to the cable.**

Zooming the backscatter signal around the loss section around length 960m as shown in Figure 12 shows that the loss is just outside the monitoring well according to the multimode fibre measurements from both ends. Figure 12 also shows that there is a slight difference in the multimode fibre loss profile compared to that of the single mode fibre. However, the monitoring equipment is optimised for use with the multimode fibre and the result for single mode fibre should be corrected by <1% to take into account the difference in refractive indices between the two types fibres.

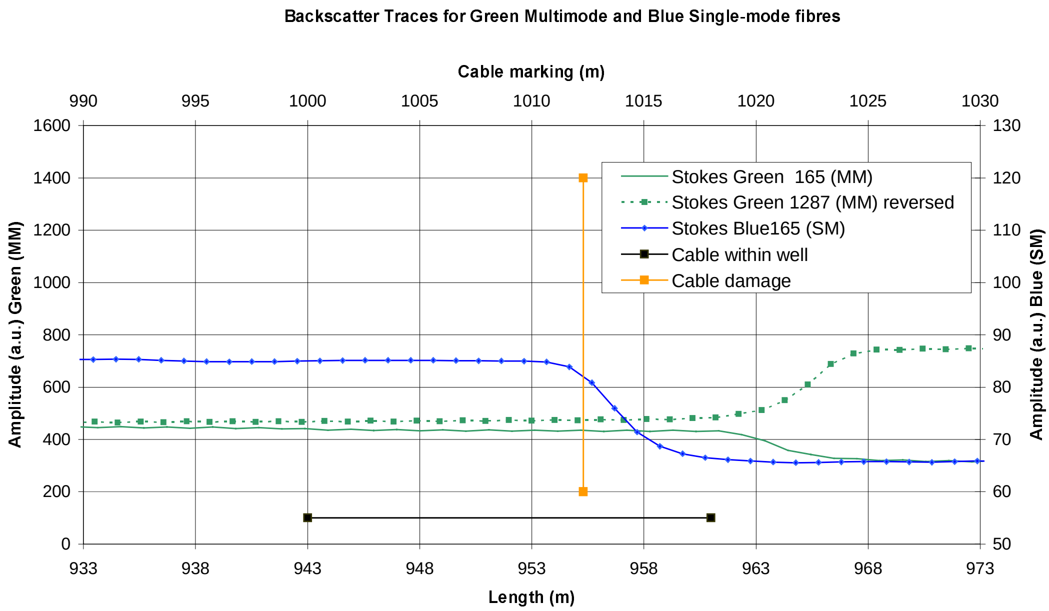

Figure 12 **Detail of the losses at the potential damage (c.f. Figure 11).**

5.4 Temperature measurements

The Green multimode fibre was used to measure the temperature distribution along the cable. Figure 13 shows the results superimposed for nine one-hour measurements taken overnight. There is a single temperature peak error due to the localised loss around the damaged section near the 1/012m marking. The temperature resolution was 0.15°C before this section, degrading to about 0.25°C afterwards due to the loss of optical power.

