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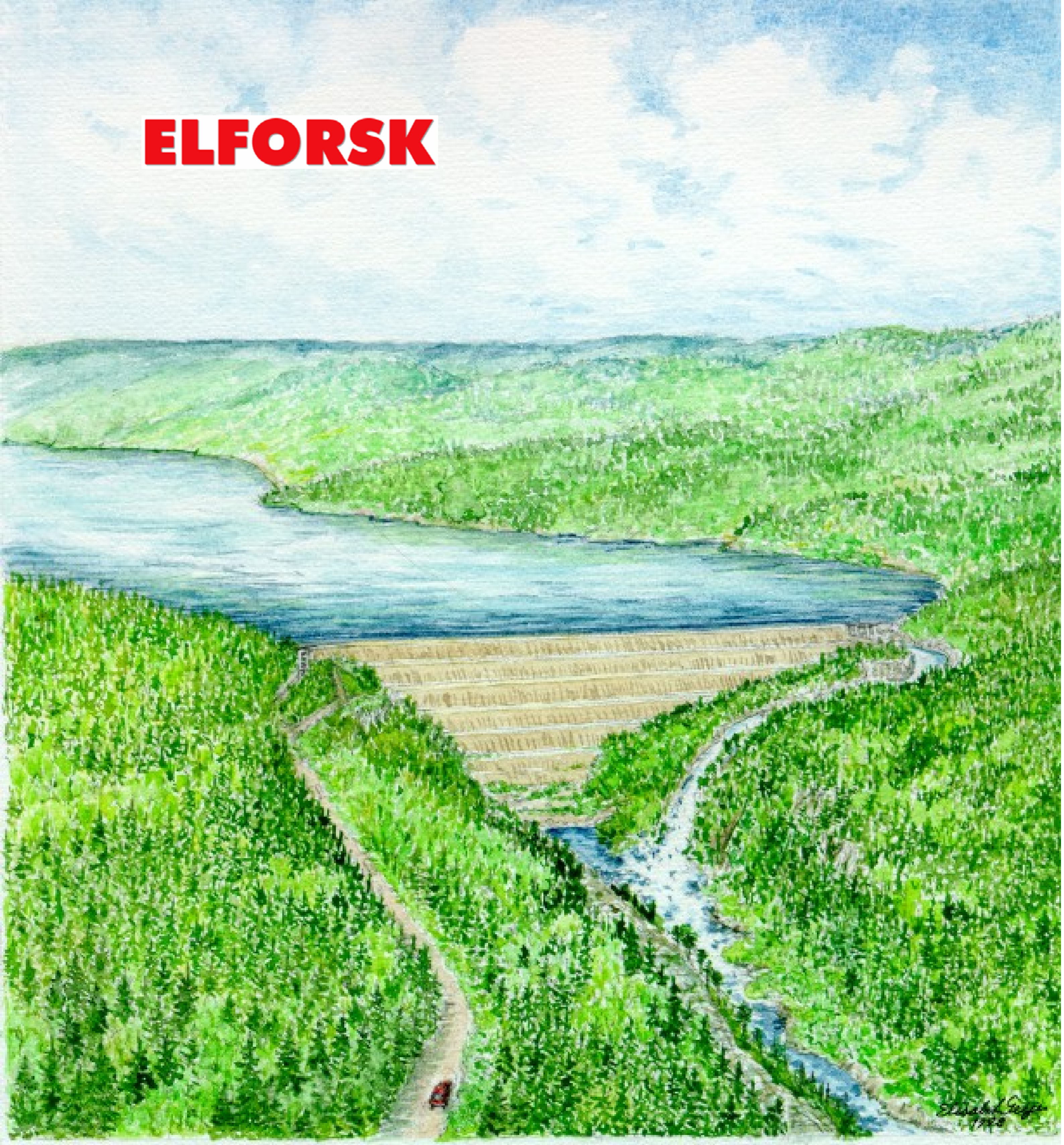

DAM SAFETY

DISTRIBUTED STRAIN MEASUREMENTS FOR EMBANKMENT DAMS – Field tests at Ajaure Dam 2004-05

Sam Johansson and Dan Watley

Rapport 05:32

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Elforsk rapport 05:32

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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 – Sydkraft Vattenkraft, Lennart Markland – Vattenregleringsföretagen, Urban Norstedt - Vattenfall Vattenkraft, Gunnar Sjödin – Vattenregleringsföretagen samt Lars Hammar - Elforsk

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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 töjningsförändringar detekteras, både beträffande läge och storlek. Elforsk AB har i tre tidigare projekt stött forskning för tillämpning och anpassning av denna teknik för mätningar på dammar.

De fösta rörelsemätningarna med denna teknik gjordes i september 2004 på Ajaure dammen, då magasinsnivån var hög. En andra mätning gjordes i maj 2005 vid lågt vattenstånd i magasinet. Skillnaden i töjning mellan mätningarna var liten och i nivå med systemets noggrannhet. Detta överensstämmer med de mätningar som görs i de två inklinometrar som finns i dammen, vilka också visar på små/marginella förändringar. Resultaten från de olika mättmetoderna är dock inte helt jämförbara eftersom de görs i olika plan. Kombinationen av vertikala inklinometrar och horisontell installerad optisk fiber bör dock kunna ge en god bild av även eventuella rörelser i dammkroppen.

Flera mätningar gjordes vid varje mättillfälle för att testa mätsystemets repeterbarhet. Dessutom gjordes test i fält för att bedöma systems verkliga förmåga att upptäcka förändringar. En del tester upprepades också i Sensornets laboratorium.

Sammanfattningsvis, bekräftar mätningarna att rörelser mindre än 5 mm kan upptäckas, vilket visar att mätsystemets prestanda redan nu är intressant för flera tillämpningar, speciellt eftersom rörelserna kan lokalisera på ett helt annat sätt än med dagens teknik. Ytterligare förbättring av mätnoggrannheten är möjlig att erhålla genom att förbättra kabelns design liksom dess installation. En bättre noggrannhet skulle också kunna erhållas om temperaturen kunde mätas med högre noggrannhet.

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.

In September 2004, the first distributed measurement of strain in an embankment dam was undertaken using the Sensornet DTSS. The system allows the strain and temperature to be measured simultaneously and independently at all points along the fibre. The measurement was carried out at Vattenfall Vattenkraft's Ajaure dam in Sweden. The aim was to compare the measurements taken during September, at full reservoir level, with measurements to be taken at low reservoir level in May 2005. The measured difference of strain between the two measurements is small, indicating no significant localized movement of the dam. These initial measurements demonstrate the potential of distributed strain measurements.

Whilst undertaking strain measurement at Ajaure, a series of tests were also performed to demonstrate the ability of the DTSS to determine the size of localized deflection in the dam which could be detected by distributed strain measurements. Similar tests were also repeated in the Sensornet Laboratory. Those tests have demonstrated that a deflection of the dam by just 5mm will be detectable.

The current sensitivity of the system is suitable for detecting very small localized changes of the dam structure. However, the sensitivity is set to improve with further development, providing enhanced temperature correction and hence much increased strain accuracy. Distributed optical sensing will be an essential tool for dam monitoring, providing location specific information which has not been available before. The distributed technology provides an excellent complement to conventional inclinometers.

Further improvements must however be made on the installation techniques and the cable design to allow a better use of the technology. Such steps will be tested in the next research project, using a new cable design to provide directional information about deformations. Care is needed during installation to avoid excessive losses i.e. at turnaround, which later compromise measurement accuracy. In particular, high losses can result in errors in the absolute measured strain, when compensated for temperature, and therefore should be avoided by good installation practice.

