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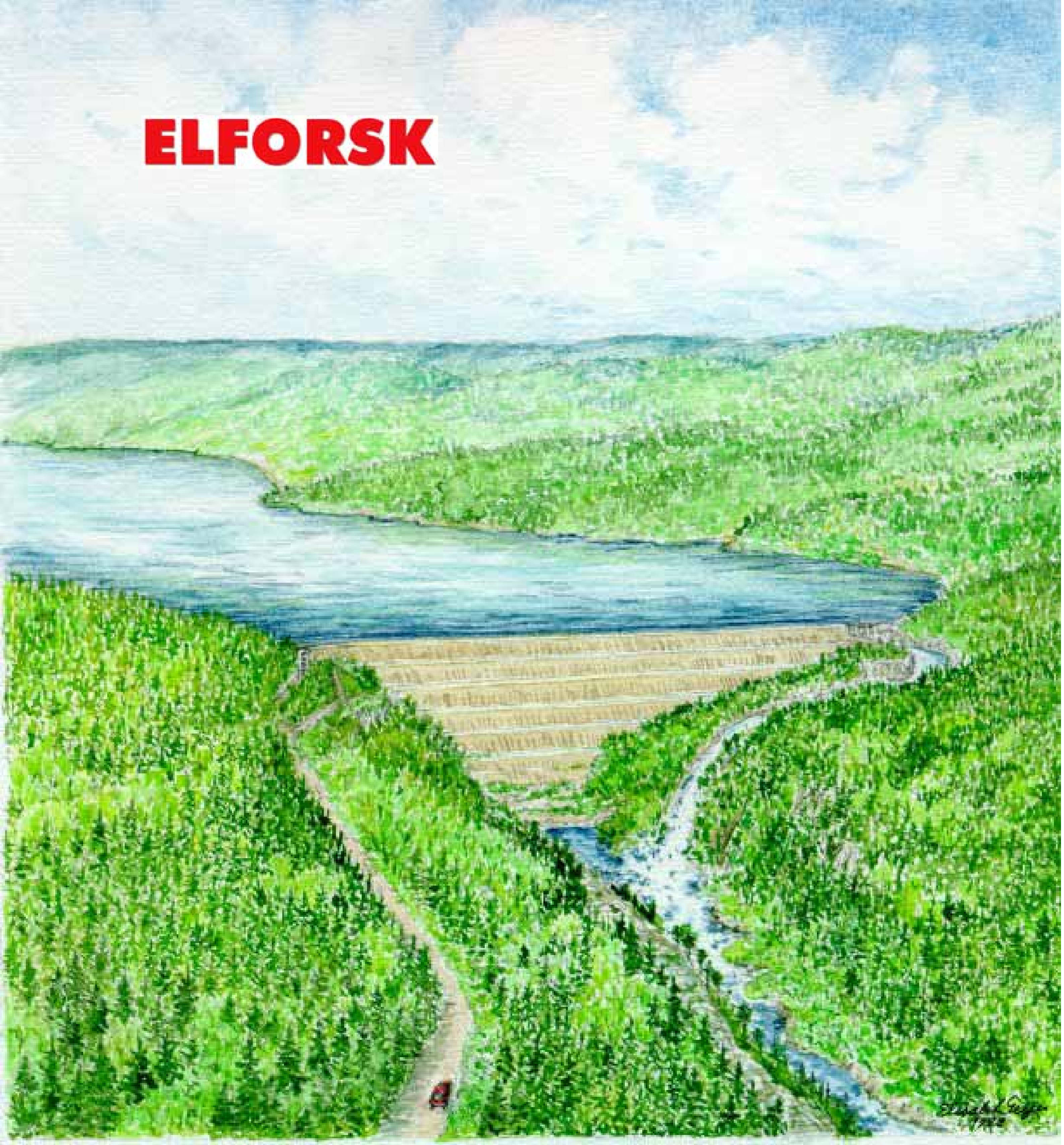

DAM SAFETY

EXPERIENCES FROM DISTRIBUTED STRAIN MEASUREMENTS IN FIVE EMBANKMENT DAMS 2004-07

Sam Johansson and Dan Watley

Rapport 07:52

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Denna rapport är ett delresultat inom Elforsk ramprogram Dammsäkerhet.

Kraftindustrin har traditionellt satsat avsevärda resurser på forsknings och utvecklingsfrågor inom dammsäkerhetsområdet, vilket har varit en förutsättning för den framgångsrika utvecklingen av vattenkraften som energikälla i Sverige.

Målen för programmet är att långsiktigt stödja branschens policy, dvs att:

- Sannolikheten för dammbrott där människoliv kan vara hotade skall hållas på en så låg nivå att detta hot såvitt möjligt elimineras.
- Konsekvenserna i händelse av dammbrott skall genom god planering såvitt möjligt reduceras.
- Dammsäkerheten skall hållas på en god internationell nivå.

Prioriterade områden är Teknisk säkerhet, Operativ säkerhet och beredskap samt Riskanalys.

Ramprogrammet har en styrgrupp bestående av: Jonas Birkedahl – FORTUM, Malte Cederström - Vattenfall Vattenkraft, Anders Isander – E.ON, Martin Johansson – Skellefteå Kraft, Olle Mill - Svenska Kraftnät, Urban Norstedt - Vattenfall Vattenkraft, Gunnar Sjödin – Vattenregleringsföretagen, Rolf Steiner - FORTUM, samt Lars Hammar - Elforsk

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Elforsk AB

Sammanfattning

Rörelsemätningar är en vanlig övervakningsmetod inom anläggningssektorn och används på olika sätt vid flertalet broar, tunnlar, dammar och vägar. Mätningar sker normalt i enstaka punkter. Ett system för att mäta töjning i optiska fiber "Distributed Temperature and Strain System", DTSS, har tagits fram av Sensornet. Till skillnad mot dagens mätningar ger fiberoptiska mätningar möjlighet att mäta rörelser kontinuerligt längs hela konstruktionens. Tekniken medför därför förbättrade möjligheter att förstå en konstruktions verkningssätt. Genom att göra upprepade mätningar kan relativa töjnings-förändringar detekteras, både beträffande dess läge och dess storlek.

Elforsk AB har i tre tidigare projekt stött forskning för tillämpning och utvärdering av denna teknik för mätningar på dammar. I detta projekt har tekniken utvärderats genom ytterligare laboratorieförsök, experiment i fält, samt fullskaliga fältmätningar. Två olika kablar har använts. Erfarenheter från olika installationer har också dokumenterats.

Mätningarna har visat att installationen måste göras omsorgsfullt för att inte skador ska uppstå, vilka försämrar mätnoggrannheten. Erfarenheterna visar att lokala enstaka skador kan medföra en drastisk sänkning av mätnoggrannheten, men också att goda installationer kan göras.

Den kabel som tagits fram för denna typ av mätningar (DamSens cable) har visat sig fungera väl, både med avseende på funktion och installation. Kabeln möjliggör dock inte att bestämma i vilken riktning som rörelsen skett. Detta kan dock principiellt göras med SMARTprofile kabeln, som har två parallella fibrer för töjningsmätning. Dessvärre visar dessa mätningar att denna kabel inte är lämplig att installera i dammar, eftersom alltför stora förluster uppkommer. Skillnaden mellan töjningen i de båda fibrerna blir därmed mindre än det mätbrus som uppkommer.

Mätmetoden baseras på att mäta den spänning/töjning som finns i de optiska fibrer som finns inuti kabeln. Resultatet erhålls längs hela kabeln och med en upplösning av 1 m. Vid mätning av rörelser på dammar förutsätts också att kontakten mellan kabeln och omgivande jord är god. Om en rörelse uppkommer i dammen överförs den till kabeln, och vidare från kabelns mantelyta in till fibern där mätning sker.

Vid kabeltillverkningen uppkommer spänningar i fibern, vilken varierar längs kabeln. Detta medför att endast relativa mätningar göras, dvs. endast förändringar sedan föregående mätning kan detekteras. Töjningar i fiberns riktning kan mätas med en noggrannhet av ca 20-50 $\mu\varepsilon$. Baserat på de tester som gjorts bedöms detta motsvara en rörelse vinkelrät mot kabeln mellan ca 0,2-2 mm, beroende på vilken friktion som antas finnas mellan kabeln och det omgivande jordmaterialet.

De första rörelsemätningarna i fiberoptiska kablar gjordes i september 2004 på Ajaure dammen, då magasinsnivån var hög. En andra mätning gjordes i maj 2005 vid lågt vattenstånd i magasinet. Mätningar har därefter skett två gånger per år fram till maj 2007. De relativa förändringarna är små, med undantag av ett område där svagt ökande töjning noterats. Dessa kan tolkas som att flera mindre rörelser (kanske någon mm)

skett i detta område, baserat på de erfarenheter som gjorts inom projektet och andra genomförda studier.

Mätningarna i Seitevare visar stabila förhållanden och god repeterbarhet i mätningarna. Ett undantag finns dock i en lokal punkt där förändring skett. Denna syns också i de båda kablar som finns installerade parallellt. Eftersom förändringen bara syns i en mätpunkt tyder detta på god friktion mellan kabeln och omgivande jordmaterial, samt att en lokal rörelse förekommer. Baserat på genomförda tester och studier bedöms denna rörelse vara liten, kanske några mm.

Mätningarna i Suorva på Östra och Västra dammen, samt Hällby har gjorts vid färre tillfällen. Inga förändringar har noterats, utan erhållna resultat kan användas för framtida jämförelser.

Eftersom mätsystemet möjliggör mätning längs dammarnas hela längd kan det också användas som dammbrottsvarningssystem. Systemet är dock för närvarande kostsamt, vilket medför att fasta installationer inte är aktuellt om inte speciella behov föreligger. Det är därför lämpligare att använda mätsystemet för regelbundna mätningar (1- 2 ggr per år) för att upptäcka eventuella rörelser i dammen.

Summary

There is growing interest to measure strain in many civil structures such as dams, bridges and tunnels. Optical fibre sensors are increasingly used to measure both temperature and strain in such constructions. Essential development of this application for dams has been made previously by Sensornet and HydroResearch, within three research projects funded by Elforsk AB. The main objectives in this research project are to: investigate different cables, evaluate different ways of installation, perform repeated measurements; and evaluate the result.

The applied strain sensing technology allows a full coverage of an entire dam. Local movements could be detected at an early stage, if the movements of the dam could effectively be transferred into the cable. This would provide useful and additional information to the local surveying points which normally are used in order to detect movements. The challenge is, however, not only to measure movements but also to design a suitable cable to imbed in the structure to be monitored, and also to understand the transfer of strain from the monitored structure (in this case an earth dam) to the cable.

Measurements, performed at five dams at several occasions between 2004 and 2007, have demonstrated the potential of distributed strain measurements in dams. Specific information concerning strain location has been provided, which has not been available before. The distributed technology seems to be a valuable complement to conventional inclinometers. The DTSS allows monitoring movements over the entire length of a dam. However, the absolute value of the movement is difficult to estimate, but will be in the order of some mm.

The experiences from the measurements show the importance of good installation work, careful monitoring and using a DTS to improve the monitoring accuracy for the DTSS. Unsatisfactory installations may result in high optical losses, which reduce the monitoring accuracy drastically. Care is needed during installation to avoid excessive losses at turnaround points, which later compromise measurement accuracy. The test with the SMARTprofile cable was not successful, and the result was not accurate enough to determine the direction of the movement.

The three significant strain changes, observed in the studied dams, seem all to be small. None have been confirmed by any changes observed or measured on the dam surface. These measured strain differences (in the order of some thousands $\mu\varepsilon$ strain) are several times larger than the noise level of the measurements (about 50$\mu\varepsilon$ at field measurements). A reasonable estimation of the friction between the soil and the cable indicate that the measured strain difference corresponds to a movement of some millimeters. Further work should also be carried out in order to better understand the interaction between the cable and the soil to allow a better use of the technology.

Finally, the system can detect strain changes (movement changes) in the dam and can therefore be used either as Early-Warning-System with continuous monitoring, or as an investigation tool to measure movements regularly.

Content

1 Introduction

Dam monitoring is an essential part of the dam safety work and several methods are normally used and a variety of parameters are measured. Information is generally obtained in single points, representing the conditions in that specific location (such as pressure and movements) or representing conditions over larger areas (especially collection of seepage water). However, during recent years distributed measurements have successfully been introduced in several applications. This allows continuous information all along a construction.

The technology is now a standard in Sweden in embankment dams for seepage measurements based on Distributed Temperature Measurements using optical fibres. This project is based on similar technologies where also information about the strain in an optical fibre can be measured. The measurements are based on a sensing instrument, Distributed Temperature and Strain Sensor (DTSS), developed by Sensornet. The unit is uniquely capable of measuring both strain and temperature at 1m intervals over long distances in optical fibres.

This strain sensing technology allows a full coverage of an entire dam. Local movements could be detected at an early stage, if the movements of the dam could effectively be transferred into the cable. This would provide useful and additional information to the local surveying points which normally are used in order to detect movements.

The challenge is, however, not only to measure movements but also 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 be able to 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 monitored structure (in this case an earth dam) to the cable must be devised. Moreover, the cable must be easy to handle and possible to install without disturbing the normal construction.

The main objectives in this research project are to:

- investigate different cables,
- evaluate different ways of installation,
- perform repeated measurements; and
- evaluate the result.

This project is mainly based on three previously research projects performed by Sensornet and HydroResearch. Those projects were also funded by Elforsk AB (Project No1286 in 1998 (Johansson et al, 1999), No1356 in 1999 (Johansson et al, 2000), (Johansson et al, 2003), and (Johansson and Watley, 2005). In order to provide a better understanding, some earlier result has been incorporated in this report, which constitutes the final report, covering all parts of these research projects.

The report presents field measurements from a four Swedish dam sites. The initially planned measurements at the dams at Ajuare, Suorva East, and Seitevare, were completed with measurements at Hällby and Suorva West, thanks to additional support from the dam owners (E.ON and Vattenfall Vattenkraft AB). All installation cost has also been covered by the same dam owners.

Except for the authors, several persons have been involved in the field measurements. Those are Erik Lindstein and Amir Fard (both from HydroResearch), and Michael Mondanos, Jochen Sturm, and Mladen Tomorov (all from Sensornet).

2 Distributed Temperature and Strain Sensing in dams

2.1 Monitoring unit

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). 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.

The DTSS used in these tests was configured to give a 1°C temperature resolution and a 20με 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). The DTSS is designed to be able to operate over lengths of up to 30km.

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).

2.2 Cables

2.2.1 The DamSens Cable

The first DamSens cable (Figure 2), was designed by Sensornet/HydroResearch for dam monitoring. The first installation of the cable was made at Ajaure in 2001. This cable has also been installed in other dams, although some minor changes have been made in order to further improve its durability. The cable 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.

Table 1 - DTSS cable specifications.

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 2 - Optical fibres' 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	50/125 graded-index	3.0dB/km+600MHz-km @850nm	DTS

and brown	multimode fibre	and 1.0dB/km+600MHz-km @1300nm	

The cable has been terminated with angled E2000 connectors for use with both the DTSS and the DTS instruments.

2.2.2 DamSens cable calibration

The DTSS determines strain and temperature by measuring the Brillouin reflections that occur in optical fibre. These Brillouin reflections are a result of an interaction between optical and acoustic waves in the fibre. Most importantly, the Brillouin reflections are not just sensitive to environmental conditions such as strain, temperature and pressure, but also to intrinsic fibre characteristics such as core size and cable structure. This means that the exact nature of the way in which temperature and strain affect a particular fibre cable needs to be calibrated to guarantee accurate measurements in the field.

The cable was calibrated in two stages. Firstly, a length of around 30m was placed in an environmental test chamber. The chamber temperature was varied from -10°C to +40°C in steps of 5°C and a DTSS measurement was taken at each setting. The measures of Brillouin power and frequency against temperature then provide the calibration coefficients for the cable. Secondly, the cable was tested for strain. A length of 10m was clamped into our strain rig, consisting of one fixed point and another moving stage attached to a winch. The winch allows us to apply considerable force to the cable under test. A digital measuring rule is also attached to the moving stage allowing accurate measurements of change in position to fractions of a millimetre (Figure 3).

By looping the cable loosely back along the same path as the strained section, accurate temperature compensation can be achieved during the calibration process. The Brillouin shift and power is measured in the strain section and then referenced to the loose section to remove the temperature effects.

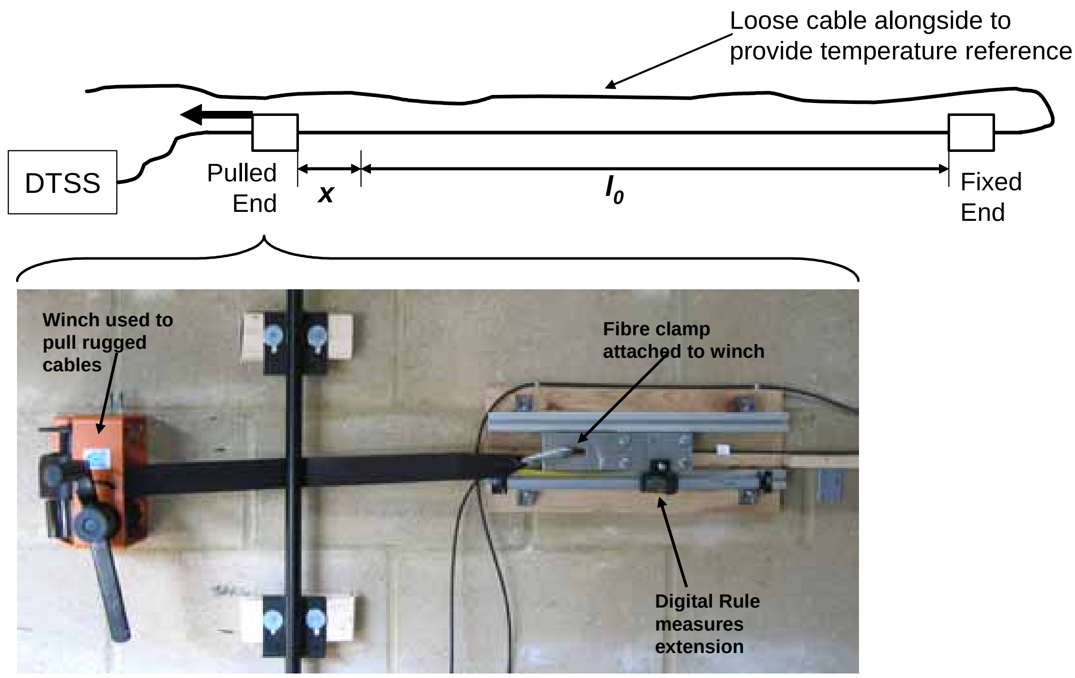

Figure 3 - Sensornet's strain rig schematic and photo of pulled end.

These calibration measurements supersede earlier tests carried out by Sensornet. The strain rig used provides a more accurate measure of strain, and temperature calibration was not previously undertaken. Figure 4 shows one example of the results of the cable calibration. Specifically the Brillouin frequency shift has been measured, using the DTSS, against differing values of strain applied to the cable. These measures have been corrected for temperature effects by plotting the difference in Brillouin frequency shift between the strained and loose sections of cable in the strain rig.

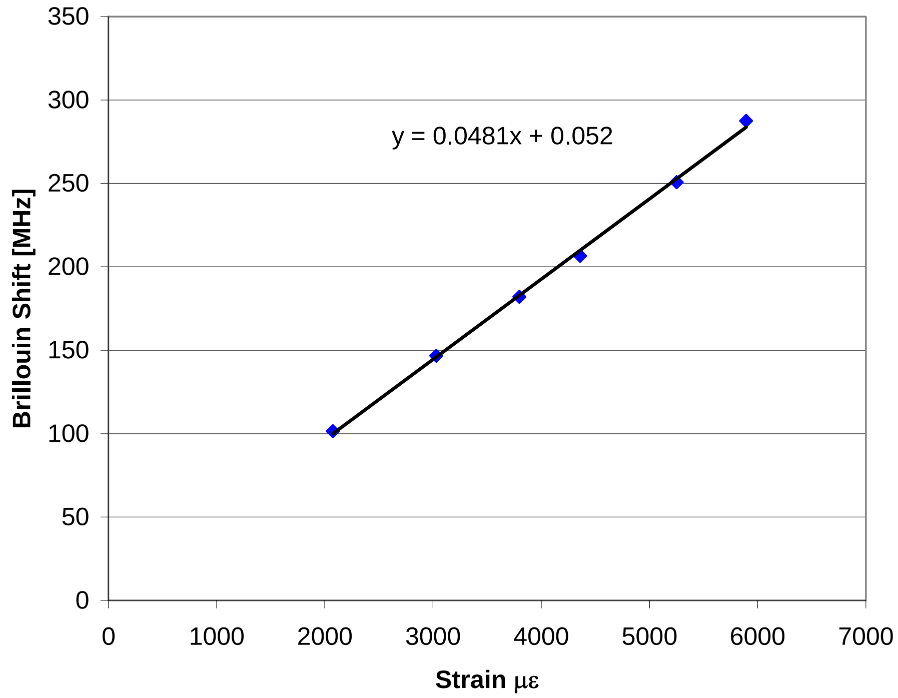

Figure 4 – Calibration of DamSens Cable for Strain.

A total of four coefficients are required to accurately calibrate the DTSS instrument to the cable installed in the dam. These coefficients describe the change in Brillouin power and frequency shift with changes in temperature and strain.

Table 3 – Cable calibration coefficients for DTSS

Coefficient	Description	Measured Value
$C_{\nu\varepsilon}$	Change in Brillouin frequency versus strain	48.1 kHz/με
$C_{\nu T}$	Change in Brillouin frequency versus temperature	2.48 MHz/°C
$C_{p\varepsilon}$	Change in Brillouin power versus strain	-1.4×10^{-3} %/με
C_{pT}	Change in Brillouin power versus temperature	0.42 %/°C

Accurate calibration of the cable ensures that the DTSS instrument provides independent measurements of strain and temperature in the dam, and hence is a vital part of the instrumentation process.

2.2.3 SMARTprofile cable

An alternative cable (SMARTprofile, supplied by Smartec), was also identified as a candidate for installation at a couple of dam sites. The SMARTprofile cable has been specifically designed for use with distributed Brillouin measurement instruments, similar to the Sensornet DTSS. However, unlike the Sensornet DTSS, all other Brillouin measuring instruments are unable to distinguish between temperature and strain. In order to provide a solution to this problem, SMARTprofile developed this cable which contains some fibres which are "loose", therefore measuring temperature alone, and some fibres which are "tight", therefore measuring both temperature and strain. By taking measurements on both types of fibre in the cable it is possible for other instruments to achieve temperature compensated strain measurements.

Whilst this feature of the cable could be used by the Sensornet DTSS, it is not necessary since the instrument itself is able to measure temperature and strain independently on any appropriate single fibre. The reason why the cable has been chosen for installation in Seitevare dam is its geometry, as shown in Figure 5, which provides the possibility to also identify the direction of a movement.

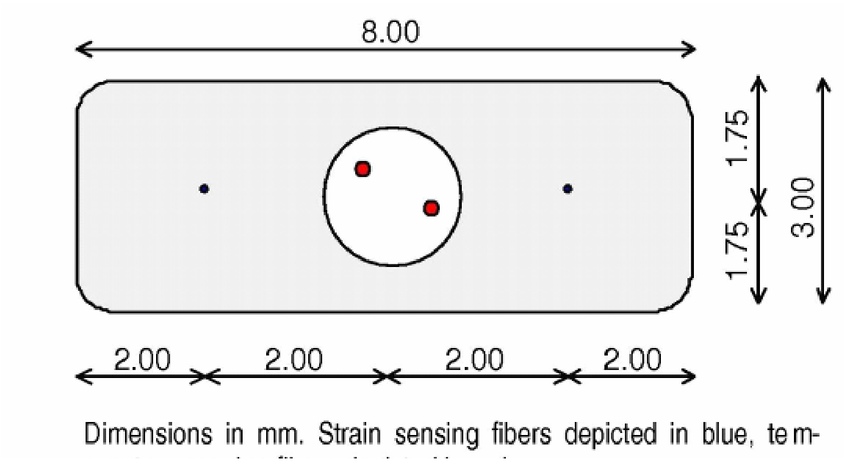

Figure 5 – Geometric structure of SMARTprofile cable

The centre of the cable includes a tube in which several fibres are included, referred to as “loose tube”. These fibres can be used for measuring temperature because they won’t experience any strain when the cable is pulled. The “tight” fibres are encapsulated into the rectangular profile of the cable either side of the loose tube. In this way any strain applied to the cable is immediately transferred to the tight fibres. The key reason for investigating this cable though is that the two tight fibres are offset from the neutral axis of the cable. Hence, if the cable is bent then the two fibres will experience different types of strain. The fibres on the outside of the bend will experience tension whilst the fibre on the inside of the bend will experience compression, as shown in Figure 6. Therefore, by measuring the strain in both fibres and comparing them we will be able to determine not only the deformation of the dam but also the direction of the deformation. The calibration process reported in the next section tests this idea with a piece of sample cable.

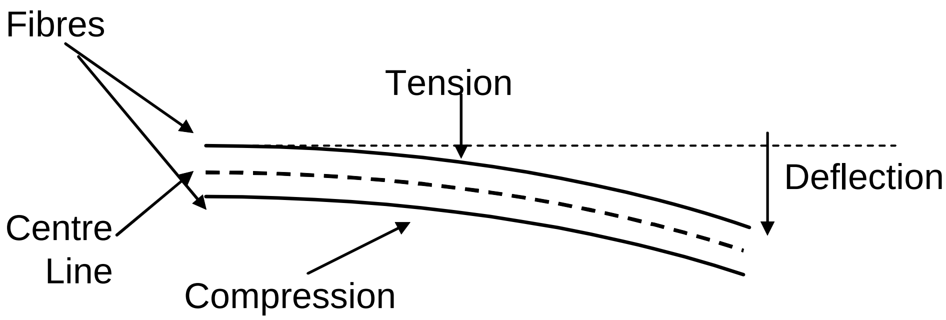

Figure 6 – Use of SMARTprofile cable as bend sensor.

