LEAKAGE DETECTION IN DAM AND RESERVOIR USING OPTICAL FIBER CABLE SENSOR (FOCS) BASED ON ACTIVE METHOD

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Abstract—Internal erosion is one of the main reasons of dams and dikes collapses. Progress of the erosion process is linked to the change of different parameters such as porous medium, especially because of its hydraulic parameters. The goal of this paper is to develop the possibility of leakages detection by fiber optics as well as the identification of the soil moisture according to active method (with heat). This fiber gives the possibility to follow temporally the temperature profile along the dam. Using the innovative monitoring systems which is fiber optic, we one deployed the principal advantage of fiber optic sensor is distributed measurement along their length with fine resolution and over long distance, making it extremely useful for monitoring dikes and dam. So, considering that the principal suitable method for analyzing the acquired data have been developed to serve either as early warning or long or long term monitoring system based on the data from real Site (Yangpeoung Reservoir, South Korea). As well as this paper demonstrate the validation of this technology, the leakage pathology practically based on the detection and the study of qualitative estimation of leakages through embankment dams. The proposed method use natural temperature measurements from the ground using optical fiber under the upstream or downstream face. The model of estimation of quantity of water content used for this paper is the active method developed and tested data from site experimental and a real site.

Keywords- leakage; dams; dikes; FOCS; monitoring; active method

INTRODUCTION

The target of this paper is mainly fiber optic sensor sensors and efficacy of the active method of using fiber optic for detecting the leakage location. Because of the recent increase of extreme weather events leads to growing solicitation of the hydraulic works of flood protection.

With Professor KiTae Chang of Kumoh National Institute of Technology and the Korean company GMG some beacons was providing for using tilt, displacement and telemetry and fiber optic cable. We naturally became responsible for leaks detection and soil moisture location with the fiber optic monitoring system in Nak Dong River and YangPyeong old reservoir.

The disorders affecting the protection hydraulic works are often related to the constitution and in particular to the presence of heterogeneities in the dike body. However, for the old hydraulic construction including - which might not have archives, the materials are sometimes poorly known.

Under the supervision of hydraulic construction, therefore it is necessary to characterize these materials, without putting the hydraulic construction out of service, and with less destructive possibility. Furthermore, the onset of destructive phenomena coincides with the presence of a preferential flow, which is making useful the detection of leaks along the hydraulic construction. We will present the active method of natural temperature measurements from the underground (the upstream or downstream face) through fiber optic. The technique of heating cable used for diagnosis the seepage location.

II. PROCEDURE AND INTEREST TO MONITORING OF MEASURING HYDRAULIC STRUCTURES TECHNOLOGIES DISTRIBUTED BY OPTICAL FIBER

A. General Problematic

Internal erosion, with erosion by overflows, is the main reason of rupture of the dikes and embankment dams. Leakage monitoring is thus a major component plan of the safety of hydraulic structures. The conventional method to perform monitoring of the hydraulic behavior are: Visual inspection portion and the other the auscultation via measurement of drainage flow in the structure (drainage or collectors drains channels) - which are direct measures of leakage - via the piezometric measurements - which can provide indirect information too.

These conventional monitoring techniques are always punctual in space and time, most often they prove incapability of pathologies detection of internal erosion and are generally not able to provide sufficient accurate information in time and space on the localization of leaks and their kinetics of evolution.

![Figure 1: Diagram of a temperature anomaly within a dike leak-related](image-url)
Since several decades ago, thermometry has been proven as one of the most relevant measurement methods to find leaks within earth structures. Based on the difference in temperature between the massif not exposed to the leak, where the temperature is regulated by the phenomenon of the limits of the work imposed heat conduction, and the area leak, where the temperature is regulated by the transport by convection of heat from water leakage (see Figure 1), conventional thermometry is used in phase of reconnaissance on works, by measurements of profiles vertical temperature in boreholes.

III. GENERAL PRINCIPLE OF HYDRAULIC STRUCTURE MONITORING BY MEASUREMENT OF DISTRIBUTED FIBER OPTICS

When sending a light pulse in a fiber optic, the strength and the temperature modify the light retro diffusion all along the fiber. The impact between the core in silica and the envelope in different silica can be measured for Brillouin a frequency shift and for Raman as an amplitude difference. Retro diffusion provides these differences and, knowing the flight speed of the light, gives the location of phenomenon.

From there, it is possible to measure strength and temperatures all along a fiber optic and to determine where the measurements are performed.

This is basically what can be done but from theory to real world there is a big gap, we will consider what can be done and how. Measure is to send a ray of light (laser beam) in a standard optical fiber installed inside a hydraulic fill work. The measuring system consists of fiber and an interrogator optoelectronics. The measuring principle is based on time domain reflectometry resolved in time.