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

Content

1 Introduction

There is a growing interest to measure strain in many civil structures such as dams, bridges and tunnels. Optical fibre sensors are increasingly been used to measure both temperature and, strain in many such constructions. Sensornet have developed a sensing instrument, the Distributed Temperature and Strain Sensor (DTSS), which is uniquely capable of measuring both strain and temperature at 1m intervals over long lengths of optical fibre.

The challenge is, 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 couple strain applied to the cable into strain applied to the fibre – this is an unusual property as most cables are designed to isolate the fibre from any cable strain. In addition, an efficient way to transfer strain from the structure to be monitored (in this case an earth dam) to the cable must be devised. Sensornet and HydroResearch are collaborating in many areas relating to dam monitoring, one of which is in the development of a cable and installation method for measuring strain in earth dams. The companies have had a cable designed for this application, a section of which has subsequently been installed in Ajuare dam. This has been done during several years in parallel with the development of the monitoring system. Such cables are now installed at more than five dams in Sweden.

This project is mainly based on three previously research projects performed by Sensornet and HydroResearch. Also those projects were funded by Elforsk AB (Project No1286 in 1998 (Johansson et al, 1999), No1356 in 1999 (Johansson et al, 2000), and (Johansson et al, 2003)).

In September 2004, the first distributed measurement of strain in an embankment dam was undertaken. The measurement was carried out at Vattenfall Vattenkraft's Ajaure dam in Sweden. The aim is to compare the measurements taken during September, at full reservoir level, with measurements to be taken at low reservoir level in May 2005. A comparison of the two measurements is presented below.

Elforsk have also decided to extend this project with two further measurements at the Ajaure dam, and additional measurements at Seitevaare dam and Suorva West dam (also owned by Vattenfall Vattenkraft AB), where a new type of cable was installed in 2005.

2 Distributed Temperature and Strain Sensing

2.1 The system

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). Although these tests only required a short sensing length (a few hundred metres) the DTSS is designed to be able to operate over lengths of up to 10km.

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

2.2 The DTSS Cable

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

Figure 2 - DTSS cable breakout.

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

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

2.3 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.

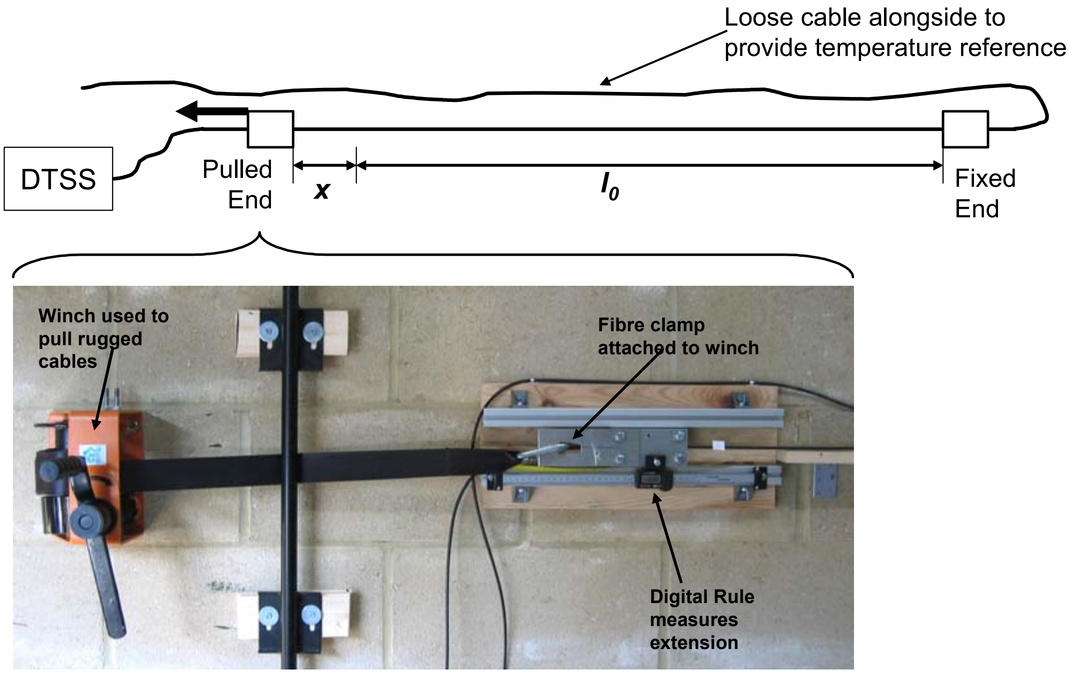


Figure 3 - Sensornet's strain rig schematic and photo of pulled end

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.

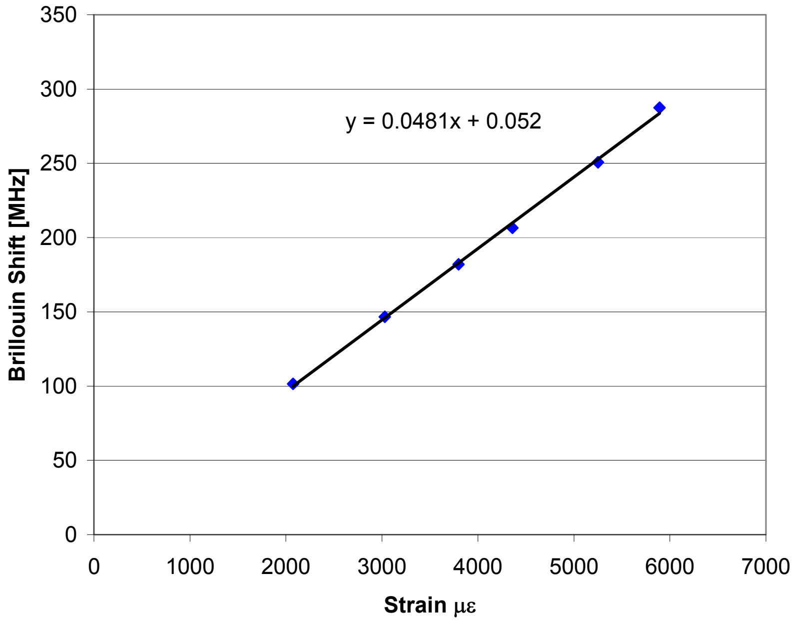


Figure 4 – Calibration of Cable for Strain

A total of four coefficients are required to accurately calibrate the DTSS instrument to the cable installed in the dam. These coefficients described 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.

3 Installation 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 m3. The dam and power station first started operation in 1967.

The dam is 46m high and 522m long, divided by a spillway and intake structure (Figure 5). The embankment dam has a vertical core of moraine, 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.

