

## Methodology applied for the installation of fiber optical sensors for AAR expansion monitoring in Peti dam

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### Abstract

*Innovative auscultation technologies based on the use of optical fiber have been used with the aim of complementing the field of research and monitoring of civil construction. Dams affected by the alkali-aggregate reaction (AAR) are a potential field of application of these new technologies. These structures should be evaluated to determine how much of this deleterious effect may influence the reduction of their service lives. This work aims to present an innovative methodology for the installation of DTSS (Distributed Temperature and Strain Sensing) optical sensors in the Peti gravity arc dam belonging to Cemig for AAR expansion monitoring. For this purpose, eight vertical boreholes with different depths were instrumented, varying from 3.00 m to 30.00 m, distributed along the dam. Utilizing the characteristics of the DTSS type sensor, all the holes were instrumented by a single cable sequentially, making it possible to collect the data by only one monitoring point. It is proposed with this research to validate, within a few years of monitoring, the use of this type of sensor in the detection of strains from the ARR in the dam under study. Results obtained in laboratory tests indicate the possibility of using this technology for monitoring concrete structures subjected to AAR expansion.*

**Keywords:** AAR; DTSS; Concrete dam; Strain

## 1. INTRODUCTION

The Peti Hydroelectric Power Plant (HPP) was built between 1941 and 1945, on the Santa Bárbara river, in the city of São Gonçalo do Rio Abaixo, Minas Gerais, Brazil. The dam of the Peti HPP shown in Figure 1.1 is an arch-gravity type dam, with a maximum height of 43 meters and a crest length between abutments of approximately 86 meters. Its structure consists of a spillway with six gates and a bottom outlet.

Since 1972, changings on the strain field of the dam structure are observed due to the action of the alkali-aggregate reaction (AAR), which consists of a deleterious chemical reaction between the alkalis released during cement hydration and certain reactive minerals present in the aggregate [1].

In order to monitor the effect of this phenomenon on the structure of the dam, two multiple rod extensometers were installed in 1997, positioned at specific points of the dam. In the year 2012, eight vertical boreholes with different depths were instrumented with fiber-optic sensors, ranging from 3 meters to 30 meters in depth, distributed along the dam.

At that time, given the originality of the application of distributed temperature and strain sensors for the monitoring of concrete deformation caused by the AAR, no previous information regarding their efficiency and durability were found.



Figure 1.1: Peti dam.

## 2. MONITORING TECHNOLOGY WITH DISTRIBUTED SENSORS

The strain assessment technology via fiber optics has been gaining gradual space in the structural instrumentation market, mainly due to the resulting precision and efficacy ([2]; [3]; [4]). For concrete structures the application is quite broad, ranging from material behavior assessment from early ages [5] and on more advanced stages [6] to structural reinforcements [7] and intelligent structures [8].

The DTSS technology used for measuring distributed strains and temperatures in fiber optics, is based on the behavior of Brillouin-scattering-peaks found on the backscattered light spectrum along all its length [9].

When the fiber-optic cable is subjected to strain or temperature variations, changes in frequency and intensity are observed, respectively from the peaks of Brillouin and Raman, what allows for the correlation with external measurements (Figure 2.1).

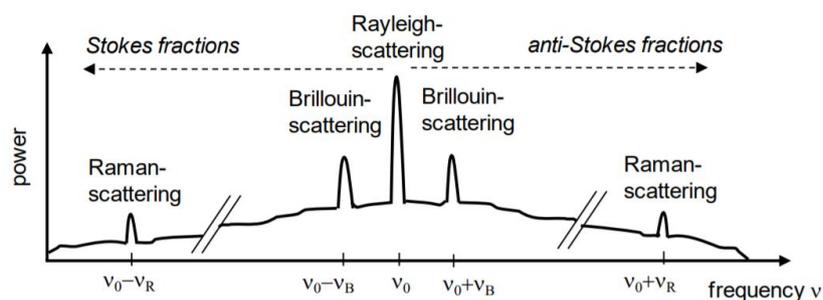


Figure 2.1: Typical spectral components in the backscattered light [9].

The position of the fiber-optic cable range affected by strain or temperature variations is determined through measurements in the time domain. This process is known as OTDR (Optical Time Domain Reflectometry). With the knowledge of the speed of light inside the material that composes the fiber, it becomes possible to identify the mean variations on the Brillouin and Raman peaks for each segment, with a pre-determined size, along the whole length of optical fiber.

Bragg sensors consist of localized gratings inscribed in the core of the fiber resulting from the lateral exposition of the center of the single-mode fiber to an intermittent pattern of high intensity ultraviolet light. These markings might be printed during or after the optical fiber's fabrication processes, which allows for the customization of optical fiber cables with points distributed along predetermined locations. This technology was integrated on the deformation monitoring system of the PETI dam, in strategically

located holes, in order to allow future comparison of strains obtained with this technique with those obtained from the traditional extensometers of the dam.