The return signal is analyzed by the interrogator combining wave round-trip time related to the distance from the camera. Backscatter spectrum includes several rays characteristic including (see Fig. 2). From there, it is possible to measure strength and temperatures all along a fiber optic and to determine where the measurements are performed.

- Skate Rayleigh corresponding to the fluctuations in density and composition of silica. It is used in the telecom reflectometers to verify the integrity of optical links;
- Brillouin acousto-optic-related lines depending on the temperature and the deformation of the fiber;
- Stingrays Raman molecular vibrations of silica-related. The two rays stokes and anti-stokes intensity ratio is directly related to the temperature of the fiber.

The use of an optical fiber type multimode allows using the Raman Effect and a measure distributed temperature along this. The Optic-electronic interrogators available on the market allow obtaining a measurement of temperature all meters for a range 10 km to 30 km. The accuracy of the temperature measurement is 0.1 °C, but it degrades to the upper 10 km reaches (values of this degradation of accuracy beyond 10 km are not yet well known lack sufficient experience feedback). The time of acquisition of the measurements by step may vary from one measurement every 10 minutes to one measurement per year or even less.

Two different methods can be used for monitoring leaks by fiber optic measurement: the passive method and the method of heating, also called active method. The use of a fiber optic Single model allows using the Brillouin effect is: Combining the same fiber within optic cable multi-mode allowing an independent measurement of temperature by Raman Effect and can deduct the measurements of fiber’s deformation in the axis this one, expressed in macrostrain (µε, or µm/m).

The calculation of deformation is performed from the following relationship:

$$\Delta V_{FO} = \frac{c_{FO} \times \varepsilon_{FO} + C_{TFO} \times \Delta T_{FO}}{1}$$

With:

$$\Delta V_{FO}$$: the frequency shift of Brillouin lines directly measured by the interrogator optic-electronic

$$C_{FO}$$ and $$C_{TFO}$$ parameters of altimeter;

$$\varepsilon_{FO}$$, deformation of the fiber optic;

$$\Delta T_{FO}$$, optical fiber temperature.

To achieve a consistent measurement one needs to be careful. Brillouin method gives both strength and temperature on same fiber optic line. To separate both measurements, one needs to use a fiber sensing strength and a fiber not subjected to strength. Thinking of a loop fiber will allow measuring the way out as strength and way back as temperature (see Fig. 3).
We pointed above pre-strength fiber. If the fiber is coated with silicone or other material, in the lab, Lorentzian motion will be clean but not significant. Reason why to offer a real zero or reference, the fiber must be pre-strengthen. Sheathing the fiber with a metal structure will offer a real reference, enhancing the sensitivity and avoiding zero fluctuations with whatever strength unexpected and with no relation with measurement that could occur.

**B. Principle of the leak monitoring fiber by the Active method**

Heat transfer in a soil column can be described by the diffusion equation,

\[
\frac{\partial T}{\partial t} = D(\theta) \frac{\partial^2 T}{\partial z^2} - k(\theta) \frac{\partial T}{\partial z} = \frac{\partial}{\partial z} \left( \frac{C(\theta)}{\alpha(\theta)} \right) \frac{\partial T}{\partial z} + \frac{1}{\alpha(\theta)} \frac{\partial}{\partial z} \left( \frac{\partial T}{\partial z} \right)
\]  

Where \( D \) is the thermal diffusivity of the soil, it is the ratio of its thermal conductivity \( (k) \) to its thermal capacity \( (C) \). These soil thermal properties are functions of soil moisture, so the objective of this feasibility study was to determine if soil temperature measurement at multiple levels are sufficient to infer soil thermal properties and hence soil moisture. Using an approach similar to that employed by Behagel et al. [2007], soil moisture was estimated by finding the diffusivity which gave the best fit between simulated and observed cable temperature.

This approach is to analyze the acquired raw data of fiber optic temperature measurement from data logger. The Detection of anomalies of the soil from the gross measurements heating temperature value from optical fiber just before during and after heating being generally impossible, so the use of analytical methods, based on a statistical physical approach or on signal processing approaches, is essential to correct and interpret these data. The time required for downloading data and their analysis by an engineer then varies the size of the structure, is between 3h and a full day. Not fully automated data processing is currently envisaged.

To correctly carry out these interpretations, additional measures of air temperature, water upstream of the structure and the water content are generally required. By using this active method for data analysis in Yang pyong old Reservoir graphs from experimental optical fiber showed that the radius of a leak around the optical fiber is located 7 to 9 m and 10 to 12 meters wet zone. Methods of analysis based on the physic-statistic approach require a continuing Chronicle of data on at least 3 to 6 months to be able to provide a diagnosis on the presence or absence of leakage. With this constraint, these methods can be used to monitor the hydraulic behavior in the long term as to generate alerts in case of sudden onset of a change of State. Some signal processing-based methods require that a Chronicle continues a few days of data to be able to provide a diagnosis on the presence or absence of leakage. These methods can then be used as well in the long term for the generation of alerts monitoring (in the latter case, the delay between the measure and its interpretation is in the order of 2 to 3 hours).