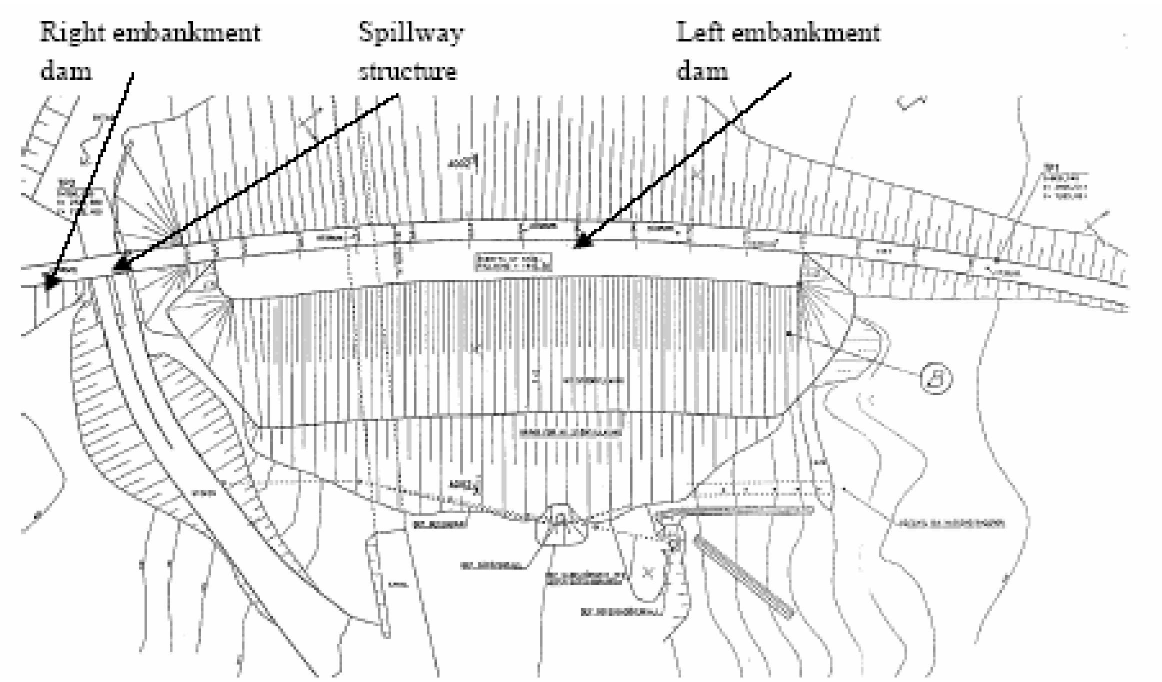


Figure 5 - Plan of the Ajaure dam

Survey measurements of the dam indicated early movements larger than in similar 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 Cable installation

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 can be exposed and allow experiments and testing (Figure 6).

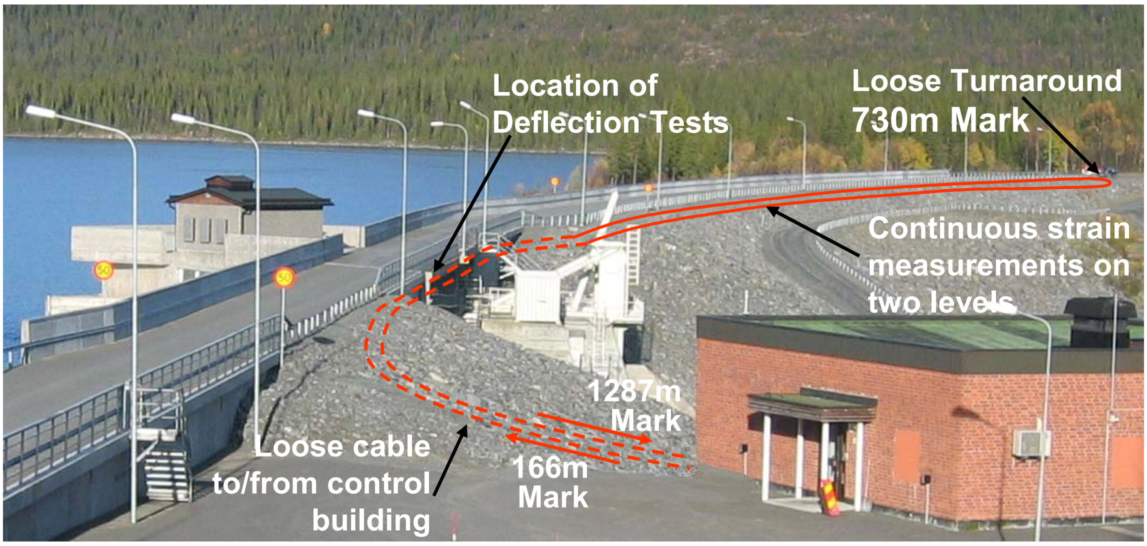


Figure 6 - Illustration of the sensing cable route at Ajaure dam.

The cable was installed at two levels (mean values +442.5 and +445.2) along the dam as 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 Inclinometer result

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, the black curves in Figure 7) 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 330 I_1.The variation between the two measurements was 3mm/m at 330 I_1 and 1mm/m at 393 I-1.

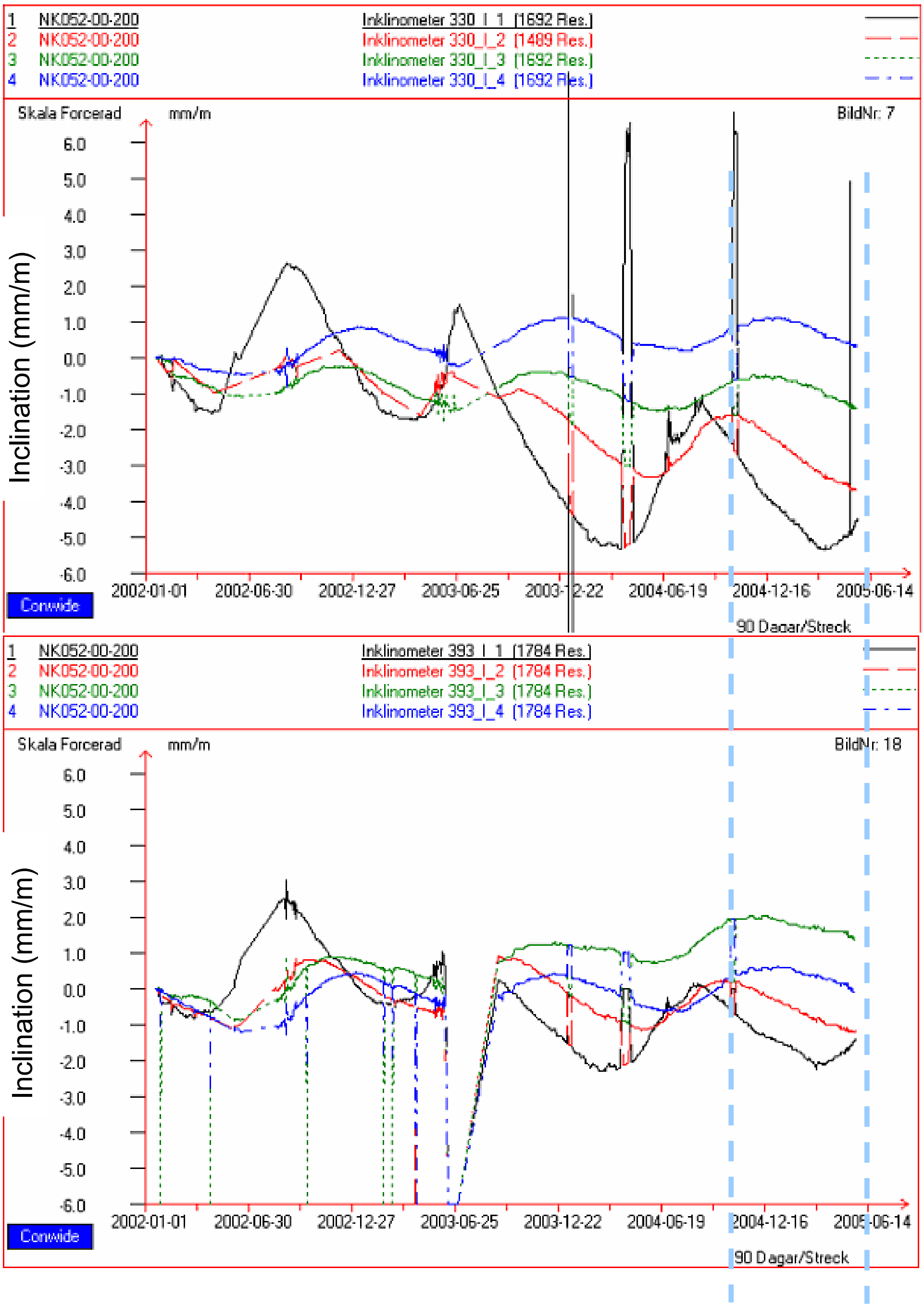


Figure 7 – **Inclinometer results from the four upper levels. Data obtained from Swedpower AB. The blue dotted lines indicate the date for the measurements (Sept 29, 2004 and May 17, 2005).**

4 Field Measurements

4.1 Measurements in the dam 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.

4.1.1 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.