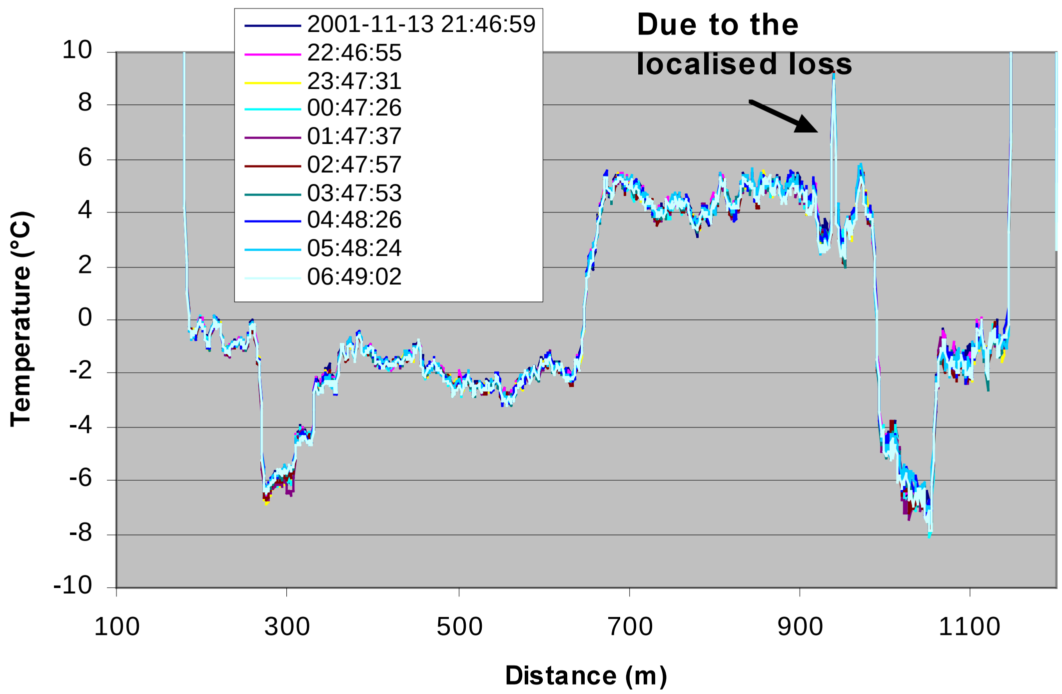

Figure 13 **Nine 1-hour DTS temperature measurements taken over the night of 13th November 2001.**

6 Installation and field tests at Sädva dam

6.1 Introduction

The installation on Sädva dam was made in 1999, when the core was heightened 0.7m according to the new Guidelines for Floods. Electrodes for SP and resistivity measurements were also installed at the same time (Johansson et al, 2000).

Two fibre-optic cables for temperature and strain measurements were installed at the dam crest as showed in Figure 14. No dedicated cable for strain measurements was available at this time, so a tiny buffer coated single-mode fibre was just strapped together with the multi-mode cable. The temperature measurements will, in this case, be used for studies of thermal behaviour at extreme weather conditions, especially freezing/thawing problems.

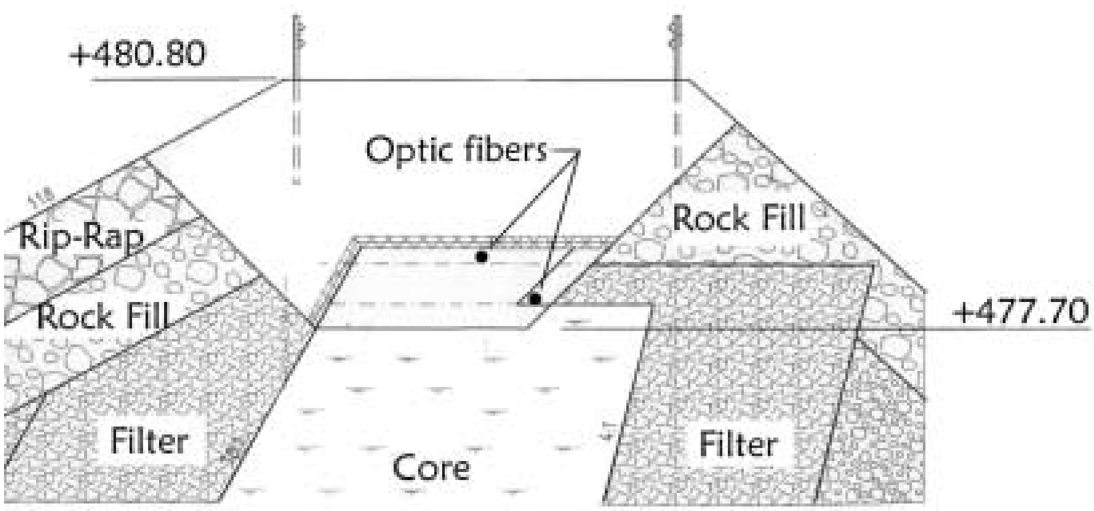

Figure 14 Cross section of the dam crest at Sädva showing the location of the optic fibres.

6.2 Measurements

Field measurements using DTS showed that the tiny single-mode fibre was damaged just outside the entrance to the small building where the monitoring equipment was placed. All fibres in the multimode cable were intact. Only temperature measurements can therefore be preformed at Sädva dam.

Short time temperature measurements were made just in order to test the cables and not in order to measure temperature. However, the result show small temperature variations along the dam as expected. The thermal insulation layer that is placed along the first 190 m gives a more constant temperature than in the rest of the dam where the cable is placed in a trench. In this part of the dam larger temperature variations could be expected due to variation of depth, and variation of the thermal properties. This is clearly seen from section 500m where the cable is placed at a smaller depth that gives a lower temperature. The peak temperature at 195m coincides with a concrete structure in the dam.

