

Article

Application of Fiber-Optic Sensors to Monitor Concrete Dams: A Case Study

Douglas Moser ¹, Araceli Martin-Candilejo ^{1,2}, Luis Cueto-Felgueroso ^{1,2} and David Santillan ^{1,2,*}

¹ Department of Civil Engineering: Hydraulics, Energy and Environment, Universidad Politécnica de Madrid, C/ Profesor Aranguren 3, 28040 Madrid, Spain

² Center for Intelligent and Sustainable Civil Infrastructure (CIVILis), Universidad Politécnica de Madrid, C/ Alfonso XII, 3 & 5, 28014 Madrid, Spain

* Correspondence: david.santillan@upm.es

Abstract

Fiber-Optic Sensors (FOSs) offer unprecedented performance for Structural Health Monitoring (SHM) of concrete dams, addressing the critical need for robust instrumentation. This study evaluates the capabilities of Raman-type Distributed Fiber-Optic Sensors (DFOSs) and Bragg grating-type Localized Fiber-Optic Sensors (LFOSs) for concrete temperature monitoring in a case study. Raman-type DFOSs offer superior spatial resolution and comprehensive thermal mapping, enabling the detection of detailed thermal phenomena, such as the cooling effects of dam galleries and significant thermal gradients, that conventional technologies cannot capture. They are also easier and faster to install, as they do not require trench construction. However, monitoring data acquisition can be more expensive with Raman-type DFOSs. Bragg-type LFOSs offer reliable localized measurements analogous to conventional thermometers. A key benefit is their multiplexing capability, which significantly reduces the total number of cables needed, making a complete LFOS-based monitoring system easier and potentially cheaper to install than an equivalent conventional system, even though individual LFOS installation still requires trenches. Overall, both FOS technologies are effective and reliable for concrete dam temperature monitoring, providing data quality comparable to conventional sensors and representing a significant advancement for SHM systems.



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1. Introduction

Structural Health Monitoring (SHM) plays a pivotal role in the safety assessment and long-term management of dams. It provides engineers with essential tools to evaluate, control, and mitigate structural changes under both natural and anthropogenic influences. As described by Li [1], an effective SHM system should facilitate a comprehensive understanding of dam behavior, guide technical decision-making throughout the operational life of the dam, and ensure safety, functionality, and minimal environmental impact.

The assessment of dam safety traditionally relies on three fundamental pillars: visual inspections, engineering expertise, and behavior modeling [2,3]. Behavior models establish relationships between external loads and the structural response of the dam using mathematical or statistical frameworks [4,5]. These models enable comparison of predicted responses with actual measurements, thereby supporting the detection of anomalies, the

evaluation of structural integrity, and the prevention of potential failures [6]. Instrumentation and sensor systems embedded within the dam structure are essential for acquiring the data necessary for such evaluations.

The selection and deployment of appropriate sensors are critical components of any SHM strategy [7]. Despite the long-standing application of SHM in dam engineering, the field has not fully embraced recent advances in sensing technologies, particularly compared to other civil infrastructure sectors such as bridges and buildings [8]. Among the most promising innovations in sensing technology are Fiber-Optic Sensors (FOSs), which offer unprecedented performance [6,9]. FOSs present several advantages over conventional sensors, including an extended operational range, multiplexing capabilities, a compact size and lightweight design, excellent transmission capabilities, immunity to electromagnetic interference, and chemical inertness [10–12]. In particular, Distributed Fiber-Optic Sensors (DFOSs) enable continuous monitoring of structural parameters over the entire length of the fiber with a great spatial resolution, a capability unmatched by traditional technologies [13].

Over the past decade, significant progress has been made in the application of FOSs to the monitoring of civil and geotechnical structures. These advances have improved the measurement of key variables such as strain, temperature, and vibration, positioning FOSs as a leading candidate for the development of smart fiber-optic-based infrastructure systems [14]. However, adoption of this technology remains limited, mainly due to the lack of familiarity among engineers and stakeholders, as well as resistance to integrating new tools into established monitoring practices [15], despite the excellent performance of FOSs in the monitoring of concrete dams [16].

One of the most important variables to monitor in concrete dams is temperature. Concrete temperature is a critical factor in the design, construction, and operation of concrete dams, particularly as it significantly influences the structural integrity [17]. During the construction phase, the internal temperature of the concrete is monitored to assess the performance of the concrete mix design, regulate placement rates and lift heights, and determine the need for artificial cooling [18]. These measures are essential to mitigate the risk of temperature-induced cracking, especially mass cracking, and to ensure the durability of freshly placed concrete. Furthermore, temperature data are vital for planning grouting operations at block joints in arch dams, where thermal behavior significantly impacts joint performance. In the operational phase, temperature monitoring continues to play a crucial role, particularly in arch dams, where thermal loads can induce substantial tensile stresses at the base of cantilevers due to arch expansion [19–21]. Therefore, continuous thermal evaluation is indispensable to maintaining the long-term safety and functionality of concrete dam structures [22].

Koga et al. [23] reported one of the first experiences using DFOSs to monitor concrete temperature in the Miyagase Dam. The Miyagase Dam is a Rolled Compacted Concrete (RCC) gravity dam built on the Nakatsu River in the Tokyo Metropolitan Area (Japan) between 1991 and 1998. The concrete temperature during construction was measured with DFOSs [23]. Other early reported experiences of concrete temperature monitoring with DFOSs took place in the Birecik dam, a Conventional Vibrated Concrete (CVC) gravity dam located on the Euphrates River (Turkey) built in the late 1990s [24], and in the Luzzzone dam, a CVC arch dam built in the Swiss Alps whose height was increased by 17 m between 1997 and 1998, where concrete temperature was monitored with Brillouin-type DFOSs during that operation [25]. Conrad [26] and Aufleger et al. [24] reported three RCC gravity dams, the Wala and Mujib dams in Jordan and the Schimenzhi RCC arch dam in China, where the concrete temperature was monitored satisfactorily using Raman-type DFOSs between 2000 and 2002. Nevertheless, observed temperatures with FOSs were not compared with other technologies.

More recent reported experiences include the use of Raman-type DFOSs to monitor concrete temperature in the Xiluodu CVC arch dam located in the lower reach of the Jinsha River, Sichuan Province, China, built from 2009 to 2014 [27,28]. The case study was used to validate a mathematical approach to interpolating the concrete temperature measured with the Raman-type DFOSs. For that purpose, the temperature was also measured for 21 days with nine conventional thermometers at points without DFOS observations. The differences between the reconstructed temperatures and the measured values were all within 1 °C. In conclusion, 54 recorded observations at nine non-coincident points were used to compare DFOSs with conventional thermometer observations, and validation was based on the difference between reconstructed temperatures measured with the Raman-type DFOSs and values monitored with conventional thermometers. Xiang et al. [29] also proposed a mathematical framework for reconstructing thermal fields measured with Raman-type DFOSs. The performance of DFOSs was assessed by comparing recorded temperatures with those from three conventional concrete thermometers over 28 days and by using statistical error measures such as mean absolute error (MAE) and root mean squared error (RMSE).