2.2.4 SMARTprofile Cable Calibration

The cable was calibrated using the same setup as was described in the previous section. Calibration of the SMARTprofile cable involved calibration of both the strain measuring fibres and the temperature measuring fibres of the cable. Figure 7 shows the calibration of one of the strain coefficients for the strain sensing fibre. The results indicate a coefficient of 48 kHz/με for the Brillouin shift strain coefficient, which is in close agreement with other cables. It should be noted that calibration measures were taken for both increasing and decreasing strain. All of these are shown in Figure 7, demonstrating that the cable behaves elastically with no hysteresis in the range of strain explored during the calibration process.

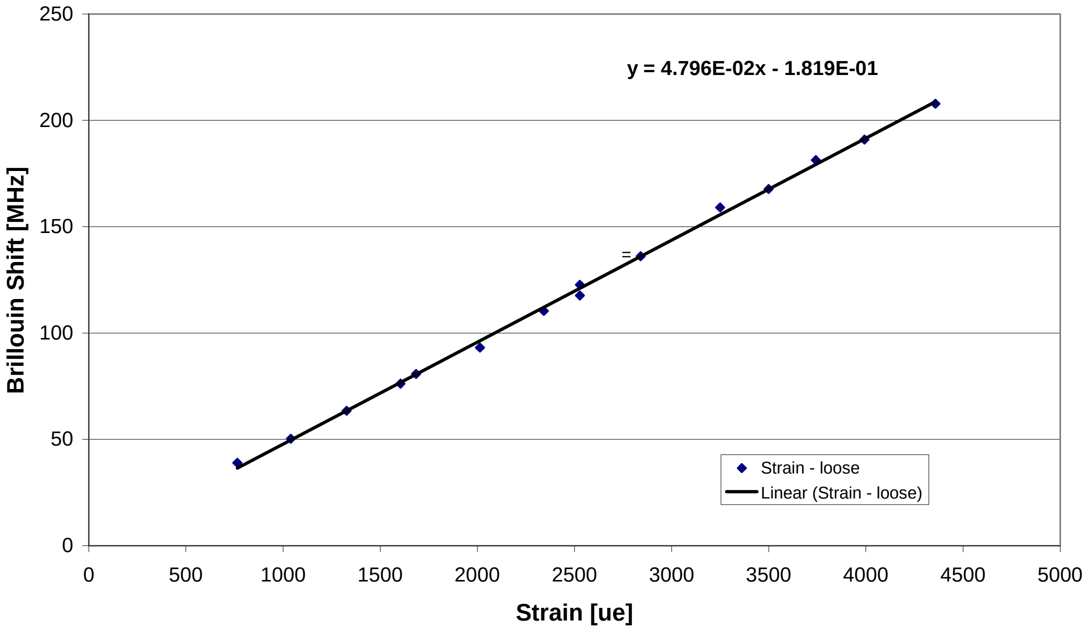

Figure 7 – Shift versus Strain Coefficient Calibration.

Table 4 and Table 5 show the results of the calibration. The strain fibre demonstrates sensitivity to temperature almost five times higher than normal fibre. This may have a detrimental affect on the resolution of the measurements taken. The coefficients for the temperature sensing fibre of the cable show negligible change with strain during the calibration process. However, it was seen that in the distributed measurements, the region under stain did show some difference compared with the rest of the cable, even for the temperature sensing fibre. Hence, we do not think that this temperature sensing fibre can be used to sense temperature without some strain cross sensitivity.

Table 4 – Calibration coefficients for strain fibre of SMARTprofile cable

Coefficien t	Description	Measured Value
$C_{\nu\varepsilon}$	Change in Brillouin frequency versus strain	48.0 kHz/με
$C_{\nu T}$	Change in Brillouin frequency versus temperature	4.75 MHz/°C
$C_{p\varepsilon}$	Change in Brillouin power versus strain	$-1.4\text{x}10^{-3}$ %/με
C_{pT}	Change in Brillouin power versus temperature	0.15 %/°C

Table 5 – Calibration coefficients for temperature fibre of SMARTprofile cable

Coefficien t	Description	Measured Value

$C_{\nu\varepsilon}$	Change in Brillouin frequency versus strain	~ kHz/με [1]
$C_{\nu T}$	Change in Brillouin frequency versus temperature	1.1 MHz/°C
$C_{p\varepsilon}$	Change in Brillouin power versus strain	~ %/με [1]
C_{pT}	Change in Brillouin power versus temperature	0.27 %/°C

[1] These coefficients could not be determined. They were not zero as would be expected by design. Brillouin frequency and power was seen to vary almost randomly with strain, showing no correlation. Variations could be as large as that equivalent to 1000με.

The cable was also evaluated for its ability to detect bending. This was done by laying it in a semicircle on the floor and varying the diameter of the semicircle. In this way measures could be taken for different degrees of bend. An important aspect of this test was to keep the fibre profile flat on the ground, and avoid any turning of it on its axis. This is also a critical issue for installation of this cable into dams, where the orientation of the cable must be both known and fixed throughout the installation. Figure 8 shows the results of the test, where strain measures in both strain fibres are shown. The strain fibre on the outside of the bend shows a decreasing level of tensile strain with increasing diameter of curvature. The strain on the inside of the bend shows a decreasing level of compressive strain with increasing diameter of curvature.

The calibration process provides the coefficients necessary to make accurate temperature and strain measurement using the SMARTprofile cable installed in the field. The bending test demonstrates the ability of the cable to be used to detect magnitude and direction of bending.

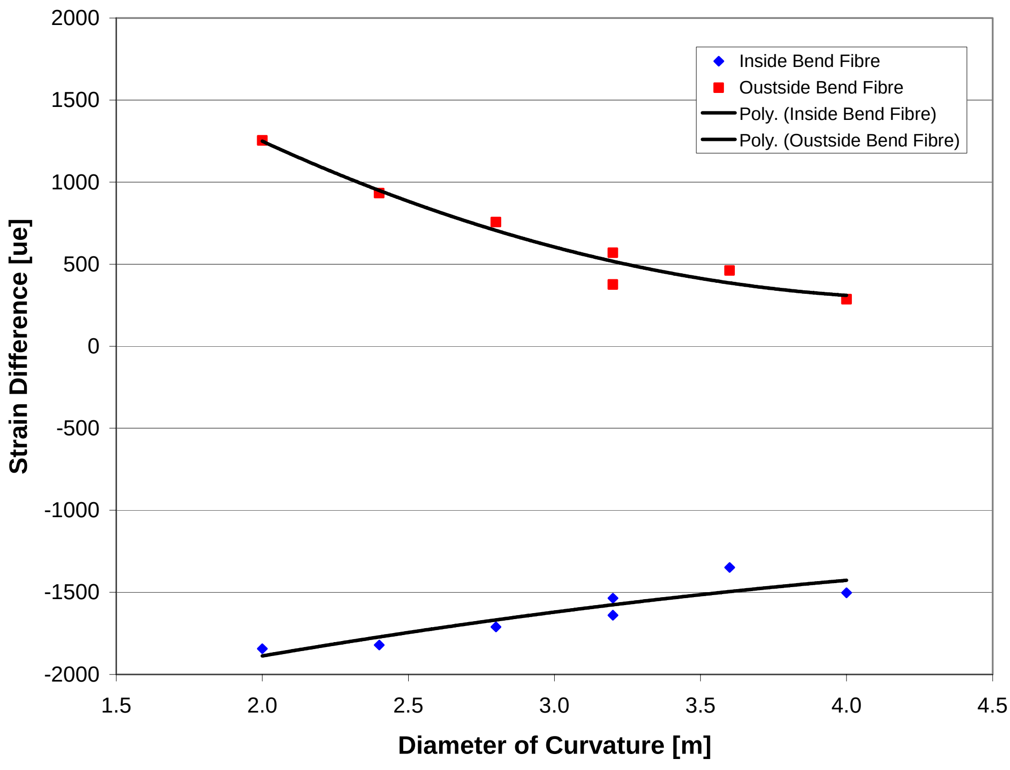

Figure 8 – Evaluation of SMARTprofile cable as bend sensor.

2.3 Methodology

2.3.1 Interaction in soil

The fundamental problem is how to transfer a movement of the dam to the cable and further into the fibre. The easiest way is just to install the fibre and backfill with homogeneous material around the fibre. The transfer will then just depend on the friction between the soil and the cable. In theory, a local movement will then cause a changed strain of the cable, which will be transferred into a distance where the total friction between and soil and cable is equalized by the pulling force caused by the movement.

If the friction is expected to be low (as is the case with the thin SMARTprofile Cable) it can be increased using clamps (Figure 9). These clamps were designed to obtain a 1 dm^2 in all three directions using a u-beam of aluminium. Surveying poles were also added to a few clamps to verify measured movements. The clamp was made in two versions to fit both cables.

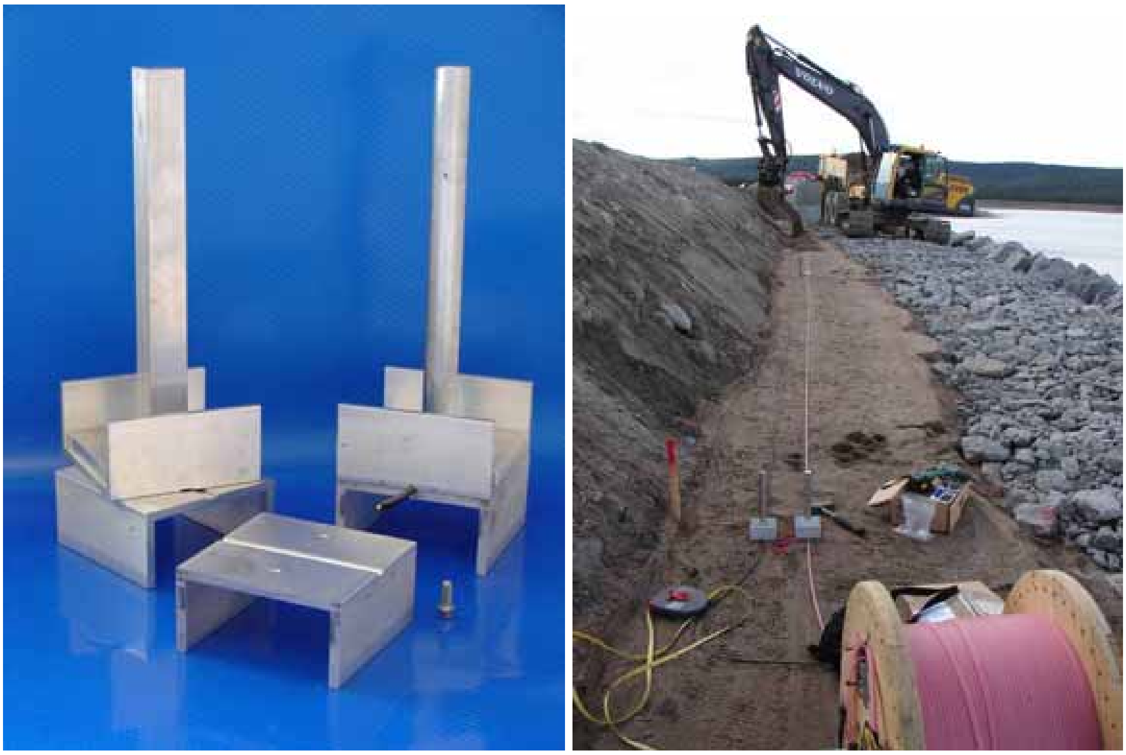

Figure 9 – Clamps used for the SMARTprofile cable and the DamSens cable, with additional surveying poles (left), and installation of the clamps at Seitevare dam.

The clamp was also needed in order to better fix the orientation of the SMARTprofile cable, thereby also allowing measuring the direction of the movement.

2.3.2 Interpretation

The methodology behind monitoring of embankment dams using distributed strain measurements is to take a baseline measurement at some initial point in time, and then compare subsequent measurements to this original baseline. Certain conditions are essential to provide the most accurate comparison over time:

1. The strain data must be accurately compensated for temperature. Any residual cross sensitivity to temperature, even in a structure with small temperature variations is still likely to cause difficulties in comparing strain measurements
2. The exact position of the cable relative to the measuring instrument needs to remain the same, so that the data exactly overlays in distance against one another.
3. The strain measuring instrument obviously has to provide exactly the same calibrated strain measurement. This will be a combination of the instruments ability to accurately determine the optical frequency of the backscatter signals reliably over time and to apply the same strain calibration coefficients each time to the measured cable.

These requirements have become clear as this research project has developed over the years. During this period a number of advances have been made to the DTSS as well as the dam monitoring methodology. Unfortunately, this means that it has not been possible to fulfil all of these requirements from the first baseline measurements through to the most recent measurements in May 2007. Future monitoring will benefit from the knowledge gained and the improvements in monitoring technology, and this will be discussed at the end of the report.

To provide an accurate comparison of measurements against one another, some additional processing of the data has been necessary, to try to achieve the requirements above, after the event. The first problem was the use of different length patchcords at the dams for different measurements. Hence the data will often need to be shifted in distance to align it with the baseline measurement. There was also a significant change to the DTSS itself since the original measurements in 2005. The way in which the instrument measures optical frequency was changed from an optical technique to an electrical technique. The electrical technique provides repeatability accurate to a few kilohertz optical frequency, which was never possible with the optical technique. So whilst the electrical technique provides a robust measurement going forward, there is sometimes need for both a change to scaling and offset of the measured strain data. To further improve temperature measurement accuracy we have also started to use DTS measured temperature, combined with the DTSS measurement. The DTS is capable of a resolution as low as 0.01°C, much better than the more typical 1°C of the DTSS, and hence can provide a much more accurate temperature correction for the strain data. It is also less susceptible to measurement error arising from improper installations. To combine the measurements all of the data has had to be post processed. In the future the DTSS will be able to retrieve temperature data directly from the DTS realtime to provide correction of the data at the time of measurement and remove the need for any post processing.

Software has been created to compare the data sets and provide any necessary scaling and distance shift adjustments. The assumption with any post processing of the data is that any changes in the dam detected by the DTSS will be localised changes, but the overall strain level should remain very similar. Figure 10 shows the user interface of the tool, which can be used in the following way:

Initially the two data sets are loaded in for comparison,①, and the distance offset between them is adjusted using the slider, ②. Secondly the strain scaling can be adjusted using slider,③. Whilst making any of these adjustments the program continually calculates the absolute difference between the two traces, given an indication of fit, ④. This score is only calculated in the region between the yellow cursors, which would be set as the region of interest. This is to exclude any external regions of cable which may have large changes from one measurement to another. Additionally, the program adjusts the strain offset between the two traces to minimise the signed difference between them to zero. Again this is done by considering the region between the two cursors. All adjustments are made by aiming to minimise the average absolute difference ④. Hence, there is a consistent, repeatable methodology applied to the comparison of every data set. When the adjustments are complete, the data is saved, provided both the original reference strain data and the adjusted comparison strain data set, and finally the measure of strain difference. It is these results that will be presented throughout this report.

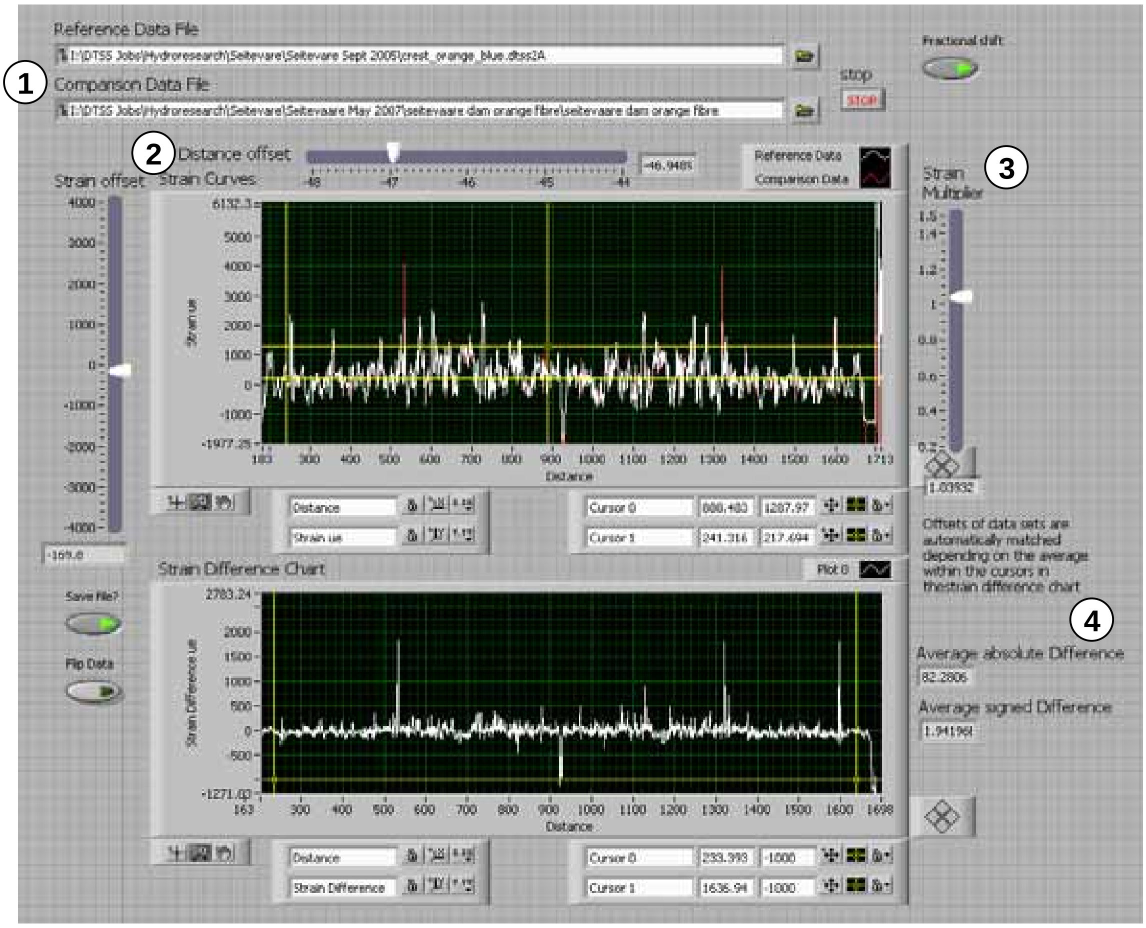

Figure 10 – Data Comparison Tool.

2.4 Installation properties

It is essential to know the losses that occur along the cable. All splices will give some loss, as well as sharp bending. Losses may also be caused by bad handling of the cable during installation, or a result of the compaction of the soil around the cable.

Optical time domain reflectometry (OTDR) is a technique used to determine the optical loss of an optical cable along its length. The Sensornet instruments are based in effect on this type of technique, although they monitor different types of light. However, the Sensornet DTSS does also provide an OTDR capability and this is usually the first measurement to be taken. It provides a measurement of the loss in the optical cable with distance and as a consequence acts as a health check for the state of the cable installation. Such measurements are therefore initially carried out at all installations.

3 Measurements at Ajaure dam

3.1 The Ajaure embankment dam

The Ajaure dam is located in the upper part of the river Umeälven. The reservoir has an active storage volume of 200 million m^3. The dam and power station was brought into operation in 1967.

The dam is 46m high and 522m long, divided by a spillway and intake structure (Figure 11). The embankment dam has a vertical core of till, surrounded by upstream and downstream filters. During construction it was decided to increase the core crest height by 1m, hence the upstream and downstream slope are steeper in the upper part of the dam.

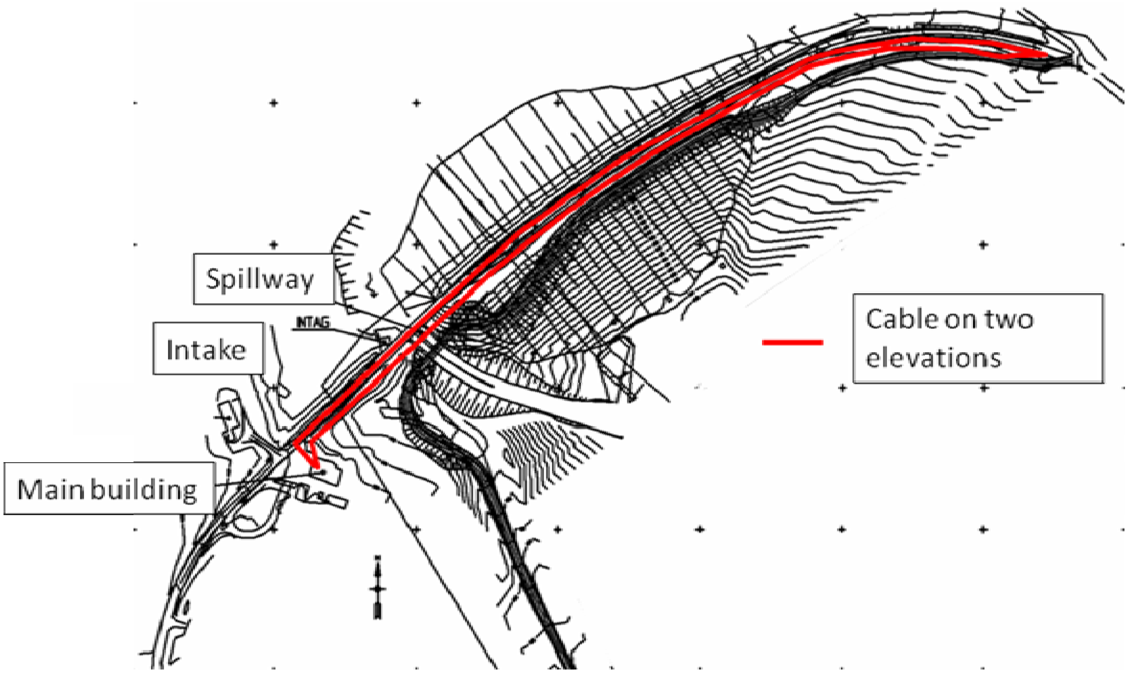

Figure 11 - Plan of the Ajuare dam with principle layout of the fibre.

Survey measurements of the dam indicated early movements larger than those occurring in similarly constructed dams. An ongoing creep of about 8mm/year was measured. Further details about the movements and its origin are explained by Nilsson and Ekström (2004). A first support berm with a height of 20m was constructed on the left dam in 1989. It was extended in 1993 almost up to the crest in order to decrease the movements and increase the stability. Further improvements were made in 2001 when the crest was raised according to the new Swedish Guidelines for Floods. The new crest was also connected to the additional toe berm. Two inclinometers were also installed at chainage 330m and 393m in order to detect movements at different levels down to the bedrock.

3.2 Installations

The sensing cable was installed in the crest of the dam during 2001 when the crest was raised according to the new Swedish Guidelines for Floods. Three inclinometers were also installed in order to detect movements in some sections. The sensing cable was installed at two levels along the dam in order to detect movements between the inclinometers.

The fibre is installed in a loop configuration. This means that each of the two strain fibres in the cable can be measured in either direction around the cable path. On its way to the dam the cable passes beneath a bridge over the spillway where the cable is accessible for experiments and testing, if needed (Figure 12).

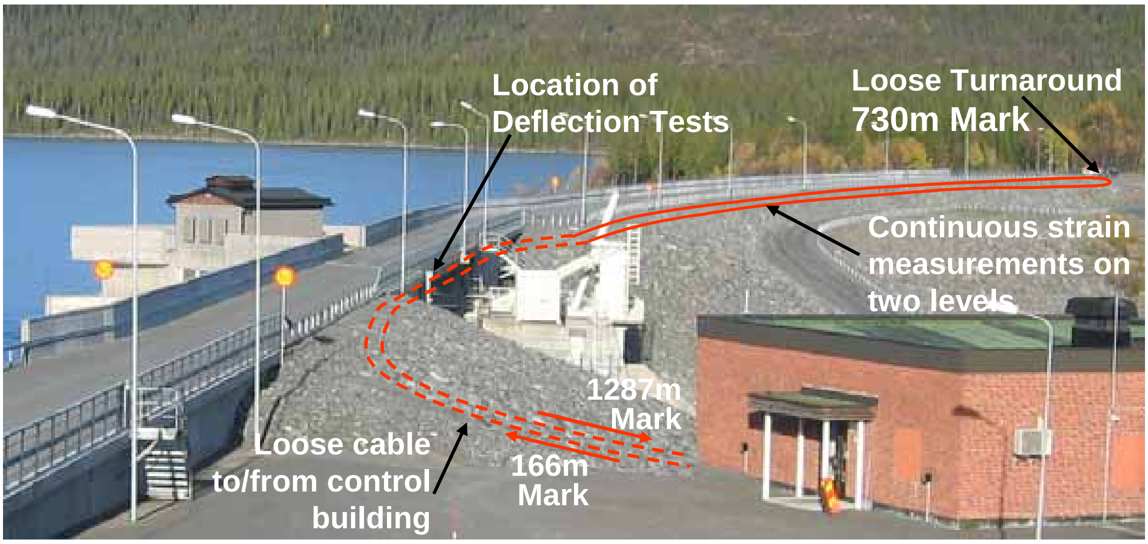

Figure 12 - Illustration of the sensing cable route at Ajaure dam.

The cable was installed at two levels (mean values +442.5 and +445.2) along the dam in a loop. Both ends of the optical cable are terminated in the monitoring room. The cable is marked at every metre interval. After cutting the cable to length, the markings on the cable were from 166m (minus a 0.5m tail) to 1287m. The total cable length is 1122.5m with an effective monitoring length of 320m on each level within the dam crest.

The location of the cable in the dam is surveyed at 5m intervals according to the markings on the fibre. The cable around the damage at marking 1012.3m was drawn into a monitoring well. There is a total of 8m length of the cable, starting at marking 1000m to 1018m, wrapped around together in the well.

3.3 Initial measurements in September 2004

The first measurements, using the Sensornet DTSS, were taken during September 2004 when the reservoir was close to full. A number of measurements and tests were carried out during a four day period.

3.3.1 Optical Loss Measurement

An integral part of a strain measurement is to take an optical loss measurement. Whilst this is carried out primarily to later calculate the temperature and strain in the cable, it also provides a check of the optical losses/attenuation in the installed cable.

