Utilising Dam Monitoring Technology for Monitoring Structural Behaviour of Foundations

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SUMMARY

Sensornet in conjunction with Cementation Foundations Skanska and the University of Cambridge have installed distributed fibre optic strain and temperature sensors in the foundations of Bankside 123 in London. The purpose of the installation is to monitor the long term structural loading effects on the foundation piles using the latest developments in fibre optic sensing technology.

The sensing instrumentation is referred to as the Distributed Temperature and Strain Sensor (DTSS) which can uniquely measure both the temperature and strain at every 1m along the length of a sensing cable, at distances up to 10km with a strain resolution of less than 10 microstrain.

The advantages of this technology over conventional sensors are that: detailed structural information is obtained throughout the foundations, not just at selected points; it has simpler system integration as there is only one sensing cable; it is a cost effective solution with lower installation costs, as well as lower costs per sensor as the sensing cable can contain up to 10,000 sensing points per cable; the system has high stability as there are no moving parts and the measurements are not affected by electromagnetic interference or vibration.

Sensornet has used developed technology in a number of industries where reliable, repeatable, rugged, durable and lightweight sensors are essential. One such application is for the monitoring of movement in dams and within this paper there will be a detailed example of how this technology has been successfully used in a dam in Sweden.

Keywords: concrete curing, distributed fibre optic sensing, foundation monitoring, pile monitoring, strain sensing, temperature sensing.

Distributed Strain and Temperature Sensing Instrumentation

Sensornet has been in operation since 1998 and has developed a number of fibre optic distributed solutions for structural monitoring for both the oil and gas industry and the dam monitoring industry. This has involved both the development of the opto-electronic instrumentation and the sensing cable.

Distributed sensing takes advantage of the fact that the reflection characteristics of laser light, travelling down an optical fibre, vary with temperature and strain. The sensor consists of a length of cable based on standard telecoms optical fibre, which is housed in a protective cable.

The measuring instrument uses a laser to fire pulses of light into the sensing fibre. A detector measures the reflections from the fibre as the pulse of light travels down its length. Measuring the change in power and colour of these reflections against time allows the instrument to calculate temperature and/or strain at all positions along the fibre. The key feature is that the fibre itself is the sensor and it can be used to measure along its entire length.

Sensornet currently offers a range of measurement instruments, including the Sentinel DTS that can measure temperature to a resolution of 0.01°C over a distance of 10km with a spatial resolution of just 1m (a measure of temperature every 1m). This means that for a 10km length of cable you have the equivalent of 10,000 point sensors. Sensornet also provides the DTSS (Distributed Temperature and Strain Sensor), a pre-production instrument capable of measuring strain to a resolution of 10 $\mu\varepsilon$, independently of temperature, over a distance of 10km again with a spatial resolution of 1m (see Figure 1).

The unique features of the Sensornet DTSS versus other fibre optic sensing systems is the capability of independently measuring strain and temperature at all points along a single length of optical fibre. Other Brillouin based sensors suffer from a temperature and strain cross-sensitivity. Sensornet's DTSS uniquely takes an independent temperature measurement to ensure there is no cross sensitivity. With appropriate cabling, the DTSS can also make fully distributed temperature-independent pressure measurements. The DTSS is optimised for single-ended measurements, needing access to just one end of the optical fibre. The system can also provide dynamic measurements at a frequency of 10 Hz. In addition, for more remote monitoring locations, the system can be controlled and interrogated remotely.

Figure 1: Sensornet's Distributed Temperature and Strain Sensor (DTSS)

Sensing Cable

To complement the instruments, Sensornet developed and tested fibre optic sensing cables specifically for dam installations. The most commonly used cable contains 4 fibres (2 x single mode fibres and 2 x multimode fibres, refer to Figure 2 below) allowing connection to both the Sensornet Sentinel DTS, for very fine resolution temperature monitoring, and to the Sensornet DTSS, for monitoring of strain.