DFOSs have also been successfully applied to monitor concrete temperature in many dams in China, such as, for example, in the Three Gorges, Jinghong, Baise, Letan, Guangzhao, Wudongde, and Xiaowan dams [29–32]. Liang et al. [30] proposed a framework to correct temperature measurement errors from DFOSs. The approach was applied to the Baihetan arch dam on the Jinsha River in China. The concrete temperature was measured at two points for 1 month using both conventional thermometers and DFOSs in the same spatial location. Data were compared using two statistical indicators, MAE and RMSE. Ouyang et al. [31] presented an approach to cracking control in mass concrete structures. The approach was applied to an intake tower of the Qianping reservoir project, located on a tributary of the Huai River in China. The approach used a DFOS system to measure concrete temperatures. Observations from the DFOS system were compared with data recorded over two weeks with two conventional concrete thermometers. No statistical techniques were used to conduct the comparison.

Previous successful applications of DFOSs to monitor concrete temperatures in dams show that FOSs are excellent tools for data collection. However, the performance of FOSs compared to conventional instruments using long observation records taken at the same point and time in real case studies has not been fully analyzed, and published reports are scarce [28–31]. Most published studies assess only one type of fiber-optic technology at very few points along the dam. In many cases, the conventional and Fiber-Optic Sensors are not in the same spatial location, and comparisons are conducted without statistical analyses. The lack of published studies leaves the notion of accuracy dependent on manufacturers' reports and ignores the potential of other types of FOSs. To fill this gap, our innovative case study compares the performance of two widely used FOSs, Raman-type Distributed FOSs and Bragg-type Localized FOSs, with conventional vibrating-wire sensors for monitoring concrete temperatures in a real RCC dam under construction. All FOSs and conventional devices are installed at the same locations in the dam, and variables are collected in time windows of hours. We analyze the observations using statistical techniques and highlight the potential of FOSs compared to traditional sensors. With this work, we show the potential of FOSs for the installation and monitoring of concrete dams, a step of great technical relevance for scientists and practitioners, thereby increasing professionals' confidence in these modern instruments and expanding the advantages FOSs offer society in SHM tasks.

Here, we assess the performance of Raman-type DFOSs and Bragg grating-type Localized Fiber-Optic Sensors (LFOSs) in a real concrete dam. Using statistical techniques, we compared DFOS- and LFOS-measured data with conventional sensor data in our case study. We highlight the potential of DFOSs to detect thermal variations that conventional devices cannot. The paper is organized as follows. In Section 2, we introduce the materials and methods used to assess the performance of FOSs: we describe the conventional and fiber-optic devices installed in our case study and explain the statistical techniques used to compare the measured data from the three device types. In Section 3, we describe our case study, an RCC gravity dam of the Fundão-Santa Clara Energetic Complex Project located in the State of Paraná (Brazil), and we explain the installation of temperature sensors during dam construction. In Section 4, we present and discuss the results of the statistical assessment and show the DFOSs' ability to detect thermal variations, such as the cooling effects of the galleries. Lastly, in Section 5, we draw the main conclusions of our work.

2. Materials and Methods

This section outlines the materials and methodologies used to evaluate the performance of FOSs. Initially, we detail the three types of devices installed to monitor concrete temperature in our case study: Conventional Vibrating-Wire Thermometers (CVWTs), Bragg grating-type LFOSs, and Raman-type DFOSs. Afterward, we describe the statistical methods applied to compare the temperature data recorded by each device and to determine whether the observed differences were statistically significant.

2.1. Concrete Temperature Devices

Three types of concrete temperature devices were installed: conventional thermometers, Bragg-type LFOSs, and Raman-type DFOSs. The devices needed to meet the recommendations of the ICOLD regarding accuracy, which during the operational phase of concrete dams is $0.5\text{ }^{\circ}\text{C}$ [2].

CVWTs were installed at representative points of the dam core to measure the concrete temperature. The sensors consist of a vibrating wire element attached to a steel transducer body. The selected devices were the Geokon model 4700, with an accuracy of $0.5\text{ }^{\circ}\text{C}$ and a resolution of $0.034\text{ }^{\circ}\text{C}$ [33], which meets the ICOLD accuracy recommendation [2].

Bragg grating-type LFOSs were also installed at the same locations as CVWTs. The sensors measure temperature over a short length, or gauge, of the fiber-optic cable, i.e., at localized points, as CVWTs do. Bragg grating-type LFOSs measure changes in the refractive index of light caused by temperature variations [34]. Using these interferences, the interrogator unit determines the temperature at the sensor's position. The installed sensors were FS 6300 devices, designed and manufactured by Fibersensing. The sensors have a sensitivity of $10\text{ pm}/^{\circ}\text{C}$, a measurement range from -20 to $80\text{ }^{\circ}\text{C}$, an accuracy of $0.5\text{ }^{\circ}\text{C}$, and a resolution of $0.1\text{ }^{\circ}\text{C}$ [35]. The probe configuration is straight and made of stainless steel. The device was calibrated by the manufacturer, providing the device's measured temperature as a function of the reference calibration temperature and the wavelength shift. The sensors were placed within a trench built in the fresh concrete, close to the other temperature sensors (conventional thermometers and Raman-type DFOSs). Afterwards, the sensors were embedded within the concrete. The performance of the devices met the ICOLD accuracy recommendation [2].

Raman-type DFOSs measure temperature with a given spatial resolution along the cable, whereas CVWTs and LFOSs measure temperature at a single point. Spatial resolution is defined as the minimum length of resolvable fiber around the measurement point [36]. Raman-type DFOSs are based on the Raman scattering principle, i.e., when a light pulse is launched into the fiber-optic cable, it is redistributed in the form of Raman scattering [37].

Furukawa provided the fiber-optic cable installed in our case study [38], and Sensa supplied the interrogator unit used to measure and interpret Raman scattering along the fiber-optic cable to assess the concrete temperature [39]. The interrogator unit model used to measure the concrete temperature with Raman-type DFOSs was a Sensa DTS 800 [40]. The device has an accuracy of 0.5 °C, a spatial resolution of 1 m, and a sensing range of 8 km. The maximum total loss is 17 dB at an operating wavelength of 1064 nm. The time required to achieve the necessary temperature resolution (defined as the standard deviation of the temperature measured in a fiber section kept at a uniform temperature) is 120 s for 1 °C with a double-ended configuration. The laser's performance was monitored by placing several meters of fiber-optic cable from the measurement loop inside a tank filled with water during all measurements. The water temperature in the tank was measured with a conventional thermometer. The temperature distributions were then calibrated by comparing the laser-measured temperatures with those from the conventional thermometer.

The previously reported devices were installed in 2005. We contextualize FOS technology from the 2005 era with modern systems in 2025, acknowledging subsequent improvements in resolution, spatial resolution, and accuracy. The accuracy of the installed CVWTs and Bragg grating-type LFO sensors, 0.5 °C, is almost the same as current sensors using the same technology [16]. Similarly, for Raman-type DFOSs, the spatial resolution of the devices installed in the dam (1.0 m) has remained almost constant over time, being the same as the current sensors available on the market [16], while accuracy has increased to 0.02 °C [16]. Nevertheless, such accurate devices are not needed for SHM tasks in dams, as Icold recommends an accuracy of 0.5 °C for temperature-monitoring requirements in concrete dams [2]. Regarding the sensing range, old and current Raman-type DFOS readers have a larger range than necessary. In fact, in our case study, we found it was more practical to divide the total cable length into shorter segments, ranging from 400 to 500 m, so lighter cable reels could be used during the dam's construction. Therefore, even if the case study were conducted today with the sensors currently available, our research conclusions would be valid. Moreover, Zhou et al. [28] and Xiang et al. [29] reported in their recent studies the use of Raman-type DFOS interrogators with identical accuracies and spatial resolutions to those used in our case study, whereas Liang et al. [30] reported the use of devices with the same spatial resolution and even lower accuracy than our sensors.

