DISTRIBUTED TEMPERATURE SENSORS SYSTEM. FIELD TESTS ON EARTH DAM

Juan Carlos Sanchez[1,2], Oscar Muñoz[1], Beniamino Russo[2,3], Alejandro Acero[1] y Andrea Paindelli[3]

[1] Tecnalia Research & Innovation. Astondo Bidea, Edificio 700 - 48160 Derio, Bizkaia (España).

[2] Universidad de Zaragoza. Escuela Técnica Superior de La Almunia (EUPLA). C. Mayor, 5 - 50100 La Almunia de Doña Godina, Zaragoza (España).

[3] Universidad Politécnica de Cataluña. Instituto FLUMEN. Carrer de Jordi Girona, 31 - 08034 Barcelona (España

Recibido: 09/dec/2021 • Inicio Evaluación: 11/jan/2022 • Aceptado: 30/sep/2022 | DOI: https://doi.org/10.6036/10418

TO CITE THIS ARTICLE:

SÁNCHEZ, Juan-Carlos; MUÑOZ, Oscar; RUSSO, Beniamino; ACERO, Alejandro; PAINDELLI, Andrea. DISTRIBUTED TEMPERATURE SENSORS SYSTEM. FIELD TESTS ON EARTH DAM. *DYNA*. DOI: https://doi.org/10.6036/10418

ABSTRACT:

The present paper examines the use of optical fiber as a distributed temperature sensor to detect leaks in earth dams. This real-time data acquisition technique complements current auscultation systems and improves monitoring of these critical infrastructures. The aim of this paper is to provide a practical illustration of this novel and promising technique and, particularly, of the precautions to consider to correctly deploy the sensor elements. For this last purpose, this document describes the field tests carried out on the Yesa dam in February 2017 and propose best practices concerning the implementation of the system.

Keywords: Dam auscultation; Distributed temperature sensor; DTS; leak detection; earth dams

FUNDING

The results presented in this article come, in part, from the research activity of the Group of Hydraulic and Environmental Engineering (GIHA) of the EUPLA (group recognized and funded by the Government of Aragon, Spain).

1. - INTRODUCTION

Infrastructure safety does not depend solely on design and construction, but also on monitoring behavior during operation throughout service life. All large dams are equipped with auscultation systems to monitor their structural and hydraulic state.

Among dam monitoring and maintenance parameters, early detection of leaks through the dam body is essential to ensure structural integrity and take corrective actions to prevent catastrophic situations such as those that occurred at Baldwin Hills (USA, 1963), Teton (USA, 1975), Quail Creek (USA, 1989) and Mosul (Iraq, 1990).

Furthermore, aging and undermaintained infrastructure combined with changing climate over the coming decades, is setting the stage for more dam disasters like the recent one that struck Midland (Michigan, USA, 2020). Currently, two main leak detection approaches are used in the field of dams engineering. The first one is based on the detection of anomalies through the sensors installed in the infrastructure and the second is done by visual inspection. This kind of structural supervision presents two main drawbacks [1]:

- *Low Spatial resolution*. Installed sensors cover certain areas of the infrastructure because their deployment cannot not massive (this fact is largely due to the high cost of monitoring). This leads to the probability of a leak detection when it is in an advanced state.
- *Late detection and unknown localization*. Many times, visual detection of a leak downstream indicates the existence of a problem but not its origin. This problem is even more severe in the case of earth dams because the leak may have already degraded the core of the infrastructure.

Due that hydraulic flow in soils can be detected through the implementation of temperature sensors and thanks to the advancement of optoelectronics currently allows to integrate many sensors of this type within a single fiber optic (FO) wire, it is possible to deploy a network of sensors for the early detection of leaks in earth dams [2]-[3]-[4] or their foundations [5] that solves the deficiencies described above. To counteract the disadvantages of traditional systems described, a leak detection system based on DTS (Distributed Temperature Sensors) technology has been implemented into Soto Terroba and Yesa dams [6]-[7]. This work presents the first field tests carried out with DTS system whose objective was the start-up of the system and the realization of the first temperature readings, obtaining as a result the thermal mapping of the infrastructure. In recent years, many other authors continued investigating this topic, deepening the knowledge about to employ fiber technology for detecting seepage in hydraulic structures [8]-[9]-[10]-[11]-[12]-[13]-[14].

2. - DTS TECHNOLOGY

DTS is based on an optoelectronic system capable of extracting the existing temperature along a fiber optic (FO) cable. This technology can be used to implement a large-scale distributed measurement system capable of monitoring huge structures. One potential application of this technique is the leak detection in earth dams. Temperature variations caused by seepage through a crack can be detected by FO sensors sited beneath the impermeable layer. The temperature reading technology used in this application is based on the RAMAN effect and requires a reading device known as an “interrogator” to extract data from the FO. FO temperature measurements based on the RAMAN effect use a laser-generated optical pulse transmitted along the FO cable. RAMAN scattering is caused by the interaction of photons from the laser with the thermal vibrations of silicon molecules and can be used to measure temperature fluctuations in an FO cable containing a network of sensors whose number is dependent on cable length. The location of the measurement point is obtained from an analysis of the “time of flight” of laser light scattering and, at present, measurement accuracy ranges between 0.5 m and 2 m. RAMAN-type sensors are not the only devices to deploy fiber optic-based DTS sensor networks, other technologies, such as those based on the BRILLOUIN effect, are capable of recording both the temperature and the deformation of the cable itself. Although, this type of device increases the capabilities in auscultation, it also significantly increases the cost of implementation, mainly since the measurement bands (Figure 1) are more difficult to detect as they are close to the band RAYLEIGHT. Moreover, Brillouin interrogators are generally more expensive due to the acquisition of more types of variables and because of the detection require to capture the Brillouin bands.