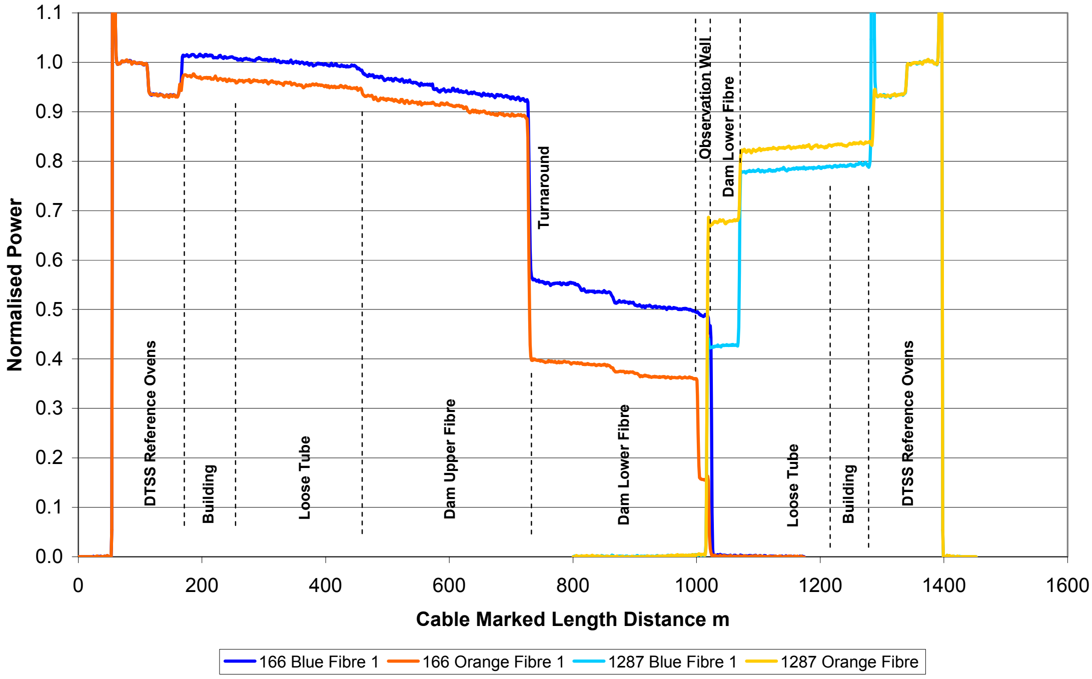


Figure 8 – Optical loss measurements of Ajaure Dam

Figure 8 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 8 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 bought 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 9.

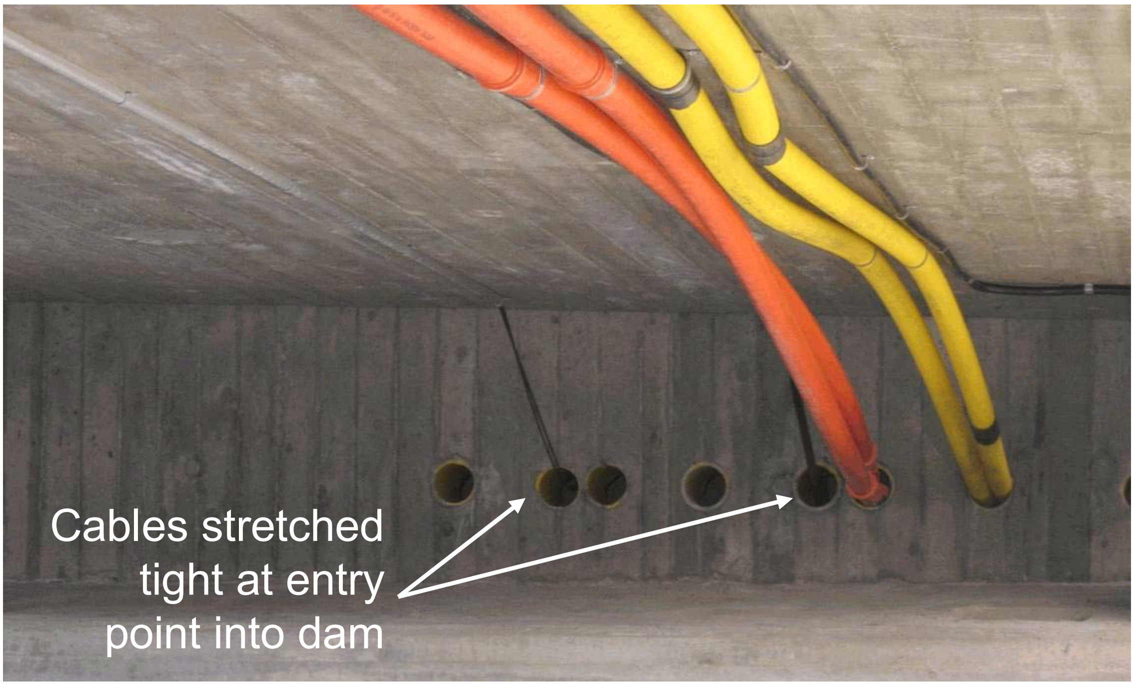


Figure 9 – Photo of cable entry point into dam above spillway

4.1.2 Strain Measurements

An overview of the first strain measurements taken during September are shown in Figure 10. 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 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 during the visit which are presented later in this report.

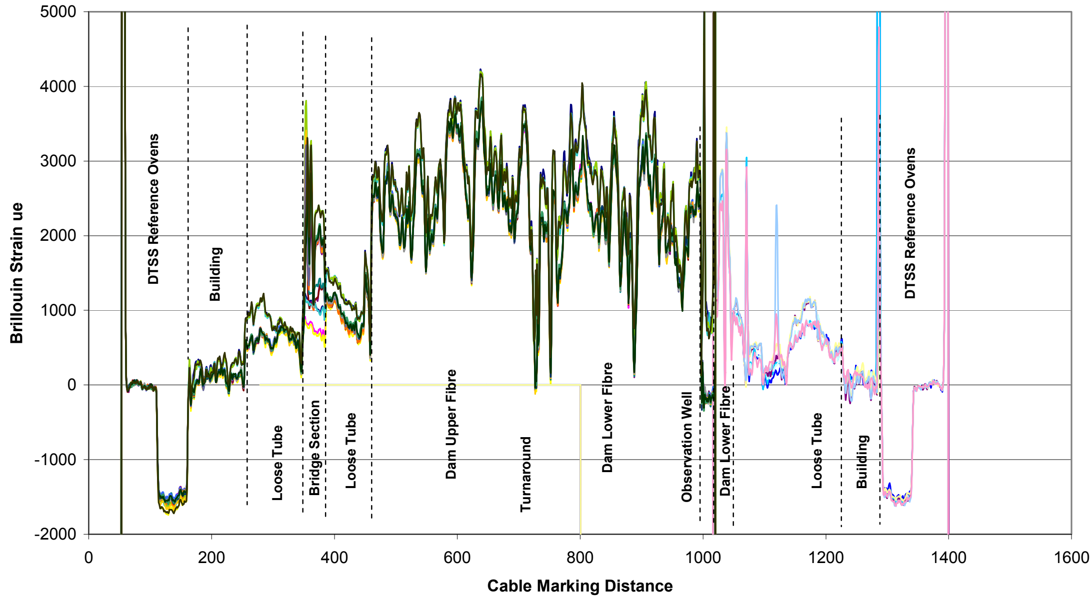


Figure 10 – September strain measurement overview

Figure 11 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 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. 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.