2.2. Statistical Analysis

We compare concrete temperatures measured in our case study by three sensor technologies—CVWTs, Bragg-grating-type LFOs, and Raman-type DFOSs—using three statistical measures of error between paired observations of concrete temperature measured at the same location and time. The measures are the mean absolute error (MAE), the mean squared error (MSE), and the mean absolute percentage error (MAPE).

MAE is calculated as the sum of absolute errors divided by the sample size and reads as follows:

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - x_i|, \quad (1)$$

where n is the number of observations and (y_i, x_i) is the paired observation i .

MSE is the sum of squared errors divided by the sample size. It reads as follows:

$$MSE = \frac{1}{n} \sum_{i=1}^n (y_i - x_i)^2. \quad (2)$$

Lastly, MAPE is a measure of prediction accuracy and reads as follows:

$$MAPE = 100 \frac{1}{n} \sum_{i=1}^n \left| \frac{y_i - x_i}{y_i} \right|. \quad (3)$$

We use Student's t -test to determine whether the differences in paired temperature observations measured with two types of sensors are statistically significant. We also test whether the temperature observations measured in pairs with two types of sensors are from two populations with the same distribution with the Mann–Whitney U -test.

Student's t -test for paired samples tests whether the unknown population means of two groups are equal or not. The null hypothesis is that the underlying population means, μ_x and μ_y , are the same:

$$H_0 : \mu_x = \mu_y, \quad (4)$$

and the alternative hypothesis is that the means are not equal:

$$H_1 : \mu_x \neq \mu_y. \quad (5)$$

The t -test statistic, t_0 , for two groups, denoted with the subscripts x and y , respectively, is calculated as follows:

$$t_0 = \frac{\bar{x} - \bar{y}}{\sqrt{S_x^2/n_x + S_y^2/n_y}} \quad (6)$$

where $\bar{x}$ and $\bar{y}$ are the averages of the x - and y -groups, respectively; S_x and S_y are the standard deviations of the x - and y -groups, respectively; and n_x and n_y are the sample sizes of the x - and y -groups. The average of the x -group, $\bar{x}$, reads as follows

$$\bar{x} = \frac{\sum_{i=1}^{n_x} x_i}{n_x}. \quad (7)$$

where x_i is the i -observation of the x -group. The average of the y -group, $\bar{y}$, is estimated with the same methodology. The standard deviation of the x -group, S_x , is given by

$$S_x = \sqrt{\frac{\sum_{i=1}^{n_x} (x_i - \bar{x})^2}{n_x}}, \quad (8)$$

and the standard deviation of the y -group, S_y , is also estimated with the same approach. The numerator of Equation (6) is the difference between the averages of the two groups. The denominator is an estimate of the overall standard error of the difference between means. It is based on the separate standard error for each group. The degree of freedom v for the t -value is given by:

$$v = \frac{\left(\frac{S_x^2}{n_x} + \frac{S_y^2}{n_y} \right)^2}{\frac{\left(\frac{S_x^2}{n_x} \right)^2}{n_x - 1} + \frac{\left(\frac{S_y^2}{n_y} \right)^2}{n_y - 1}}. \quad (9)$$

We compare the t -statistic with the score of the t -Student distribution for the 95% confidence level and v -degrees of freedom ($t_{0.05, v}$) to conclude whether the null hypothesis is statistically valid or not. If $t_0 < (t_{0.05, v})$, there is no statistical significance between the x - and y -groups.

The Mann–Whitney U -test is a nonparametric statistical test used to assess whether two sampled groups are likely to come from the same population. The test compares every observation x_i in the first group with every observation y_j in the other group. The total number of pairwise comparisons that can be made is $n_x \times n_y$, with n_x and n_y being the

sample sizes of the x - and y -groups. The null hypothesis is that randomly selected values x_i and y_i from two populations have the same distribution. The Mann–Whitney U statistic, U_0 , is defined as

$$U_0 = \min(U_x, U_y) \quad (10)$$

where

$$U_x = n_x n_y + \frac{n_x(n_x + 1)}{2} - R_x, \quad (11)$$

and

$$U_y = n_x n_y + \frac{n_y(n_y + 1)}{2} - R_y, \quad (12)$$

with R_x and R_y being the sums of the ranks in groups x and y . For large samples, R_x and R_y are estimated as follows: (1) First, all the observations are arranged in order of magnitude, and numeric ranks are assigned to all of them. (2) The ranks for the observations in group x are summed to obtain R_x . (3) Since the sum of all the ranks $R_x + R_y$ equals $N(N + 1)/2$, where N is the total number of observations $N = n_x + n_y$, R_y is then given by $R_y = N(N + 1)/2 - R_x$. For large samples, U is approximately normally distributed. In that case, the standardized value z_0 is given by:

$$z_0 = \frac{U_0 - \mu_U}{\sigma_U}, \quad (13)$$

where μ_U and σ_U are, respectively, the mean and standard deviation of U , given by

$$\mu_U = \frac{n_x n_y}{2}, \quad (14)$$

and

$$\sigma_U = \sqrt{\frac{n_x n_y (n_x + n_y + 1)}{12}}. \quad (15)$$

z_0 follows a standard normal distribution. We compare the z -statistic with the score of the z -standard normal distribution for the 95% confidence level $z_{0.05}$ to conclude whether the null hypothesis is statistically valid or not. If $z_0 < z_{0.05}$, there is no statistical significance between the x - and y -groups.

3. Case Study

Our case study is an RCC dam built for the Fundão-Santa Clara Energetic Complex Project [41]. In the following sections, we describe the dam and detail the installation process of the temperature sensors within the dam core.

3.1. Fundão-Santa Clara Energetic Complex Project

The Fundão-Santa Clara Energetic Complex Project consists of a hydroelectric complex, composed of Fundão and Santa Clara Hydroelectric Power Plants, both located in Jordão River, State of Paraná (Brazil). The Fundão Hydroelectric Power Plant is composed of a 45 m high RCC gravity dam, the Fundão dam, and a 120 MW hydroelectric plant. The dam is 250 m long at the height of the crest. Figure 1a illustrates the central block of the dam. The spillway is located on this block, which is 41.5 m high. The upstream face is vertical, and the downstream slope face has a gradient of 0.75. A 50 cm thick layer of CVC was placed on both faces. The dam was built between 2005 and 2006. Figure 1a shows the dam under construction, and Figure 1b shows the dam after construction.



Figure 1. Pictures of the Fundão dam: (a) Under construction, (b) after construction [42].