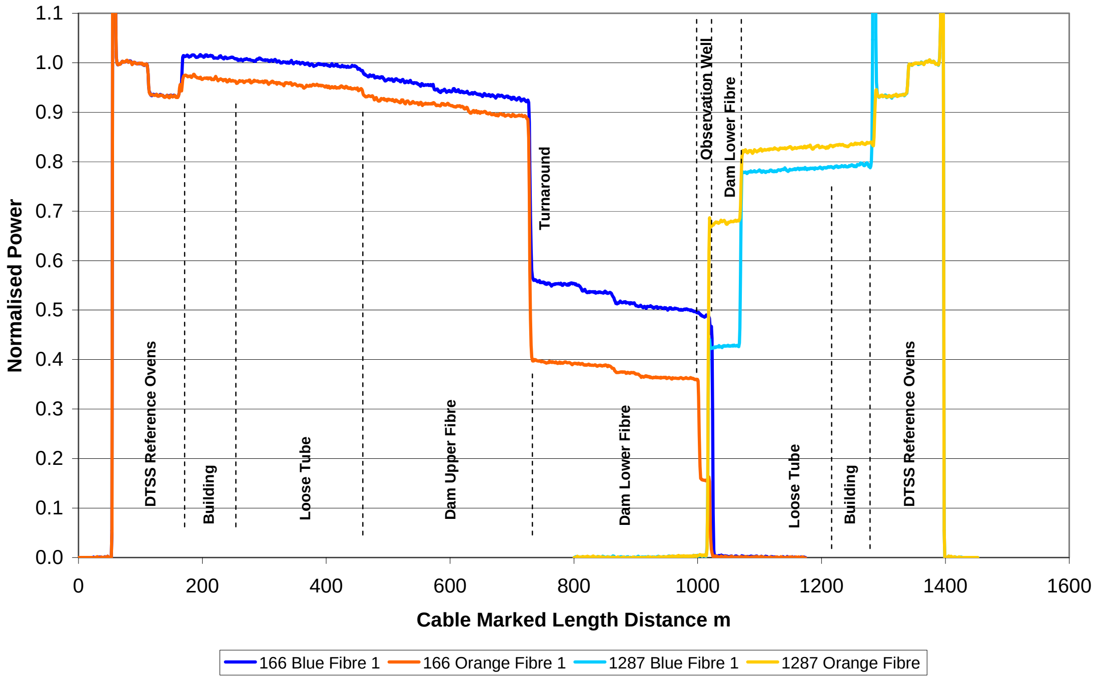

Figure 13 – Optical loss measurements of Ajaure Dam.

Figure 13 shows four different loss measurements. Although the cable was originally installed in a loop configuration, damaged at a position in the lower path of the cable means that the loop is effectively broken. Hence, to measure both paths in their entirety, measurements must be undertaken from both ends of the loop i.e. 166m marking and 1287m marking. Additionally, there are two fibres included in the cable for these measurements; the blue and the orange fibres. Figure 13 shows the measured losses and provides annotations of various features in the cable path along the dam.

Important features are the large point loss (>3dB two way loss) experienced at the turnaround point at the far end of the dam. Also of particular importance are the losses in the region of the observation well. At this position the cable was brought into the observation well through a hole in its wall. The entry point causes a severe loss on the orange fibre but not on the blue fibre. However, losses imposed on both fibres are too severe for light to pass beyond the exit point of the observation well. This is the reason that we have needed to measure from both ends. The fibre was bought into this observation well after some damage during installation. The idea being that the observation well provided a safe place to house the splice required to repair the damaged cable. This point will be returned to later. There are also considerable losses, looking from the far end, at the point where the fibre leaves the loose tube and enters the lower path of the dam. Observations at the dam site indicated that the installation had resulted in a couple of positions where the cable was pulled very tight, possibly resulting in losses. The positions where the cables are pulled taunt are shown in Figure 14.

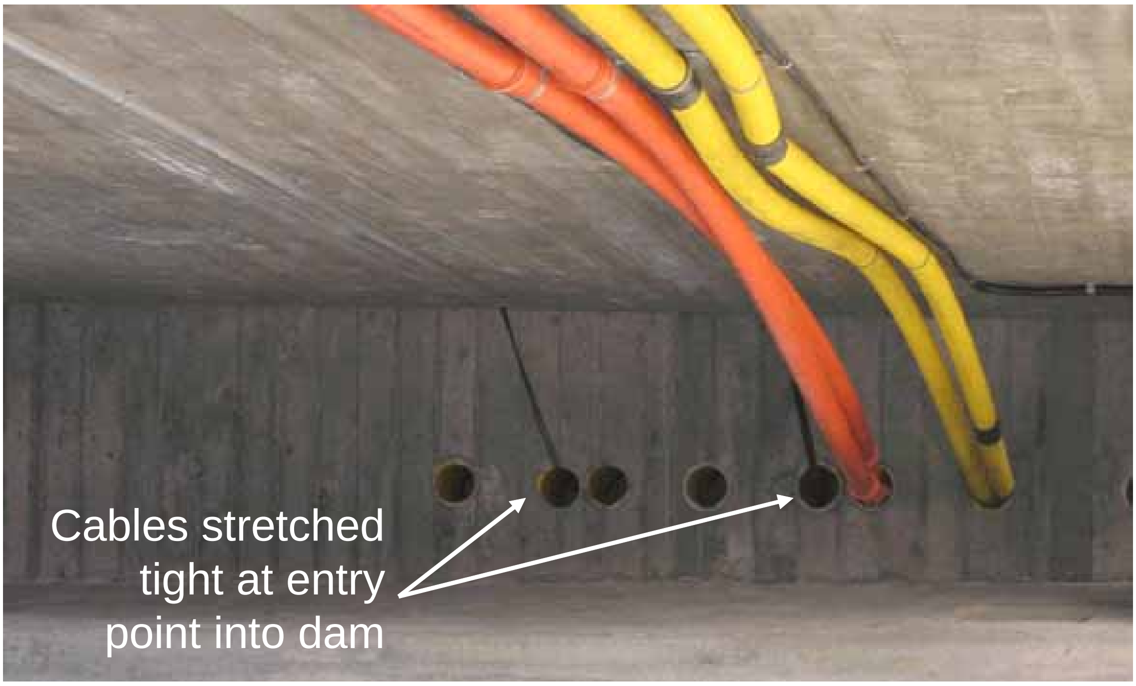

Figure 14 – Photo of cable entry point into dam above spillway.

3.3.2 Strain Measurements

An overview of the first strain measurements taken during September are shown in Figure 15. Again the figure has been annotated to highlight the various features of the cable path along the dam. The sections of cable within the control building and the loose tube out to the dam show reasonably low strain levels. The sections actually within the dam crest show much greater strain and a lot of variation. This is associated with compaction during construction of the new dam crest. Variations in the strain may also been seen at the bridge section above the spillway. These variations arise from the deflection tests undertaken, which were presented in the previous report. (A small summary is also included in this report, section 7.4.1).

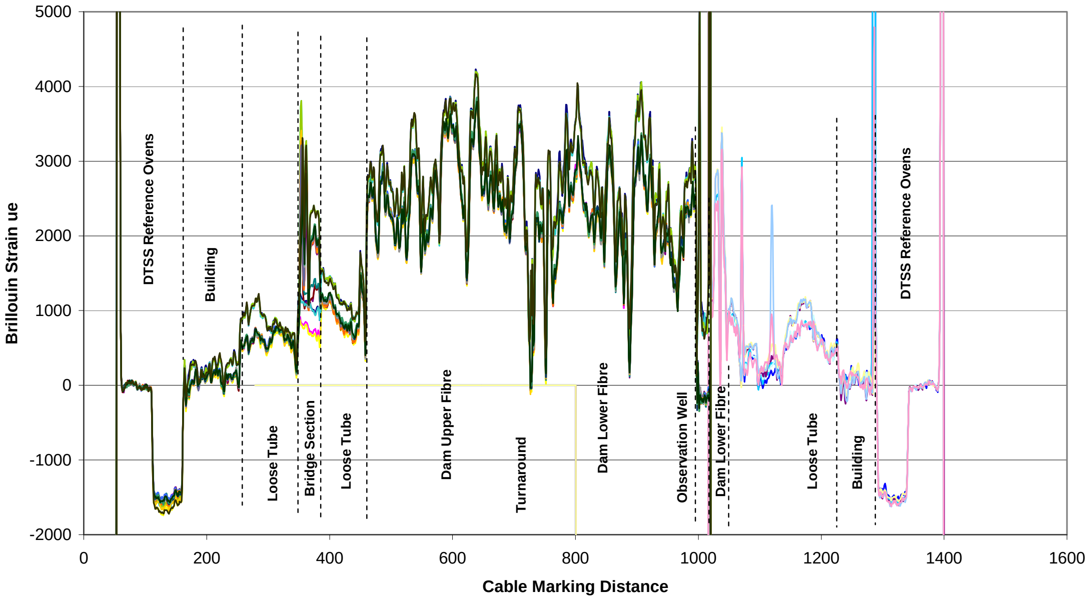

Figure 15 – September strain measurement overview.

Figure 16 shows an average of four measurements taken in each of the fibres within the cable. The figure is focused on the main area of interest, the embankment dam. It is clear that the two fibres within the cable are closely correlated, tracking the significant variations caused by the compaction of the dam after installation. There is a small difference measured by each of the fibres most likely arising from differences during fibre manufacture. These differences are not significant since we are looking for relative changes in the strain over time.

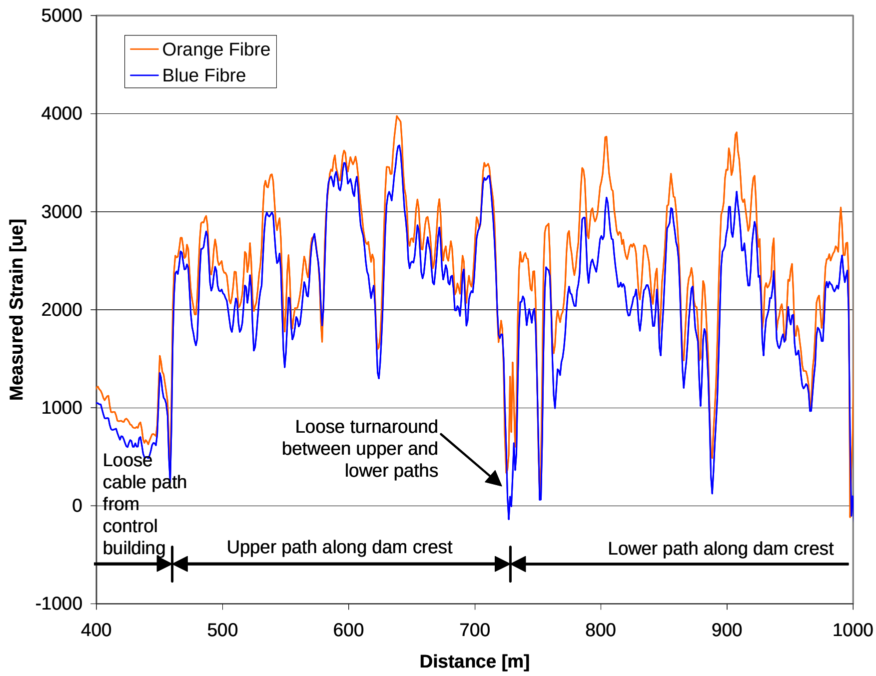

Figure 16 - September measured strain along dam sections of cable.

Another feature to note is the strain level of the turnaround at the far end of the dam, which is relatively unstrained. It is important to realise that few detailed interpretations of the state of the dam can be made at this stage, given the variations in strain arising from the installation process. A second measurement is necessary to look at differential changes.

3.3.3 Temperature Measurements

Figure 17 shows the measured temperature in the dam during September. The temperature measured in the upper section shows a reasonably stable profile, as is expected, and the measurement from both fibres agrees well. However, the temperature measured in the lower section does not agree between the two fibres. It should be remembered that there will be a natural difference in temperature between the upper and lower cables, of a few degrees for that time of year. Measured temperature should however be similar in the tow fibres in the cable, which is not the case for the lower cable.

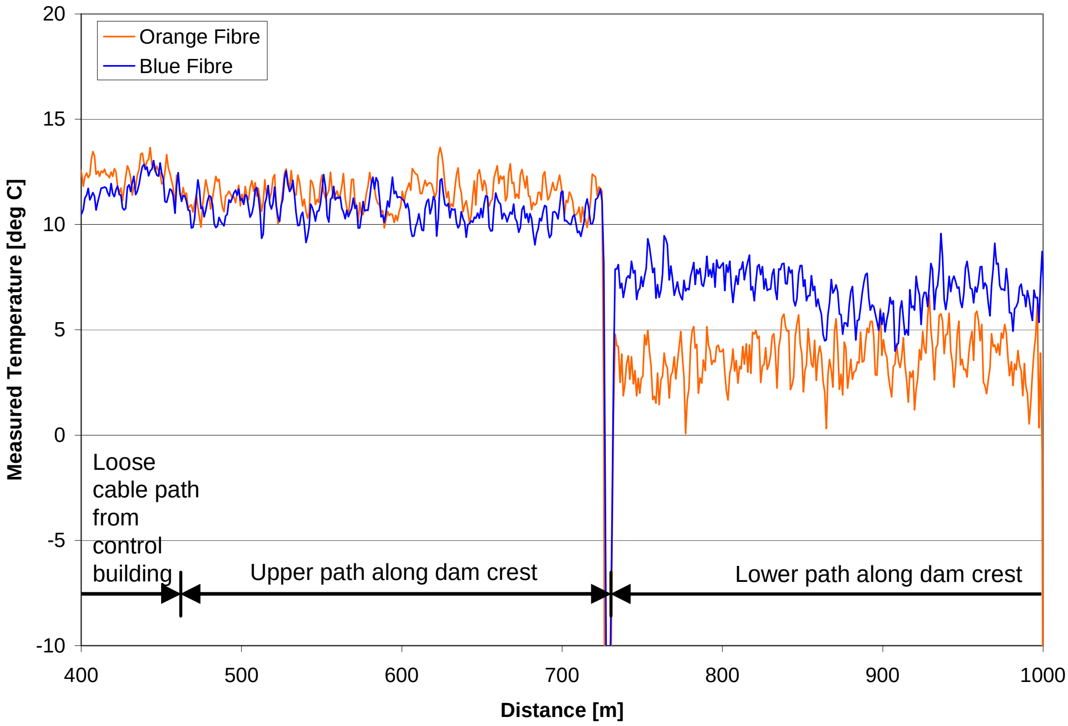

Figure 17 – September measurements of temperature.

The lack of agreement between the two co-located fibres highlights a problem arising from the installation. The incorrect absolute temperature arises as a consequence of the excessive point losses at the turnaround. Figure 13 showed that the orange fibre suffered a greater loss at this point than the blue fibre. The magnitude of the loss is equivalent to an additional 9km of cable at that position. The nature of the loss, arising from a severe bend, or similar, at that location is likely to have exacerbated the temperature error which can be seen in Figure 17. Ideally the DTSS would correct for this, but bending losses cause a temperature inaccuracy which cannot be resolved when the losses are of such large magnitude. Despite this, the relative measured temperature in the two dam sections, up to the fibre failure at the observation well, can be trusted for detecting localised changes in temperature.

The true impact of this installation fault is that there might be a small error in the absolute measured strain between these two dam sections. This will become clear when two measurements are compared.

3.3.4 Repeatability

Strain measurements taken at different times during the September visit to Ajaure have been compared to assess the accuracy of the DTSS instrument. Figure 18 shows the results of this comparison, where two sets of measurements from each of the two fibres have been subtracted from each other to highlight any differences in the measured strain.

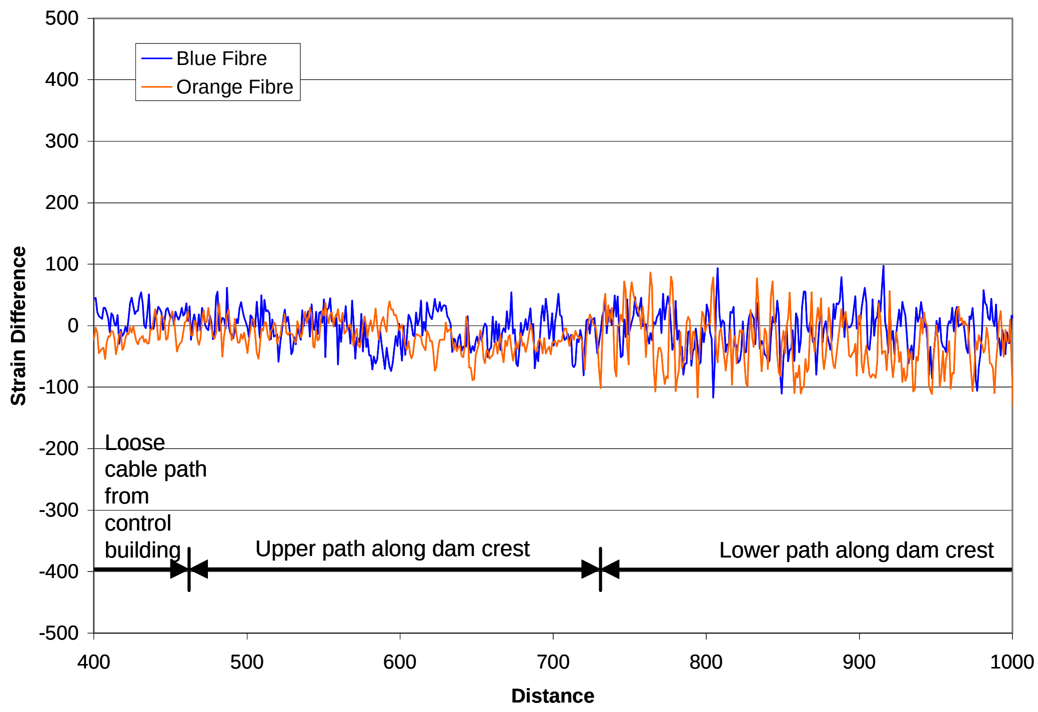

Figure 18 – Strain difference between separate measurements during September

The results indicate very good repeatability of the strain measurements, with all measurements being centred around a zero strain difference. The increase in measurement noise after the turnaround point is a consequence of the high losses at this point.

The close agreement of the strain measurements confirms the repeatability of the instrument and the ability to trust strain measurements taken on the installed cable at different points in time.

3.3.5 Observation Well

A particular point of interest is where the cable had been brought into an observation well to provide protection to a splice that was required after damage to the cable during installation. The survey data indicates that the splice was in the lower path of the cable, and hence the cable needed to be led up the outside of the concrete wall of the well, and then into it. Figure 14 shows the entry of the cable into the well. The cable was grouted into the concrete wall. Any movement outside the well is likely to result in snagging of the optical cable on the outside edge of the entry hole through the concrete well wall. The consequent excessive bending losses have resulted in failure of the fibre at this position, and highlight the problems associated with introducing a cable into a structure such as this. Ideally the hole would have been positioned on the downstream side of the well, and used a large smooth slot or hole at the entry point to minimise any damage to the cable.

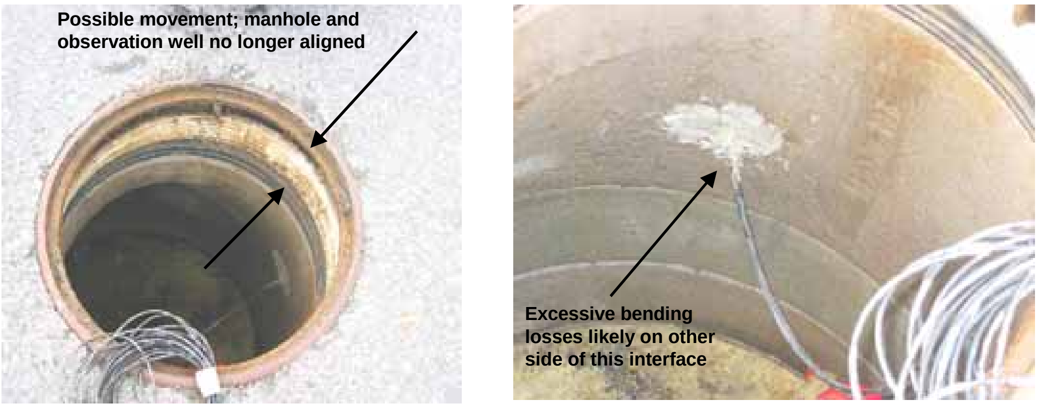

Figure 19 – Optical Cable entering Observation Well.

3.4 Second measurement in May 2005

A second round of strain measurements were carried out at Ajaure during May 2005, over a 2 day period. The aim of repeating the measurements was to take samples of the strain when the reservoir level was around its lowest point. Figure 20 shows the dam during May, and the water marks on the dam structure indicating the considerable decrease in water level.

Figure 20 – Photos of water level at Ajaure in May 2005.

3.4.1 Optical Loss Measurement

The excessive losses induced during installation have been highlighted earlier in this report. Optical loss measurements were repeated as part of the strain measurement process upon returning to Ajaure during May 2005. Figure 21 shows the difference in measured loss from May 2005 to September 2004. The figure shows clearly that there have been no significant changes in the measured loss along the cable route.

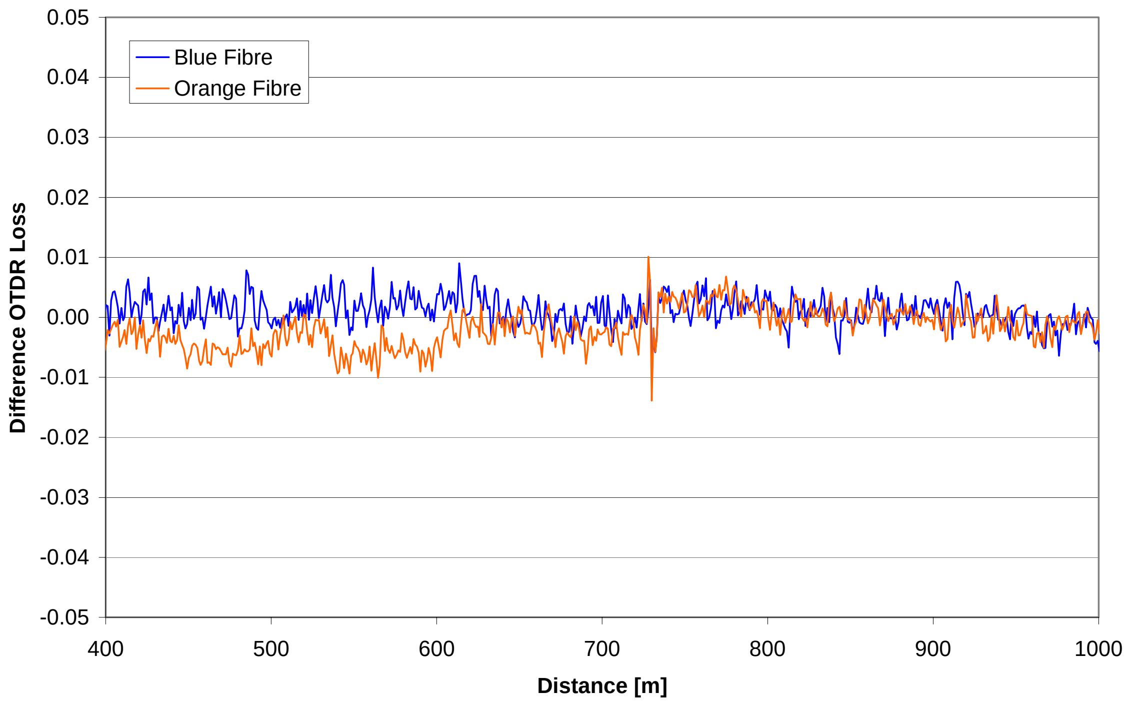

Figure 21 – Difference in optical loss between September 2004 and May 2005.

3.4.2 Strain Measurements

Again measurements were taken of the strain in the cable. Problems associated with the cable terminations at the control room meant that the orange and blue fibres could only be measured from the near end. This provides data up to around 1000m where the fibre is crushed in the observation well.

The strain measurements were repeated, and then compared with those taken during September. Since the cable is known to have considerable variation in strain due to installation, it is necessary to look at the difference between two sets of measurements to ascertain any changes. Figure 22 shows the difference in the strain measured by the two fibres for the region in the dam, between September and May. A positive strain difference indicates an increase in strain during May relative to September.

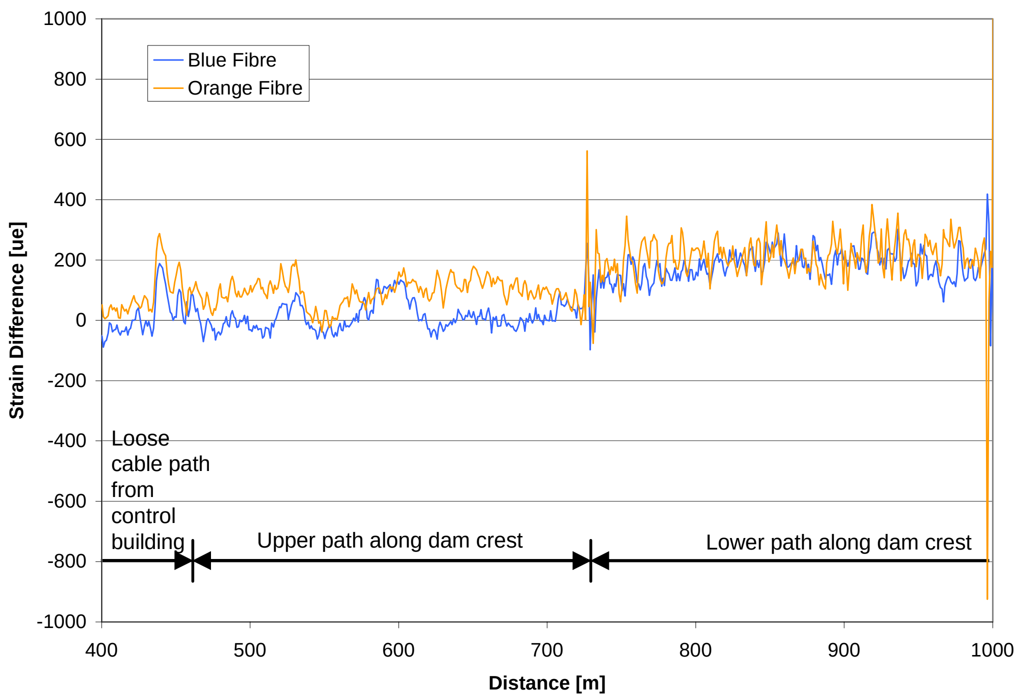

Figure 22 – Difference in strain measurements from September 2004 to May 2005.