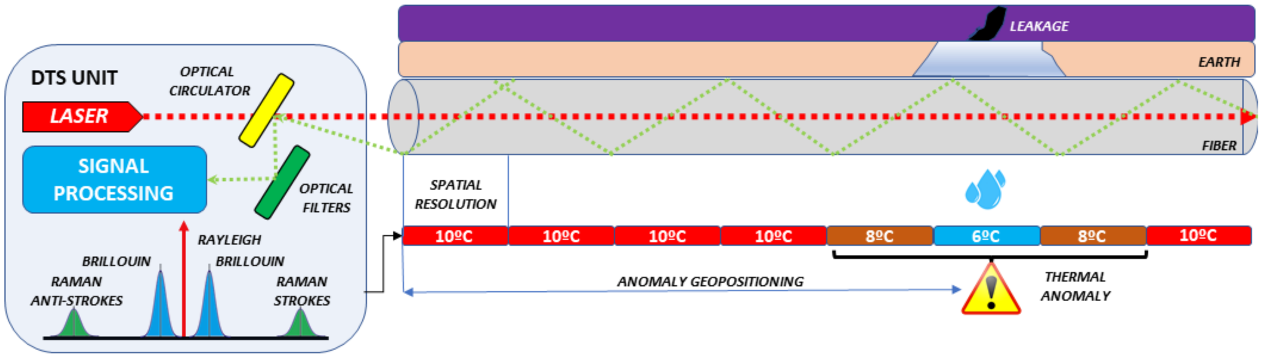


Figure 1. Reading topology in RAMAN effect interrogator.

When considering the application of such technology, it is important to remark the evolution of the cost registered throughout the years. During 2015, the cost for installing a complete operating system was nearly 46.000 euros, while today is about 60.000, a 23% more. Although the interrogator cost has decreased by a 35% during this 7 years, software, setup and Optical Fiber price per meter has increased. The following table (Table 1) provides a comparison of the total cost for a complete system setup for the Terroba Dam in 2015, the Yesa Dam in 2018 and the most updated prices (June 2022).

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA DOI: https://doi.org/10.6036/10418

PROJECT	TERROBA 2015	YESA 2018	Current 2022
Interrogator (REF)	ORYX DTS	HALO_DTS	K_FS22-01-010-120
	22.900,00 €	17.585,00 €	14.800,00 €
Optical Fiber (REF) 100m	BRUSTEEL LLK-BST	A-DSQ(ZN) B2Y	B-DSQ(Z) B3Y_1
	500,00 €	685,00 €	825,00 €
Setup	14.400,00 €	23.925,00 €	29.875,00 €
Software	8.245,00 €	12.820,00 €	14.470,00 €
TOTAL	***46.045,00 €***	***55.015,00 €***	***59.970,00 €***

Table 1. Evolution of the price of the different components of the proposed system over the past 7 years.

DTS Measurement technique oriented to leak detection

Accurate identification of a leak in a dam requires a measurement procedure based on thermal stress of the DTS cable, known as the "heat pulse method". This method consists of a first phase in which the sensor element (FO) is subjected to a heating cycle using the copper pair incorporated in the cable and a second phase corresponding to an analysis of the time the fiber takes to return to the initial temperature once the heating cycle ends.

In line with this measurement procedure, the following basic parameters can be defined to detect any leaks in the infrastructure:

- T_0 (Initial temperature). Initial temperature of the measurement point.
- ΔT. (Temperature gradient). Difference between the initial temperature of the measurement point and the maximum temperature reached when applying the heat pulse.
- ΔH. (Dissipation gradient). This is the time that the FO takes to return from the maximum temperature reached during the heating phase to the initial temperature of the test.
- *D*. (Position of the measuring point). Location of the measurement point within the FO. Relating this point with the installation coordinates of the FO accurately locates the position of the measurement point.

To detect a leak in the dam, it is necessary to relate the parameters for each measurement point with those of its closest neighbors. For installations of this nature, it is not possible to establish a specific threshold for all the measurement points since they are distributed along the length of the infrastructure and therefore the boundary conditions may vary from one end to the other (Figure 1).

It must be considered that seasonal conditions (among others) could affect the magnitude of the thermal pulse measurement. In this aspect and under normal conditions, the points located at the same elevation ideally should have a similar thermal differential as they are subject a priori to the same boundary conditions.

Because solar radiation can affect locally the temperature of certain points of the dam, it is strongly recommended to take the readings first thing in the morning. In the case of catastrophic events, a potential breakage of the fiber cable can be detected by the system as well. This event could be indicative of a radical change in the physiognomy of the structure and therefore a cause for alarm that could cause a structural revision of the dam itself. Eventually, the appearance of air pockets caused by internal movements in the dam can be localized too, considering that in these areas the amplitude of the thermal pulse would be substantially greater, since the air is a worse heat sink than the earth itself.

Laboratory tests

The earth dam leak detection system (the CHEDAM system) consists of an interrogator together with a regulated heat pulse control system and an industrial computer for processing and reading measurement signals. This combination of equipment is used to obtain DTS cable readings during execution of a programmed heat pulse, generating a measurement report that is subsequently analyzed according to the topology of the infrastructure to monitor. To test the system, a DTS cable 3-meter long DTS was embedded in a laboratory test bench simulating real conditions (Figure 2). The test bench was used to conduct an initial validation of the measurement technique and to assess operation of the CHEDAM system. The results obtained from the tests indicated differences between measurements taken with dry earth and with wet earth.

