DFOT monitoring in CFRDs – Technical gimmick or useful complementary monitoring system?

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Abstract: Temperature measurements have been used for different purposes in geotechnical and hydraulic engineering for more than 50 years now. Nowadays distributed fibre optic temperature measurements for leakage detection are conducted in numerous projects throughout the world. The paper shows on the basis of reference projects the possibilities and advantages if distributed fibre optical temperature measurements are employed as a complementary monitoring system in CFRDs. The experience gained from numerous projects proves the benefits in terms of reliability, durability and information density of such a complementary monitoring system.

Key words: Leakage detection, distributed fibre optic sensing, innovative monitoring.

1 Introduction

CFRDs are beside RCC dams the most popular dam type at sites with rock foundations and often considered as an option at sites with alluvial deposits. Generally CFRDs behave safely even with large leakage. According to [1] failure due to throughflow is limited to a single case: the Gouhow Dam, a concrete face sand gravel dam [2]. Even though CFRDs are relatively insensitive against distinct seepage flow a large number of design and construction efforts aim at improving the water tightness of the sealing element. Especially the joints always imply an elevated risk of leakage. According to experience, due to settlement of the embankment fill and the contraction of the concrete, the perimetric joint can be burdened with tensile stress at the bottom of the valley, which can lead to an opening of the joint and increased seepage water flow. Besides, all other joints of the concrete facing have a risk of leakage. In the past even rupture of the concrete slab has occurred due to compressive stresses that developed between vertical joints after settlement of the embankment fill. This possible damage spots lead to an increase of seepage water flow and can not be tolerated unlimited. All rehabilitation steps aiming to minimize leakage water flow can be done more efficiently if leakage can be located exactly. Distributed fibre optic temperature measurements offer a well suited and economic method for exact leakage detection and locating with a high spatial resolution.

2 Water tightness of the face slab and the perimetric joint

Water tightness of a CFRD is provided by the external concrete layer consisting of reinforced concrete slabs, which are placed on a transition layer. Along the vertical joints typically two lines of water barriers are used for the water stop system and along the perimetric joint between the plinth and the concrete slab three lines of water barriers are installed. Fissures due to concrete shrinkage and thermal induced stresses or deformations smaller than 0.3 mm generally have no effect on the slab performance of CFRDs and can be tolerated without any treatment [1]. Cracks that occur during the construction phase can be easily surveyed and treated. Most of the observed leakage is because of cracks in the concrete face or failure of the waterstop system provoked by deformations of the face slap and the fill under reservoir loading. Table 1 gives an overview of reported leakage in CFRDs. The measured flows may not include all flow through the dam and the foundation since most probably some of the leakage will not be captured. Additionally it is not possible to gather information on the origin of leakage water from the measuring data, since in CFRDs separate measurements of leakage through the foundation and the face slab are not available with conventional monitoring systems. However, the values give an indication of the functionality of the sealing element. [1] estimated the portion of leakage through the foundation on the basis of flow measurements in the foundation of concrete dams and concluded that flow through the rock foundation would seldomly exceed 50 to 100 l/s. This leads to the assumption that in CFRDs with larger leakage some cracks in the concrete slab or defects in joints have occurred.

As a consequence of high leakage at the Paradela Dam in Portugal a continuous sealing membrane covering the whole upstream face has been placed. Further examples of CFRDs where geotextile membranes have been placed to restore the watertightness of the face slab are Midtbotnvatn (Norway), Ruchain (France), Salt Springs and Strawberry (both USA) [3]. At Golillas Dam water was seeping through the slab joint and the foundation. Even though the reservoir was lowered and the presumed defects were treated, the causes for the leakage are still unknown. At Barra Grande and Campos Novos ruptures of the face slab along vertical joints occurred during reservoir impounding and resulted in leakage of more than 1300 l/s. In order to reduce the leakage extensive structural repair works at the concrete slab have been conducted. However only at Barra Grande leakage could be reduced to 600 l/s after dumping silty sand material from the crest over damaged areas. At Campos Novos no significant reduction of leakage took place after the repair works and the placement of silty material, so that finally the reservoir was emptied through the diversion tunnel to show the extend of the damages and to facilitate the required repair works. At TSQ 1 similar failure along the vertical joint of the central face slabs occurred three years after impounding of the reservoir. But in this case no significant leakage has been reported after this rupture. At many CFRDs the reduction of leakage over time is attributed to silting phenomena.