The results indicated that generally there are two different strain levels in the two different sections of the dam cable. The upper path is more closely centred around a zero strain difference, whilst the lower path indicates a strain difference of around 200με. The difference in strain might result from a measurement error associated with the excessive losses at the turnaround point. One way of eliminating this possibility would be to use a DTS temperature measuring instrument to provide an independent measure of temperature, and then combine this with the strain data for more accurate temperature correction. Another possibility is to use a different type of cable which includes one tight and one loose fibre. The loose fibre is measured to provide an indication of temperature, and this is then used with the tight fibre measurement to provide strain measurements with increased temperature independence.

Other points of interest are those where the strain difference in the two fibres is highly correlated. One particular feature of note is that around 450m. A similar localised increase in strain is apparent in both fibres. This position corresponds to the entry point into the dam. This region has already been highlighted as one where high losses were experienced at the far end of the cable, and the cable appeared taunt (Figure 14). Most likely a slight change in the physical arrangement of the fibre in that area is resulting in a localised increase in strain.

3.4.3 Repeatability

Strain measurements taken at different times during May have been compared again to assess the accuracy of the DTSS instrument. Figure 23 shows the results of this comparison, where two sets of measurements from each of the two fibres have been subtracted from each other to highlight any differences in the measured strain.

Once again the results indicate good repeatability, with the measurements being centred around a zero difference in strain. There is a noticeable increase in measurement noise after the turnaround resulting from excessive losses at that position.

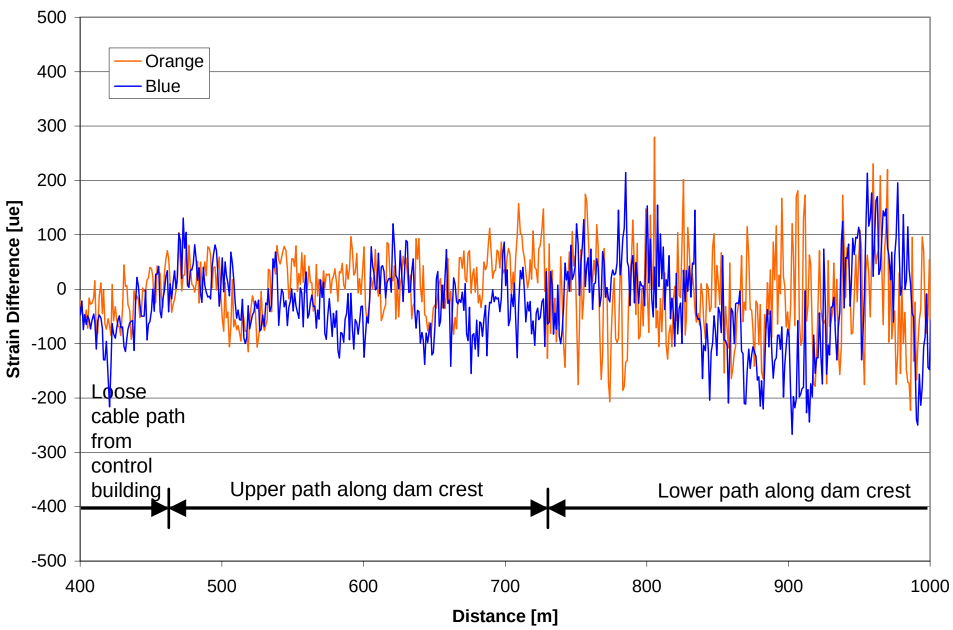

Figure 23 – Strain difference between separate measurements during May.

3.5 Additional measurements through to May 2007

In total, six trips have been made to Ajaure to measure strain in the cable. Since September 2005 a Sentinel DTS has also been taken along to the measurements. The purpose of this was, as proposed earlier, to use the much more accurate DTS temperature measuring capability to enhance the accuracy of the strain measurements. Now the DTS temperature data is used as the temperature to correct for any cross sensitivity in the strain measurements. The DTS is typically less susceptible to signal changes at high point losses such as have been seen in the installation at Ajaure.

Figure 24 and Figure 25 show the results of comparing all the strain measurements that have been taken at Ajaure. These results highlight some of the trends in the data. Typically the variations in the strain are low in the upper cable path, up to the turnaround at fibre distance 725m. The excessive losses at the turnaround tend to results in ambiguity about the absolute level of strain in the lower cable path. The localised losses also appear to results in different offsets between the orange and blue strain sensing fibres within the cable. However, it is of interest that pairs of measurements appear to correlate in the lower cable path, particularly for the orange fibre. Figure 25 shows that the May 2005 and May 2006 measurements have a similar strain difference to the Sept 2004 reference measurement, whilst the Sept05 and Sept06 also have similar strain difference to the reference measurement. However, the offset in absolute strain difference between the two May readings and the two September readings is around

300με. The latest May 2007 readings on both fibres appear to show quite a considerable further difference.

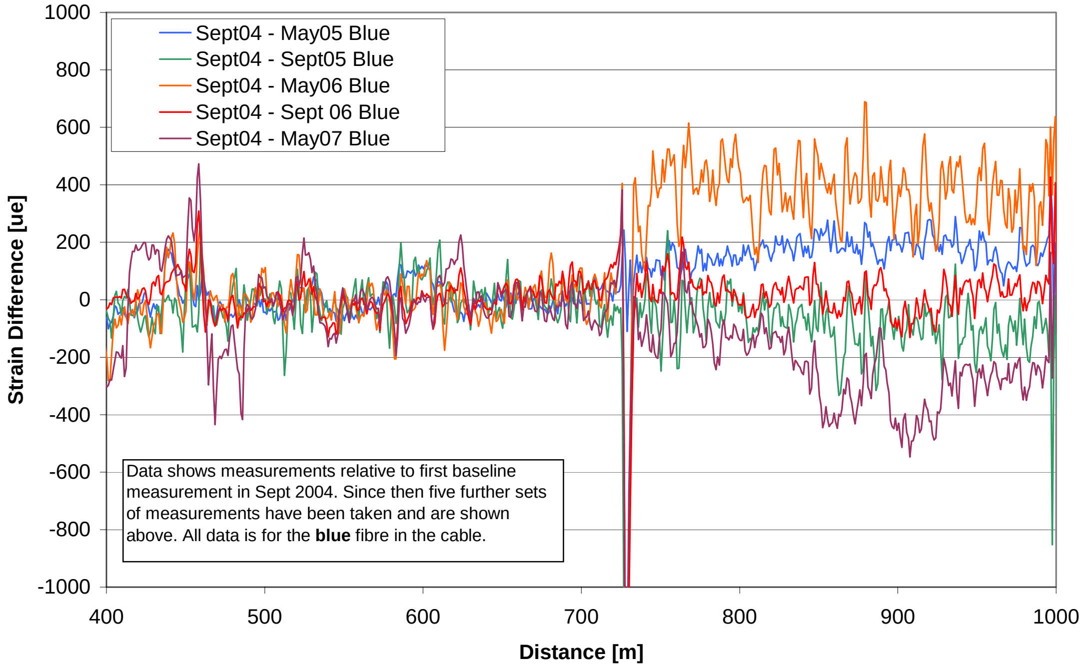

Figure 24 – Strain difference for all measurements sets on the blue fibre at Ajaure.

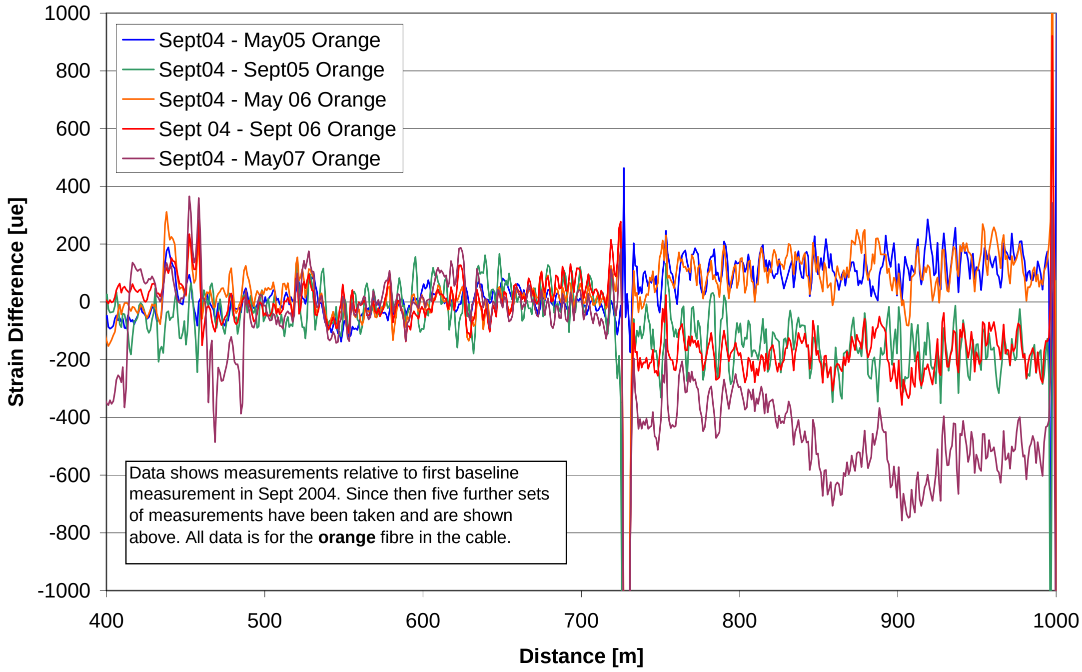

Figure 25 – Strain difference for all measurements on the orange fibre at Ajaure.

Another feature of interest in the May07 readings is a raised strain difference between 450m and 460m fibre distance, followed by two peaks of negative strain difference at

468m and 486m, shown in Figure 26. The region of increased strain has exhibited an increasing strain difference since September 05, with each new measurement being consistently higher in strain difference. This region is within the dam. No other signs of any movements have been observed in this area, and the reason for the measured change is further discussed in sec 7.4.

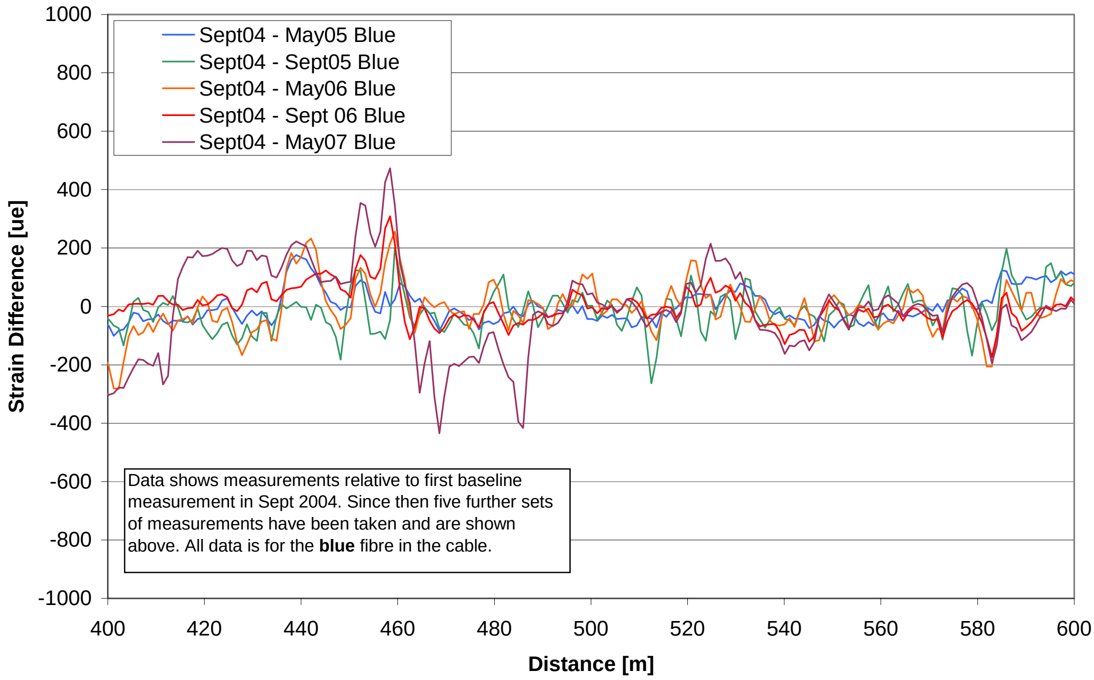

Figure 26 – Detail of features seen around entry into the dam.

3.6 Future Considerations for Installation and Instrumentation

The measurements have highlighted a few considerations for future installations. In particular, the excessive losses at the turnaround point have indicated that care is needed in positions like this. The loss has effectively degraded the resolution of the data captured beyond that point. In a similar vein, the routing of the cable into the observation well has resulted in complete failure of the fibre at that point. The original intention was to provide protection to a splice, but has in fact achieved the opposite effect. Possibly some sort of inline protector might provide a more appropriate solution.

The impact of high bending losses has led to inaccuracies in some of the measurements of temperature within the installed cable. This in turn can result in a small error in the measured strain. These types of losses need to be minimised to provide the best measurement opportunity.

During the series of measurements a Sensornet DTS was utilised to provide one solution to some of the inaccuracies associated with the excessive bending posses. It is fortunate in this installation that the cable includes both singlemode and multimode fibres, allowing both DTSS and DTS measurements to be undertaken.

3.7 Result from inclinometer and settlements measurements

Vattenfall Power Consultant collects and evaluates result from all measurements of the dam. This data can be compared to the DTSS measurement, but the manual measurements are not designed to allow direct comparison between the DTSS measurement.

There are two inclinometers for continuous monitoring in the dam, placed at chainage 0+330 and 0+393. Measurements are performed at 2m height intervals from the bedrock, to which the inclinometers are fixed. The most upper sensors (330I_1 and 393I_1) are placed at 442.7m (i.e. similar to the level of the lower cable). The largest variation of the inclination is found at the most upper level, where the annual inclination is about 4mm/m at inclinometer 330 I_1, and 2mm/m at 393 I_1. The variation between the two measurements was 3mm/m at 330 I_1 and 1mm/m at 393 I_1. This variation is small and is not expected to be seen by the DTSS measurements.

Manual surveying measurements are also performed by Vattenfall Power Consultant of movements and settlements in 44 points along the dam crest surface. Generally a seasonal variation of ±<5mm. can be seen A general trend of downstream movement in the order of 4-8mm/year, has also been found over the entire dam. This general movement, parallel to the damline/cable orientation will not be possible to detect if the movement is perfectly parallel. However, if some small local variations may occur they will be possible to detect.

4 Measurements at the Seitevare dam

4.1 The Seitevare dam

The Seitevare dam is located in the Lilla Luleälven River, in the northern part of Sweden. With a length of 1450km and maximum height of 106 m, the dam is among the largest dams in Sweden. The main purpose of measurements taken at the dam was to evaluate the seepage flow at the toe, and movement detection on the crest.

Figure 27 – The Seitevare dam

The first distributed measurements of strain and temperature in the crest were carried out at Seitevare dam in September 2005, followed by measurements in May 2006, September 2006 and May 2007.

4.2 Installations

The cable installation at Seitevare was designed in order to compare the result from two different cables. Therefore the standard DamSens cable was installed alongside the SMARTprofile cable as shown in Figure 28. There are also clamps at each 10m of the SMARTprofile cable, but only three clamps for the DamSens cable, at chainage 0/150, 0/450 and 0/750m. The cable has been positioned every 10 metre.

Only the highest part of the dam is covered by the cable, and measurements ends in a well at 0/780m. However, fibres are here spliced together so measurements can be done both inwards and outwards.

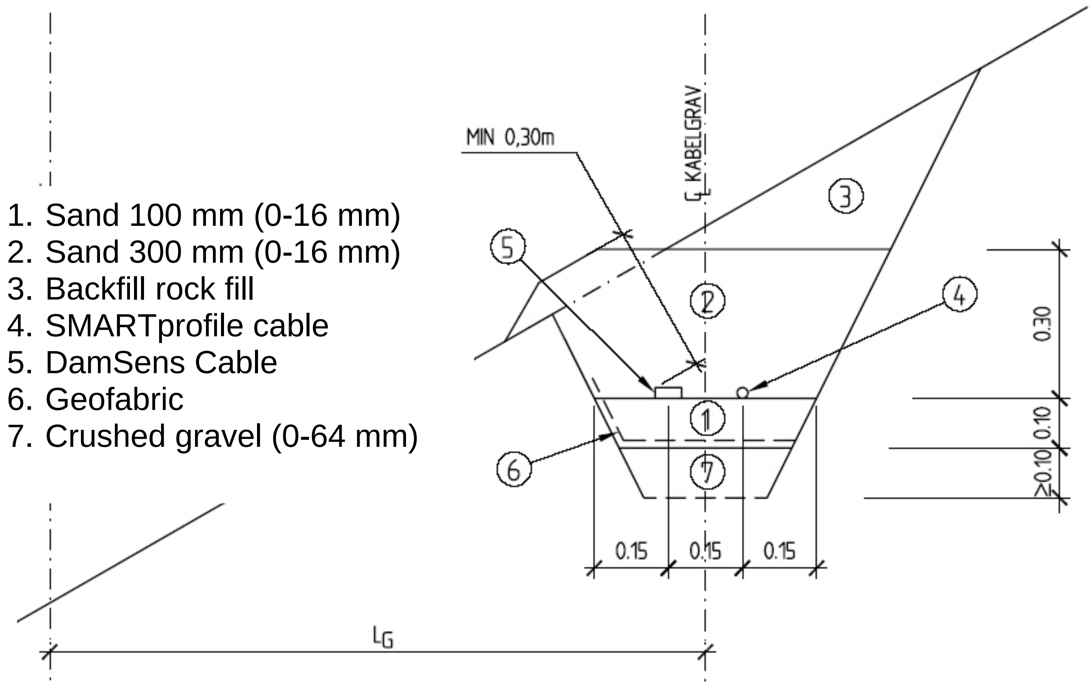

Figure 28 – Cable installation at Seitevare dam..

4.3 Measurements in September 2005

At the first visit to Seitevare measurements of OTDR, temperature and strain were taken using each of the fibres within the installed SMARTprofile cable, as well as in the DamSens cable.

4.3.1 OTDR Measurements

OTDR measurements were taken on all fibres as part of the DTSS measurement process. This is critical for evaluating the health of the cable after installation. Figure 29 and Table 1 show the results of the loss measurements on the four fibres in the SMARTprofile cable. The loss measurements indicate very different results for the two different types of fbre in the SMARTprofile cable.

Table 6 – Measured loss in each of the SMARTprofile fibres

Fibre	Connector loss dB	Optical Loss dB/km
Strain fibre, S1	1.78	1.15
Strain fibre, S2	0.69	5.73
Temperature fibre, T1	0.49	0.17
Temperature fibre, T2	0.72	0.17

The temperature sensing fibres have a very low optical loss, slightly better than the usual 0.2dB/km expected for singlemode fibre. However, they do suffer from fairly high connector losses. These connector losses should be 0.2dB or lower. The strain sensing fibres have much higher optical loss. In the case of fibre S2, the loss is almost so high as to render the fibre unusable. The OTDR trace shows that almost no light is reaching the end of fibre S2. The connector losses are also very high, in particular for strain fibre S1. Together these issues mean that the resolution that will be achievable with these fibres will be significantly lower than the usual specification of the DTSS, due to the decreased signal power.

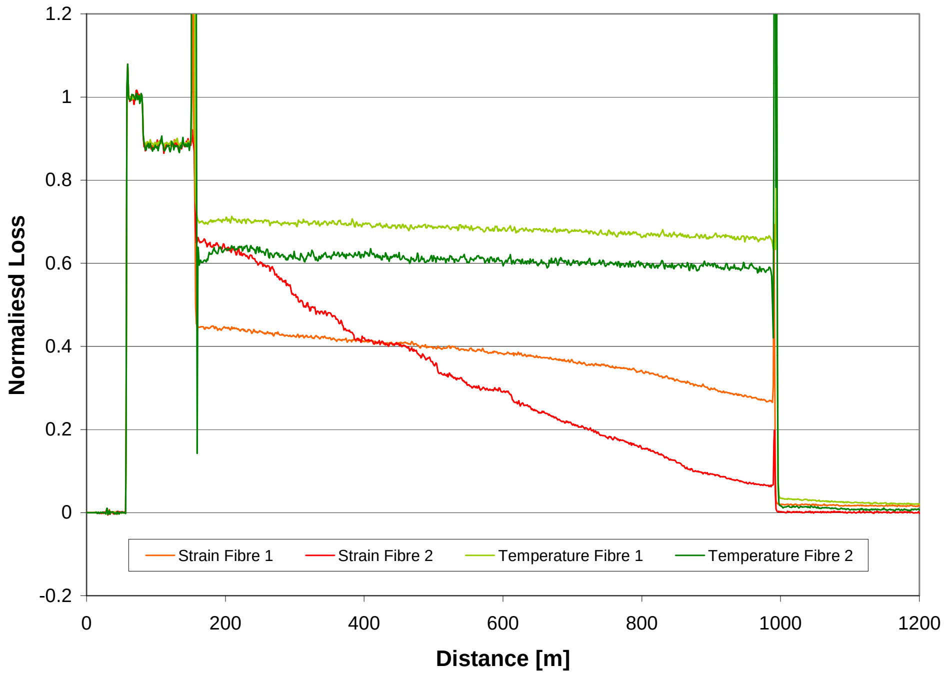

Figure 29 – OTDR measures of the installed SMARTprofile cable.

Optical loss measurements were also taken on the DamSens cable installed in the crest of the dam at Seitevare. This result is shown in Figure 30, where the two singlemode fibres within the cable have been connected to each other at the far end to create a continuous measurement there and back.

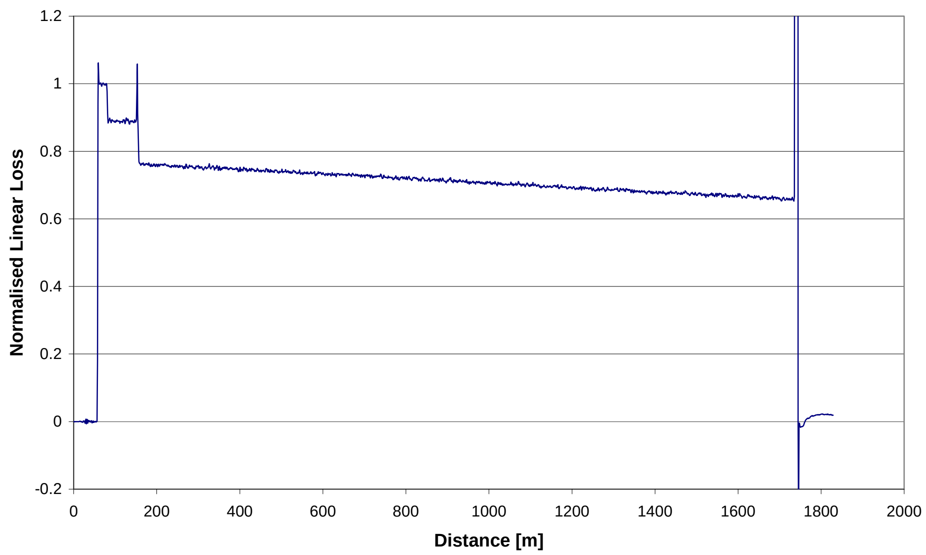

Figure 30 – OTDR measure of the installed DamSens cable.

The measurement indicates a fibre loss of 0.2dB/km, exactly in line with expectation. There is also no sign of any point losses, implying an excellent installation. The connector loss is also better at just 0.38 dB.

4.3.2 Temperature Measurements

Temperature measurements were taken in the SMARTprofile cable using the DTSS. However, given the very large losses in the fibre, the data is very noisy and quite probably inaccurate. The results are shown in Figure 31. Interestingly, a measurement of temperature was also obtained on the temperature sensing fibre within the SMARTprofile cable. This shows that a trace with considerable variation in temperature and inaccuracies, with temperatures as low as -20°C being measured in the dam. This is a consequence of the fact that the temperature sensing fibre does not appear to be completely strain free. Hence, any variations in the strain of the temperature sensing fibres will results in inaccuracies.

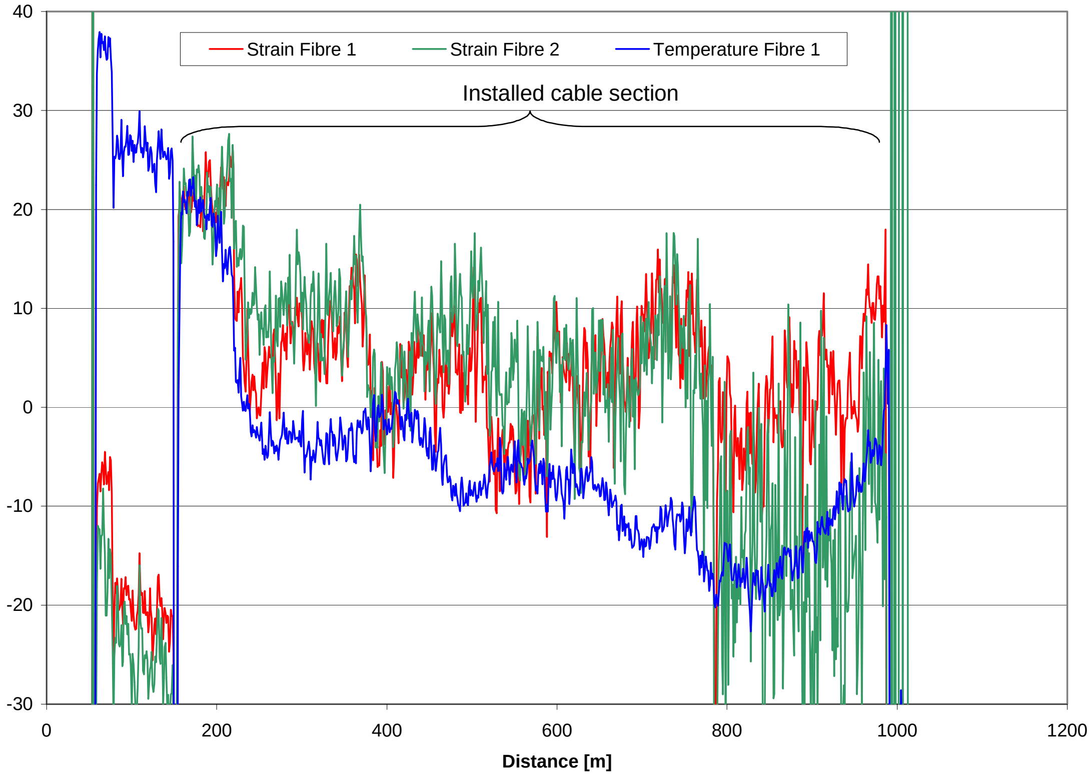

Figure 31 – Temperature measurements in the SMARTprofile cable.