The sensing cable is based around standard telecoms fibre and so is very cost effective, simple (no specialised sensor is required) and long life (telecom components are designed with a 30 year plus lifetime). The key for this sensing cable is that it can both withstand the extreme forces experienced during the compaction of dam construction and still measure the strain and movements within the structure. On this basis and experience the same cable design was installed into the foundations at Bankside 123.

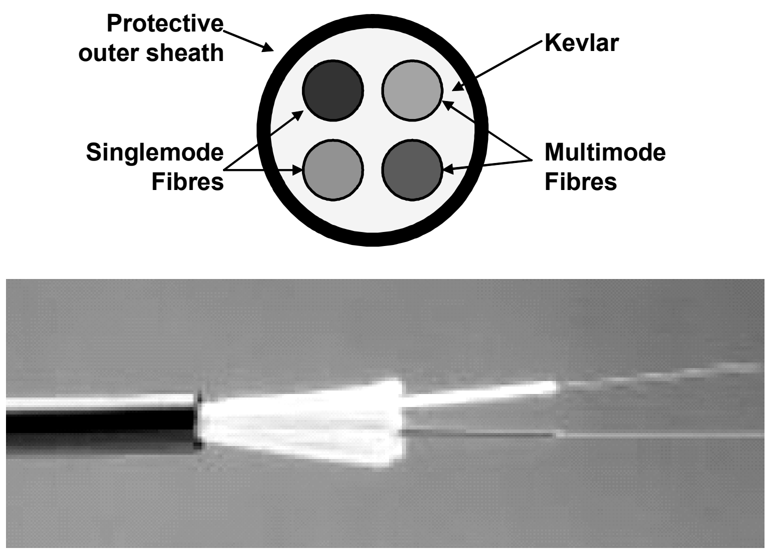

Figure 2: Fibre optic strain sensing cable

The key to the cable’s strength and protection of the fibres is the Kevlar stranding that surrounds the fibre. Because of Kevlar’s unique properties, the cable is rugged, lightweight, flexible and easy to install. Surrounding the Kevlar is a layer of Polyurethane which provides the water blocking layer. During manufacture of the cable this Polyurethane outer sheath is applied under vacuum conditions, which results in the surrounding fibres having a very good mechanical/friction bonding with the fibres. It is this tight friction fit which enables the strain from the outer sheath to be mechanically transmitted to the sensing fibres and enables the cable to measure strain.

TECHNOLOGY TRANSFER FROM THE DAM MONITORING INDUSTRY

Dam Monitoring using DTSS

Since 1999 HydroResearch Sam Johansson AB Ltd and Sensornet Ltd have installed optical fibres in sixteen embankment dams in Sweden, using different installation techniques depending on the dam. These include: embedding of the fibre inside the dam (at new constructions); in the crest during raising of a dam; within new toe berms at upgrading work and just downstream of the dam toe or vertically in standpipes. Once the fibre is installed, seepage and movement can be measured as periodically or continuously as is required.

An example of distributed measurement of strain in an embankment dam at Vattenfall-Vattenkraft's Ajaure dam in Sweden is described below (see Figure 3). The aim was to compare the measurements taken during September 2004, at full reservoir level, with measurements to be taken in spring at low reservoir level. A comparison of the two measurements will show the change in deflection of the dam caused by the different reservoir water levels.

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, a total length of 1122.5m with an effective monitoring length of 320m on each level within the dam crest, was installed at two levels along the dam in order to detect movements between the inclinometers.