3.2. Installation of Sensors

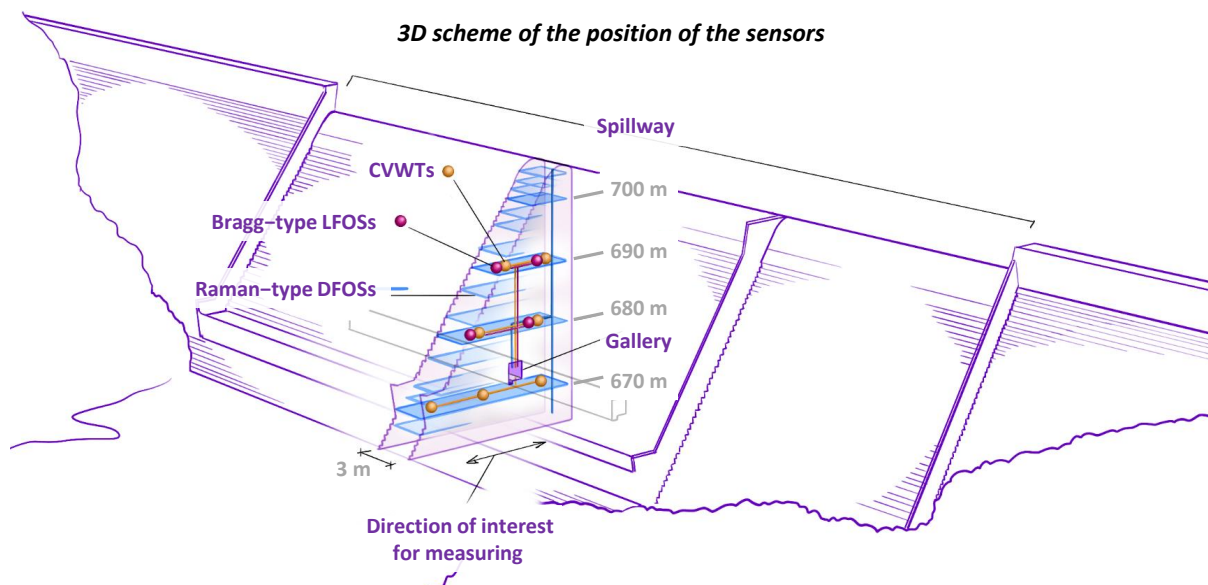
Fundão dam is equipped with three different sensor technologies to monitor concrete temperature during construction and service life, as well as to assess the performance of the three technologies. Figure 2a,b illustrate the position of the sensors installed in the central block of the dam. Three types of sensors were installed: Conventional Vibrating-Wire Thermometers, Bragg-type LFOs, and Raman-type DFOs. The features of the devices are described in Section 2.1.

Seven CVWTs were installed in the central block: three close to the foundation at an elevation of 670 m, two at 680 m, and two close to the crest at 690 m. Four Bragg-type LFOs were installed at elevations of 680 and 690 m. The positions of these sensors coincide with the four CVWTs installed at those elevations in order to compare the readings of both technologies. The positions are enumerated from 1 to 7 in Figure 2a.

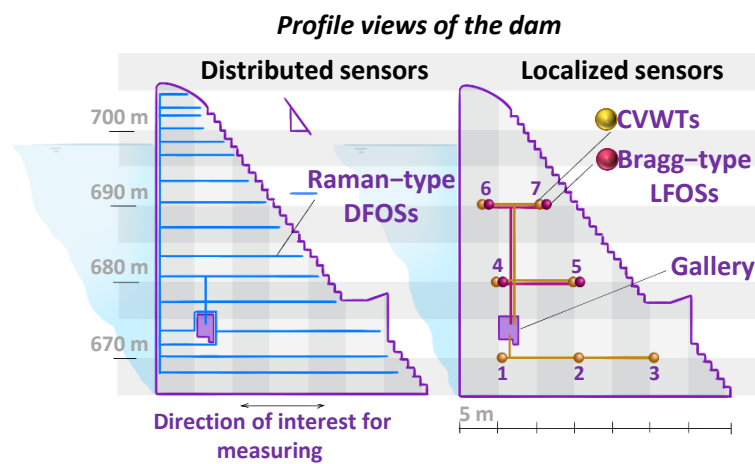
The installation of CVWTs and Bragg-type LFOs was carried out at the same time, as shown in Figure 3. First, wood strips were placed on fresh concrete before compaction to create a trench for cables and sensors—Figure 3a. Once the concrete was compacted, the wood strips were removed—Figure 3b—and both fiber-optic and conventional cables and sensors were placed in the trench—Figure 3c. Afterward, the trench was filled with conventional concrete—Figure 3d—and after it had hardened, the next concrete lift was placed and compacted.

Two fiber-optic cables compatible with Raman DFOS technology were installed in the central block. Each cable was approximately 400 m long and equipped with Raman-type DFOs. In the following text, the figures in parentheses are heights measured from the base of the central block, whose elevation is 665.00 m. The first cable was installed between 667.70 m (height 2.70 m) and 680.00 m (height 15.00 m) of elevation, and the second cable was installed between 683.00 m (height 18.00 m) and 701.90 m (height 36.90 m) of elevation. The loops are rectangular in shape, as shown in Figure 2a. The width of the loops is 3.00 m and they are parallel to the dam's faces at a distance of 0.20 m. Loops are separated in the vertical direction by approximately 3.20 m between elevations 667.70 m (height 2.70 m) and 696.50 m (height 31.50 m), and 1.80 m between elevations 696.50 m (height 31.50 m) and 701.90 m (height 36.90 m). In addition, some segments of the Raman-type DFOs are located in the same position as those of the other two sensor types.

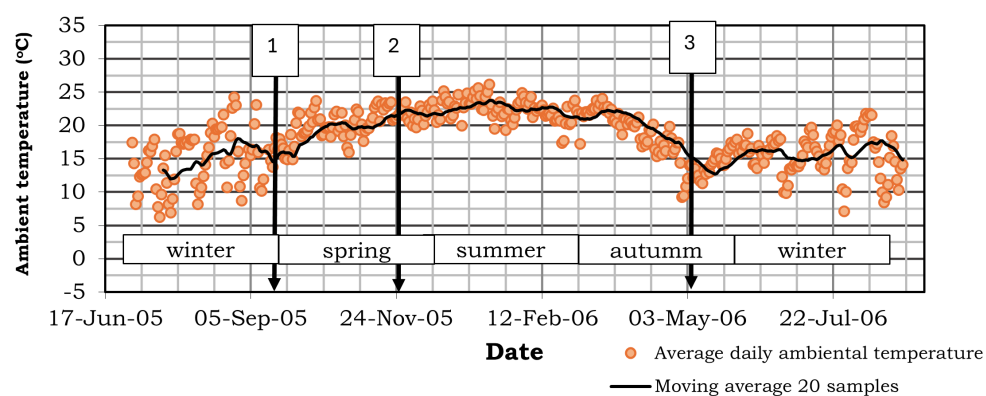
The installation of Raman-type DFOS cables is illustrated in Figure 4. Since high-strength cables were installed, the placement operation was carried out without cutting trenches. Fiber-optic cables were laid on the surface of the last compacted concrete layer and fixed to the surface with nails to guarantee their positions, as shown in Figure 4a. Once the concrete was hard enough, the next concrete layer was poured and compacted, as shown in Figure 4b.



(a)



(b)



(c)

Figure 2. (a) Sketch of the temperature sensors installed in the central block of Fundão dam. (b) A central cross-section of the dam with the installed sensors. (c) The ambient temperature during the construction of the dam.