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA DOI: https://doi.org/10.6036/10418

Figure 2. CHEDAM laboratory test bench.

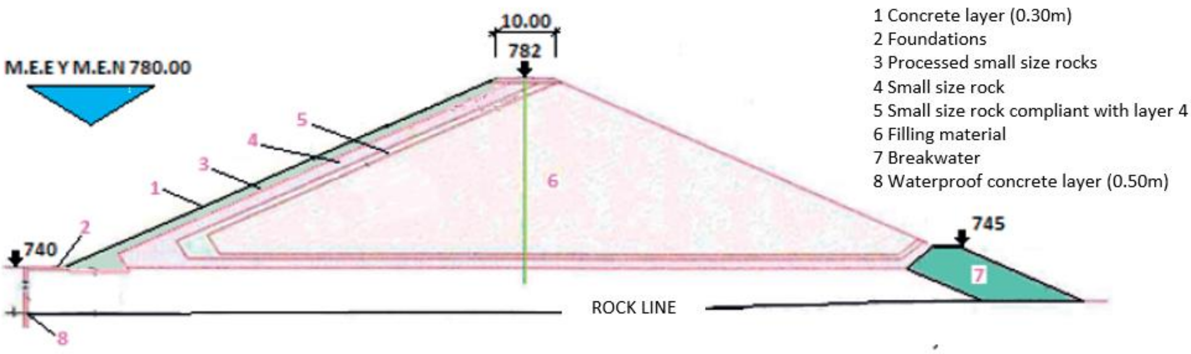
The design of the test bench will make it possible to carry out future leak detection and quantification studies aimed at assessing the danger degree presented by the leak detected and the urgency of the pertinent corrective actions.

3. - SOTO-TERROBA DAM

The Soto-Terroba dam is a homogeneous loose materials dam with an asphalt screen 45.6 m high and 356 m long crowning, which has been built in La Rioja on the Leza River with a storage capacity from 8.14 hm (Figure 3). The distribution of the monitoring of possible leaks in the body of the Soto-Terroba dam has been carried out by deploying three fiber optic branches together with a pair of copper so that they form the monitoring system. Because the installed elements lack sufficient mechanical protection against the possible stresses to which they may be subjected in their installation, the cables were wrapped with geotextile fiber. The branches are arranged at different levels within the infrastructure, the first one being at a nearby level to the base of the dam. The location of the following DTS cable runs is at higher elevations with a separation approximately 5 meters.

Despite the precautions in the assembly of the DTS cable during the installation and subsequent coating cycle, the element suffered a break due to movement of the construction machinery. By detecting it early, it was possible to proceed with the joining of the elements, these being verified once the coating of the asphalt layer was completed.

You can also see the installation of hot spots, "fiber optic resistors", where the copper pair was reinforced to provide a greater thermal gradient at these points. The objective of these hot spots is to limit, in the system readings, the exact positioning of the optical fiber along the body of the dam.