Table 1: Reported leakage in CFRDs after [1]

Dam	Country	Completion date	Foundation	Rockfill material	Height H (m)	Crest length (m)	Leakage l/s
Paradela	Portugal	1955	Granite	Granite	112	600	1750/25*
Cethana	Australia	1971	Riolite	Quartz	110	213	7/7*
A. Anchicaya	Colombia	1974	Schist	Diurite	140	240	1000/400*
Bailey	USA	1979	Sandstone	Sandstone	95	550	300/30*
Foz do Areia	Brazil	1980	Basalt	Basalt	160	828	260/60*
Salvagina	Colombia	1984	Sandstone	Gravel	148	350	60/60*
Golillas	Colombia	1994	Sandstone	Gravel	125	120	1080/200*
Shirodo	Nigeria	1984	Granite	Granite	130	1400	1700/100*
Chengping	China	1989	Volcanic tuff	-	75	232	70/10*
Zhushoquiao	China	1990	Slate-limestone	Slate-limestone	78	245	2500*
Xibeikou	China	1990	Karst-limestone	Karst-limestone	95	222	1700*
Aguamilpa	Mexico	1993	Riodasite	Gravel-rockfill	187	660	260/150*
Segredo	Brazil	1993	Basalt	Basalt	145	720	390/45*
Xingo	Brazil	1994	Gneiss	Gneiss	140	850	200/100*
Xiaoshan	China	1998	Andesite	Andesit	86	295	300*
Ita	Brazil	1999	Basalt	Basalt	125	881	1700*
TSQ 1	China	1999	Limestone	Limestone	178	1137	120*
Machadinho	Brazil	2002	Basalt	Basalt	125	700	900*
Itapebi	Brazil	2003	Granite-gneiss	Gneiss	120	583	902*
Hongijadu	China	2004	Limestone	Limestone	180	465	28*
Barra Grande	Brazil	2005	Basalt	Basalt	185	666	1300*
Campos Novos	Brazil	2005	Basalt	Basalt	202	592	1300*

* residual flow

The study of leakage measurements in several CFRDs shows that leakage is caused by several phenomena, ranging from karstic foundation to cracks in the face slab or defects in the water stop system. Generally conventional seepage monitoring systems give only an overall impression on the amount of leakage water and do not provide information on the source of leakage water. Detailed information on the intactness of the face slab is only obtained by visual inspection or underwater inspection by divers or remotely operated vehicles (R. O. V.). Therefore to obtain more detailed information on watertightness of the face slab and the water-stop system at the joints, it would be appropriate to install a leakage detection system based on distributed fibre optic temperature measurements complementary to the seepage monitoring system.

3 Leakage detection and locating system

3.1 General

In hydraulic structures, specifically in embankment dams and dikes, the internal temperature field is a function of the flow field. External temperature variations propagate within the dam body by means of conductive and convective heat transport processes, influencing the internal temperature distribution. This close interaction between the flow field and the temperature field allows using temperature as an easily measurable parameter to detect variations in the seepage pattern ([4], [5], [6]). Distributed fibreoptic temperature (DFOT) measurements allow comprehensive temperature monitoring and consequently comprehensive leakage detection [7].