Temperature measurements were also taken in the installed DamSens cable using a Sentinel DTS. This temperature measurement shows excellent resolution and good symmetry about the turnaround point at 933m, as shown in Figure 32.

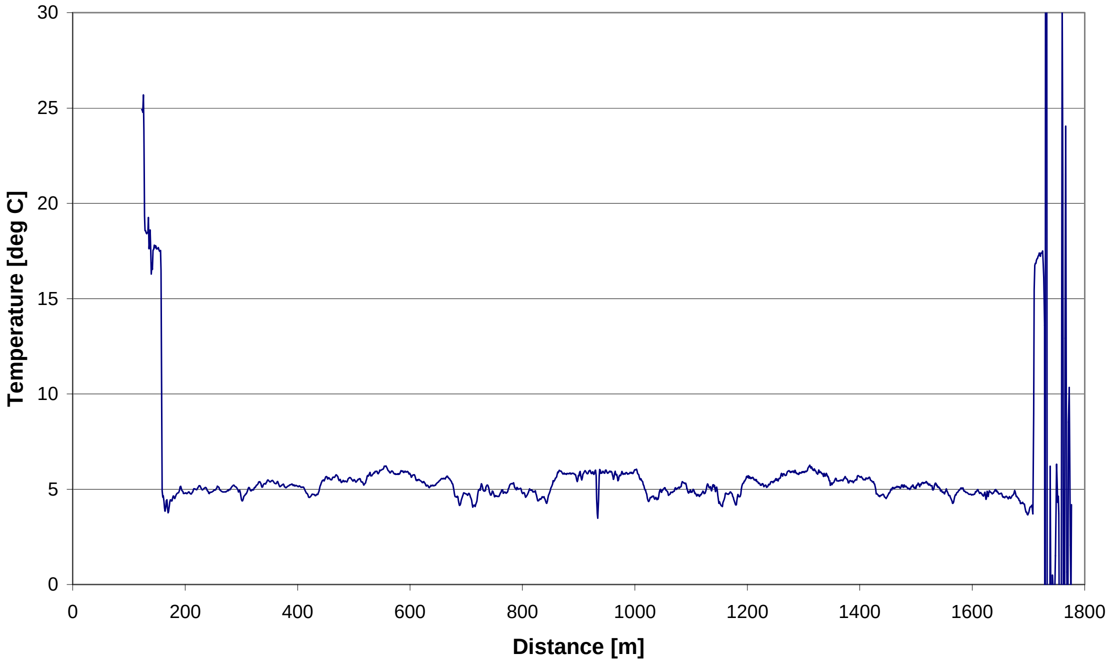

Figure 32 – DTS measured temperature in crest.

4.3.3 Strain Measurements

Strain measurements were taken using the Sensornet DTSS of both the installed SMARTprofile cable and the DamSens cable.

Figure 33 shows the measured strain in the SMARTprofile cable. The reference sections inside the DTSS instrument (the sections up to 150m) show high strain simply because they are a different type of fibre. Hence, the strain trace is calibrated for the SMARTprofile strain sensing fibres and not those of the DTSS resulting in an error in these sections. The section of interest, the installed cable, is correctly calibrated for though. Generally the two strain fibres of the cable display similar trends. Clearly the measures of strain become very noisy with distance due to the significant decrease in signal level arising from the high losses of the cable. The low quality of the data will make detection of deformations in the dam in the future more difficult but not impossible. One feature to note from the data collected so far is the increased strain at around 627m from the start of the installed cable (786m). This might have arisen from movement of a clamp at this position during installation. This position will be monitored carefully in future measurements.

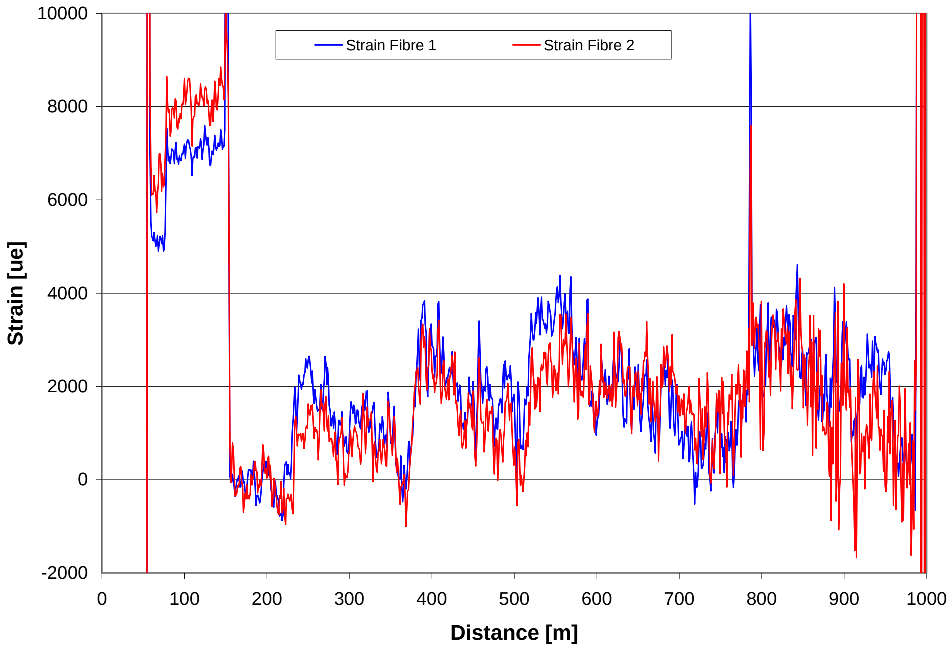

Figure 33 – Measured strain in SMARTprofile cable.

Strain measurements were also taken on the DamSens cable, as shown in Figure 34. The Sentinel DTS temperature data has been combined with the Sensornet DTSS data to provide increased strain resolution. It has already been stated that the loss measured in this cable was very low, and hence the quality of the strain data is considerably better than that measured in the SMARTprofile cable. The two singlemode fibres of the dam cable were looped together at the far end, and this can be seen in the data where there is good symmetry around the turnaround point. The magnitude of the random strain imparted during installation/compaction is much lower than has been seen in other installations.

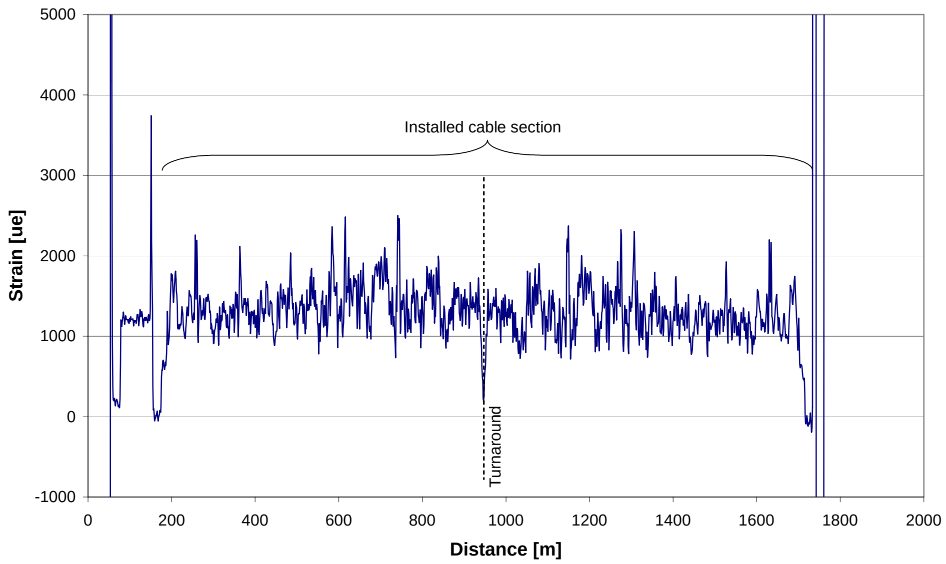

Figure 34 – Strain measured in the DamSens cable.

These strain measurements taken during this first visit to Seitevare will be used as baseline measurements for future visits to the dam. Any future measurements will be referenced to these measurements to determine if there have been any changes in the structure of the dam, resulting in increased strain on the cable.

4.4 Additional Measurements Through to May 2007

4.4.1 DamSens cable

In total, a further three sets of measurements were taken at Seitevare after the initial baseline measurements. Figure 35 shows the results of subsequent measurements at Seitevare on the dam cable. A localised strain increase is noted at approximately 545m and 1350m fibre distance. This symmetry, about 400m from the turnaround position (947m), confirms the feature. The scale of the feature is almost identical on both of the fibres. Closer analysis of the feature in Figure 35 shows that the increase in strain occurred after the first baseline measurement, and has been present for all subsequent measurements. Figure 36 shows the actual measured strain data in the region of interest. It shows that from the earliest measurement there was always a strain spike at this location. In subsequent measurements this strain spike has increased in magnitude.

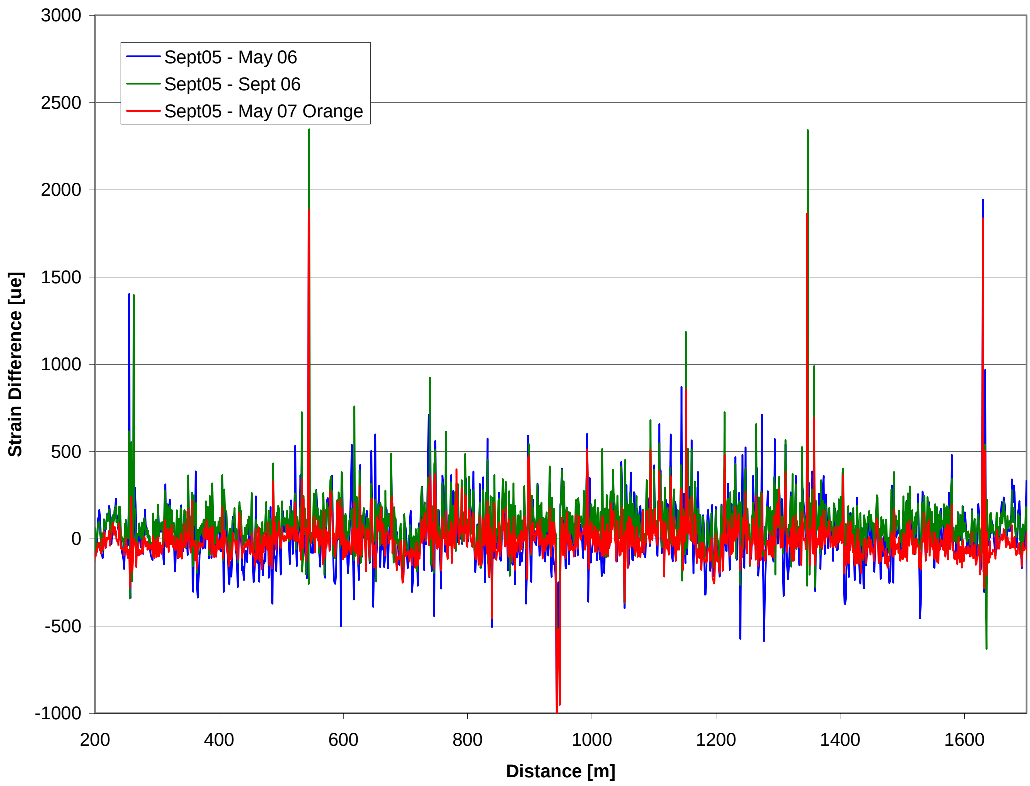

Figure 35 – Strain difference measurements at Seitevare dam.

Another large strain difference occurs at the turnaround but this is expected since the cable is more open at this location, and it does not represent any meaningful data about the movement of the dam.

The fibre distance has now been converted to chainage, and we will just consider the outbound fibre for the moment (Figure 36 and Figure 37).

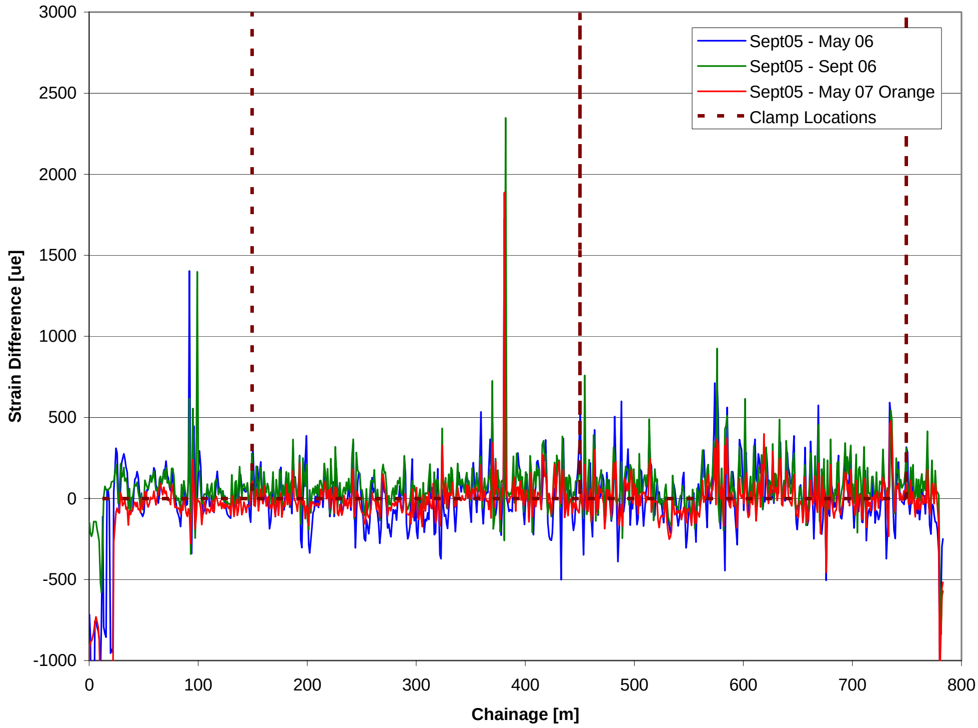

Figure 36 – Strain difference measurements at Seitevare dam against chainage.

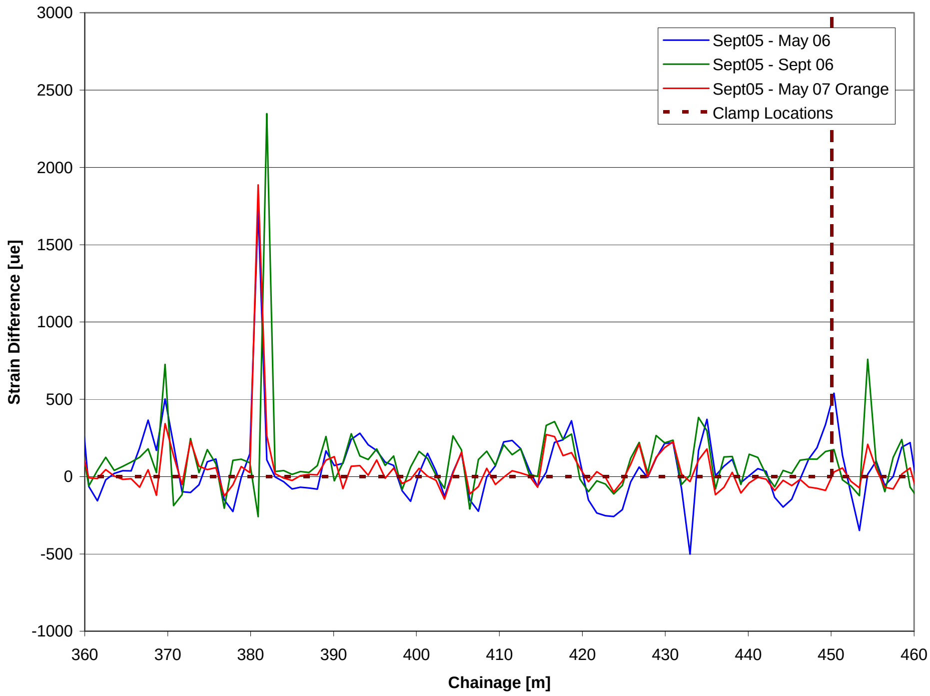

Figure 37 – Localised large strain difference at Seitevare dam.

The feature is clearly visible at 381m chainage as seen in Figure 38. Measured strain in the remaining parts of the dam is constant, indicating a good repeatability.

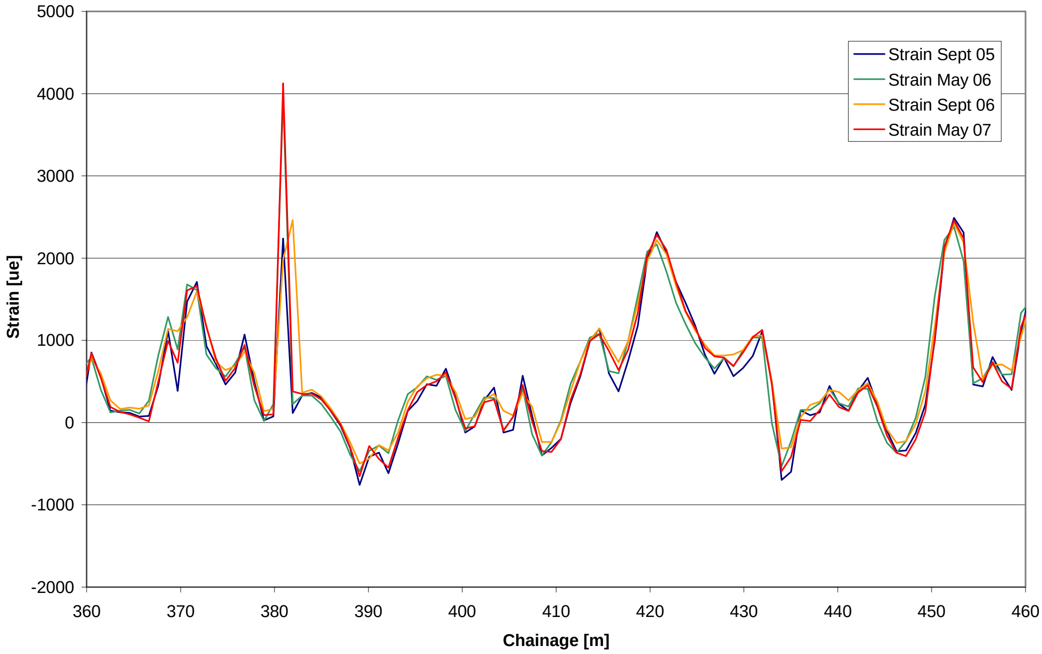

Figure 38 – Actual measured strain at Seitevare in region of interest.

4.4.2 SMARTprofile Cable

Despite the difficulties with attaining a good signal in the SMARTprofile cable, measurements were taken at every visit to the dam site. Figure 39 shows the measured strain in fibre 1 of the SMARTprofile cable. In general there is accurate agreement from one reading to the next. The strain measure during September 2006 does show some points of clipping of the data. The fibre within the SMARTprofile cable has quite a different natural Brillouin frequency compared with normal fibre. This manifests itself as around a difference of 8000$\mu\varepsilon$ compared with normal fibre. As a consequence the measurement parameters must be adjusted to give a wider effective strain sweep range. The clipping of the data during September 2006 results from not quite extending the strain sweep range far enough. Since these clipping areas can cause strain difference anomalies, the data from September 2006 has been removed from the strain difference analysis.

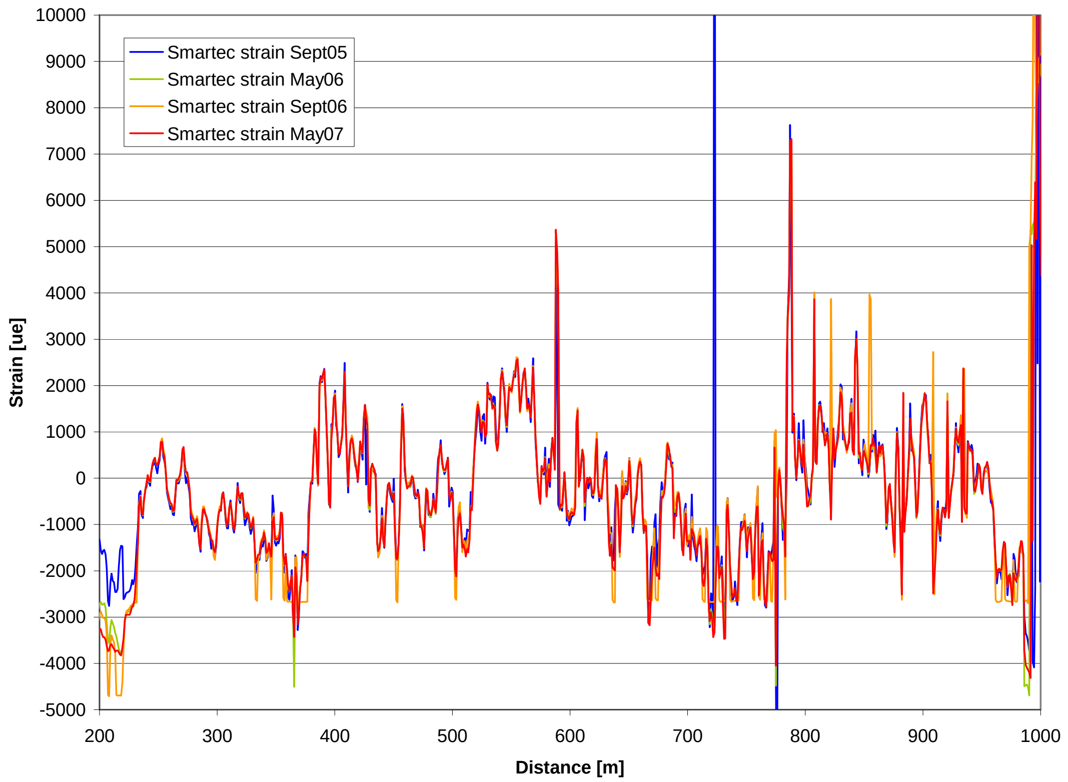

Figure 39 – Measured strain on SMARTprofile cable fibre 1 at Seitevare.

Figure 40 shows the difference in strain in fibre 1 of the SMARTprofile cable for the measurements of May 2006 and 2007 relative to the baseline measurement taken in September 2005, now in terms of chainage. Although we see several strain difference spikes, the most noticeable of these is located again at 381m chainage, around 400m from the turnaround of the cable. This is the same position as the strain spike noted in the dam cable earlier, and confirms that further investigation at this location should be considered. Figure 41 shows an analysis of the strain difference measured in the second strain fibre of the SMARTprofile cable. Due to higher losses the data is of much lower quality. However, a strain spike is still visible at the same location in both May 2006 and May 2007.

The result from the strain measured in the two fibres in the SMARTprofile cable confirms the result from the measurements in the DamSens cable. Some change in the dam is therefore probable in this part of the dam.

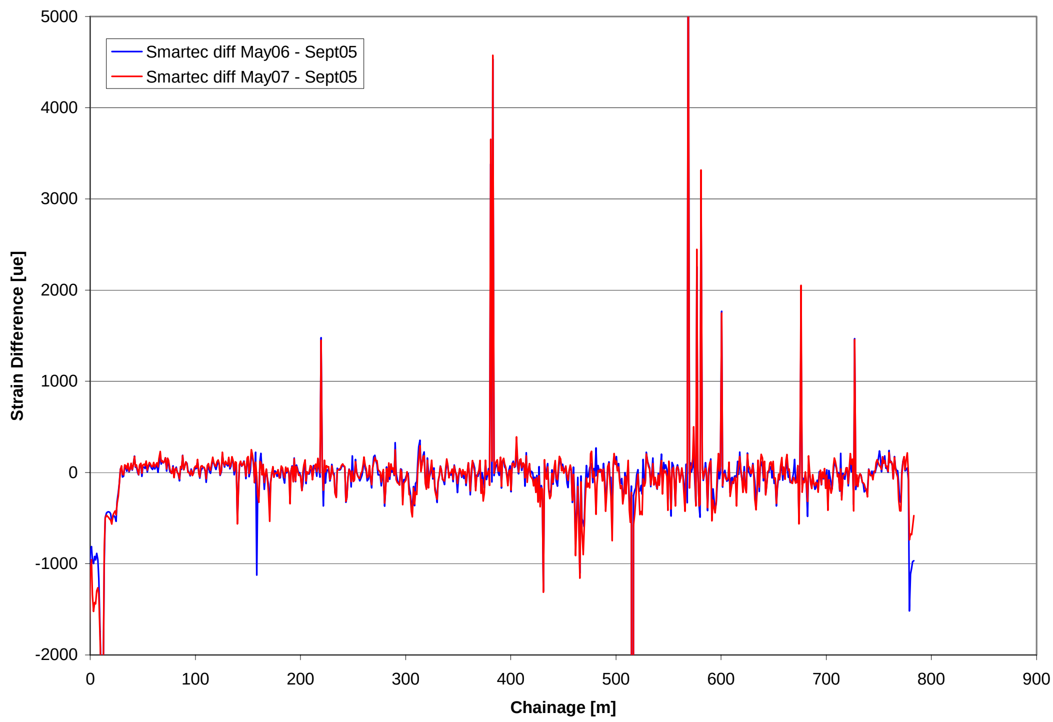

Figure 40 – Strain difference in SMARTprofile cable fibre 1 at Seitevare.