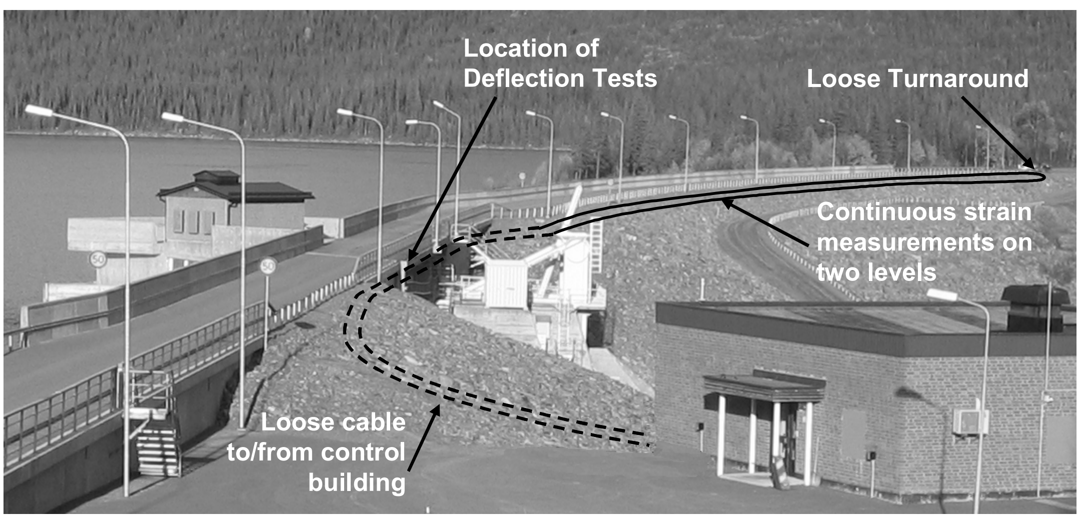

Figure 3: Installation of cable within dam crest

The first strain measurements taken during September are shown below in Figure 4 for the upper cable path.

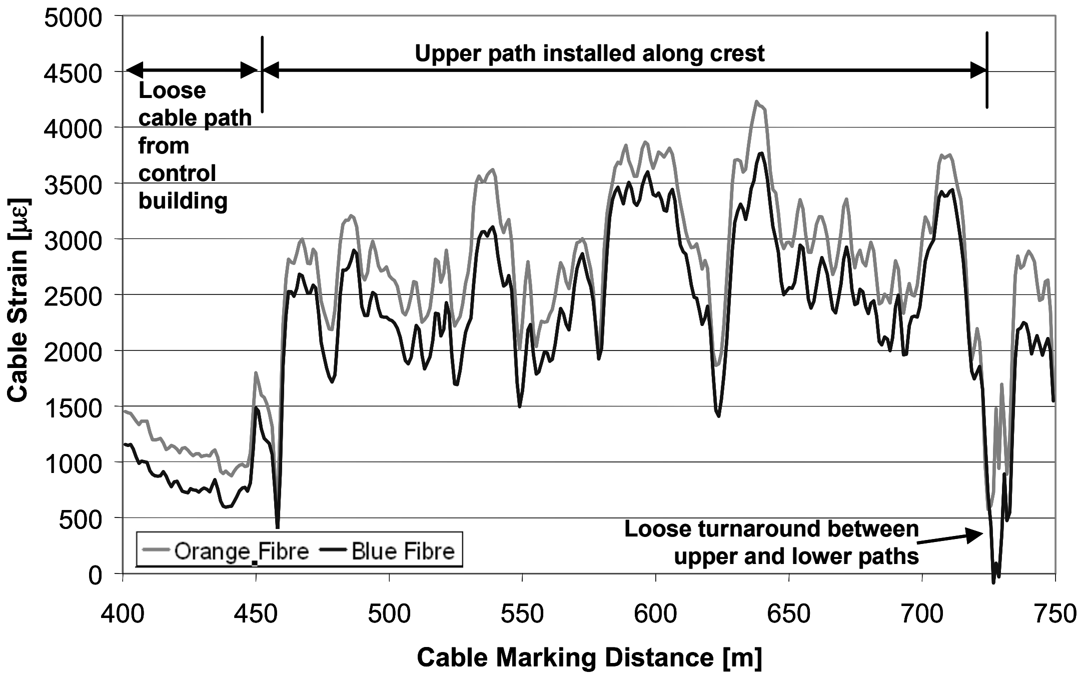

Figure 4:Measured strain of cable with distance once installed in dam

There is agreement between the two cables measuring the strain variations measured on the two embedded fibres; any difference between them relates to differences in manufacture and can be corrected for. It should be noted that the measured strain varies considerably along the installed length of cable. This variation arises from the dam construction process, where the soil has been compacted on top of the cable causing strain variations in the cable. However, these variations cause no problem since this set of measurements will act as a reference to which future measurements will be compared.

