ABSTRACT

In this work the suitability of fibre-optic methods in the monitoring of an earth dam was tested. The purpose of the work was to obtain information on the water flow inside a soil structure and to measure the temperature distribution of an old earth dam during thawing using a fibre-optic system based on the Raman backscatter technique.

1 INTRODUCTION

During floods, earth dams are under the greatest stress, and their shoulder parts are at their weakest due to rain or frost. Especially in these kinds of extreme weather conditions, the observation of earth dams and spillways should be increased in order to ascertain the safety of the dams.

Statutory dam safety monitoring puts pressure on the creation of monitoring systems that require less and less manpower. To this end, fibre-optic measuring systems are potential new methods. The attractiveness of these monitoring methods lies in the advantageous price of optical fibre, the possibility to use the fibre as a measuring sensor of hundreds of metres in length, and the possibility to implement the monitoring automatically either as a continuously operating solution or, e.g., a method that gives an alarm signal.
This paper presents experimental results that demonstrate the usability of a distributed fibre-optic temperature measurement system in monitoring an earth dam. Optical fibres were installed in two different test sites. The first one was a soil material test structure where the purpose was to obtain information on the water flow inside the test structure. The second site was an old earth dam where optical cables were installed in order to measure the temperature distribution during thawing.

2 MEASUREMENT METHOD

A distributed fibre-optic system consists of an optical fibre for temperature sensing and a measuring unit. A short laser pulse is sent into the sensing fibre. As a result of spontaneous Raman scattering, some anti-Stokes and Stokes photons are generated along the fibre. A fraction of these scattered photons is captured in guided modes of the fibre and then propagated back and detected by a fast photodetector.

The generation of Stokes photons involves the creation of optical photons, which is slightly temperature sensitive. On the other hand, the generation of anti-Stokes photons involves the annihilation of photons. Since photon distribution is temperature dependent, the number of anti-Stokes photons is very temperature sensitive.

By measuring the signal received at differing times after the pulse is sent and relating this to the speed of light, it is possible to identify which part of the fibre the backscattered light came from (Fig 1).

![Operation principle of a fibre optic temperature sensor.](image_url)

3 SOIL TEST AND FIBRE-OPTIC MONITORING

When studying the soil material of the earth dam to be built in Northern Finland, it was found out that there was enough moraine material needed for the building of the dam in the vicinity of the construction site. However, finding filter material with properties that meet the standard values, which is important in respect of the functioning of earth dams, has turned out to be a problem. There are gravel and sand formations in the area, but for the majority, their fine aggregate content (d < # 0.06 mm) has been found to be too high in view of the general filter structure criteria. The high fine-aggregate content also means that the water permeability of the materials is insufficient to dry the amount of water that is filtered through the compaction part.
A test structure was designed to test the functioning of the soil structures. The tests were performed during unfrozen periods in 1998, 1999 and 2000. A cross-section of the test structure under water pressure can be seen in Fig. 2 a). The objective of the tests carried out in this structure was to determine the actual mutual functioning of local materials and the possible use of various synthetic materials in the filter structures.

The suitability of fibre-optic methods in the constant monitoring of an earth dam was tested the first time in 1999. The purpose was to obtain information on the water flow inside the test structure.  

### 3.1 Installation of an optical sensor

The water flow inside the soil test structure was indirectly observed by measuring the water-induced temperature distribution of the soil layers with an optical sensor cable. To better illustrate water migration it was decided to heat the water used in the test.

An optical cable was installed in four layers in the soil structure that had been compacted in layers. The total length of the sensor cable was over 350 m. In each layer, there were about 10 metres of cable (Fig 2b). The total length of the cable installed in the soil structure was 48 m (269 m to 317 m). The position of the cable was documented at every one-meter distance during installation.

Fig. 2       a) A cross-section of the test structures, and b) An optical cable installed in four different layers in the soil structure.
3.2 Measurement results

The temperature measurement took place from 16–26 September 1999 and information was collected at 20–minute intervals.

The water pressure test started on 20 September 1999. The first detected changes in the temperature took place on 21 September 1999 at about 3:30 a.m. in the range of about 302 and 303 metres. At about 6 p.m. of the same day, temperature changes were also detected at points 282 m and 283 m (Fig 3).

Warm water entered the soil first at a point that was at a height of about 1 m (corresponding to the 3rd installation layer), and viewed from the filter side on the left-hand edge. In the afternoon, the water drained to the front edge of the second layer on the left-hand side (Fig 2 and Fig 3).