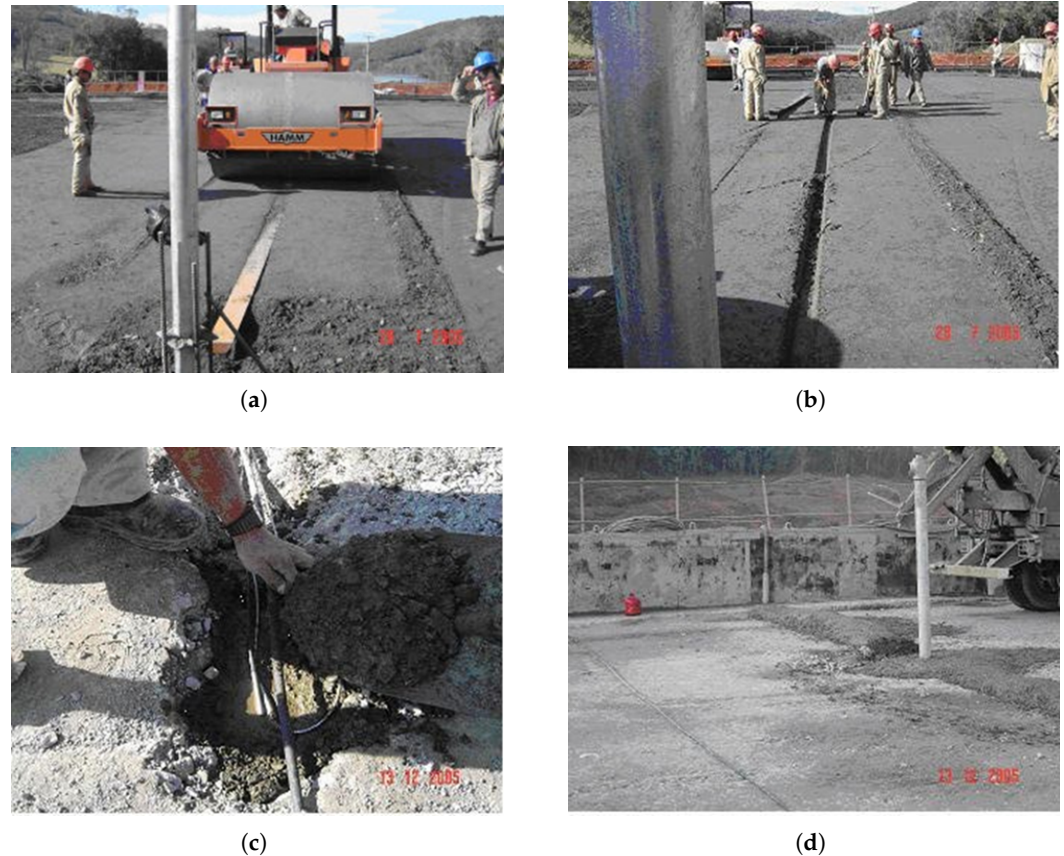


Figure 3. Installation process of the Conventional Vibrating-Wire Thermometers and Bragg grating-type Localized Fiber-Optic Sensors. (a) Wood strips were placed on the fresh concrete before steam-roller compaction to create a trench. (b) After concrete compaction, wood strips were removed to access the trench. (c) Cables for the CVWTs and the Bragg-type LFOs were placed in the trench. (d) Once cables and sensors were installed, the trench was filled with conventional concrete. Once that concrete had hardened, the next concrete lift could be poured.

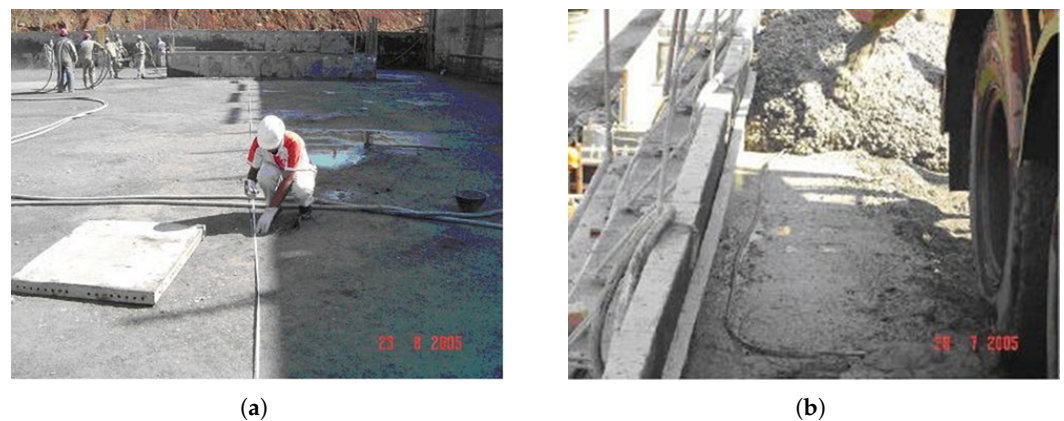


Figure 4. Installation process of the Raman-type Distributed Fiber-Optic Sensors with high-strength cables. (a) Since temperature is measured along the fiber-optic cable in this technology, no sensors were installed; only fiber-optic cables were laid on the surface of the last compacted concrete layer. Cables were nailed to the concrete to guarantee their position. (b) Once concrete was hard enough, the next concrete layer could be poured and compacted.

4. Results and Discussion

The concrete temperature was measured with the three technologies during the construction of Fundão dam. In the following section, we present the recorded concrete temperature data from the observation campaigns and perform several statistical analyses to test whether differences in measured temperatures across technologies at the same location and time are statistically significant.

4.1. Concrete Temperature Monitoring: Observations

The concrete temperature of Fundão dam was measured during the construction of the dam with three types of sensors: Raman-type DFOSs, Bragg-type LFOs, and Conventional Vibrating-Wire Thermometers (CVWTs). The positions of the sensors in the central block of the dam are illustrated in Figure 2a,b, and the main characteristics of the sensors are described in Section 2.1. The evolution of the ambient temperature during dam construction is plotted in Figure 2c. In the following section, we present the observations and analyze the recorded temperatures.

4.1.1. Raman-Type DFOS

The temperature of the concrete was monitored using Raman-type DFOSs installed in the central block of the dam, as illustrated in Figure 2a,b. Temperature was measured only three times—(1) on 19 September 2005; (2) on 27 November 2005; (3) on 5 May 2006—but with high spatial resolution, allowing us to draw the temperature field in a vertical section. The temperature fields are shown in Figure 5. The reading campaigns were conducted by the Technical University of Munich (TUM). Personnel and equipment were mobilized from Germany to Brazil to carry out the readings. The high costs of international visits and the availability of the equipment by TUM limited the number of campaigns to three. Nevertheless, campaigns were planned at key stages of construction and during the weather seasons. The installation and use of this technology in our case study were unprecedented in Brazilian dam construction at that time. They were aimed at validating the Raman-type DFOS technology in the eyes of stakeholders, engineers, and infrastructure managers, among others.