ISSN: 0012-7361 eISSN: 1989-1490 / DYNA DOI: https://doi.org/10.6036/10418

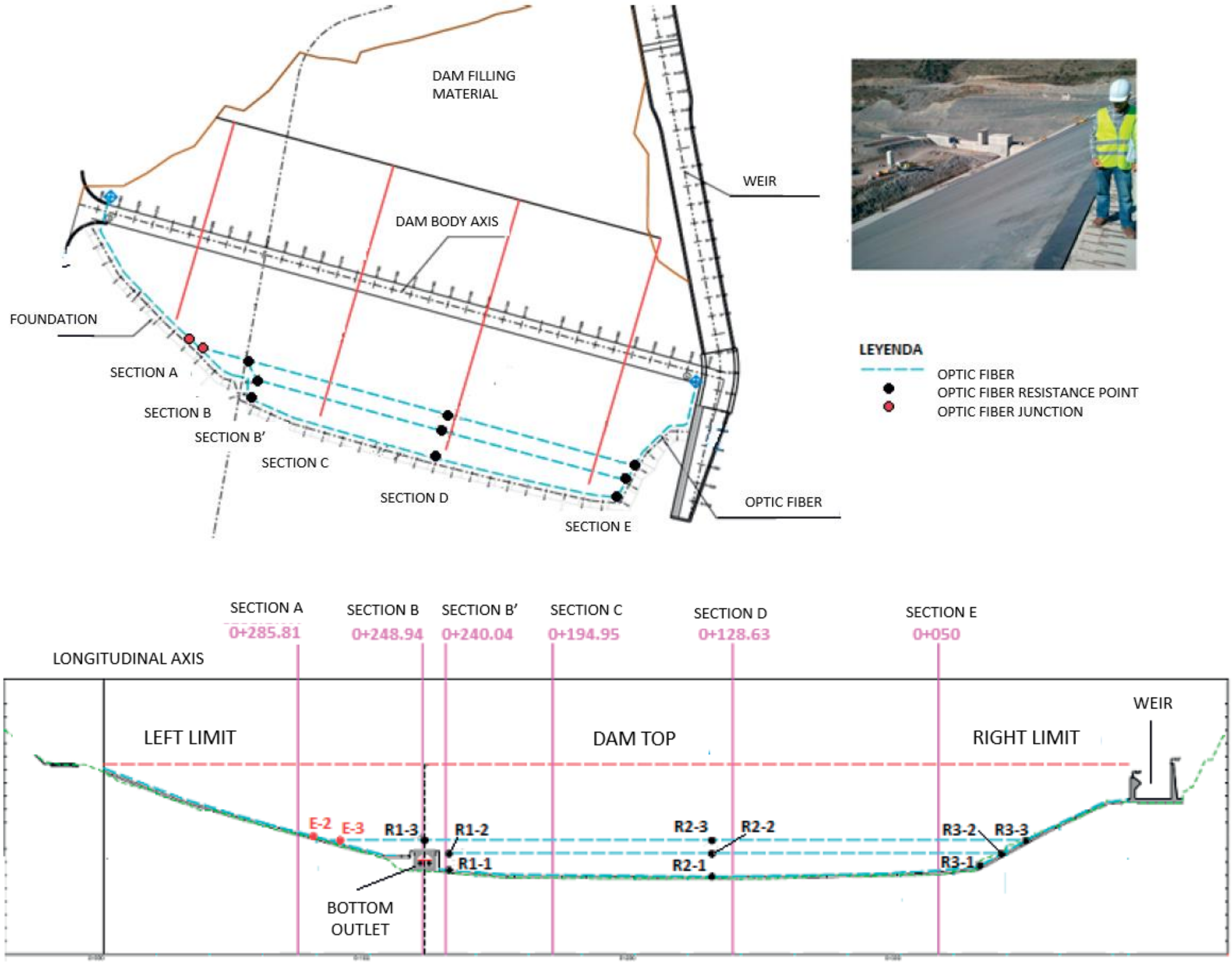


Figure 3. Source [6]. Dam section and DTS Cable distribution along the dam.

4.- YESA EARTH DAM

The old Yesa dam (Navarre) was put into commission in 1959. It is a concrete gravity dam with a vertical face upstream and a stepped face downstream with a slope equivalent to 0.78 H: 1 V. Measuring 78 m high and 398 m long at the top, with a capacity of 447 hm3, it is located on the Aragon River, a tributary of the Ebro, in northern Spain (Figure 4). This dam has behaved satisfactorily throughout its 56 years of operation, but as a result of crop changes (initially cereals but now diversified to include alfalfa, corn, vegetables, rice, etc.) in the irrigation area of Bardenas, covering 1.1·105 hectares, and the new requirements concerning water supply to the city of Zaragoza and surroundings (with over 800.000 inhabitants), it has become necessary to heighten the dam in order to increase capacity to 1079 hm^3 without affecting the operation of the existing dam. This heightening consists of the construction of a new earth dam downstream the existing one. The upstream face is covered by a concrete screen to a height of 108 m.

FO distribution

In the Yesa earth dam (Figure 4), DTS cables have been laid in three main lines to measure temperatures along critical sections of the infrastructure. Four checkpoints have been defined for the position of the cable terminals.

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA DOI: https://doi.org/10.6036/10418

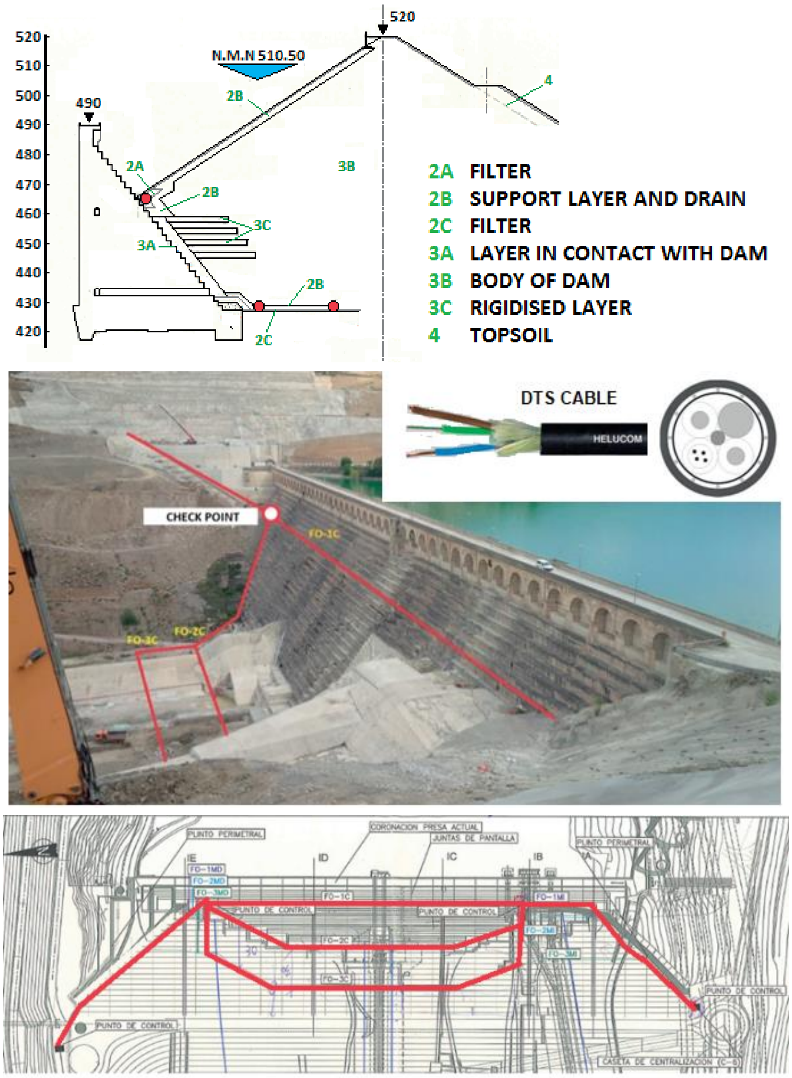


Figure 4. Source [6]: Dam section and DTS cable distribution along the dam.