The total length of the cable installed in the soil structure was 48 m (from 269 m to 317 m). The first detected changes in the temperature took place on 21 September 1999 at about 3:30 a.m. in the range of 302 and 303 metres.
It can be seen in the measurement data that the temperature continues to spread evenly, first through the front edge of the third installation layer to the front edge of the fourth layer (about 1.5 m high) and to the left-hand side of the layer. At about the same time, also the front edge of the second and first layer is warmed up. It is also noteworthy that the fibre hardly warms up in the range 287–297 m, 268–277 m and 310–318 m. This probably means that the water cannot get to the fibre sides of the first, second, and third layers. If the test had continued further, the water would evidently have warmed the filter side of the fourth layer, because the temperature rise in the fibre from 308 m onwards was significant compared with the temperature of the rest of the fibre.

3.3 Conclusions on the soil test

The temperature distribution obtained from the optical fibre showed that in the soil test structure there was an area near the edges that permeates water significantly better than the rest of the area, although efforts have been made to make it smaller with surface roughing. The greater permeability is caused, in addition to the interface, because the waterproofing in the edge area cannot be as efficient as elsewhere. It can be estimated that about 80% of the water that penetrated the test structure comes from both edge zones (1/3 of the chute width). The greater water permeability of the edge zones can be detected in some measurements carried out on the surface of the test structure during the tests. However, there are some fluctuations in the measurements, and in some tests it seems that only the other edge was clearly more permeable in the middle section.

4 MONITORING OF OLD DAM WITH FIBRE-OPTIC SENSOR

Optical cables were installed in an old earth dam situated in the Northern Finland in order to measure the temperature distribution of the dam structure during thawing. Another purpose of the measurement was to ascertain the changes in the water flow inside the dam structure at different times of year.

In the autumn, six almost 20-m-deep holes with a diameter of about 20 cm were drilled into the earth dam structure of the hydro power plant directly from the surface of the earth dam all the way down to the bedrock. Three holes were drilled on the poolside edge of the road on top of the dam and three on the sluice river edge symmetrically, see Figure 4.
An optical cable was installed in each of the six holes. The holes were filled alternately to make water permeable and impermeable layers. The total length of each cable installed into the holes was about 20 m.

The cable used was NK Cables’ underground cable, which, due to its strong cable clamp, was estimated to withstand the strain required by the installation work, water and frost. Shrink stoppers were installed in the cut end of the cable to protect the fibres.

The cables were installed into the holes, and the holes were filled alternately to make water permeable and impermeable layers. The cables were led to the nearest cable chute leading to the dam gate control house next to the road on top of the dam.

4.1 Temperature measurements

When the cables had been led to the terminal boxes, an installation inspection and temperature signal positioning measurement were carried out. The purpose was to measure the fibres in the cable using the so-called "cut-off fibre measurement" principle, because the cables ended on the bottom of the drill-holes. The equipment usually carries out the measurement as a loop, so by combining the cables suitably, it is possible to measure all the cables simultaneously. The cables that were installed symmetrically on the opposite sides of the road were chosen as the measurement pairs (measurement loop). Cables 1 and 4 were in the drill-holes at a distance of about 2.5 m from the concrete wall. Cables 2 and 5 were at a distance of 2.5 m from cables 1 and 4, and cables 3 and 6 were at a distance of about 10 m from cables 1 and 4.
The measurements were continued during the winter and spring. The first measurement was taken at the end of 1999. After that, there was one more wintertime measurement and a continuous measurement that was carried out in the spring (April-June) at the time the snow was melting (Fig 5).

Fig. 5  The temperature distribution of the earth dam (cables 1 and 4)
9 September 1999, 27 January, 2 March, 6 April and 4 July 2000. Cables 1 and 4 were symmetrically installed on the opposite sides of the road and were chosen as the measurement pairs (measurement loop). The total length of each cable installed in the holes was about 20 m.

5 CONCLUSIONS

The results obtained in this work indicated that fibre-optic temperature measurement is suitable for testing the functioning of earth dam structures and the long-term monitoring of a dam. This method is particularly suitable for northern dams, as in the north the varying seasons result in extensive temperature differences between soil structures and water. The temperature measurements made it possible to monitor water flow inside the soil structures and the thawing of ground frost.

The temperature measurements taken in the first year in the old earth dam do not confirm or eliminate the possible risk of dam core erosion due to freezing and thawing near the concrete structure (the winter was not particularly severe), but they indicate that the rock foundation downstream can be frozen at least below the downstream shoulder. However, it seems more probable that the springtime groundwater well fluctuations are due to periodical changes in fissure permeability, rather than due to moraine erosion in the concrete contact.