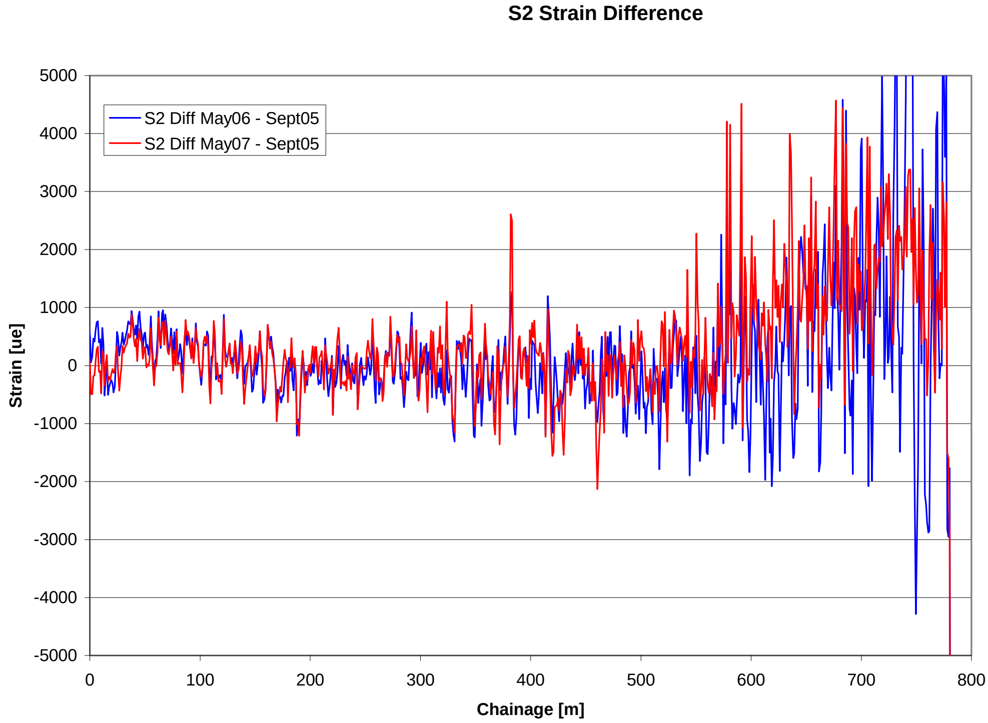

Figure 41 – Strain difference in SMARTprofile cable fibre 2 at Seitevare.

5 Measurements at the Suorva dams

5.1 The Suorva dams

The Suorva reservoir is the largest man made reservoir in Sweden positioned in the upper part of the Lule älv River north of the polar circle. It is 60km long with a total capacity of $5900 \cdot 10^6 m^3$. The Suorva dams (Eastern, Western, and Sågvik dam) are all rock fill embankment dams, and were completed in 1972.

The fibre optic installations in 2004-2005 were made in order to measure movements (strain) on the crest of the East and West dams. Another cable is installed in the downstream part of the West dam, in order to measure the seepage flow. Only the measurements in the crest of the East and West dam are presented in this report.

5.2 Installations

A DamSens cable was installed all along the East dam as showed in Figure 42. The cable is placed in the upper part of the core at El. +454.5m, i.e. about 6.5m below the dam crest.

Pairs of fibres have been spliced/connected together at the far ends in a splice box, to provide a loop back configuration for the measurements. Measurements are taken from the instrument house.

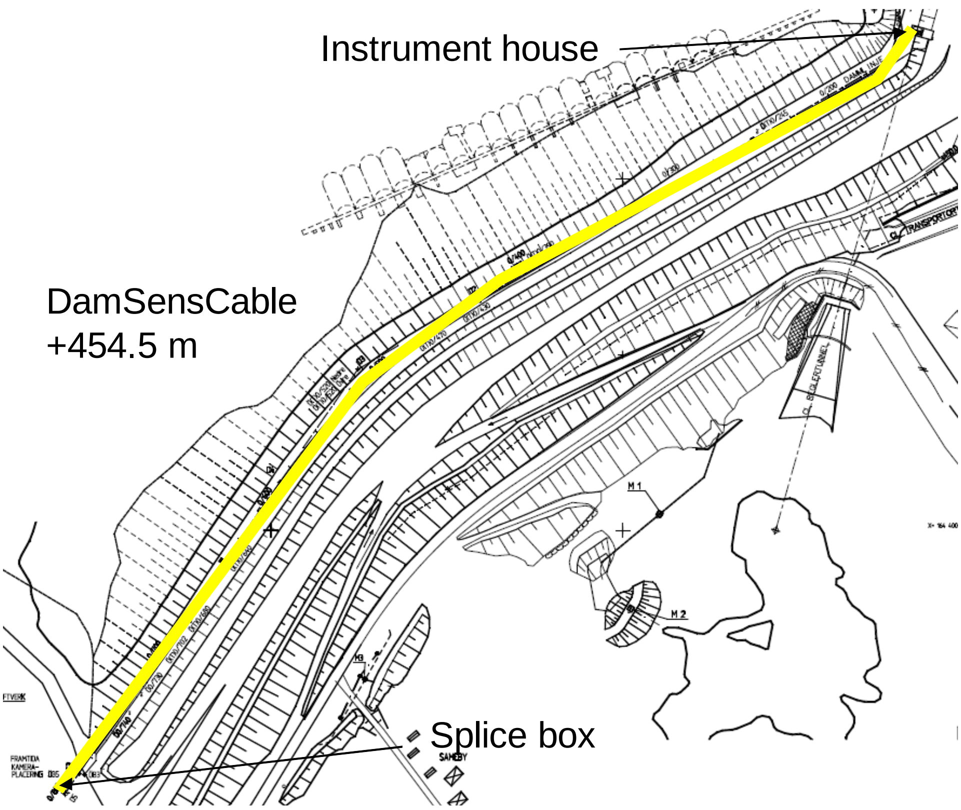

Figure 42 – Cable topology for Suorva "East".

The two cables on the West dam are placed on two different levels along the centre dam line. The ends of the cables are spliced, and measurements are performed from the instrument house in the highest part of the dam.

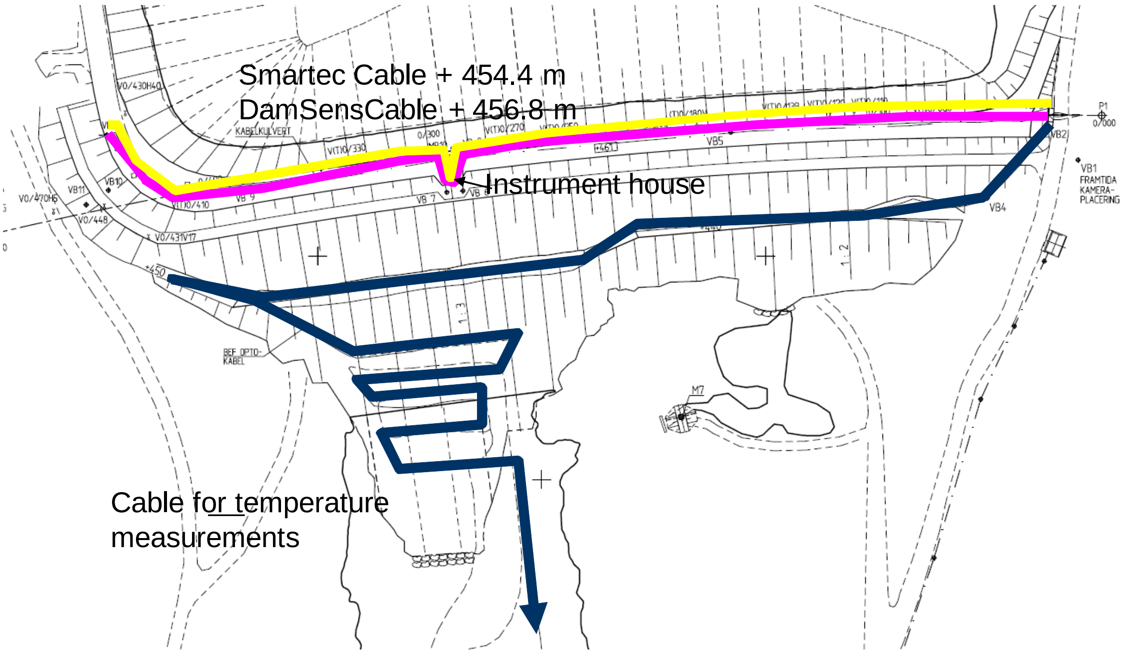

Figure 43 - Cable topology for Suorva "West".

The upper cable, which is the DamSens Cable, is placed on the core crest about 4.2 m below the dam crest. The SMARTprofile cable is installed in the downstream filter about 6.5m below the dam crest. The same clamps as were used at Seitevare have also been used here. There are also three surveying poles installed in chainage 0/125, 0/153, and 0/273.

5.3 East dam

5.3.1 OTDR measurements

The OTDR measurement of Suorva "East", taken on the installed strain sensing fibre, shows a good installation (Figure 44). The measured fibre length in each direction is approximately 702 m, matching closely the cable markings. There are no intermediate point losses along the installation, simply a splice loss at the turnaround as would be expected. The fibre loss is exactly as would be expected for normal cable, 0.19dB/km, demonstrating an excellent installation. Any records of the installation technique/ methodology used at this dam should be referred to for future installations.

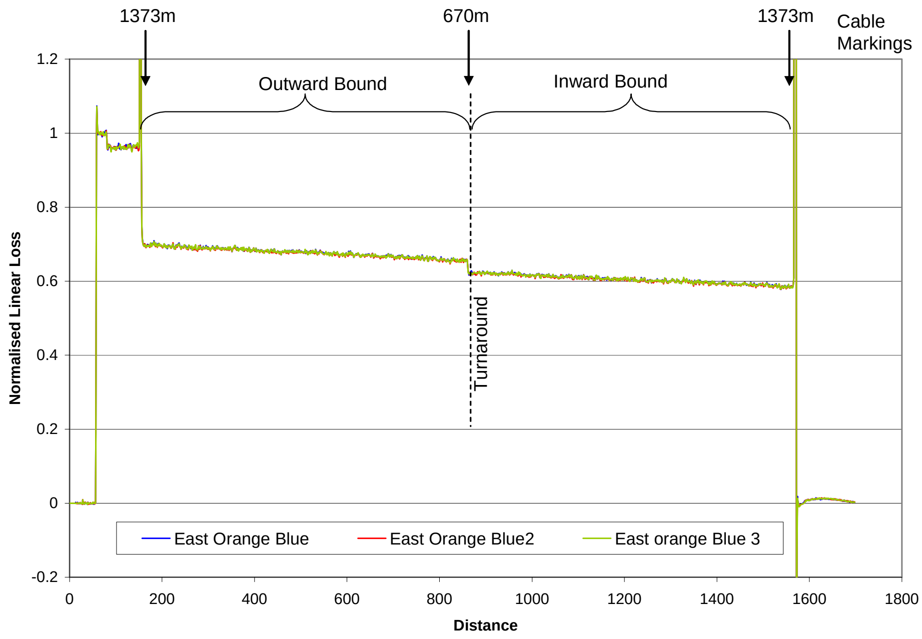

Figure 44 – OTDR Data, Suorva "East".

5.3.2 Temperature Measurements

Temperature measurements were taken using the Sensornet Sentinel DTS instrument. A sample data set is shown for Suorva "East" in Figure 45. The data demonstrates the fine temperature resolution of the DTS. An over ground section of cable close to the turnaround is visible due to its raised temperature profile. Moreover, the data shows good symmetry around the turnaround point as is expected for a good installation.

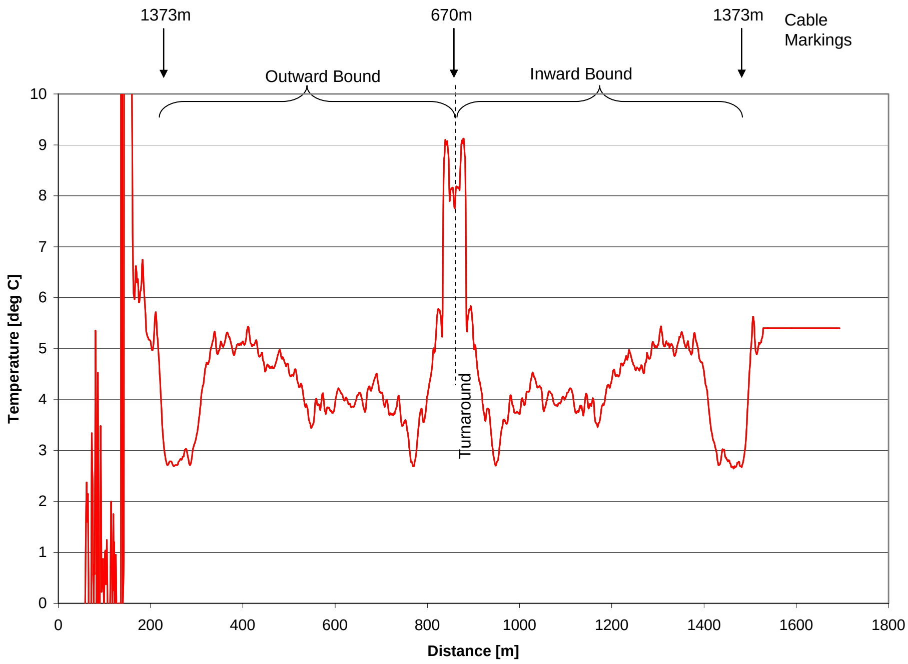

Figure 45 – Temperature Data from Suorva "East".

5.3.3 Strain Measurements

Strain measurements were taken in the Suorva "East" dam using the Sensornet DTSS. In this situation though, since the highly accurate temperature data was available from the DTS, this temperature has been used to provide further increases in accuracy of the strain measurements.

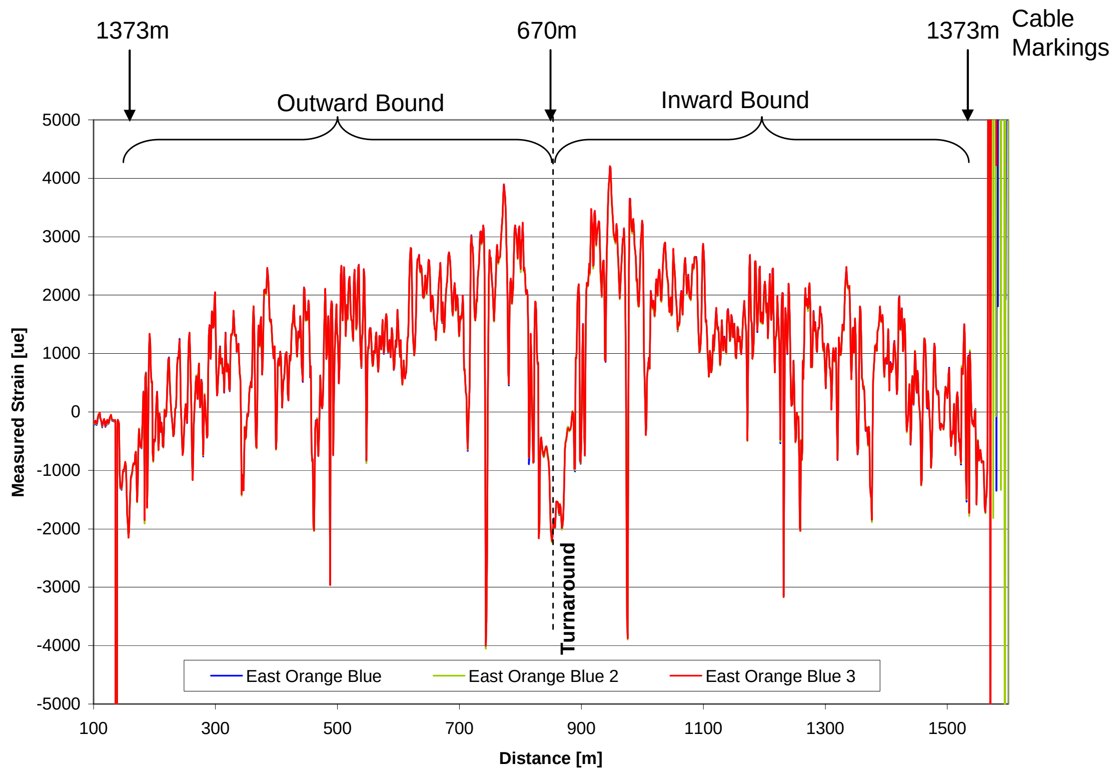

Figure 46 – Strain Measurements, Suorva "East"

Figure 46 shows the results of the strain measurements in Suorva "East". They demonstrate a reasonable symmetry about the turnaround point. Although the trace appears noisy, most features are suitably wide, indicating that they are not a feature of measurement error, but genuine physical features. Having made this point it is important to note several positions of high compression on the cable, possibly due to a high local load on the cable. The figure shows three traces, but the repeatability of the strain measurement is so good that it is difficult to make out any variation in the figure above. This is encouraging for future measurements of the strain in this dam. This set of baseline measurements will be used for comparison against later measurements, allowing us to detect any small changes in deformation of the dam.

5.3.4 Measurements through to May 2007

In total, three sets of measurements have been taken at Suorva, providing two comparison sets against the original baseline measurements of September 2005. A comparison of the measurements is shown in Figure 47. The figure just shows a comparison of data on the outbound fibres. The return path showed almost identical results. The highlight of the figure is the substantial strain difference at chainage 488m

The strain difference is localised to a 2-3m section as can be seen in more detail in Figure 48.

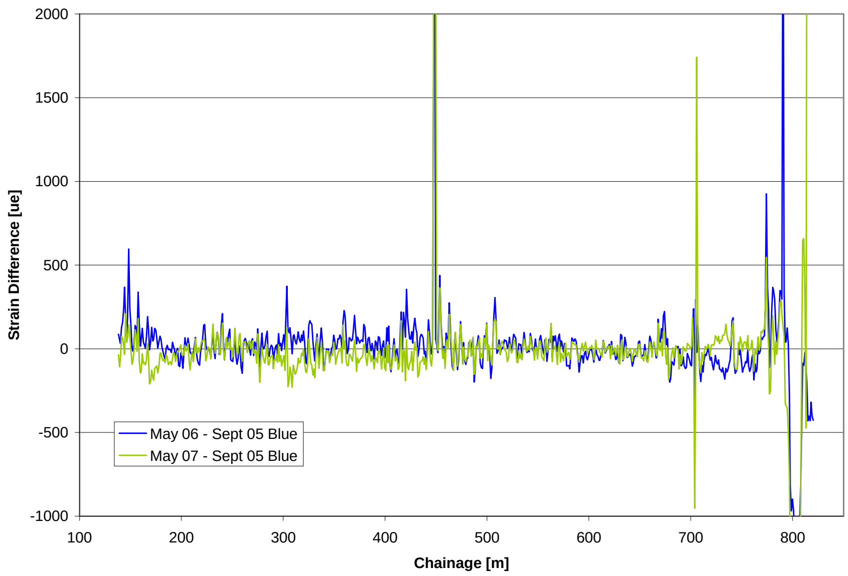

Figure 47 – Comparison of strain measurements at Suorva East

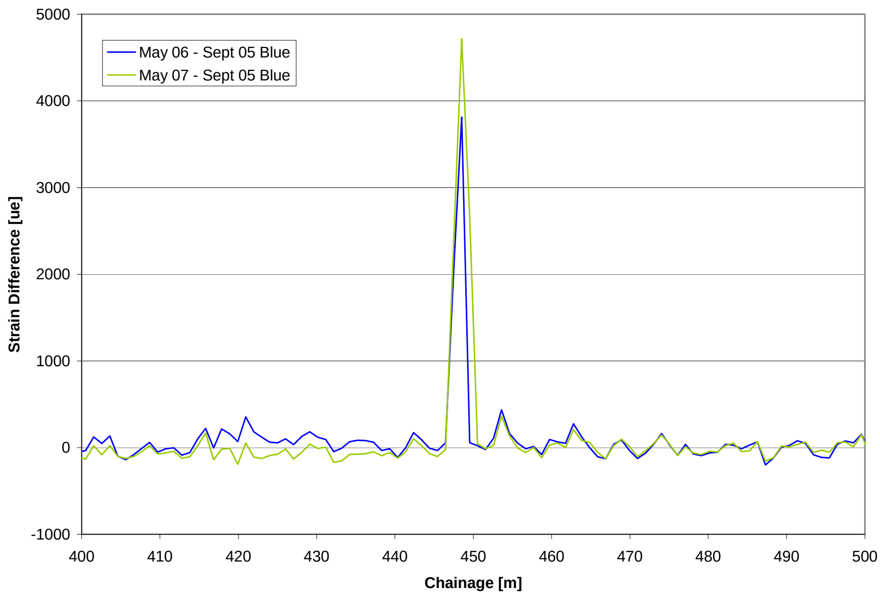

Figure 48 – Detailed view of large strain difference at Suorva East.

The strain difference shows as a large increase in strain relative to the original baseline measurement in September 2005. However, looking in more detail at the absolute strain measured in this location (Figure 49) provides a more thorough insight. The area of interest was commented on earlier in this report as being a localised high compression region. The later measurement taken in 2007 shows a more expected level of strain at this location, of the same order as the data points around it. Hence, the point region of high compression has disappeared.

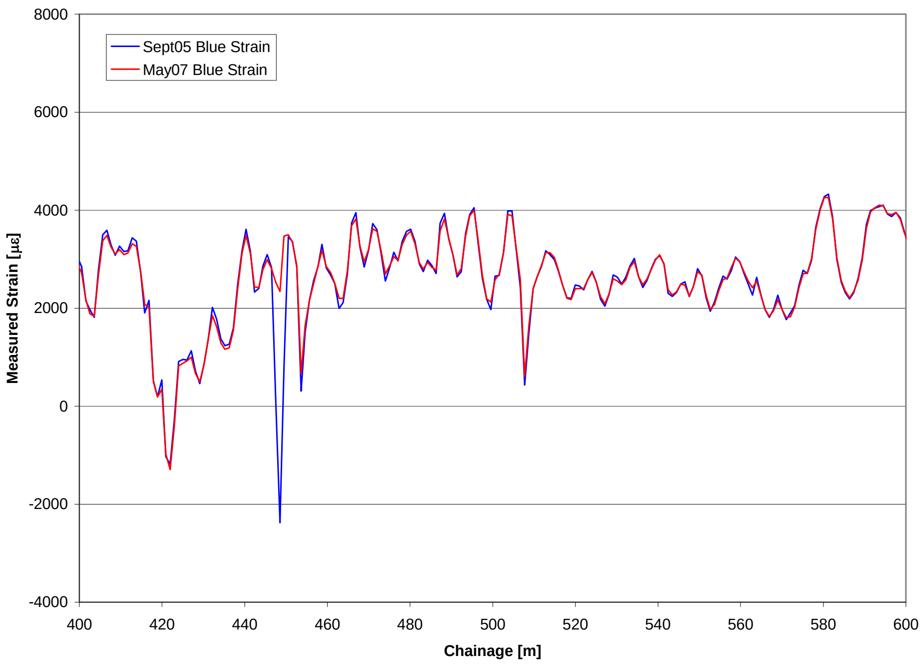

Figure 49 – Actual strain measurement data in region of large strain difference at Suorva

There was no indication in the baseline measurement of any sort of measurement fault that could have resulted in this feature. So we must presume that after some settlement in this region over time, the cable has become strained to a similar level to the surrounding area. Given this conclusion there is no reason to investigate the anomaly any further.

5.4 Suorva West dam

5.4.1 Installations

A DamSens cable was also installed in the West dam at Suorva as well as a SMART profile cable as shown above. Unfortunately, they were not available for measurement until May 2007. Only one set of measurements have therefore been taken of the cable, which can be used in the future as a baseline.

5.4.2 OTDR and strain measurements in DamSens cable

The instrument house is placed at the centre of the dam at chainage 0/290. Measurements have been taken out to the right abutment (chainage 0/420) and the looped back to the instrument house, and further out to the left abutment (chainage 0/020). The two sets of OTDR measurements of the DamSens cable at Suorva West dam that provide complete coverage are shown in the Figure 50. Generally the losses in the cable are low. There are a few step losses at the positions of splices and transitions of the cable.

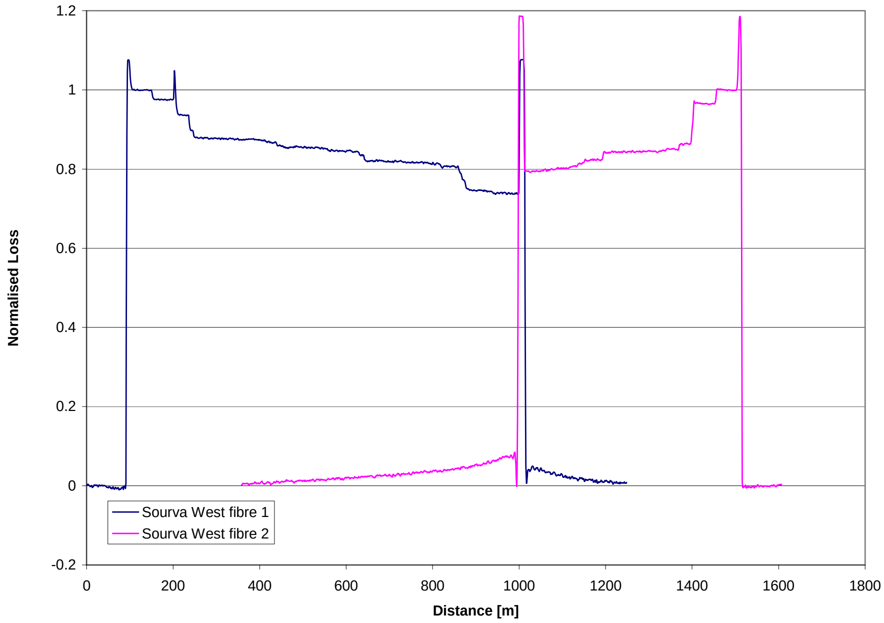

Figure 50 – OTDR of DamSens cable at Suorva West Dam.

A single set of strain measurements was taken at the West dam in the DamSens cable in May 2007. These are shown in Figure 51 and demonstrate good symmetry in the two halves of the dam. Temperature measurements were also in this case made using the DTS. There is considerable variation in the measured strain, arising from different regions of cable either being buried or loose in a duct, which is the case close to the turnaround point at the right abutment (around 450m distance) . The measurements provide a good baseline for any future measurements.