For practical reasons, cable installation during dam construction must be carried out in several stages; thus, the abovementioned checkpoints were located where the various sections of the DTS cable are connected to yield three measurement lines in the Yesa dam system. As the Yesa dam is heightened and the different sections of the DTS cable are added, periodic inspections should be carried out to monitor the integrity of the element installed according to the DTS cable inspection protocol designed for installation of the heightened Yesa dam system. This procedure also includes contingency plans in the event of partial or total breakage of the cables.

DTS cable

The Yesa dam system's hybrid fiber optic cable (Figure 4) consists of three main parts: the first is the main element of the FO sensor, composed of 4 multi-mode optical fibers; the second comprises two copper pairs used to implement the heat pulse method; and the third consists of a special coating to protect the cable while being installed in a context of civil works. In contrast to the installation of the Sototerroba dam system [5], where the FO cable was installed simultaneously with the copper pair, the use of a hybrid cable presenting the characteristics described above simplifies installation of the element by providing greater mechanical protection. In addition, the uniformity of heat transfer between the copper pair and the optical fiber yields better temperature readings along the length of the cable.

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA DOI: https://doi.org/10.6036/10418

5.- CHEDAM SYSTEM. FIELD TEST

Currently, the heightened Yesa earth dam is under construction (Figure 5). Nevertheless, a large proportion of the FO cables was already installed and geolocated, so it was possible to test the system in February 2017.The first step in implementing this kind of system is to correlate interrogator measurements and the geographical position of the measurement points. Since it is impossible in practice to geolocate all kilometric points (PK) of the fiber, it is necessary to analyses the measurements to identify the points of interest located in the dam body (ruling out cable sections running through pipelines, the gallery, etc.).

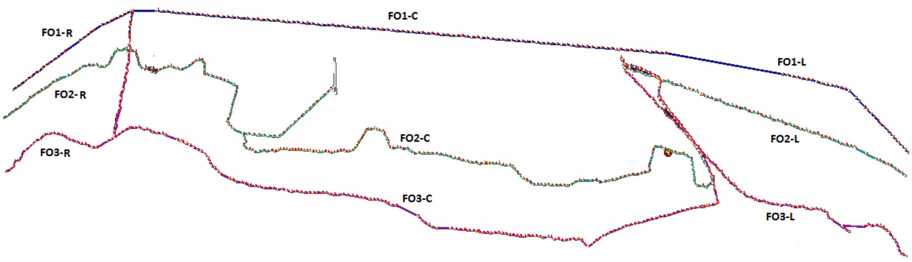


Figure 5. Current georeferenced DTS cable distribution at Yesa earth dam.

FO cables were installed in three lines that were subdivided according to their location. R indicates the right side; L the left one and C the central body of the dam (Figure 5). Due to the complexity of the installation, each of the R, L, and C sub-sections was installed independently and subsequently connected to the dam checkpoints. The total length of the lines installed is shown in Table 2.

FO reference	Deployed meters	Georeferenced meters
FO1 (FO1-C and FO1-L)	807 meters	339 meters
FO2 (FO2-C and FO2-R)	995 meters	730 meters
FO3 (FO3-C)	567 meters	440 meters
TOTAL	2369 meters	1509 meters
Measurements points	1184	754

Table 2. DTS cable length at Yesa earth dam and available measurement point with CHEDAM Systems, (February 2017).

Heat pulse configuration

The heat pulse deployed in the system during preliminary tests was of relatively low power (Table 3). This was because some sections had not yet been installed and the corresponding cable was still on the reel. In electrical terms, these parts of the DTS cable consequently constituted a very large coil which could overheat or become damaged if exposed to an excessive heat pulse.

Excitation time	30 min
RMS voltage	217 V
Copper pair resistance	27 Ohm
Total copper length	2369 m
Total pulse power	1.736 kW
Pulse power per meter	0.732 W/m

Table 3. Heat pulse configuration.

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA DOI: https://doi.org/10.6036/10418

Correlation of interrogator measurements with geopositioning references (PK)

Once the measurements were taken, the data were displayed using multidimensional graphs, visualizing both the raw and the incremental temperature data. The initial value at time t=0 is 0ºC for all measurement points. Incremental temperature measurements showed uniform patterns equivalent to the geolocated distances of the DTS cable. With this rendering it is possible to correlate the DTS cable positions with the measurements obtained by the interrogator by extracting the temperature measurement points corresponding to the dam body (Table 4).

<table>
<tr><th>PK ref.</th><th>PK distance</th><th>DTS reading</th><th>DTS distance</th><th>Comment</th></tr>
<tr><td></td><td>—</td><td>0 m - 5 m</td><td>5 m</td><td>Interrogator connection distance</td></tr>
<tr><td></td><td>—</td><td>5 m - 66 m</td><td>59 m</td><td>Section through gallery</td></tr>
<tr><td>PK3803</td><td rowspan="2">207 m</td><td>66 m</td><td rowspan="2">211 m</td><td>Dam body input</td></tr>
<tr><td>PK4010</td><td>277 m</td><td>Dam body output</td></tr>
<tr><td></td><td>—</td><td>277 m - 405 m</td><td>128 m</td><td>Section through gallery</td></tr>
</table>

Table 4. F01-C DTS readings and PK correlation.