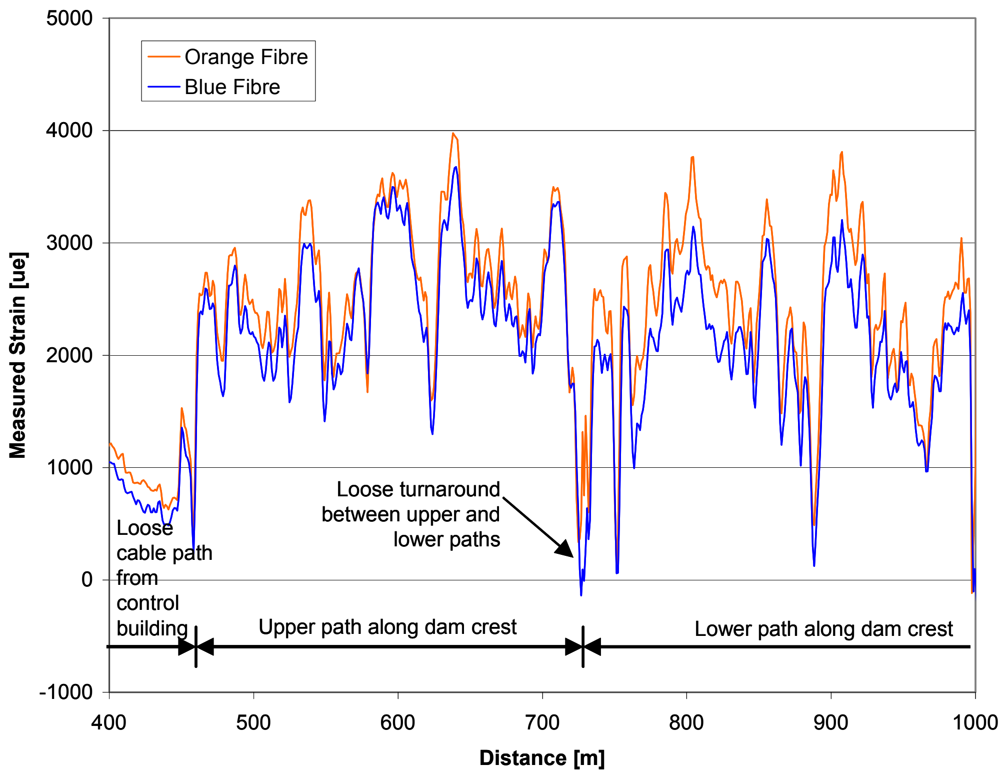


Figure 11 - September measured strain along dam sections of cable

4.1.3 Temperature Measurements

A unique feature of the Sensornet DTSS is the ability to measure both temperature and strain independently. This allows the instrument to provide measurements of strain with no temperature cross sensitivity, a common problem for other optical technologies. Figure 12 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.

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 8 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 12. 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.

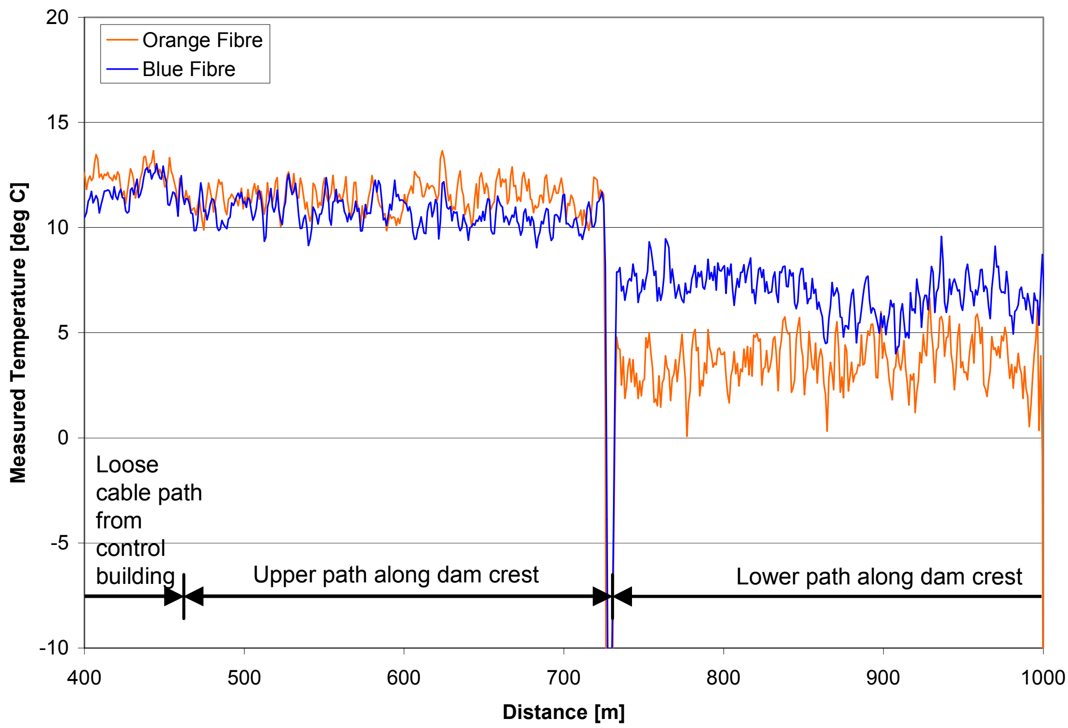


Figure 12 – September measurements of temperature

4.1.4 Visualisation of the measurement data

When the sensing cable was installed into the dam it was also surveyed, providing XYZ coordinates at 5m intervals along the cable. The 1m distance markings on the cable itself allowed these surveys points to be accurately recorded and correlated to the DTSS strain measurements taken. Figure 13 shows one possible use of the strain data. In the figure, the survey points have been used to provide an approximate overlay for the dam plan. The strain is represented by colour coding from blue to red, indicating low to high strain respectively. The strain pictured is for the first measurements at Ajaure in September and therefore some of the variations in strain are simply representative of the variations caused by compaction. However, the loose sections in the loose tube prior to entering the dam, and at the turnaround, are clearly indicated by blue sections of the cable routing.

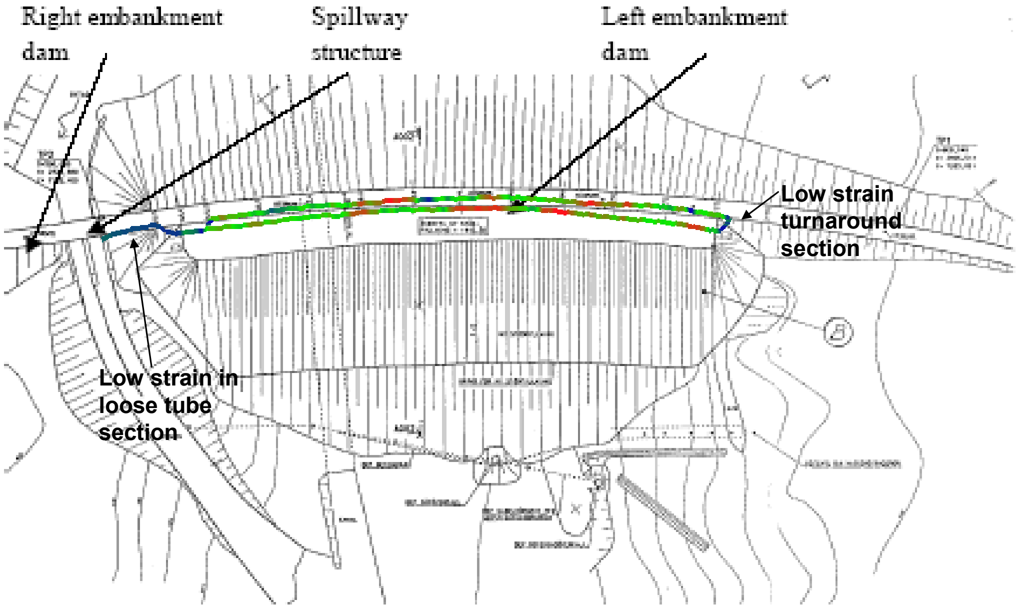


Figure 13 – Visualisation of strain in the Ajaure dam

4.1.5 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 14 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.