3.2 Distributed temperature measurements using optical fibres

DFOT measurement is based on the temperature-sensitive properties of the fibre. Normally a standard telecom optical fibre which is housed in a protective cable is used. By means of a laser, an optical signal is sent into the fibre and is reflected with low intensity at every point of the fibre. A certain range of the back scattered light, which is directly correlated with the temperature, can be extracted by using frequency analysis. The distance x_i from the measured point to the light source can be estimated by the runtime of the laser. The resulting measured temperature values reach an accuracy of up to ± 0.1 °C and a spatial resolution of ± 0.25 m. The measurement length of standard devices is up to 10 km. The monitoring system is typically implemented by two major approaches: the gradient method (passive method), which uses temperature as a tracer to detect anomalies in the flow pattern, and the heat-up method (active method) describing presence and movement of water in soil by evaluating the thermal response caused by the heat pulse.

3.3 The heat-up method

The method requires an adequate distributed heat input along the cable for a certain time interval. A.C. or D.C. voltage produces the required linear heat input if applied to the copper wires integrated in a heat-up cable. The heat-up method exclusively evaluates the temperature difference between the reference stage before the heating is started and the heated stage. The temperature increase in the cable depends on the thermal properties of its surroundings. In the absence of seepage around the cable, the temperature increase is dominated by conduction. Dry and saturated conditions can be differentiated. If the relation between the water content and the thermal conductivity of the surrounding material is known, the moist content can be estimated by the Heat-up Method. In case of seepage around the cable, the conductive heat transport is surpassed by the more effective convective heat transport. The heat input from the cable is therefore transported away more quickly and a steady temperature state is reached. Consequently, the sections with seepage water flow show a much smaller temperature increase than those without.

3.4 Design and installation

Like with all monitoring systems the installation of the sensor is a crucial point regarding the functionality of the whole system. Losses caused by damage during construction or due to improper design may severely disturb the measuring results. Therefore it is important to adjust the cable layout to the way of construction and the construction equipment used, so that the cable can be installed easily, without interference of the construction process. Any damages of the cable or unnecessary fibre splices are avoided. The design of the cable should be chosen that it will meet requirements of the monitoring system in terms of durability, strength, redundancy and heat input. For data interpretation and presentation it is essential, that the cable location is known at specific points, so that the measured temperature along the cable can be related to the actual location of the cable in the dam structure. Therefore a durable and easily visible length marking should be stamped on the cable coating and the position of the cable should be surveyed in regular intervals and at every turnaround. To avoid damages the cable should not be placed directly in crushed material. It is recommended to use some cushion material around the cable which has similar hydraulic properties to the surrounding material.

4 Typical applications

4.1 Monitoring of face slab

Generally the leakage detection system can monitor the watertightness of the whole concrete slab. However in most cases it is sufficient to concentrate on areas where cracks may occur most likely. Exemplarily the layout and results of a system installed to monitor a surface sealing is shown. The Ohra dam (Germany) is a 60 m high embankment dam with an asphalt surface sealing. Increased leakage indicated deterioration of the existing sealing layer. In particular a 30 m long and in parts several centimeters wide crack was detected at the transition region to the right abutment. In order to guarantee the serviceability of the surface sealing in the long term, a new asphalt sealing layer has been placed on top of the existing one. For advanced monitoring of the critical area close to the right abutment a complementary leakage detection system based on DFOT measurements has been installed. A 30 m wide and 110 m long section is monitored by an approximately 720 m long fibre optic cable which is placed in 21 loops with a distance of 5.60 m between the loops (Figure 1).
Artificial leakage of various intensities has been applied in order to check the functionality of the system. For that reason a tank wagon has been positioned at the dam crest and has been connected to the intended infiltration openings. The inflow has been varied between 0.01 l/s and 0.05 l/s. On the basis of the measuring results the progression of the infiltration can be followed easily (Figure 1 right). Also significant is the dependence of the resulting abnormality of increase of temperature from the intensity of the leakage flow. Additionally it has been shown that even leaks with small inflow (0.02 l/s) can be detected.