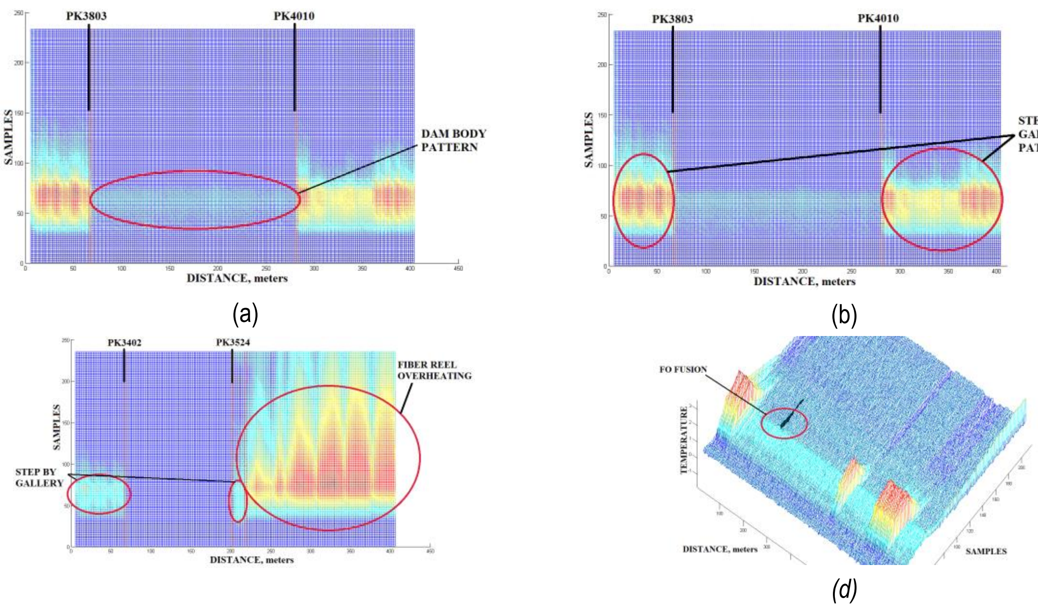
The data captured by the system indicated various types of fiber response patterns to the applied heat pulse (Figure 6). Among other things, these patterns are useful for geolocating the measurement points of the interrogator and are described below.

Dam body Pattern. Dam body patterns are defined by interrogator readings of measurements taken by the system in the dam body and are chiefly characterized by responding to the heat pulse with a temperature increase of approximately 0.5 ºC.

Gallery section pattern. Gallery section patterns are defined by interrogator readings of measurements taken by the system in air ducts or chambers inside the dam galleries and are mainly characterized by responding to the heat pulse with a temperature increase of between 1.5 °C and 3.5°C.

Fiber reel overheating pattern. The fiber reel overheating pattern is defined by interrogator readings of measurements taken by the system of fiber sections that are still coiled on the reel (not installed). The fiber response to the heat pulse is characterized by a temperature increase more than 6.5 ºC.

Embedded fiber fusion pattern. The embedded fiber fusion pattern is defined by interrogator readings of measurements taken by the system in the junction box where the optical fiber has been fused. The response to the heat pulse is characterized by a longer relaxation time mainly due to the air chamber in the junction box.



ISSN: 0012-7361 eISSN: 1989-1490 / DYNA DOI: https://doi.org/10.6036/10418

(c)

Figure 6. Patterns. (a) Dam Body pattern, (b) Gallery section pattern, (c) Gallery section pattern, (d) Embedded fiber fusion pattern.

Leak detection test

Once the system had been installed in the heightened Yesa dam, an initial leak detection test was conducted by discharging water onto a section of the optical fiber (FO1-L) (Figure 7). Because of the state of execution of the works, the water was discharged from a tank onto one end of the cable at a rate of about 6 liters a minute for approximately 45 minutes. The basic objective of this test was to observe the behavior of the system in response to an abrupt change in temperature at a specific section of the DTS cable.

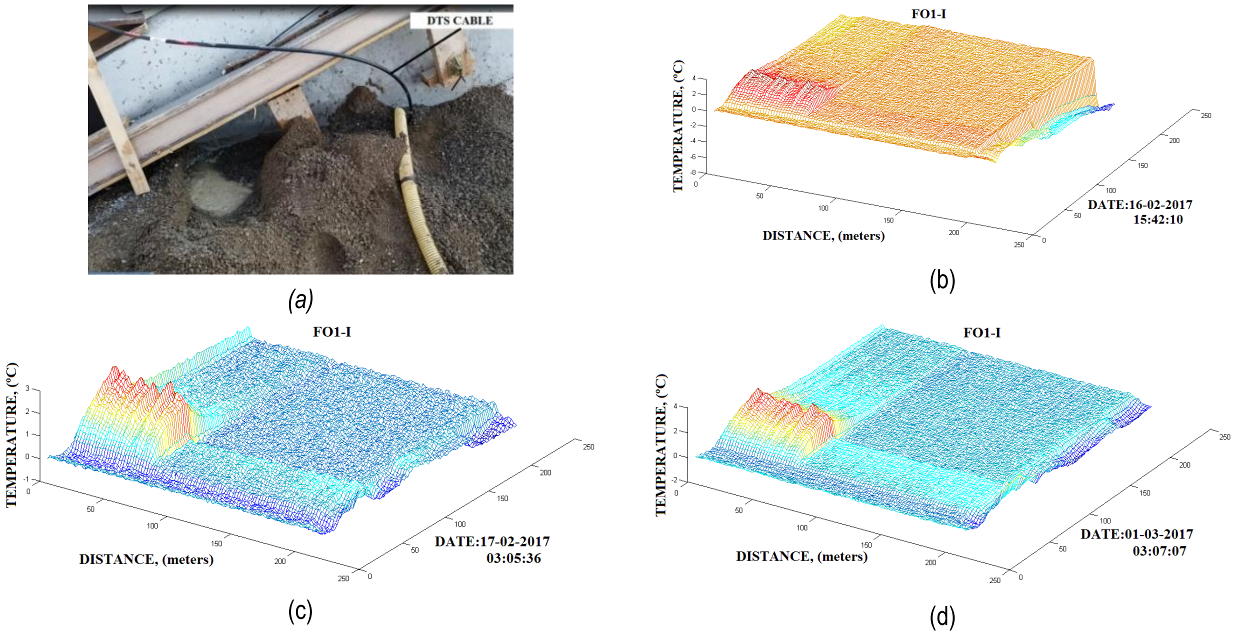


Figure 7. Evolution of FO1-L DTS readings. (a) Water discharge test on DTS cable. (b) Date: 16-02-2017. Discharge test day; (c) Date: 17-02-2017; (d) Date: 01-03-2017.