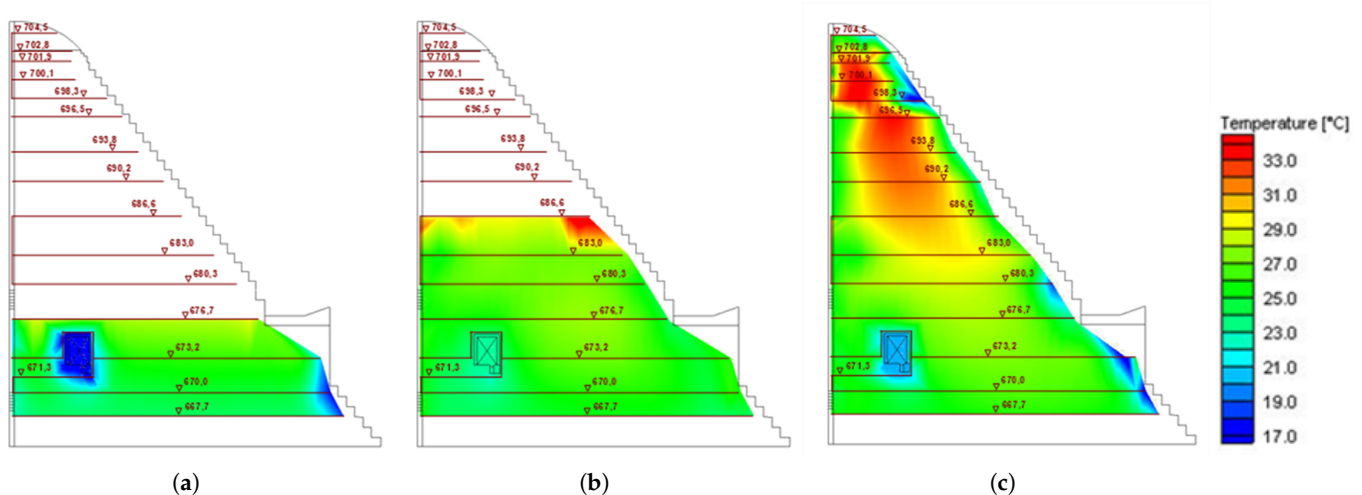


Figure 5. Temperature fields measured with Raman-type DFOSs. (a) The first campaign was on 19 September 2005. (b) The second campaign was on 27 November 2005. (c) The third campaign was on 5 May 2006.

The first campaign took place on 19 September 2005, at the end of winter in Brazil—Figure 5a. The elevation of the dam was 676.7 m, approximately 15 m in height, and the

mean ambient temperature was 15 °C. Since Raman-type DFOSs enable us to measure the dam's thermal field at a given time, we can capture thermal effects that other technologies cannot, such as the thermal cooling effect of the galleries in winter. As the mean ambient temperature was 15 °C, Figure 2c, the concrete temperature around the gallery was about 15 °C, as well as on the downstream face of the dam. In addition, this technology enables us to assess the thermal gradients in the dam. The concrete temperature near the gallery is approximately 15 °C, while the temperature of the recently poured concrete is about 25 °C, implying a thermal gradient of 10 °C in a few meters.

The second campaign took place on 27 November 2005, at the end of spring in Brazil—Figure 5b. The elevation of the dam was 686.6 m, approximately 25 m in height, and the mean ambient temperature was 22 °C. The concrete temperature around the gallery is equal to the mean ambient temperature, 22 °C, Figure 2c, due to the cooling effect of the galleries. In addition, the higher ambient temperature in spring did not promote the release of hydration heat in the most recently poured concrete. The increase in temperature is especially pronounced on the downstream face of the dam, where the temperature is approximately 33 °C, while on the upstream face it is approximately 30 °C. In both areas near the faces, conventional concrete with high cement content was poured instead of RCC. In addition, the cement content on the downstream face is particularly high because the spillway is located there. Both factors—high ambient temperature and high cement content in the CVC—contribute to a significant increase in concrete temperature on the dam's faces.

The third campaign took place on 5 May 2005, at the end of the autumn in Brazil: Figure 5c. The elevation of the dam was 704.5 m, approximately 39.5 m in height, and the mean ambient temperature was 15 °C, Figure 2c. The concrete temperature inside the upper part of the dam is especially high, exceeding 30 °C. Three reasons may explain such a high concrete temperature: (1) that part of the dam was built during summer when the ambient temperature is high and does not promote the release of hydration heat to the atmosphere, plus the hydration reaction is faster; (2) the use of conventional concrete with a high cement content on the downstream face, where the spillway is placed; (3) the evolution of the dam height is faster in this area due to the shorter width of the dam.

4.1.2. Bragg-Type LFOS

The concrete temperature was also monitored using four Bragg-type LFOSs installed at two levels in the central block of the dam, as illustrated in Figure 2a,b. Two sensors were installed at an elevation of 680 m and the other two at an elevation of 690 m. The observations are shown in Figure 6d–g. We also plot the observations obtained with Raman-type DFOSs and the conventional thermometers. The Bragg-type LFOSs generally yield observations that are quite similar to those from the other technologies, except for the device at position 5, where a clear deviation occurs. This Bragg-type device in position 5 underestimates the concrete temperature compared to the Raman-type DFOSs and the conventional devices installed at the same position.

4.1.3. Conventional Temperature Sensors

Seven conventional temperature sensors were installed in the dam: three at an elevation of 670 m, two at 680 m, and two at 690 m. The recorded values are plotted in Figure 6. Temperatures observed with conventional thermometers are qualitatively very similar to the thermal records obtained with fiber-optic technologies, except at location 5, where the Bragg-type LFOSs underestimated temperatures relative to the Raman-type DFOSs and the conventional devices.