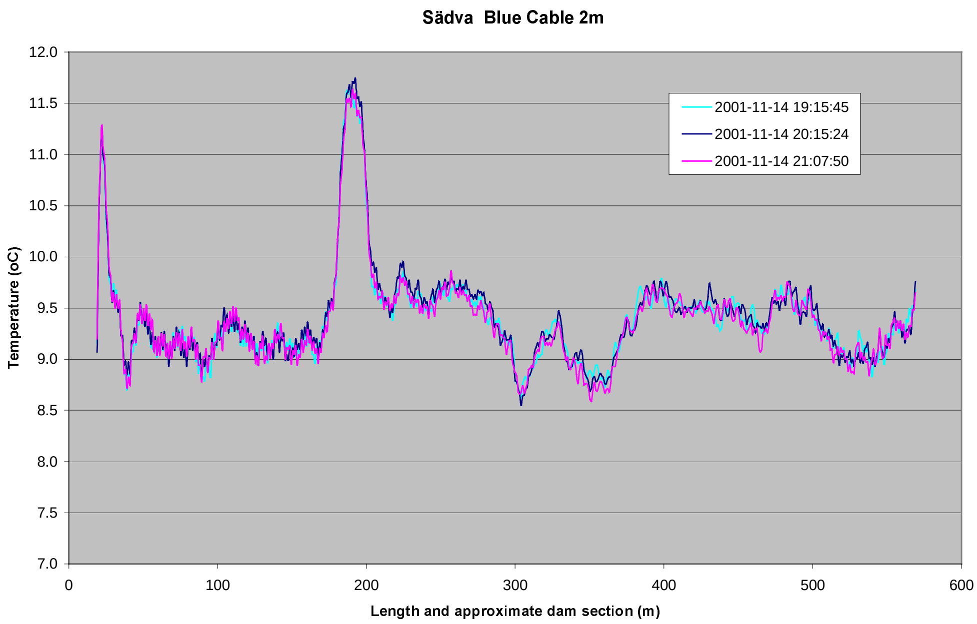

Figure 15 Temperature profiles from Sädva dam, from short time measurements.

7 Conclusions

The DTSS and DTSS cable have been shown to accurately measure both temperature and strain along a test length of cable. The DTSS was shown to measure temperature with a resolution of 1.6°C and strain with a resolution of either 7με or 40με, depending upon whether a temperature correction algorithm is used, for an 8minute measurement with a 1m spatial resolution. Increasing the measurement time and/or the spatial resolution would improve the temperature and strain resolutions.

The DTSS cable efficiently transferred strain to the sensing fibre, with no loss of sensitivity. The cable was shown to have a low, constant loss for all applied strains and suffer no measurable hysteresis or non-linearity with respect to applied strain. A length-varying strain of up to 200με was measured in the relaxed cable, showing that sensing measurements which require systematic accuracy below this level need a calibration scan to be taken following installation. These results show that the cable and DTSS operate as expected and that they are both suitable for the target application: strain monitoring in dams.

The same DTSS cable as was used in the laboratory test is installed at the crest of Ajuare dam. The installation has been tested using DTS. The observed damage on the cable coating at marking 1/012.3m gives no significant losses in the fibre. Another loss has however been detected just outside the well. The effect of the loss due to the single damaged, or bent, section of the fibre can be minimised by measuring from the 165m marking end. Measurements through the damage are also possible, but it will reduce the accuracy. The correction factor for the cable length and actual fibre length inside the cable has been determined.

The first experimental installation at Sädva in 1999 was also tested. No dedicated cable for strain measurements was available at this time, so a tiny buffer coated single-mode fibre was just strapped together with the multi-mode cable. Field measurements using DTS showed that the tiny single-mode fibre was damaged. Only temperature measurements can therefore be performed at Sädva dam.

The installation at Ajaure dam can be used to monitor movements on the crest by strain measurements. Field measurements using DTSS can therefore be carried out as the next step in the further development of this technique.

The DTSS allows monitoring movements over the entire length of a dam. The location as well as the strain in the fibre will be detected, while the direction of the movement will be unknown. The system can be used either as an Early-Warning-System with continuous monitoring, or as an investigation tool to measure movements regularly.

8 Acknowledgements

This work has performed within Elforsk project No 1500. The measurements at Ajuare were funded directly by Vattenfall Vattenkraft AB.

9 References

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