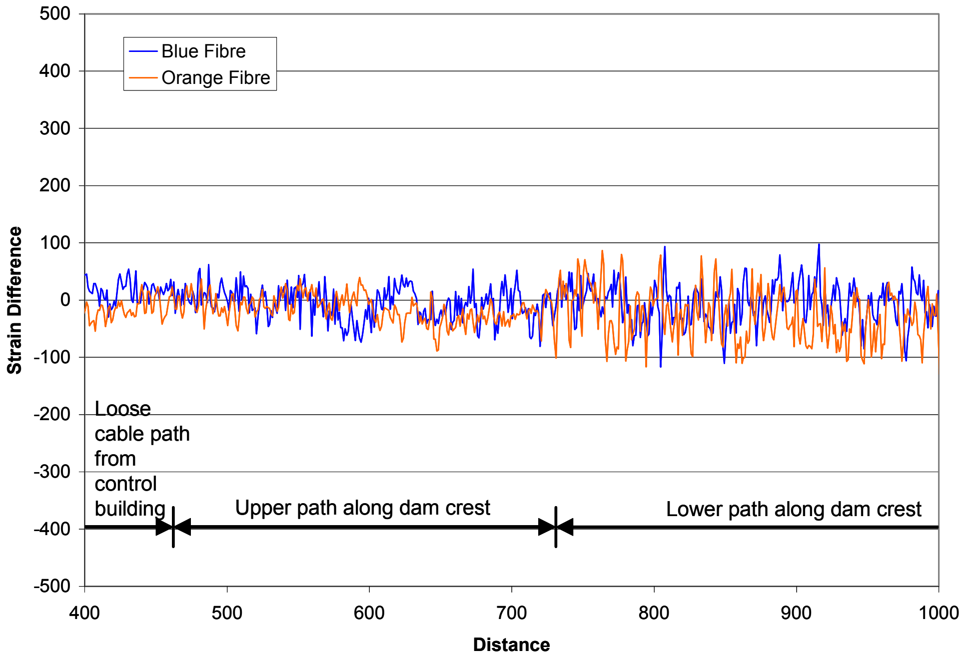


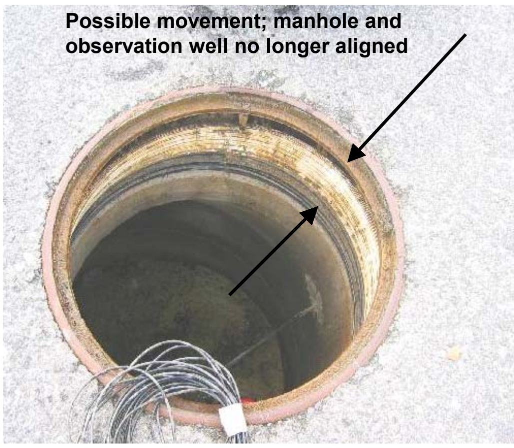
Figure 14 – Strain difference between separate measurements during September

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. As has already been stated, the magnitude of the losses is equivalent to around 9km of additional fibre at that 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.

4.1.6 Observation Well

A particular point of interest is where the cable had been bought 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 9 shows the entry of the cable into the well. The photos also show movement of the observation well relative to the roadway. This movement is likely to have resulted 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.



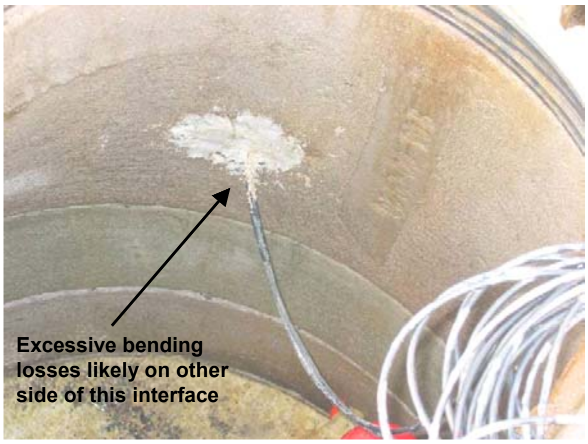


Figure 15 – Optical Cable entering Observation Well

4.2 Measurements in the dam 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 these repeat measurements was to take samples of the strain when the reservoir level was around its lowest point. Figure 16 shows the dam during May, and the water marks on the dam structure indicating the considerable decrease in water level.

Figure 16 – Photos of water level at Ajaure in May 2005

4.2.1 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 17 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.

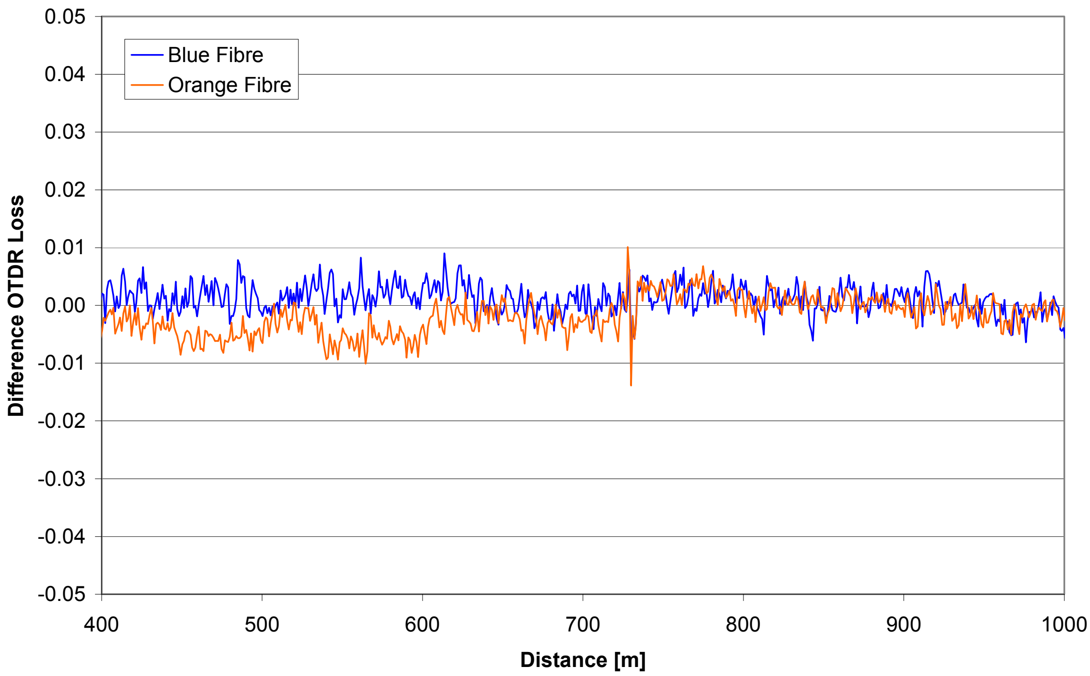


Figure 17 – Difference in optical loss between September 2004 and May 2005

4.2.2 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 18 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.