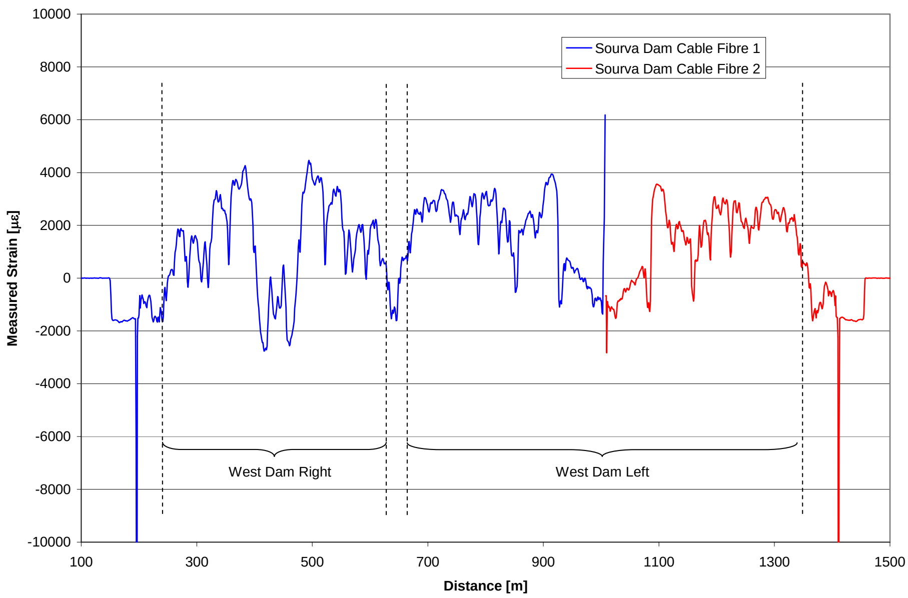

Figure 51 – Strain measurement of the DamSens cable at Suorva West dam.

5.4.3 OTDR and strain measurements in SMARTprofile cable

Figure 52 shows the captured OTDR measurements from the Smartprofile cable installed at Suorva West dam. Measurements were also here performed from the instrument house, to the right abutment, looped back towards the left abutment.

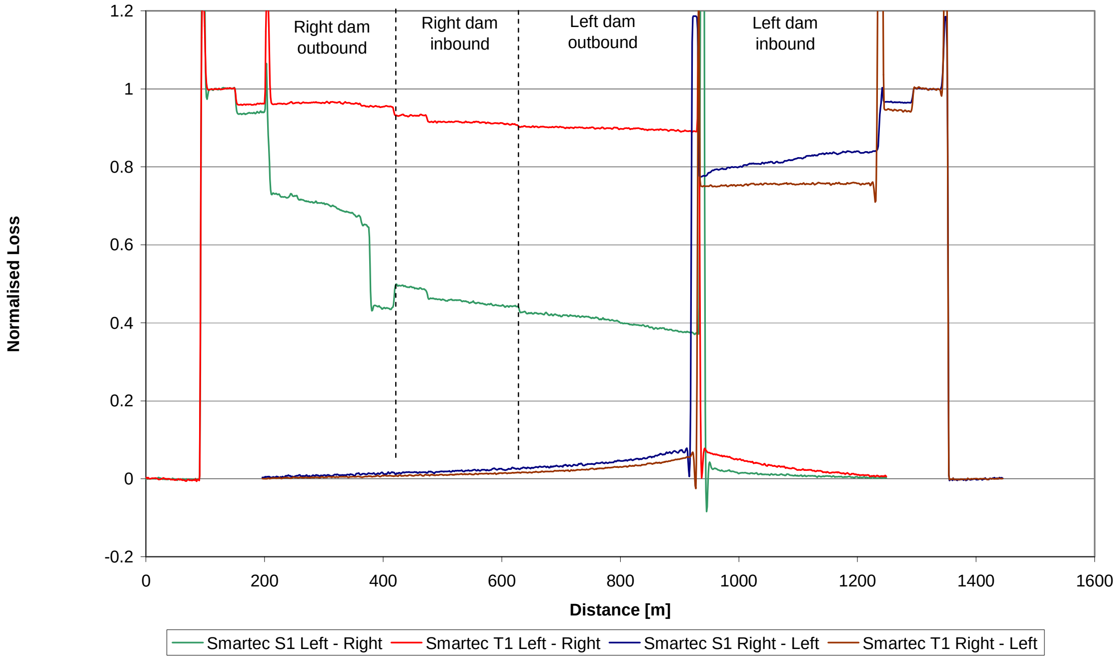

Figure 52 – OTDR of SMARTprofile cable at Suorva West dam, right and left side.

Strain measurements were taken on the strain sensing fibres of the SMARTprofile cable and are shown in Figure 53. There does appear to be good symmetry at the first turnaround location of around 424m fibre distance (at the right abutment), and again at the second turnaround location of around 935m fibre distance (at the left abutment). There is an offset between the data of right dam S1 and S2 fibres, but this is likely due to slight differences in the reference section used for each measurement, and can easily be adjusted for in the future.

The loss of the SMARTprofile cable at Suorva is better than that installed at Seitevare. There is a stronger possibility of success in trying to use these strain measurements as a baseline for future measurements. However, a DTS cable route was not exactly alongside the SMARTprofile cable and therefore it will not be possible to provide the greater accuracy of combining the DTS and DTSS data sets.

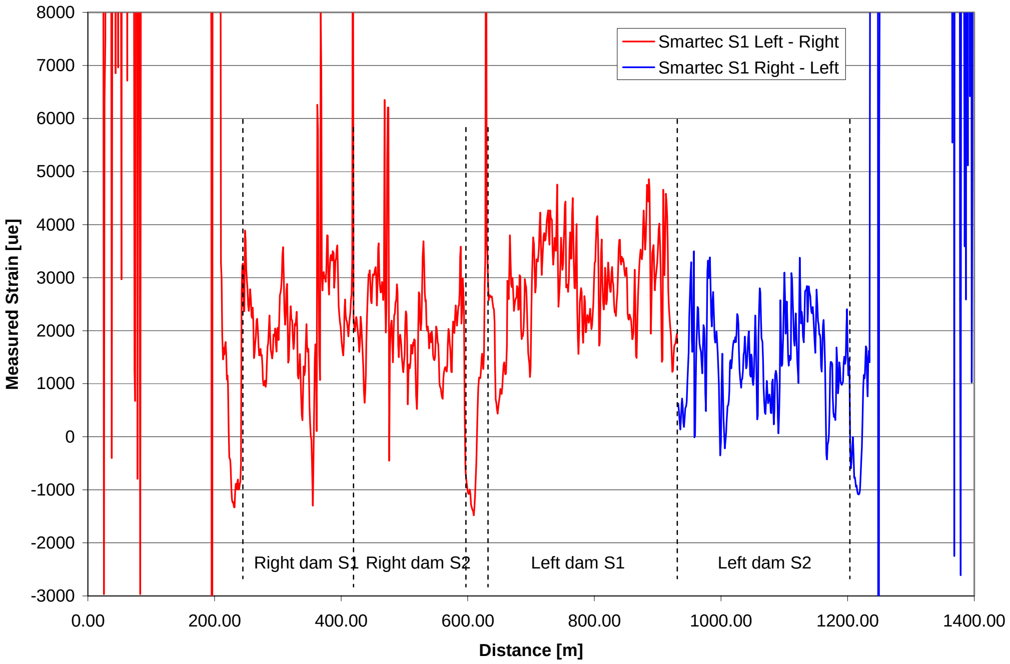

Figure 53 – Strain measurements of SMARTprofile cable at Suorva.

6 Measurements at the Hällby dam

6.1 Hällby dam

The embankment dam at Hällby is divided into a left and a right part by the centrally placed power plant and spillway. The left dam is 120 m and the right dam is 200 m long. Both dams have a maximum height of around 30 m and are constructed as a zoned rockfill embankment dam with a vertical central core of glacial till.

Distributed measurements of strain and temperature have been carried out at Hällby dam in September 2005 and in September 2006. Both the Sensornet DTSS and DTS were used to provide the most accurate combination of measurements.

6.2 Installations

Hällby consists of two dam sections, referred to as “Left” and “Right” with the power station between the two dam sections (Figure 54). The optical monitoring cable has been installed in the crest of the dam, running outwards from the power station, where also the terminations are made in each of the abutments. The cable was installed in 2005 in connection to dame safety upgrading work including a new toe berm and increased core crest.

Figure 54 – Hällby Dam.

The optical cable that has been installed is the standard DamSens cable, providing two multimode fibres (for temperature monitoring) and two singlemode fibres (for strain monitoring). The cable was placed on the core crest.

The topologies of these cables, and approximate cable markings are shown in Figure 55 and Figure 56. Pairs of fibres have been spliced/connected together at the far ends/turnaround points, to provide a loop back configuration for the measurements.

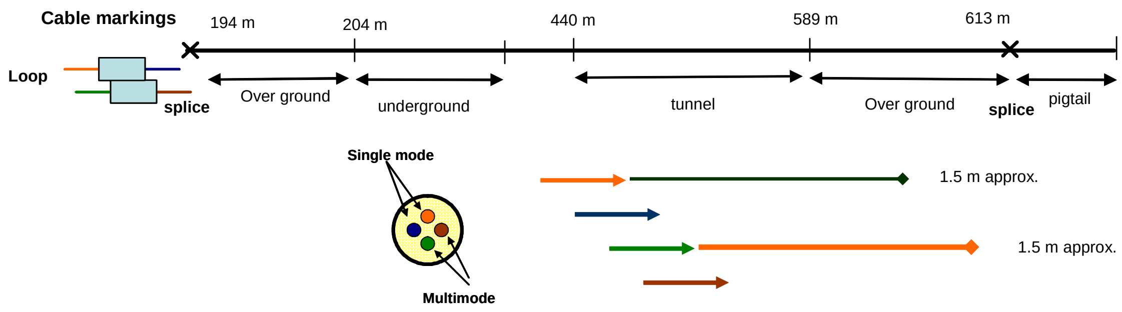

Figure 55 – Cable topology for Hällby “Right”.

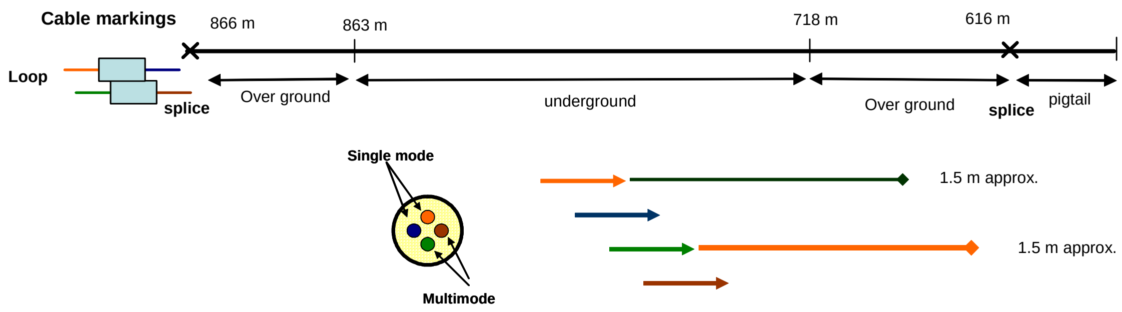

Figure 56 – Cable topology for Hällby “Left”.

6.3 Measurements Sep 2005

6.3.1 OTDR

The OTDR measurement of Hällby right, taken on the installed strain sensing fibre, shows good installation (Figure 57). The fibre loss is close to that expected. There is one change in loss at cable marking 351m, the reason for which is unclear. It does not appear in the return path and therefore is likely to be a tight bend on the cable, affecting just one of the fibres. The actual effect is not big enough to cause any degradation of data quality.

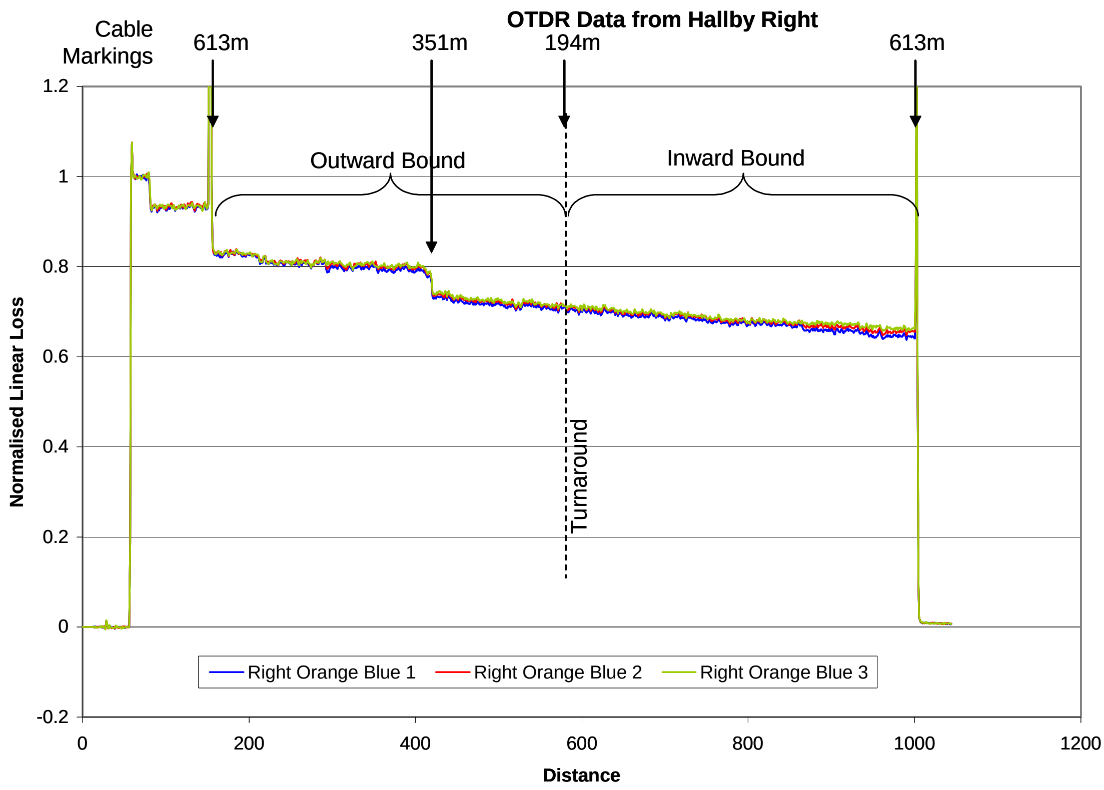

Figure 57 – OTDR Data, Hällby "Right".

The OTDR data from Hällby Left shows a different picture of installation conditions, Figure 58. There are a number of discrete positions of high loss, possibly transistion between loose ducting and the dam structure. These point losses accumulate to quite a considerable amount. However, it should be remembered that is not actually necessary in these dam installations to measure to the end of the dam and back in "one go", as has been done here. Each of the fibres could be measured alone, with no loopback at the far end. Although they would still see half of these losses, this is not enough to cause a serious degradation of data.

Table 7 provides further details of the point losses, and the measured loss of the fibre in Hällby Left. The distances have been offset so that they correspond to the cable markings for the outward bound direction. Important features to note are that the measured fibre losses along its length are considerable within the dam structure itself. The possibly arises from compaction stresses on the cable, although the cable used is an extremely rugged cable. The measured fibre losses in the dam structure are anything from 2 to 4dB/km, as opposed to the normal 0.2dB/km.

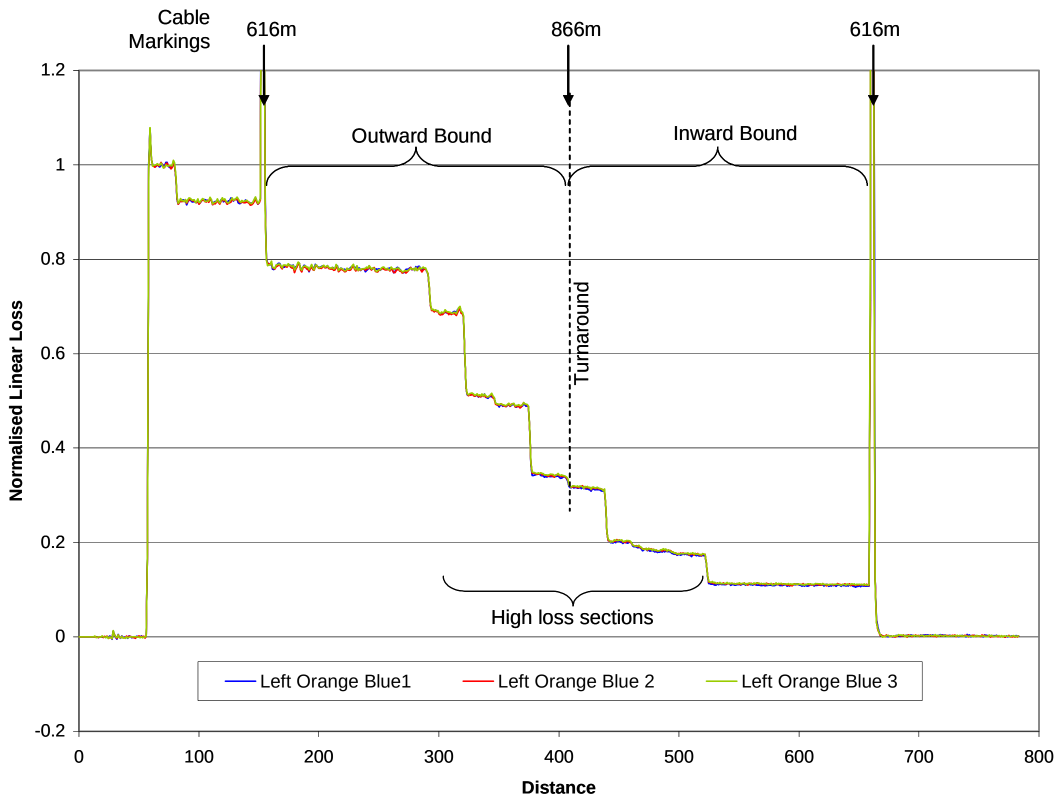

Figure 58 – OTDR Data, Hällby "Left".

Table 7 – OTDR Analysis of Hällby "Left".

Location m	Feature	Step Change dB	Fibre Loss dB/km	Fibre Length
516.3	fibre start	NaN		
521.9	fibre loss		-0.17	15.8
539.7	point loss	0.2		
543.7	fibre loss		0.01	64.2
608.2	reflection	3.19		
617.4	fibre loss		0.16	131
750.8	point loss	0.27		
756.6	fibre loss		-0.73	21.1
780.3	point loss	0.64		
786.2	fibre loss		1.2	18.7
805.8	point loss	0		
805.7	fibre loss		0.34	26.3
834.6	point loss	0.78		
839.7	fibre loss		1.92	26.4
866.5	point loss	0.07		
867.3	fibre loss		1.83	28
898	point loss	0.95		
902.8	fibre loss		4.86	77.4
982	point loss	0.95		
986	fibre loss		0.51	129
1115.8	fibre end	13.47		

6.3.2 Temperature Measurements

Temperature measurements were taken using the Sensornet Sentinel DTS instrument. A selection of data sets is shown for Hällby "Right" in Figure 59. These were taken at different times in the day, and clearly show positions where the cable is exposed to the outside air, as opposed to be being buried within the dam structure. These positions indicate the considerable change in temperature due to air temperature changes. The data shows good symmetry about the turnaround point as is expected for a good installation.

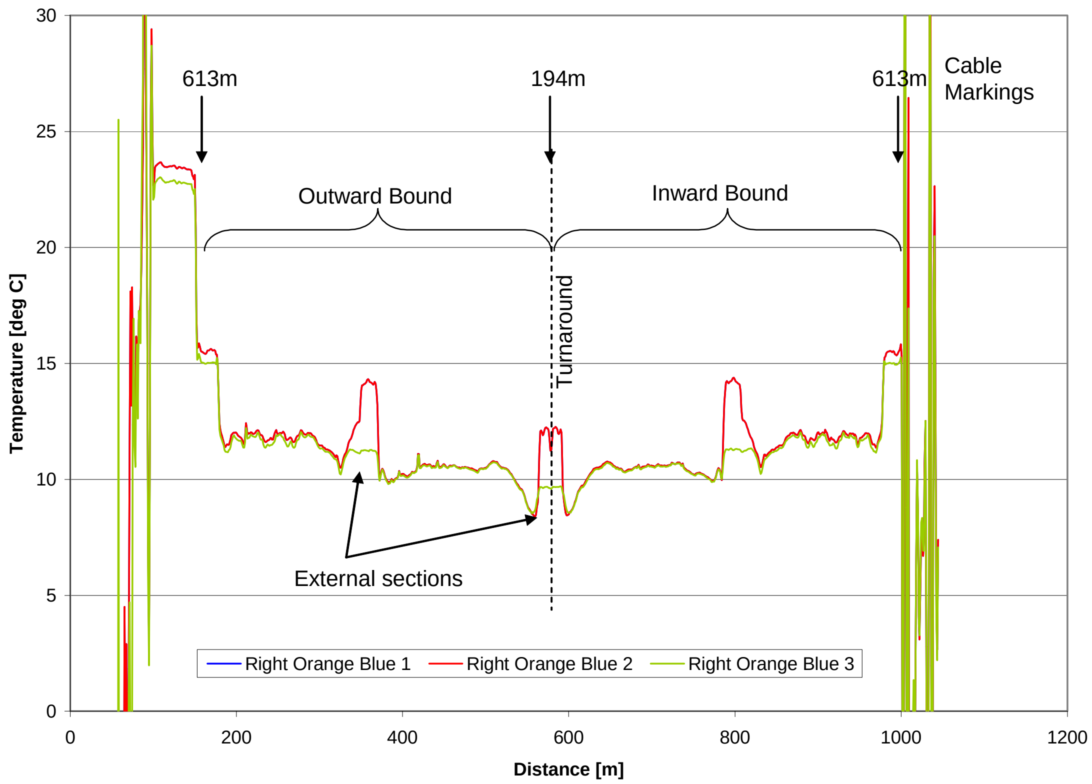

Figure 59 – Temperature Data from Hällby "Right".

Temperature measurements were also taken in Hällby "Left", and these are shown in Figure 60. Despite the considerable losses in the fibre, good temperature data has been obtained using the Sentinel DTS. A selection of temperature data is shown again, demonstrating the change in outside air temperature in the sections of cable exposed to the outside. The temperature trace also shows good symmetry again about the turnaround point.

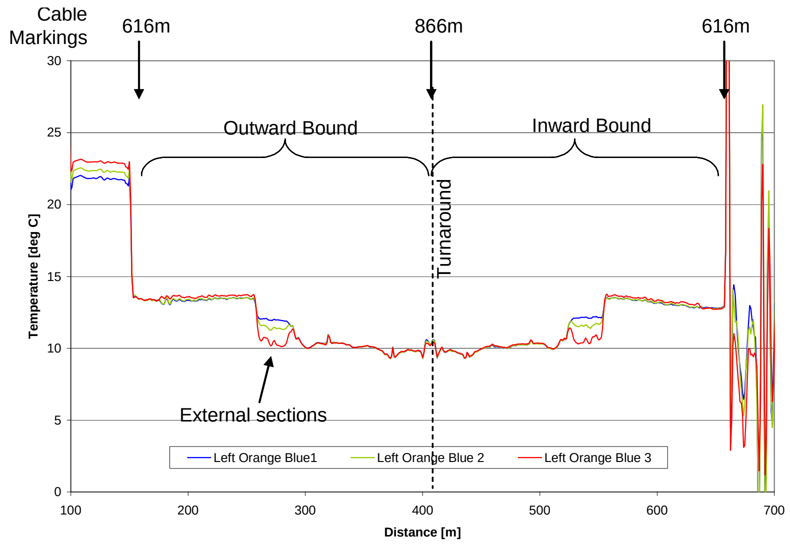

Figure 60 – Temperature Data from Hällby "Left".

6.3.3 Strain Measurements

Strain measurements were taken in the Hällby dams using the Sensornet DTSS. The DTSS data has been combined with the DTS measurement data to provide increased accuracy of the strain data.

Figure 61 shows the results of the strain measurements in Hällby "Right". They demonstrate a reasonable symmetry about the turnaround point. The section of the cable which is in the dam structure itself is also clearly recognisable, by the large variations in strain arising from the construction process. The strain outside this area is much lower as the cable is routed through ducts.

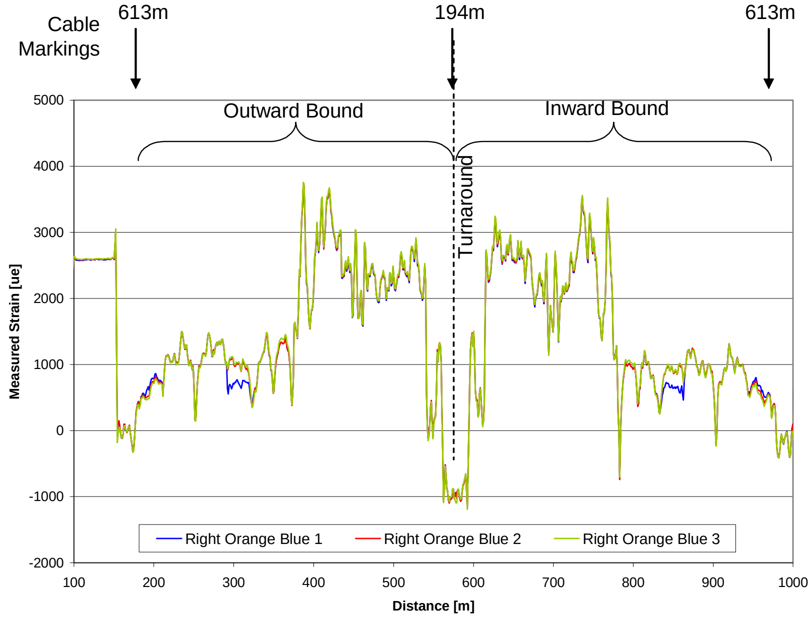

Figure 61 – Strain Measurements, Hällby "Right".