The Sensornet DTSS is capable of resolving changes as small as 10 με in every metre of a 10km fibre cable. To complement these first measurements of the installed cable, an experiment was performed where the cable where was clamped at 4m and 2m separation points. The cable between these points was then deflected using a series of spacers as shown in Figure 5.

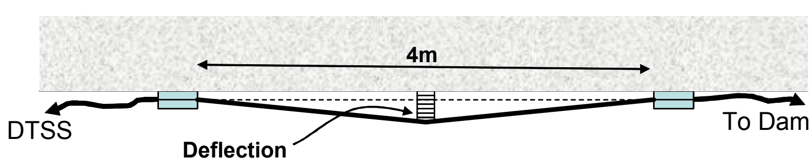

Figure 5: Showing deflection on cable created with spacers

The results of this test and a similar field comparison are show in Figure 6 below.

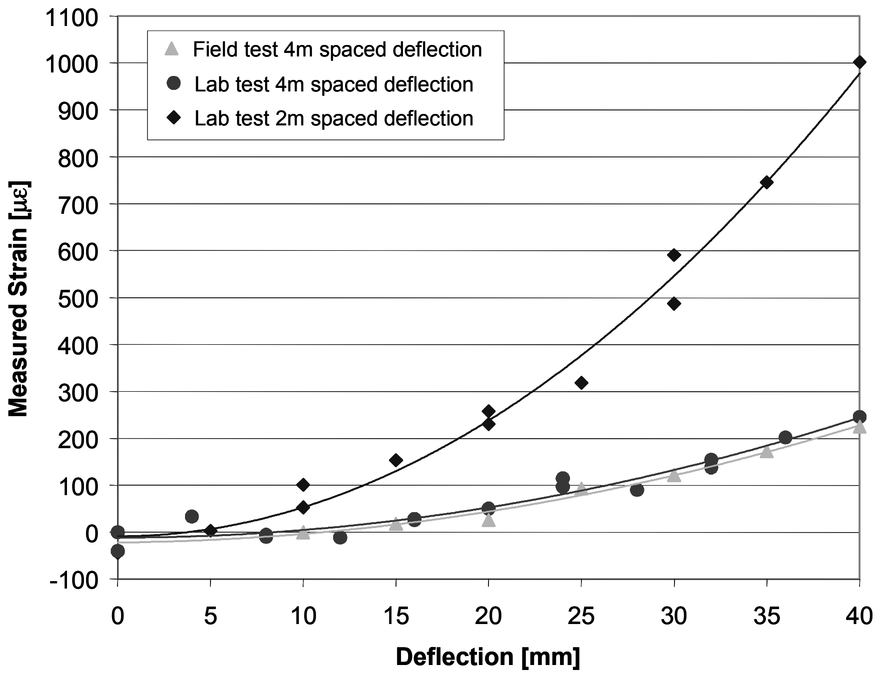

Figure 6: Measurement results demonstrating agreement between laboratory and field results

A quadratic trend line has been fitted to the data, 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 behavior of the cable, since it is effectively clamped at very small intervals due to the surrounding material of the dam.

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 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 will also be detected.

In addition to the Ajuare dam, Sensornet and HydroResearch have installed cables in 16 dams in Sweden and it is this installation and sensing experience that Sensornet brought to the foundation monitoring project at Banskide 123.

FOUNDATION MONITORING AT BANKSIDE 123

Installation Details

In September 2004 in conjunction with Cementation Foundations Skanska and University of Cambridge – Sensornet installed a fibre optic strain sensor into the foundation piles during the construction phase of Bankside 123, a major new London development. The installation was carried out as part of the RuFUS program (Re-use of Foundations for Urban Sites) and the aim of the testing was twofold.