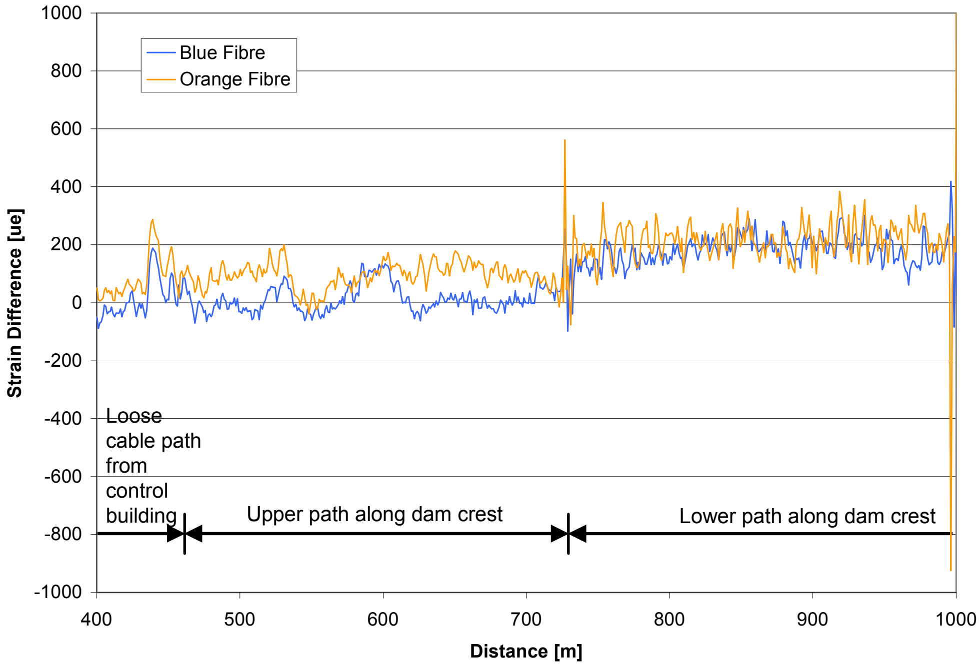


Figure 18 – Difference in strain measurements from September 2004 to May 2005

The results indicated that generally that 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 9). Most likely a slight change in the physical arrangement of the fibre in that area is resulting in a localised increase in strain.

4.2.3 Temperature Measurements

Temperature data was obtained as part of the strain measurement. This has been compared with the temperature measurements obtained from September. The temperature in the crest has also been calculated using 1D heat conduction and sinusoidal temperature variation as an approximation. Table 4 shows the calculated temperature in the two cable paths for September and May, and compares this with the measured values from the DTSS instrument. Additionally, the difference in temperature between September and May has been calculated for each depth of cable.

Cable	Theoretical			Measured		
	September	May	Difference	September	May	Difference
Upper path, depth 1m	5.91°C	4.82°C	**-1.09°C**	11.12°C	8.23°C	**-2.89°C**
Lower path, 4m depth	4.63°C	-0.24°C	**-4.87°C**	5.12°C	-3.03°C	**-8.15°C**

Table 4 – Theoretical and measured temperatures in Ajaure during September and May

It should be remembered that the temperature measurement in the lower path has been distorted by the excessive losses at the turnaround point. Therefore the absolute temperatures measured by the DTSS may include some temperature error. However, by looking at the temperature difference we get a better idea of whether the measurements agree with the trend predicted by the theory. In this case the DTSS is seeing a larger change in temperature for the two cable sections between the two measurement periods, but the trend agrees with theory. The temperature in May is lower than September in both cases and the deeper cable experiences a greater change in temperature. Improved installation, with lower losses, would increase the accuracy of this temperature measurement.

4.2.4 Visualisation of the measurement data

Figure 19 shows another visualisation of the strain changes in the dam at Ajaure. The colour coded plot of the cable route in the dam depicts the measured strain difference as shown in Figure 18. Red indicates increases in strain in the cable between May and September, whilst blue indicates little change in strain. The localised strain at the entry point into the dam is clearly visible as a short section of red. The lower path is generally redder in colour than the upper path, indicating the increased level of strain changes in the lower path. This is not supported by the result from the inclinometers, which indicates a larger inclination change at the upper level than at the lower level. However, the inclination measured by the inclinometers cannot be directly compared to the measured strain difference, because they are measuring in different planes. Further analysis of how the different measurement data can be combined will be considered during the next phase of this project.

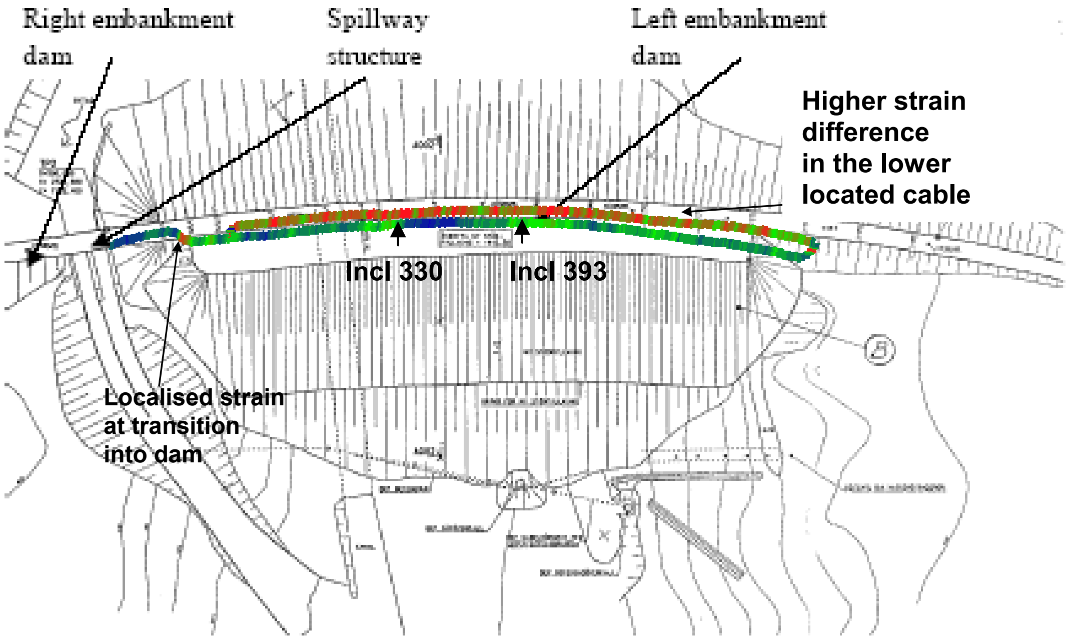


Figure 19 – Visualisation of change in strain at Ajaure between May and September

Combining a plan of the dam with the measured strain changes along the entire cable provides a powerful tool for understanding the relative changes in the dam. Localised movements will be clearly seen, although movements spread over larger areas will be more difficult to detect.

4.2.5 Repeatability

Strain measurements taken at different times during May have been compared again to assess the accuracy of the DTSS instrument. Figure 20 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.

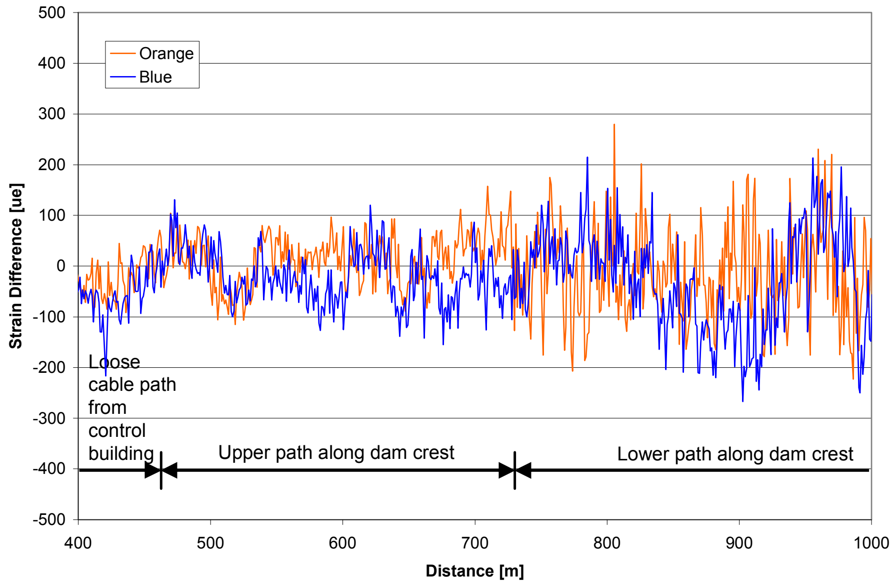


Figure 20 – Strain difference between separate measurements during May

4.2.6 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. Possible some sort of the inline protector might provide a more appropriate solution.