4.2 Monitoring of joints

A further field of application is the monitoring of joints. In CFRDs the perimeter joint is the critical point in terms of infiltration, because it is where the main leaks happen. Its movement is three dimensional caused by the fact that the plinth is anchored to the foundation rock and the concrete slabs of the face rest on the compressible rockfill. The installation of fibre optic heat-up cables to monitor this joint is a highly efficient application of the leakage detection system. The cable is installed on the mortar bed below the bottom copper water stop (Figure 2).

A DFOT leakage detection system to monitor the plinth is installed at the Merowe CFRD in Sudan [8]. Similar systems will also be installed at the Siah Bishe CFRDs in Iran, the Kalivac CFRD in Albania and the Nam Ngung 2 CFRD in Laos [9].

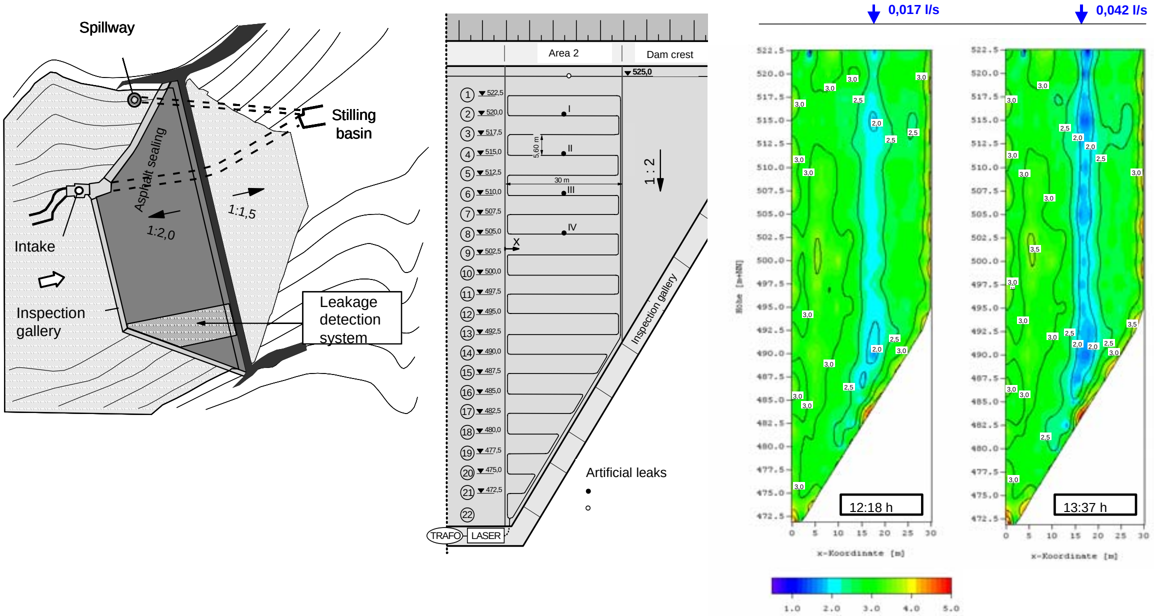

Figure 1. Leakage detection system at Ohra Dam

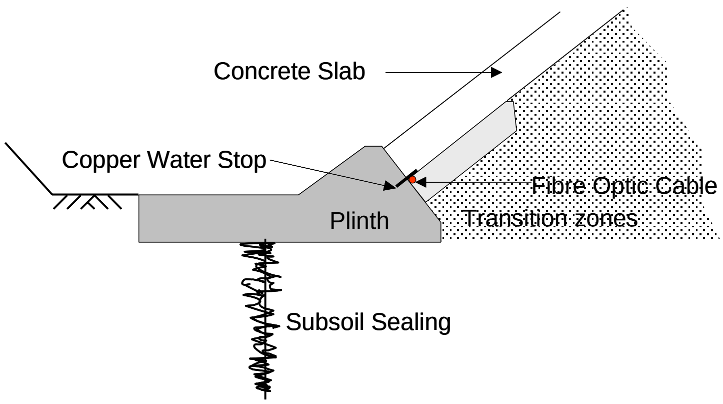

Figure 2. Location of fibre optic cable at the perimetric joint

The gain in information of the leakage detection system for monitoring the perimeter joint can be shown best on the basis of the monitoring data of the Midlands Dam in Mauritius. The 30 m high and 2450 m long dam with an asphaltic concrete facing is founded on clayey soil with sand lenses and boulders. Sealing of the foundation is achieved by a cut-off wall. A total of 2,850 m of fibre optic cable were installed to monitor the connection of the cut-off wall with the asphaltic concrete facing. After impounding the reservoir, seepage water was pouring out of several drainage outlets. The results of the performed fibre optical temperature measurements to detect the leaks are shown in Figure 3. The temperature differences have been calculated by subtracting the temperature along the cable in the unheated state from the temperatures along the cable measured while heating the cable. The results of the zero measurement with an empty reservoir are displayed as a green line. The results of the measurement after seepage has occurred are shown by the red line. The temperature increase is not uniform along the length of the cable. Locations of significantly lower temperature between position 200 and 250 indicate several leaks in this section. Outside this area leaks can be excluded for the displayed section.

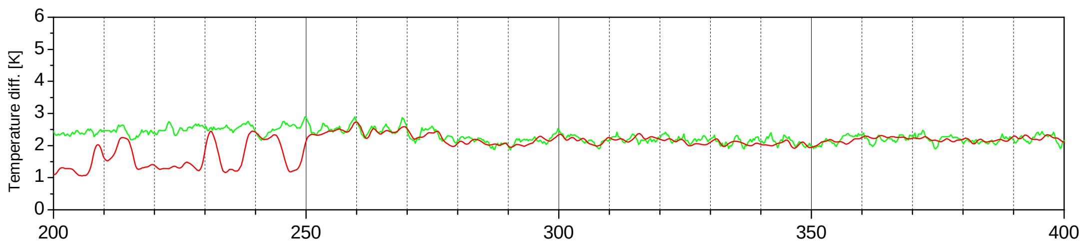