- To analyse the loading effects on the piles once the building is constructed.
- To investigate the long term strain and stress effects in foundation piles and whether the foundations can be re-used.

The aim of this trial is to investigate the possibility of extending the lifetime of the building foundations. At present modern office buildings in London typically have a 30-year lifetime before being replaced. The cost of the foundations is a major part of the overall project and so if the foundations can be re-used, this can present a major saving.

The technology used for structural monitoring of piles at present are vibrating wire sensors, however there are concerns over the long term drift of such sensors and also the increased complexity and cost of having to install numerous cables and sensors in the case of vibrating wire sensors versus one cable for the DTSS. For this installation both vibrating wires and fibre optics sensors were installed (see Figure 7).

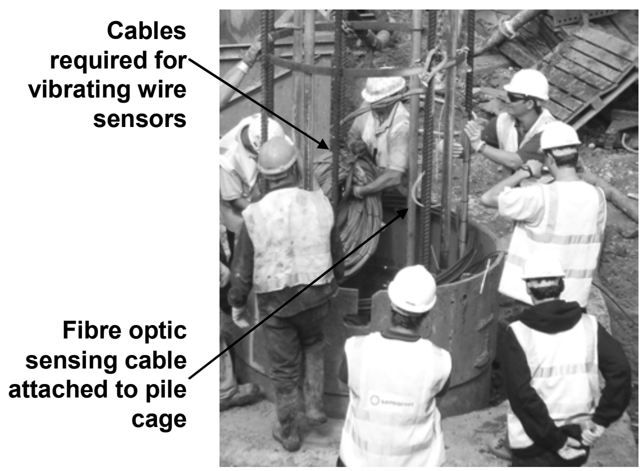

Figure 7: Installation of fibre optic sensors in pile re-enforcement cage

The fibre optic sensing cable was attached to the re-enforcement bars of the pile cage and was run longitudinally along the length of the cages (refer to Figure 8). The total length of the sensing cable profile along the cages was 35m. The cables were pre-stressed and then attached to the pile cage using epoxy cement.

Figure 8: Fibre bonded to pile cage

Thermal Profile of Concrete Curing

Although the primary purpose for the installation is for long-term structural monitoring of the foundations. There are a number of shorter term effects which can be useful to monitor. One such application of this technology is the ability to measure the temperature profile of the concrete as it cures. Depending on the heat distribution during curing and the absolute maximum temperature you are able to analyse the quality of the curing.

Figure 9 shown below is an example of the Sensornet thermal mapping visualisation software throughout a 180 minute period. The display shows how the temperature profile in the pile changes as the concrete is poured in.

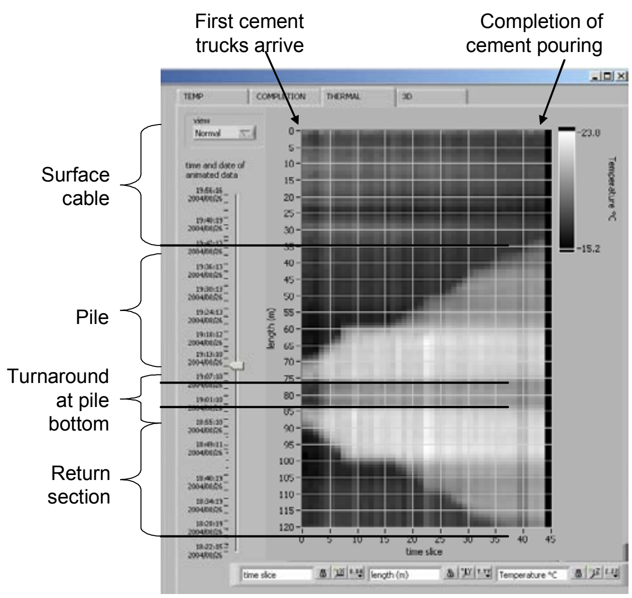

Figure 9: Thermal profile during cement pouring

The vertical axis represents the length along the pile cage, the horizontal axis the progression in time and the colour of the data points is proportional to the temperature – with light grey representing the hottest temperature and dark grey the coldest. What you can see in the diagram above is two separate pouring session of concrete, with the first filling at a warmer temperature of 23°C and the second batch at 19°C.