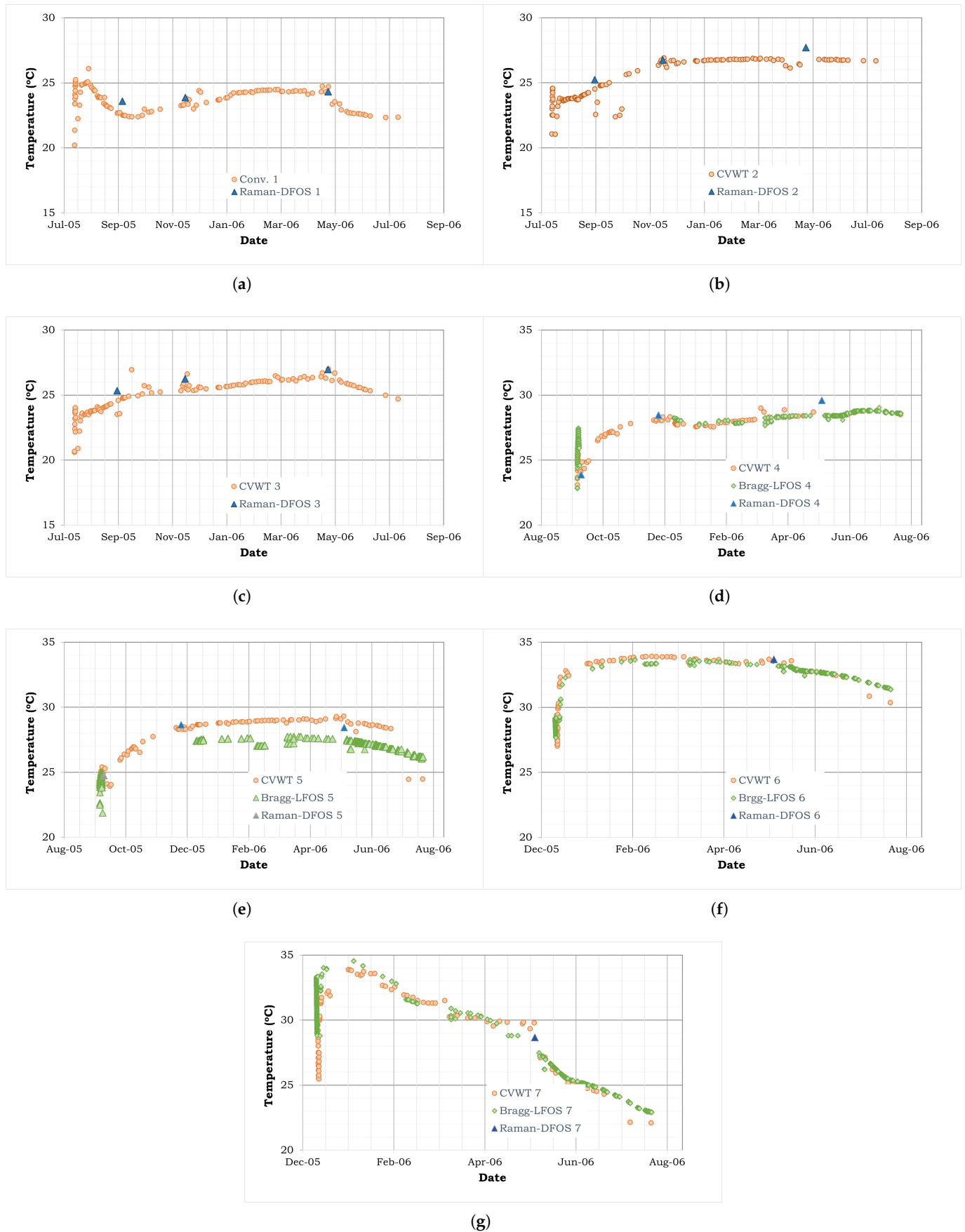


Figure 6. Temperature fields measured with CVWTs (denoted as Conv. in the legend of the plots), Bragg-type LFOs, and Raman-type DFOs in positions (a) #1, (b) #2, (c) #3, (d) #4, (e) #5, (f) #6, (g) #7.

4.1.4. Paired Observations

The temperature fields measured with Raman-type DFOSs are plotted in Figure 5. The observed temperature measured with conventional thermometers, Bragg-type LFOSs, and Raman-type DFOSs at the seven considered positions (Figure 2b) are shown in Figure 6. The number of available observations is listed in Table 1, as well as the paired observations of the FOS with conventional devices. We paired observations with a time window of less than one day, i.e., observations that were collected on the same day. We did not apply either interpolation or averaging to pair observations. This criterion reduced the available data for statistical analysis of results. For pairs of Bragg-type LFOSs and conventional devices, 100 paired observations were available. The time lag for 76% of the pairs was less than 1.5 h. For pairs between Raman-type DFOSs and conventional devices, 17 paired observations were available. The time lag for 18% of the pairs was less than 1.5 h. However, given concrete's thermal inertia, at a fixed location, the variation in concrete temperature with time lags shorter than 1 day is almost negligible.

Table 1. Available observations. Figures in parentheses are paired observations collected with conventional concrete thermometers.

Position	Elevation (m)	Conventional	Bragg-Type LFOSs	Raman-Type DFOSs
1	670	116	--	3 (3)
2	670	112	--	3 (3)
3	670	117	--	3 (3)
4	680	114	5702 (32)	3 (3)
5	680	118	5702 (32)	2 (2)
6	690	83	4999 (18)	2 (2)
7	690	83	4999 (18)	1 (1)

4.2. Statistical Analysis of Observations

We evaluate the differences between paired observations of concrete temperatures with fiber-optic technology sensors and conventional temperature sensors using three measures: MAE, given by Equation (1); MSE, computed with Equation (2); and MAPE, given by Equation (3).

We list the values of those measures for paired observations with Raman-type DFOSs and conventional sensors in Table 2. MAE and MSE values are, respectively, always lower than 1.00 °C or 0.50 °C², except for the thermometer installed at position 7, where they are higher than 1.00 °C and 1.00 °C², respectively. MAPE is lower than 3.00% in all positions except, as expected, in sensor #7. The results at position 7 may not be representative, due to discrepancies between the readings of conventional sensors compared to the temperature evolution curves.

The values of the measures for paired observations with Bragg-type LFOSs and conventional temperature sensors are listed in Table 3. MAE and MSE values are, respectively, always lower than 1.00 °C or 1.00 °C², except for the sensors in position 5, where the measures increase to 1.50 °C and 2.40 °C², respectively. MAPE is less than 3.00% in all positions except, as expected, in sensor #5. The evolution of the observations at position 5 measured with Bragg-type LFOSs, shown in Figure 6e, shows a clear deviation from those obtained with the other two technologies, Raman-type DFOSs, and conventional sensors. We hypothesize that differences in temperatures measured with the Bragg-type sensor at position 5 may arise from a damaged sensor, among other causes, such as equipment detection data failures or an isolated anomaly during installation. The authors do not have equipment-detection data or additional installation records to propose other causes of the deviation in Bragg-type LFOS data at position 5.

Table 2. Statistical measures of error between paired observations of Raman-type DFOSs and conventional temperature sensors.

Position	Elevation (m)	MAE (°C)	MSE (°C ²)	MAPE (%)
1	670	0.51	0.45	2.21
2	670	0.31	0.12	1.22
3	670	0.45	0.29	1.77
4	680	0.67	0.52	2.61
5	680	0.60	0.48	2.27
6	690	0.13	0.02	0.40
7	690	1.13	1.28	3.80

Table 3. Statistical measures of error between paired observations of Bragg-type LFOSs and conventional temperature sensors.

Position	Elevation (m)	MAE (°C)	MSE (°C ²)	MAPE (%)
4	680	0.14	0.04	0.52
5	680	1.52	2.45	5.67
6	690	0.36	0.28	1.17
7	690	0.65	0.79	2.43

We determined whether the difference between the paired temperature observations measured with Raman-type DFOSs and conventional temperature sensors is statistically significant using Student's *t*-test. The test results are listed in Table 4. The *t*-test statistic for the two groups of observations, Raman-type DFOS observations and conventional temperature sensor observations, is given by Equation (6) and equal to $t_0 = 0.2897$, and the degree of freedom v for our recorded temperatures is $v = 28$, as included in Table 4. Loosely speaking, the *t*-test statistic is a “standardized measure” of the difference between the mean temperatures recorded with the DFOSs and those recorded with conventional technologies. For a 95% confidence level and 28 degrees of freedom, Student's *t* distribution is $t(0.05, 28) = 1.6991$. Since $t_0 < t(0.05, 28)$, the difference between the two groups of observations is not statistically significant with a 95% probability. The critical value *t* depends on the adopted significance level of the test, 95%, and quantifies the probability of erroneously rejecting the null hypothesis, which means that the measured data with the Raman-type DFO and the conventional temperature sensors are from the same population and, consequently, there is no significant difference in the performance of the DFO sensors and the conventional devices.