The impact of high bending losses has been 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.

Two further solutions to the temperature inaccuracies associated with high bending losses should also be considered. Firstly a Sensornet DTS unit could be used on the multimode fibres in the cable to achieve a much more accurate measurement of temperature. This could then be used with measurement data from the DTSS to provide a more accurately temperature compensated set of strain measurements. Secondly, an alternative cable design could be used. This other design incorporates a combination of tight and loose fibres. The tight fibres can be used to measure strain, whilst the loose fibres provide a measure of temperature without any strain effects. The measurements from the loose fibre are then used to correct for temperature cross sensitivity in the tight fibre. This type of cable would still only need the DTSS measurements, and has been proposed for installations later this year in another embankment dam.

5 Deflection tests

Whilst undertaking strain measurement at Ajaure, a series of tests were also performed to demonstrate the ability of the DTSS to detect small localized changes in the dam. The purpose of the test was specifically to determine the size of localized displacement in the dam which could be detected by distributed strain measurements.

5.1 Field Test

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 21. 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.

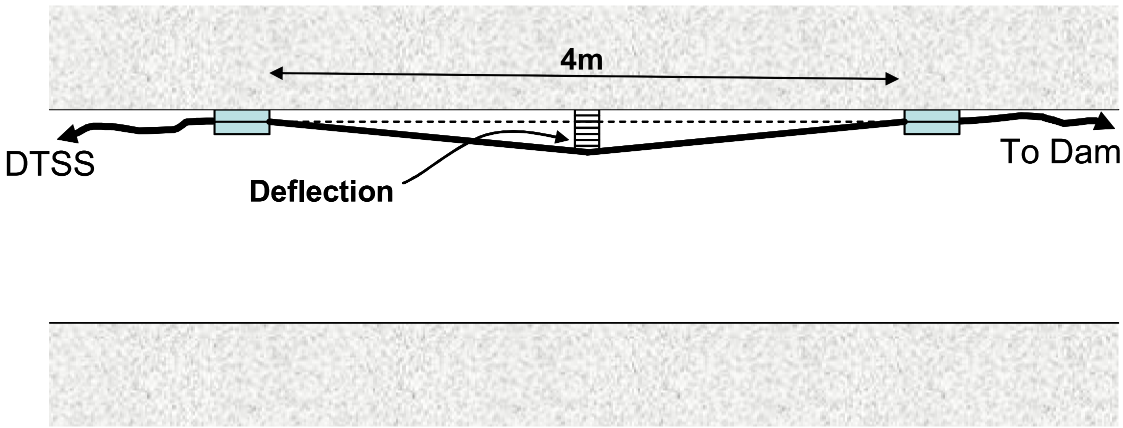


Figure 21 - Deflection experiment arrangement

The measurements were carried out for deflections up to a distance of 40mm. The results of this test are shown in Figure 22.

5.2 Laboratory tests

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 vefiy the field measurements whilst also providing data for a different distance between the clamps.

5.3 Results

The results of all three tests are shown in Figure 22 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.

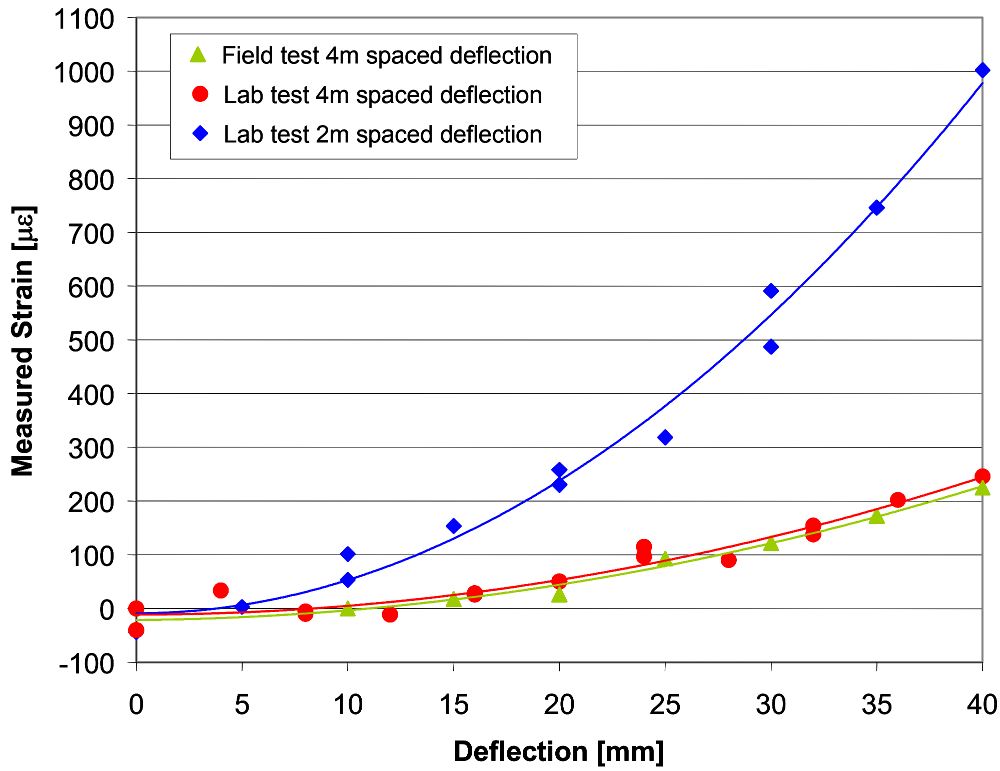


Figure 22 - Measurement results for deflection tests in the field and laboratory.

5.4 Discussion

These tests have demonstrated that a deflection of the dam by just 5mm will be detectable. The Sensornet DTSS has a spatial resolution of 1m, meaning that a measure of strain is provided for every single metre of cable installed in the dam. Hence, small localised movements of the dam can be both detected and located to any position along the installed cable. This will provide important information on the overall performance of a dam at different loads. Eventual weaknesses in the dam structure and long term creeping will also be detected. However, the resolution is currently not fine enough to detect the very small seasonal movement of the crest as measured by the inclinometers.

6 Conclusions

Difference of strain between two measurements performed at low and high pool level has been measured. The measured difference is small and close to the practical monitoring accuracy. The result from the inclinometers indicates also small movements in the upper part of the dam, although the result cannot be compared directly.

These initial measurements clearly demonstrate the potential of distributed strain measurements. The displacement tests have demonstrated that a deflection of the dam by just 5mm will be detectable. Distributed optical sensing will be an essential tool for dam monitoring, providing location specific information which has not been available before. The distributed technology provides an excellent complement to conventional inclinometers.

The current sensitivity of the system is suitable for detecting very small localized changes of the dam structure. However, the sensitivity is set to improve with further development, providing enhanced temperature correction and hence much increased strain accuracy. One possible route to increased sensitivity will be to adopt DTS technology for accurate temperature measurement alongside the DTSS for strain measurement.

Further improvements must however be made on the installation and the cable design to allow a better use of the technology. Such steps will be tested in the next research project, using a new cable design to provide directional information about deformations. Care is needed during installation to avoid excessive losses i.e. at turnaround, which later compromise measurement accuracy. In particular, high losses can result in errors in the absolute measured strain, when compensated for temperature, and therefore should be avoided by good installation practice.

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

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