Figure 62 shows the results from Hällby, “Left”. Again they demonstrate reasonable symmetry around the turnaround point, despite the large losses in this cable section. The section of the cable which is in the dam structure itself is also clearly recognisable, by the large variations in strain arising from the construction process. The strain outside this area is around zero as the cable is routed through ducts.

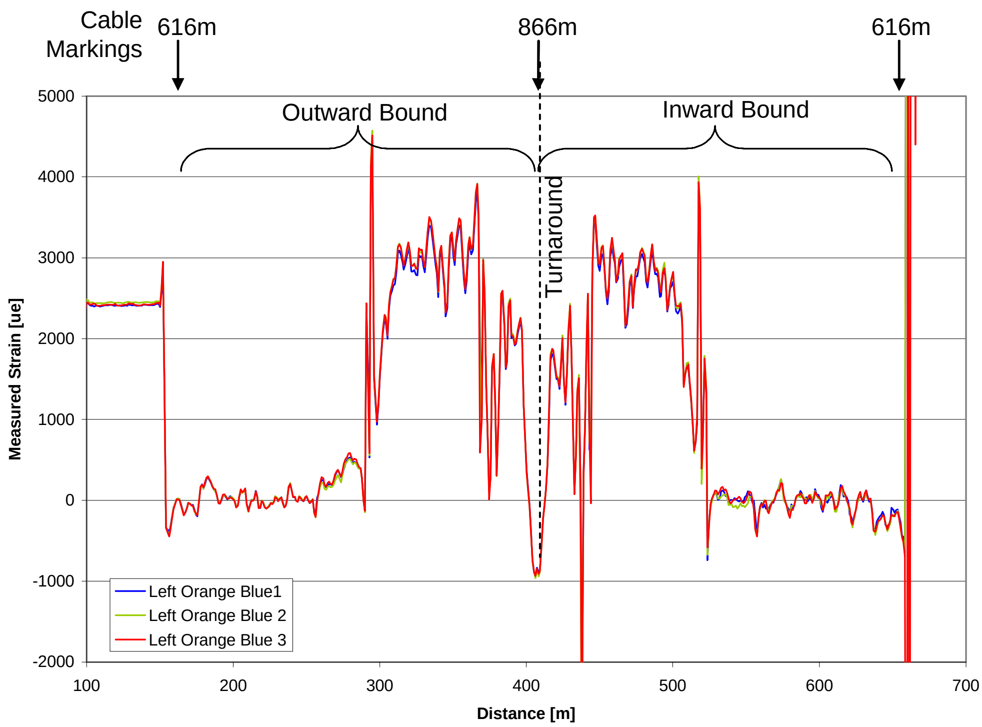

Figure 62 – Strain Measurements, Hällby “Left”.

6.4 Measurements Sep 2006

Additional measurements were taken at Hällby dam during September 2006. This time only measurements were taken of the right dam. The DTS and DTSS measurements have been combined once again to further increase the accuracy of the strain measurements. These strain measurements have then been compared against the baseline taken during September 2005, Figure 63. They demonstrate fairly small changes in strain in the sections that are actually buried in the crest of the dam. The sections overground and in ducts obviously result in greater variations of measured strain.

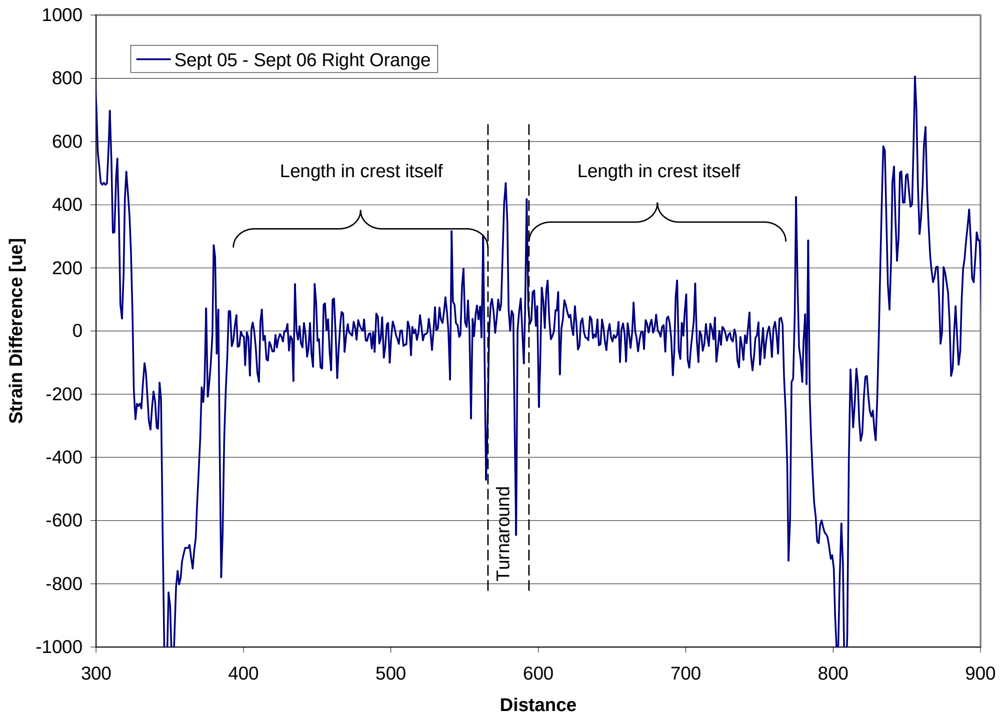

Figure 63 – Strain difference measured at Hällby right dam.

7 General Discussion

This section will be used to discuss the achievements of the measurement program and the lessons learnt. Earlier in this report we outlined what we believe are the essential requirements for successful monitoring of strain in embankment dams:

1. The strain data must be accurately compensated for temperature. Any residual cross sensitivity to temperature, even in a structure with small temperature variations is still likely to cause difficulties in comparing strain measurements
2. The exact position of the cable relative to the measuring instrument needs to remain the same, so that the data exactly overlays in distance against one another.
3. The strain measuring instrument obviously has to provide exactly the same calibrated strain measurement. This will be a combination of the instruments ability to accurately determine the optical frequency of the backscatter signals reliably over time and to apply the same strain calibration coefficients each time to the measured cable.

A number of changes and recommendations have arisen from the measurement programme and will be discussed here.

7.1 Temperature compensation

The Sensornet DTSS is unique in being able to provide independent, simultaneous measurement of both strain and temperature. This is achieved by measuring both the Brillouin backscatter frequency and power. Typically the instrument is able to achieve a temperature resolution of 1°C and a strain resolution of around 20με. However, these resolutions are partly dependent on the calibration coefficients of the sensing cable being used, and obviously on a good installation. The DamSens cable is more sensitive to temperature than normal secondary coated fibre, typically 2.5 times more sensitive. Hence, this will impact the achievable strain resolution, reducing it to around 50με. It is possible to explore alternative cable designs with lower temperature sensitivity, however we now have a good experience with the dam cable and know it is sufficiently rugged for the job. An alternative means of increasing the temperature resolution, and hence the strain resolution is to use a Sensornet DTS alongside the DTSS. The DTS is used to capture very accurate temperature data, which is then combined with the DTSS measurements of Brillouin frequency to provide a more accurately temperature compensated strain measurement. Another big benefit of using the DTS is that it is less susceptible to point losses that may arise from unsatisfiying installations.

Throughout the measurements presented here, the DTS and DTSS data has had to be combined after the measurements have been taken. This post processing is not fully automated and can take quite a lot of time. Recently, and partly based on the experiences in this project, Sensornet has adapted the DTSS software to provide a fully automated option. Now the DTSS and DTS can be set up alongside each other to measure the same cable at the same time. Obviously the DTSS will measure strain in the singlemode fibre of the cable, whilst the DTS will measure the multimode fibre in the cable. With a few small changes in the configuration of the DTSS and connection to the DTS using a network lead, the DTSS will automatically retrieve collected temperature data from the DTS and combine this into strain data at the time of measurement. This will provide a more robust solution in the future for the monitoring of embankment dams, where temperature compensation is critical, and alleviate the time needed for post processing.

7.2 Cable Positioning

A clear problem identified during the early measurements at Ajaure and Hällby was the positioning of the cable. This was exacerbated by the fact that there was no permanent installation of the cable could be made at the first visits to the site. Each time a different length of cable would need to be spliced ready for measurements. This meant that there would be a difference in the length of the cable between different measurement samples, making comparison difficult. This problem was solved when the installation could be finalized.

The recommendation for the future would be to change the way in which the sensing cables are terminated. Ideally all fibres of the sensing cables are brought into a junction box. At this point they should be spliced to patchcords long enough that they can be used as “flying leads” to directly connect to the instrument. In this way, there would be no need to use an additional patchcord between the instrument and a patch panel as has sometimes been the case in the past. The cable sensing length would remain a constant and help greatly in the comparison of data. Figure 64 depicts the this configuration of junction box terminations which have been used in the installations made since 2006, and one example is showed in Figure 65.

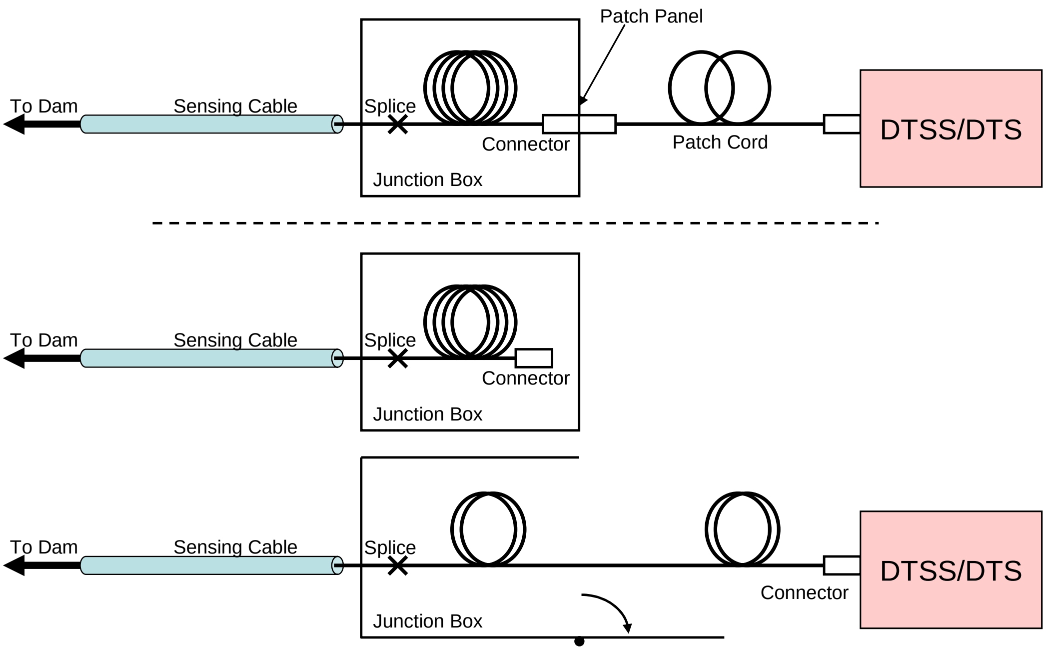

Figure 64 – Proposed junction box configuration for future installations

Figure 65 - Junction box installed in 2006.

7.3 Strain Measurement Accuracy

An essential element of periodic strain surveys is the ability to guarantee that from one measurement to the next the measured strain will match, in terms of offset and scaling. The first architecture of the DTSS instrument used an optical filtering technique to determine the optical frequency of the Brillouin backscatter. Unfortunately the optical filter was quite sensitive to temperature changes, making absolute calibration more difficult. Since then Sensornet has introduced a new detection architecture in the DTSS which uses an electrical crystal oscillator in determining the optical frequency of the Brillouin backscatter. By it is very nature, the crystal oscillator is accurate to a few kilohertz, providing excellent absolute accuracy when measuring the optical frequency. It also guarantees that the accuracy of the optical frequency will be the same from instrument to instrument, and from measurement to measurement.

7.4 Data interpretation

The strain measurements show generally small strain differences between the measurements, probably in the order of the monitoring accuracy. However in some areas significant strain differences have been measured. The remaining problem is then to explain the origin of this change and, if possible, also to relate the strain change to a lateral change.

The friction between the cable and soil is fundamental to the monitoring accuracy. In this case we can assume that if a crack or movement occurs, it will create a pulling of the cable. At a certain distance from the crack there will be no movement of the cable due to friction between the cable and the soil. The result from the tests performed in the previous project (assuming low friction between cable and soil), together with a new test within another research project (with high friction between cable and concrete) is summarized below in order to provide improved interpretation possibilities.

7.4.1 Field Test performed at Ajaure dam

The method was to clamp a section of the cable at two positions, a set distance apart. The centre of this clamped section was then deflected by fixed amounts and the strain measured in the cable for each condition. A simple illustration of this set-up at Ajaure dam is shown in Figure 66. The section of cable used was that suspended from the underside of the roadway above the spillway. The cable was deflected in 5mm steps using small aluminium blocks as spacers. The cable was pulled taunt before being clamped to eliminate any sag, and ensure that an accurate measure of strain due to deflection was measured. The measurements were carried out for deflections up to a distance of 40mm.

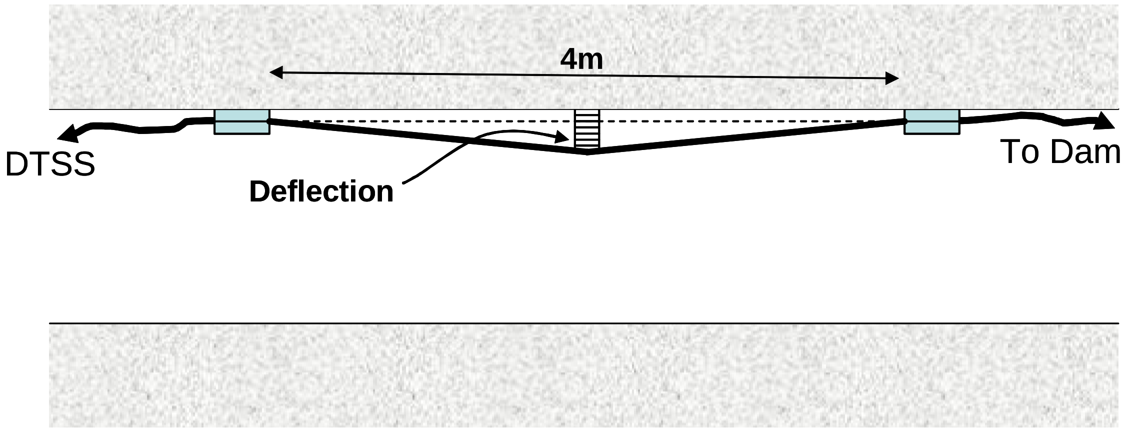

Figure 66 - Deflection experiment arrangement.

In addition to the deflection tests carried out at Ajaure dam, repeat tests were carried out in the Sensornet Laboratory for both 4m separation and 2m separation between the cable clamps. The method was exactly the same as that used in the field, and aimed to verify the field measurements whilst also providing data for a different distance between the clamps.

The results of all three tests are shown in Figure 67 for deflections up to 40mm. A quadratic trendline has been fitted to each data set, showing excellent agreement between the field and laboratory measurement for 4m spacing between the cable clamps. The 2m spacing data points show a good quadratic fit and a magnitude four times that of the 4m spacing data sets, agreeing well with theory. The 2m clamping interval is a closer representation of the behaviour of the cable installed in the dam, since the dam cable is effectively clamped at infinitely small intervals due to the surrounding material of the dam.

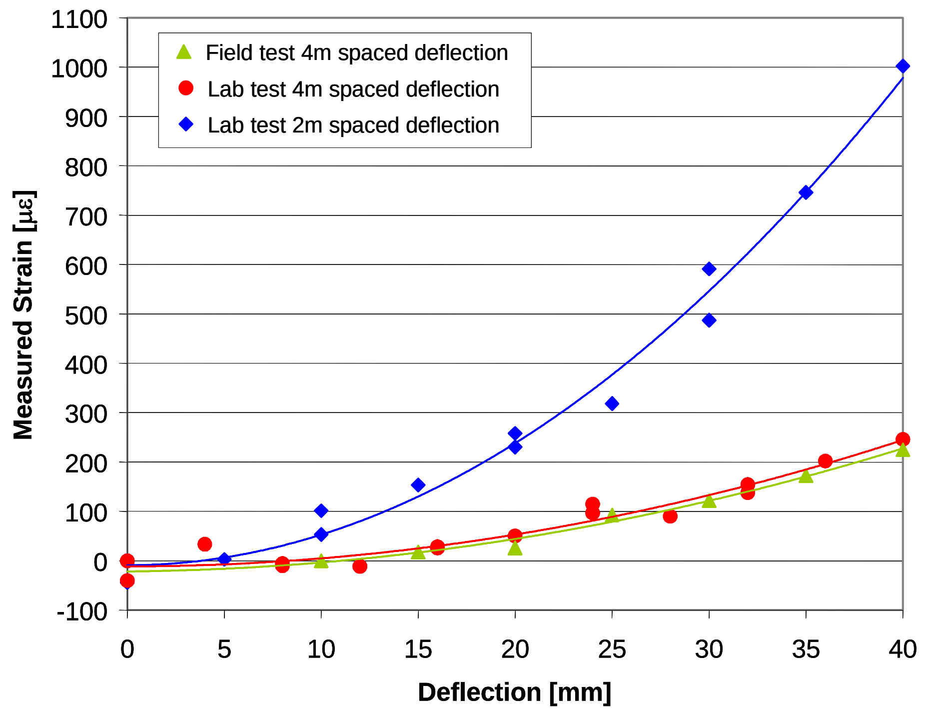

Figure 67 - Measurement results for deflection tests in the field and laboratory.

These tests have demonstrated that a pure lateral deflection of just 10mm over a 2m length will be detectable, since it results in a 50με change. However, these results also demonstrate that as the distance between the deflection points is reduced, the incurred strain increases. A fully buried cable obviously should be considered more like a cable that has very little separation in distance between holding points.

7.4.2 Laboratory test performed at a RCC dam

An alternative analysis is to consider what happens to a cable when it experiences shear between two sections of ground movement, as depicted in Figure 68. Such movement is not untypical, and it is clear that it would result in a very much more localised strain on the fibre, as opposed to a lateral deflection over several metres.

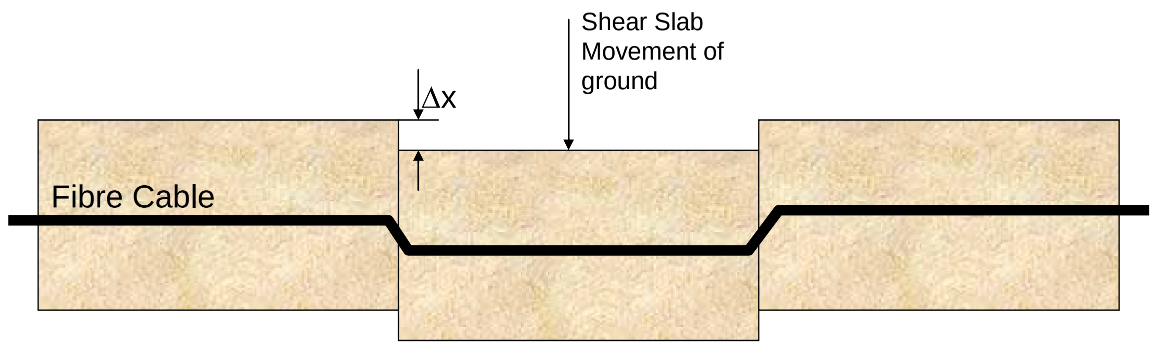

Figure 68 - Diagram of slab movement of ground.

The closest representation to this that has been tested is the cracking of a concrete slab in which was embedded a strain sensing cable (Figure 69). Tests were carried out using

Sensornet's DTSS by the Technical University of Munich (Moser et al). A cable was installed in a RCC block, where the fibre was laid back and forth along the block in 9 different lengths. Some steel pins were driven into the block to create a crack through the block approximately 1mm in magnitude. This crack ran perpendicular to the cable lengths.

Figure 69 - Photos of the RCC block with the strain sensing cable embedded within it (Moser et al).

Strain measurement before and after the crack was created clearly showed that the DTSS was able to detect the small 1mm crack. These results are shown in Figure 70.

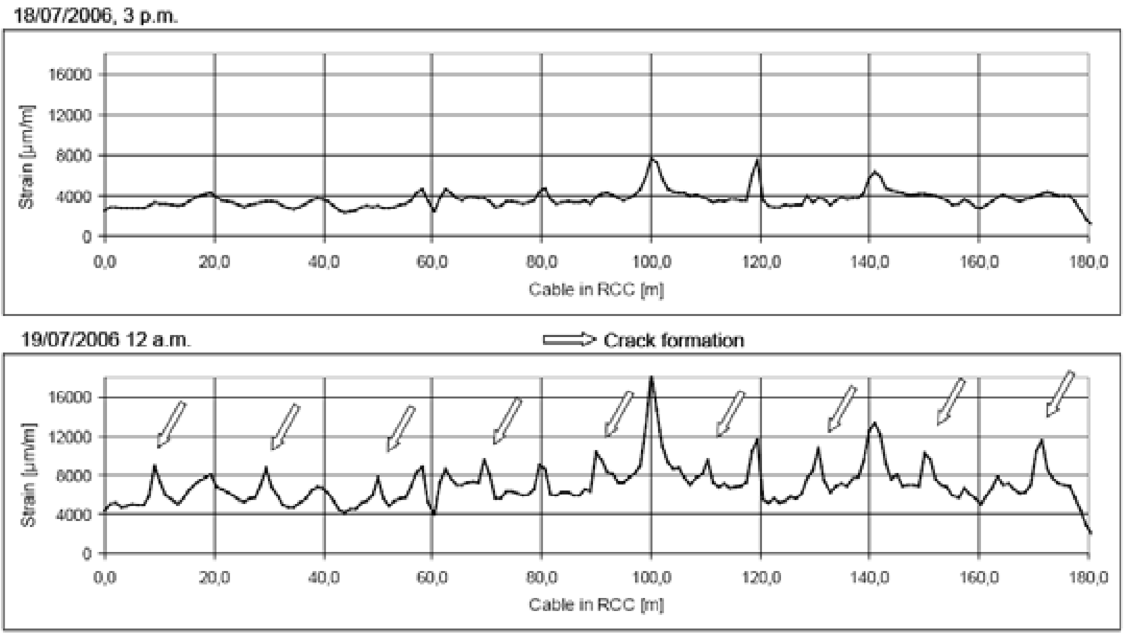

Figure 70 - Strain measurements of concrete block before and after creation of crack (Moser et al).

Despite the short 10 m length of the block and the 1 m spatial resolution of the DTSS, the measurements showed clear indications of the crack at the 9 positions as the cable went backwards and forwards along the length of the concrete block. The magnitude of the change in strain at these positions is as much as 4000με (0.4%). This implies that the crack width may have actually been as much as 4mm. It also demonstrates that very small changes in longitudinal length of the cable can be detected. A change of just 0.02mm over 1 m length is equivalent to the 20με strain resolution of the instrument.

7.4.3 Comparison

These two different types of strain test demonstrate the potential lower and upper limits of movement detection for this application. The very conservative lateral deflection tests demonstrated that movements of between 5 and 10mm, will be detected by the 20με strain resolution of the instrument. The crack detection, where the deflection was directly applied to the cable in its longitudinal direction demonstrated that a deflection of just 0.02mm could be detected by the Sensornet DTSS.

7.5 Interpretation of field data

The strain changes measured in Ajaure and Seitevare are both in the order of some thousands με strain. At Ajuare this is measured over a distance of about 8m, while the strain change at Seitevare is only measured at 1m, by both the DamSens cable and the SMARTprofile cable. The friction between the cables and the soil must then be good at Seitevare, and a concentrated movement is probable.

The friction between the soil and cable in Seitvare seems therefore to be similar to the tests in the concrete blocks. If the friction between the soil and the cable is similar to the friction between the concrete and the cable (as in the tests carried out in Germany), the measured strain difference would correspond to a movement of about 1mm. A slightly higher value may also be a reasonable estimation, since the friction between the cable and soil should be lower than the friction between the cable and the concrete. A reasonable estimation of the movement will then be some mm.

If the friction between cable and soil is low, the situation should be similar to the test made at Ajaure dam. This would also explain the measured strain change of the large distance (about 8 m). Measured strain changes would then correlate to large movements (in the order of a decimeter). However, this is not reasonable since no movements of this order have been detected on the dam crest. The installations at Ajaure and Seitevare are also similar, and a similar friction between the cable and soil is therefore expected. One possible explanation of observed strain changes in Ajaure, may be that several small movements (in the order of some mm) occur in this area of the dam.

Generally, it is also our judgment that as a result of these different strain scenarios, a lateral deflection detection of just 1 mm or 2 mm will be possible to detect in dam monitoring. The absolute value will however be difficult to estimate since large variations of the friction between the soil and the cable may occur, due to soil characteristics, different compaction, installation methods etc.

8 Conclusions

These measurements, performed at four dam sites during at several occasions, have demonstrated the potential of distributed strain measurements in dams. Specific information concerning strain location has been provided, which has not been available before. The distributed technology seems to be a valuable complement to conventional inclinometers.

The experiences from the measurements show the importance of good installation work, careful monitoring, using a DTS to improve the monitoring accuracy for the DTSS. Unsatisfactory installations may result in high optical losses, which reduce the monitoring accuracy drastically. Care is needed during installation to avoid excessive losses at turnaround points, which later compromise measurement accuracy.

The three significant strain changes, observed in the studied dams, seem all to be small. None have been confirmed by any changes observed or measured on the dam surface. These measured strain differences (in the order of some thousands $\mu\varepsilon$ strain) are several times larger than the noise level of the measurements (about $50\mu\varepsilon$ at field measurements). A reasonable estimation of the friction between the soil and the cable indicate that the measured strain difference corresponds to a movement of some mm. Further work should also be carried out in order to better understand the interaction between the cable and the soil to allow a better use of the technology.

The test with the SMARTprofile cable was not successful, and the result was not accurate enough to determine the direction of the movement.

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. However, the absolute value of the movement is difficult to estimate.

Finally, the system can detect strain changes (movement changes) in the dam and can therefore be used either as Early-Warning-System with continuous monitoring, or as an investigation tool to measure movements regularly.

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