As it can be seen from the readings shown in Figure 8, the temperature at the end of the fiber fells by 8 degrees on the day of the test. Although this type of test is not ideal for validating the heat pulse measurement method, the system is sufficiently sensitive to capture and locate temperature gradients caused by temperature differences between the DTS cable embedded in the dam body and the water in the reservoir.

Dam thermal mapping

The main objective of the initial tests conducted at the heightened Yesa dam was to geolocate the measurement points obtained by the CHEDAM system. Once the fiber behavior patterns had been identified and the ends of the fiber installed in the dam body had been geolocated, it was possible to visualize dam body temperatures corresponding to installed fiber sections (Figure 8).

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA DOI: https://doi.org/10.6036/10418

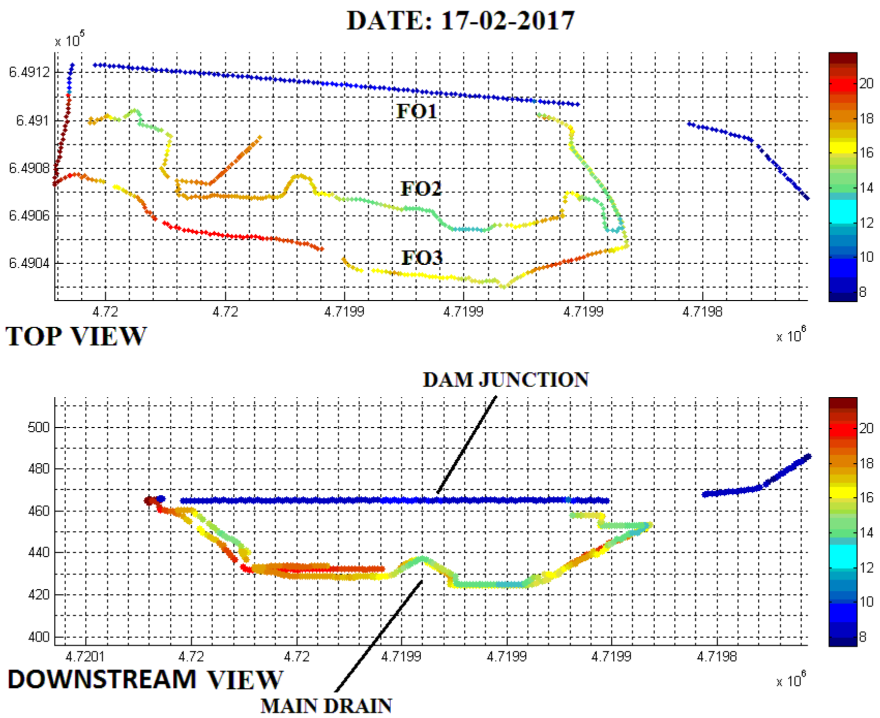


Figure 8. Yesa DTS thermal mapping.

Visualization of dam body temperatures provides additional information to leak detection and confirms the need to normalize temperatures during application of the heat pulse. Obviously, temperatures are not evenly distributed throughout the dam body and therefore leak detection algorithms must be applied depending on the location of the leak detection point and an analysis of temperature increase and relaxation during execution of the heat pulse. It should also be noted that the global temperature of the FO1 fiber will most probably vary according to season since it is in an area close to the dam contact layer. The dam is not currently in operation and, consequently, the temperature obtained by the FO1 is close to local atmosphere temperature; however, once the impermeable layer has been applied, it is probable that there will be a temperature difference between the fiber and the contact surface.

6.- DISCUSSION

To counteract the disadvantages of traditional systems for earth dam auscultation, a leak detection system based on DTS (Distributed Temperature Sensors) technology was implemented into Soto Terroba and Yesa dams. This work presents the first field tests carried out with DTS system whose objective was the start-up of the system and the realization of the first temperature readings, obtaining as a result the thermal mapping of the infrastructure. As described in the section on heat pulse configuration, the pulse applied was not appropriate for final operation of the system since the temperature increases at dam body measuring points did not exceed 0.5°C. For security reasons, it was not possible to apply more energy because the FO cable at the ends of the installation was still on the reel. Application of a higher pulse could have caused cable overheating, with the attendant risk of damaging the FO section not yet installed.

One of the main objectives of the initial system tests was to geolocate the system measurement points. The tests conducted to date have yielded this correlation and it has therefore been possible to visualize temperatures throughout the dam body.