Figure 3. Comparison of temperature increase along a section of the dam (green line: zero measurement / red line: measurement during the appearance of leaks)

4.3 Monitoring of geotextile membranes

Installing an impervious synthetic geomembrane over the upstream face to stop leakage has been applied at ceveral CFRDs. The geomembrane is installed in sheets which are watertightly joint by heat welding. It is anchored at all peripheries generally with mechanchical anchorage, designed to withstand the hydraulic head applied. Fibre optic leakage detection systems to monitor the geomembrane have been applied at several dams. Among others are the Winscar Dam (UK), the upper reservoir of the pumping storage scheme Waldeck I (Germany) and the Kadamparai Dam (India). All installed systems excel as reliable and durable monitoring systems.

5 Research and development

The further development of DFOT measurements for dam monitoring is pushed. Ongoing research projects concentrate on the broadening of the field of application and the increase of measuring accuracy. In the meantime it is possible to measure the filter velocity in soil in a distributed way. So that in addition to the detection of a leak, also an assesment of the intensity is possible. In cooperation with commercial parters the heat-up cables are optimised and possibilities to integrate the sensors in geotextiles are investigated.

6 Conclusions

Distributed fibre optical temperature measurements contain a number of important technological advantages such as high information density, the suitability for rough site conditions and the simple and flexible installation of the cables. Experiences gained by the various projects prove the benefits of distributed fibre optic temperature measurements if used as a complementary system for leakage detection. In particular with CFRDs where an allocation of measured leakage water to different measuring sections and the differentiation between leakage through the foundation and leakage through the dam is more challenging, such a monitoring system will help to find the source of potential leakage. Additionally over the past years the prices for the monitoring system have dropped considerably while the performance has been improved. In conclusion it can be said that it will be difficult to find an argument against installing the leakage detection system complementary to the conventional seepage monitoring system.

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