Generally, it is necessary to have a wide range of complementary methods to be able to correctly answer all the needs of the monitoring, long-term monitoring terms of the behavior of the work for the…

**C. Leak Detection by the active method (heating)**

These days one of the most effective and promising methods for the identification of leaks in dams and dikes is the method of thermal analysis. Heat transport in the body of the hydraulic structure of the Earth is described by equation of energy (1). The second and the third part of this equation describe respectively the driver transport process and advection of heat. Where the advection process is defined as the heat transfer to the mass of the water fluid.

The method of measurement with heating takes the same basic principles of distributed measurement temperature by optical fiber, using the Raman Effect presented before. The optical fiber is increasingly surrounded by copper cables heated by Joule effect over a short period of time. Electric power to the heater is 3 to 15 W/m according to studies conducted in the laboratory on a small scale. Power recommended, based on the feedback, to use this method however is 10 to 15 W/m. The evolution of the temperature measured during the implementation of this method is shown in Figure 4 below.

![Figure 3: Brillouin and one Raman compensation](image)

![Figure 4: Evolution of the temperature of the optical fiber during a test of heating (according to [2])](image)
A measurement of heat conducting and interpreting lasts about 3 to 5 hrs. This method does not require purchasing beforehand a history of measurements. It is therefore well suited to certain problems of monitoring on short time scale (for example: handing water to the hydraulic structure).

However, this method requires virtually, in particular for reasons of security, the presence of an intervener on site during the measurement, which limits strongly its use in situations of surveillance when fast-charging and not predictable of the structure.

Method of heating is thus well adapted to relatively low length embankment dams and channels (≤5 km) in particular for monitoring resetting in water or any other type of surveillance characterized by a short time scale (a few hours to a few days) and when the presence of intervening specialized on site for the operation of electric power equipment is possible.

IV. PRODUCTION AND ENGINEERING HYDRAULIC APPROACH FOR INTEGRATING TECHNOLOGY OF OPTICAL FIBER OF DAMS AND DIKES TO RESERVOIR

Our research group with Professor KiTae Chang at Kumoh National Institute of Technology leads an ongoing effort since 2 years to use distributed fiber temperature measurements to monitor leaks in hydraulic structures in embankment. During this phase of research and development, experiments of leak by optical fiber monitoring were conducted according to the scheme of classical development of any new technology:

- The experiments in laboratory;
- Experiments on site controlled;
- Experiments on real sites.

These experiments helped to validate a wide range of complementary models of analysis of raw data temperature measurements from fiber developed by our research team in the context of this research effort and to specify their domain of validity. They were also allowed showing the ability of these models to detect minimum leakage between 0.1 l/min and 1 l/min, depending on the type of structure. They have also shown that this technology can be used both to monitor long-term hydraulic behavior and as a means of early warning in the event of a significant anomaly within the hydraulic structure, linked to a leak.

While the Professor KiTae Chang and our team members research effort continues on the qualification of leaks and interpretation of deformation measurements, the results obtained on the location of leaks were sufficiently successful to engage an approach by step up futures lead to an industrial deployment of this technology on a part of the Structures.

The deployment of monitoring of leakage through fiber optic now follows the following process:

- Experimental phase: implemented on some real sites, installation is the scale of the work. The objective is to control the realization of the installation (quality, costs and deadlines), to validate methods of interpretation of raw data, to test human organization in charge of the operation of this surveillance, to ensure compatibility and the insertion of this monitoring data in the Information System.

- Pilot phase: the technology is deployed on various actual sites, procedures to realize the installation are defined, methods of interpretation of raw data are secured and hardened, human organization for the operation and maintenance of the system are controlled.

- Industrial phase: the technology is deployed according to the needs...

Validation of a phase and the transition to the next phase is a specific Committee on the follow-up to this deployment.

V. SITE INSTALLATIONS OF LEAKS DETECTION BY FIBER OPTIC MONITORING

D. Monitoring by optical fiber installations so far by Kumoh National Institute of Technology

Thus having a measure distributed temperature within the hydraulics structure, positioned appropriately according to the objective to be achieved (e.g.: control with a seal control of leaks in foot of slope downstream or upstream face).

The monitoring is based on the principles of Thermometry applied to leak detection: where fiber intercepts a leak, it measures a temperature regulated by the transport of heat by convection along the leak elsewhere it is conduction which controls the temperature.