Compared to the Soto-Terroba [5] dam, the topology of the installation at the Yesa dam is much more complex, primarily since the dam is still under construction and therefore the cable must be laid in stages. This means that fiber must be laid through the galleries for subsequent connection with the different sections of the installation. Although the FO sensors detected the presence of water in the leak detection test, it is important to note that the leak was only detected by a drop in temperature. Due to the low heat pulse applied, it was not possible to analyses the response elicited. However, the results are promising as there are two factors to consider for leak detection: a temperature difference with respect to the measurement points and the presence of thermal impedance (analysis of the heat pulse response). As demonstrated, the feasibility of detecting the groundwater level in the dam body paves the way for a range of alternative system applications. Besides groundwater level detection, measurements could be used to estimate reservoir

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA DOI: https://doi.org/10.6036/10418

levels by conducting thermal analyses of sections FO1-L and FO1-R, which are installed very close to the area in contact with the water and located on the vertical axis of the infrastructure. It is expected to see an increase of FO technology adoption as support to classic dam monitoring systems such as for detecting filtration during emptying processes, inside the drain chimney coupled with piezometers as well as for slope leveling and collimation [15]. Specifically, this kind of techniques is expected to be implemented also in ponds used in agriculture for irrigation and in farms to storage and manage slurry with significant hydraulic and environmental benefits. An analysis of drainage in the dam body is another possible application of interest; however, this would require a more in-depth study of the infrastructure and its boundary conditions. In this case, development of a technique for measuring flow using a DTS system would add considerable value to analyses of earth dam behavior.

REFERENCES

[1] Colegio de Ingenieros de Caminos, Canales y Puertos (CICCP) (2004). Auscultación de presas y sus cimientos. Guías Técnicas de seguridad de Presas. Comité Español de Grandes Presas. Servicios de Publicaciones del CICCP. ISBN 84-380-0277-3.

[2] Aufleger M., Conrad M., Goltz M., Perzlmaier S., Pablo Porras. (2007). Innovative Dam Monitoring Tools Based on Distributed Temperature Measurement. Jordan Journal of Civil Engineering, 1(1), 29-37.

[3] Côté A., Carrier B., Leduc J., Noël P., Beauchemin R., Soares M., Garneau C., Gervais R.. (2007). Water Leakage Detection Using Optical Fiber at the Peribonka Dam. Geotechnical Special Publication. 1-12. DOI 10.1061/40940(307)59

[4] Khan A. A., Cunat P., Beck Y. L., Mars J. I., Vraibe V., Fabre J-P. (2010). Distributed fiber optic temperature sensors for leakage detection in hydraulic structures. Proceedings 5th World Conference on Structural Control and Monitoring. Shinjuku, Tokyo, Japan.

[5] Muñoz O., Gómez R., Russo B., Sánchez J. C. (2013). Detección de fugas en presas de materiales sueltos mediante sensores distribuidos en fibra óptica. III Jornadas de Ingeniería del Agua. Valencia, October 2013.

[6] Muñoz O., Gómez R., Russo B., Sánchez J. C. (2016). Sistema de detección de fugas en tiempo real en presas de materiales sueltos mediante sensors distribuidos en fibra óptica. Revista de Ingeniería del Agua Vol.20.1. Valencia, España. DOI 10.4995/ia.2016.4450

[7] Nikles M., Vogel B. Briffod F., Grosswig S., Sauser F., Luebbecke S., Bals A., Pfeiffer T. (2004). Proceeding of the 11th SPIE Annual International Conference Symposium on Smart Structures and Materials. San Diego, California, EE.UU.

[8] Bersan, Silvia & Koelewijn, Andre & Simonini, Paolo. (2018). Effectiveness of distributed temperature measurements for early detection of piping in river embankments. Hydrology and Earth System Sciences. 22. 1491-1508. DOI 10.5194/hess-22-1491-2018.

[9] Čejka, F. & Beneš, Vojtěch & Glac, F. & Boukalova, Zuzana. (2018). Monitoring of seepages in earthen dams and levees. International Journal of Environmental Impacts: Management, Mitigation and Recovery. 1. 267-278. DOI 10.2495/EI-V1-N3-267-278.

[10] Cola, Prof. phD. Eng. Simonetta & Girardi, Veronica & Bersan, Silvia & Simonini, Paolo & Schenato, Luca & Polo, Fabio. (2021). An optical fiber-based monitoring system to study the seepage flow below the landside toe of a river levee. Journal of Civil Structural Health Monitoring. 11. DOI 10.1007/s13349-021-00475-y.

[11] Ghafoori, Yaser & Vidmar, Andrej & Riha, Jaromir & Kryžanowski, Andrej. (2020). A Review of Measurement Calibration and Interpretation for Seepage Monitoring by Optical Fiber Distributed Temperature Sensors. Sensors. 20. DOI 10.3390/s20195696.

[12] Ling, Chengpeng & Qi, Youzheng & Abdulsamad, F. & Shi, Peng & Nicaise, Sylvie & Peyras, L.. (2019). Application of the Mise-à-la-Masse method to detect the bottom leakage of water reservoirs. Engineering Geology. 261. 105272. DOI 10.1016/j.enggeo.2019.105272.

[13] Miah, Khalid & Potter, David. (2017). A Review of Hybrid Fiber-Optic Distributed Simultaneous Vibration and Temperature Sensing Technology and Its Geophysical Applications. Sensors. 17. 2511. DOI 10.3390/s17112511.

[14] Su, Huaizhi & Cui, Shusheng & Wen, Zhiping & Xie, Wei. (2019). Experimental study on distributed optical fiber heated-based seepage behavior identification in hydraulic engineering. Heat and Mass Transfer. 55. DOI 10.1007/s00231-018-2431-2.

[15] Guias para el proyecto, construcción, explotación, mantenimiento, vigilancia y planes de emergencia de las balsas de riego con vistas a la seguridad – Generalitat Valenciana 2009 - ISBN: 978-84-482-5322-6

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA DOI: https://doi.org/10.6036/10418