Strain Measurement

The strain measurement was taken both before the concrete was poured in and also at various intervals during the pouring process. As can be seen in Figure 10 the strain can seen to be increasing as the concrete level rises. This increase in strain shows that the cable is sensitive enough to measure changes in strain.

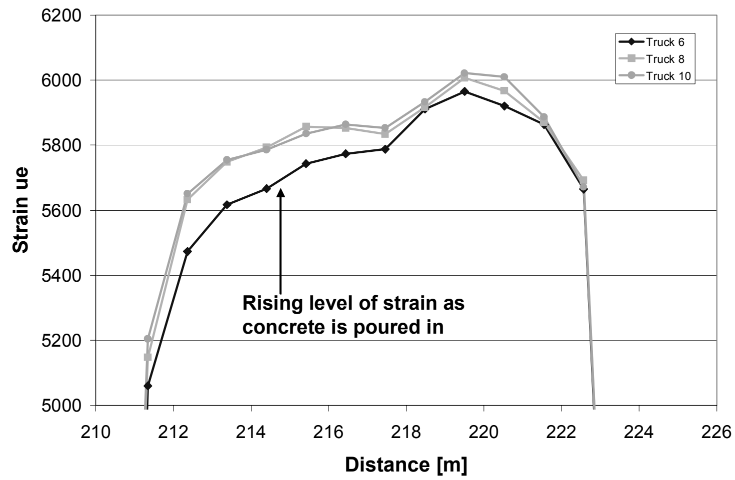

Figure 10: Increasing strain as concrete is poured

Once the concrete was fully hardened a final strain trace was taken (see Figure 11). This data proves that the cable was robust enough for this type of installation (other sensing cables that were tested failed during the installation) and will form the benchmark trace from which any changes in strain will be measured.

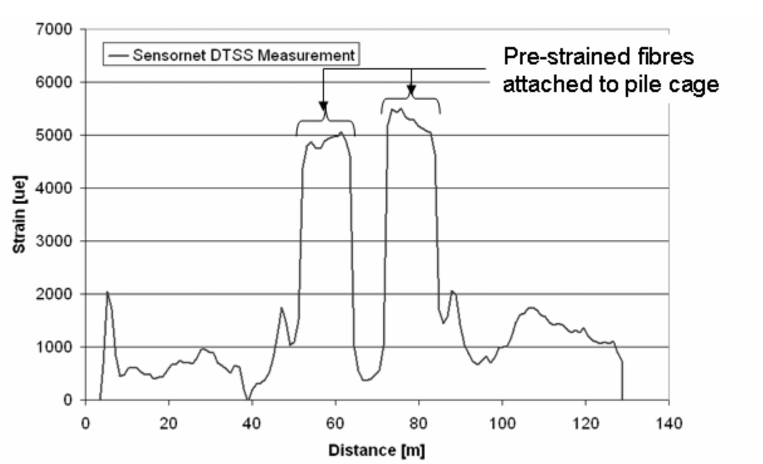

Figure 11: Strain in cable post-installation

CONCLUSION

The distributed fibre optic sensing technology proved successful in the structural monitoring of foundations on two counts. Firstly the sensing cable was robust enough to survive being embedded in a concrete foundation and was very simple to install in comparison to the numerous point sensors that would be required to replace these sensors. Secondly the cable was obviously sensitive enough to detect strain changes – and it clearly showed this during the pouring of the cement.

The initial strain reading of the foundations has been taken and once the building has been completed, further measurements will be recorded throughout the life of the building and thus a picture of the structural health of the foundations can be compiled.

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