Monitoring facilities of leakage through optical fiber made to date by Kumoh National Institute of Technology in the context of its program of research and development:

In the field of monitoring facilities design by fiber optic the main points for the design of monitoring facilities by optical fiber from the hydraulic structures in embankment are as follows:

- As for any installation of a hydraulic structure
monitoring, it is imperative that the design of a monitoring by optical fiber facility uses as input the results of a study of diagnosis of safety of the structure. This diagnostic study should in particular to determine the level of performance of each guardrail of the structure and specify the path of (proven or potential) leaks through the structure, so that can be the ideal position of the fiber where they will have the greatest chance to intercept these leaks.

- The design of a monitoring facility must include the installation of optical fibers and the installation of additional conventional testing equipment, whose nature and positioning must be defined on the basis of proven or potential risk to monitor.

- It is necessary during the design phase of the installation of optical fibers, to validate the ability of analysis models of raw temperature data to detect temperature departures expected in the structure. For this, the designer must be able to carry out a hydraulic modeling of the work, typically using the vertical 2D finite element models representing representative cross-sections of different homogeneous segments of the structure, which allow obtaining synthetic temperature of data with consideration of anomalies of type leak. These synthetic temperature data are then used as input for the analysis of raw temperature data models and verified that these latest models are well able to detect simulated leaks. This modeling approach also allows optimizing the positioning of the fiber within the structure, by determining the position of the fiber which allows obtaining the best leak detection. Implementation of this modeling requires in most cases, the acquisition, by measurements in situ, temperature data acquired during several months, to be used for the model boundary conditions: temperature of water held groundwater temperature up and downstream of the structure, the air temperature and other possible heat the model boundary conditions.

- The choice of the materials used in the installation of optical fibers is also a milestone for the success of the installation. This choice must be based on a very good knowledge of the materials available on the market by the supervisor responsible for the design, both for optical fiber for optoelectronic interrogators. A bad choice of fiber (for example a cable whose resistance is poorly adapted to the installation on the site conditions) can be crippling for the sustainability of the installation. A bad choice of interrogator Optoelectronics (for example, a device that is not reliable) can cause strong monitoring system unavailability.

VI. MEASUREMENT RESULTS

The temperature measurement took place from May 2015 September 2015 and information was collected at 2minutes,5minutes and 30minutes intervals.

The graphs below are by order: heating graph (on 08-15 May 2015, 03-30 June 2015, and 01-31 July 2015). We detected that changes in the temperature took place on May, and July and August2015 in the range of about 88 and 96 meters (Fig 6,7,8,9); we have the wet zone totally clear but more visible from the Heat graph and the visualization graph. With different month with the same condition of experimentation, temperature changes were also detected at all peak points just after 88 meter and around location 61m (Fig 7, 8).

Warm water entered the soil first at a point that was at a height, 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 8 and Fig 10).

Seepage-Heat Coupled Analysis

![Figure 5: Fiber Optic Sensor Installation](image)

![Figure 7: Graph with heat (Active method) on May 2015](image)

![Figure 8: Graph with heat (Active method) on July 2015](image)

![Figure 9: Visualization of raw temperature data measured by optical fiber before during and after heating of side test Easting: longitudinal axis of the dam. Ordinate: transversal axis of the dam Temperature Profile over Time on Lower Fiber Line](image)
The results presented above are based on analysis of variations in daily temperature in all categories. As a result, the setting of detection has a temporal resolution and a spatial resolution of 1 m it is possible to improve the temporal resolution from an intraday analysis (12 h) without significant increase in computing time. The appearance and disappearance of different leakage can be highlighted from an analysis of heating graph.

The method of daily analysis helped to implement easily different variants, chosen according to the characteristics of the instrumented site and goals, as the analysis on hours with sliding windows and a recovery on a few hours. This type of analysis tool proved decisive for issuing early warnings of suspicions of leaks.

Measures of leakage through optical fiber from the GMG with Kumoh National Institute of Technology were in perfect agreement with baseline measures installed in the dam (pore-water pressures) and were considered among the most efficient and most reliable range of auscultation systems tested.

CONCLUSION

The results obtained in this work indicated that fiber-optic temperature measurements are suitable for testing the functioning of earth dam structures and the long-term monitoring of a dam. This method is particularly suitable for old reservoirs in Yang Pyong, as in the South Korea 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 May with passive methods in the old earth dam do not confirm or eliminate the possible risk of core erosion due to underground temperature change but they indicate the wet zone clearly. However, it seems more probable and visible with the active method that show a big difference for each zone groundwater temperature well fluctuations are due to periodical changes in permeability, soil properties, rather than due to aeration in the ground.

REFERENCES


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