We also checked whether the paired temperature observations from Raman-type DFOSs and conventional temperature sensors are from two populations with the same distribution with the Mann–Whitney *U*-test. The test results are listed in Table 4. The standardized *U*₀-test, z_0 , is given by Equation (13) and equal to $z_0 = -0.021$. For a 95% confidence level, the two-tailed standard normal distribution is $z(0.05/2) = 1.960$, as included in Table 4. Loosely speaking, the *U*₀-test statistic is a “standardized measure” of the difference between the median values of the temperatures recorded with the DFO devices and the conventional sensors. As $z_0 < z(0.05/2)$, the recorded temperature data with both types of sensors arise from populations with the same statistical distributions with a 95% probability. Therefore, the differences between the observed temperature data measured with both types of sensors are not statistically significant and are due only to chance.

Table 4. Student’s *t*-test and Mann–Whitney *U*-test for paired temperature observations measured with Raman-type DFOSs and conventional temperature sensors.

Student’s <i>t</i> -Test	
t_0	0.2897
v	28
$t(0.05, v)$	1.6991
Mann–Whitney <i>U</i> -Test	
z_0	−0.021
$z_{0.05/2}$	1.960

Lastly, we tested whether the differences between paired temperature observations at each position measured with Bragg-type LFOs and conventional temperature sensors were statistically significant using Student’s *t*-test. We list the test results in Table 5. The values of the *t*-test statistics indicate that the differences between the two groups of observations are not statistically significant with a 95% probability, except for the temperatures recorded in sensor #5. Then, the difference in the observed temperatures at position 5 between the LFO device and the conventional sensors may not be due only to chance, and differences may arise for other underlying reasons.

The values of the Mann–Whitney *U*-test listed in Table 5 yield the same conclusions. The recorded temperature data from both sensor types follow the same statistical distributions with a 95% probability, except for those recorded by sensor #5. Both technologies have a similar performance, and differences between recorded temperatures are due only to chance, except for at position 5, where other causes produce the differences in the observations.

We have assumed that temperature observations are independent to apply Student’s *t*-test and the Mann–Whitney *U*-test. Temporal autocorrelation violates the independent assumption and may lead to an inflated Type I error rate, i.e., a higher chance of falsely rejecting the null hypotheses (the null hypotheses are that the population means are the same for Student’s *t*-test and that data have the same distribution for the Mann–Whitney *U*-test). Therefore, temporal autocorrelation may lead to a rejection of the hypothesis that paired observations are from the same population.

Table 5. Student’s *t*-test and Mann–Whitney *U*-test for paired temperature observations measured with Bragg-type LFOs and conventional temperature sensors.

Position	4	5	6	7
Student’s <i>t</i> -test				
t_0	0.3180	4.2970	0.0418	0.3562
v	59	58	34	33
$t(0.05, v)$	1.6711	1.6716	1.6909	1.6924
Mann–Whitney <i>U</i> -test				
z_0	−0.2180	5.4980	−0.2210	0.1900
$z_{0.05/2}$	1.9600	1.9600	1.9600	1.9600

4.3. Economic and Practical Issues

Raman-type DFOSs are easier and faster to install than conventional devices because they do not require trench construction to place sensors and cables, and no conventional concrete needs to be applied to filled trenches once the sensors and cables are placed. Moreover, the economic cost of Raman-type DFOS cable is much lower than the cost of conventional device cables. However, monitoring data is more expensive with Raman-type DFOSs than with conventional devices.

Bragg-type LFOs must be installed following the same procedure as conventional devices. However, the possibility of producing a multiplexed sensor system, i.e., one where multiple sensors can be used in series over the same transmission cable, abruptly reduces the number of cables to be installed for a dam's monitoring system. Therefore, a whole monitoring system based on LFOs is easier to install than an equivalent system based on conventional devices. Moreover, since the economic cost of Bragg-type LFOs and conventional devices is similar, a dam monitoring system based on LFOs is cheaper than an equivalent system with conventional devices, as the total length of transmission cables is shorter.

5. Conclusions

We evaluated the performance of two types of Fiber-Optic Sensors (FOSs) for monitoring concrete temperature in a case study, comparing them with Conventional Vibrating-Wire Thermometers (CVWTs). Our case study is the Fundão Hydroelectric Power Plant, equipped with a 45 m high Rolled Compacted Concrete gravity dam. The dam is part of the Fundão-Santa Clara Energetic Complex Project, located on Jordão River, State of Paraná (Brazil). The main findings of our work highlight the significant potential of both Raman-type Distributed Fiber-Optic Sensors (DFOSs) and Bragg grating-type Localized Fiber-Optic Sensors (LFOs) to enhance Structural Health Monitoring (SHM) of dams.

Raman-type DFOSs demonstrate superior spatial resolution and comprehensive thermal mapping. These sensors effectively provided a high-spatial-resolution thermal field of the dam, enabling the detection of detailed thermal phenomena that would otherwise not be observable with conventional technologies. This included identifying the cooling effect of the dam galleries and significant thermal gradients, such as a 10 °C difference over just a few meters between the galleries and the dam faces. The observations also captured the influence of ambient temperature, concrete lift placement, and varying cement content on the dam's internal temperature distribution.

We also performed statistical tests to assess whether differences in concrete temperature observations obtained with two technologies, Raman-type DFOSs and conventional sensors, were statistically significant. Despite their unique capabilities, the temperature data measured with Raman-type DFOSs showed no statistically significant differences from those of CVWTs with a 95% probability, as validated by Student's *t*-test and the Mann-Whitney *U*-test. The mean absolute error (MAE) and mean squared error (MSE) values were consistently low, generally below 1.0 °C and 0.5 °C², respectively. Lastly, Raman-type DFOSs are easier and faster to install compared to conventional devices, as they do not require trench construction or subsequent concrete infilling. Although the cable costs less, data acquisition for monitoring can be more expensive.

Bragg grating-type LFOs offer reliable localized measurements with multiplexing benefits. These sensors provide localized temperature measurements, analogous to CVWTs. Bragg grating-type LFOs also yielded statistically comparable results to those of conventional sensors, with low MAE and MSE values generally below 1.0 °C and 1.0 °C², respectively. Although individual Bragg-type LFO installations follow a procedure similar to conventional devices, requiring trenches, their multiplexing capability is a key advantage. This feature significantly reduces the total number of cables needed, making a complete Bragg grating-type LFO-based monitoring system easier and potentially cheaper to install than an equivalent system using conventional devices.

Our study confirms that Raman-type DFOSs and Bragg-type LFOs are effective and reliable technologies for concrete dam temperature monitoring, providing data quality comparable to that of conventional sensors. Raman-type DFOSs offer unprecedented spatial resolution for detailed thermal analysis, while Bragg grating-type LFOs offer practical

advantages in installation and overall system cost through their multiplexing capabilities. The successful application and validation of these FOS technologies mark a significant step towards more advanced, comprehensive SHM systems for ensuring the long-term safety and functionality of concrete dams.

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Abbreviations

The following abbreviations are used in this manuscript:

CVC	Conventional Vibrated Concrete
CVWT	Conventional Vibrating-Wire Thermometer
DFOS	Distributed Fiber-Optic Sensor
FOS	Fiber-Optic Sensor
LFOS	Localized Fiber-Optic Sensor
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MSE	Mean Squared Error
RCC	Rolled Compacted Concrete
SHM	Structural Health Monitoring

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