With that in mind, laboratorial studies on specimens were performed aiming for technology validation. Afterwards, sensors were installed on the dam with the objective of monitoring the advance of AAR on the dam structure.

## 2.1 Methodology applied on the laboratorial specimens' tests

According to Rocha et al. [10], a laboratory test was performed aiming to evaluate the potential use of distributed fiber optic strain sensors (DTSS) for monitoring concrete expansion due to AAR. For this purpose, specimens with 0.10 x 0.10 x 1.40 m sizes were molded using a potentially reactive mortar. The DTSS cables were installed longitudinally within 12 specimens according to Figure 2.2.

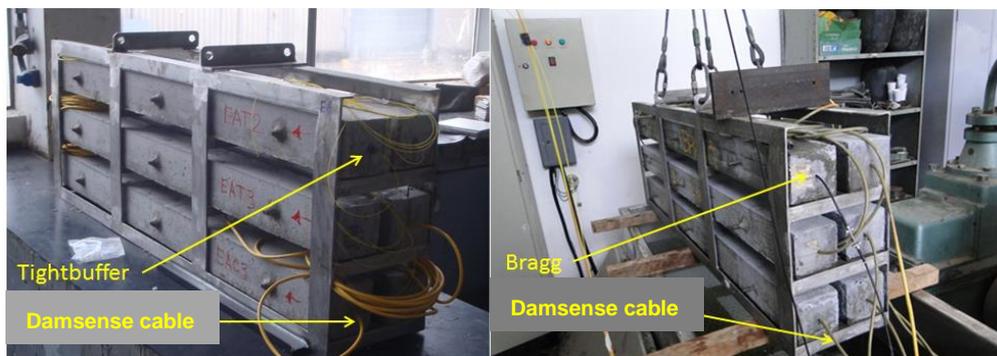


Figure 2.2: Specimens kept inside the metal structures.

The two metallic structures with 12 specimens were immersed in a tank, initially filled with water at ambient temperature. After placement, the tank heating system was initiated rising the water temperature with a constant 10 °C/hour rate, up to 80 °C. Once the top constant temperature was reached, a NaOH solution (40 g for 900 ml of water) was added and daily verified to ensure concentration of 1.00±0.01 N.

The adding of a NaOH solution stablished the inception of the tests, which lasted for 30 days. In the monitoring routine, daily measurements for data collection were performed through the use of a dial indicator. However, the strain monitoring via the DTSS system was performed automatically each 30 minutes, 24 hours per day.

For the external strain measurements with dial indicators a chain hoist was used for completely lifting the metal structures from the tank. After the measurements, the structures were again positioned inside the tank. Figure 2.3 shows the stages of the laboratorial tests. The temperature of the water was kept constant by the thermostat instrumented in the immersion tank.

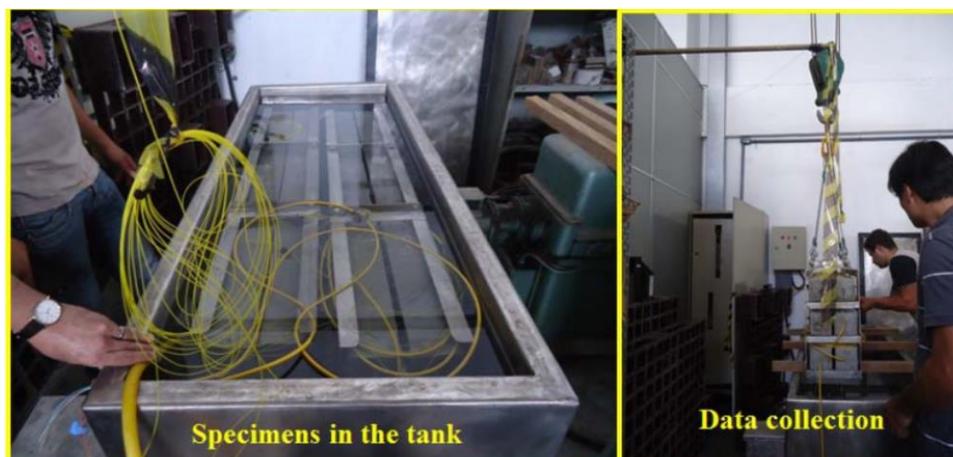


Figure 2.3: Data gathering process.

## 2.2 Methodology for instrumentation on the Peti dam

The installation of fiber optics sensors on the PETI dam was determined according to the distribution of boring holes and by the positions of the extensometers already instrumented in the dam.

The criteria used in choosing which boring holes would be instrumented was based on aiming for the position of sensors in such a way that the whole structure would be instrumented. A higher number of sensors was positioned on the left abutment, due to the fact that higher strains were observed on this region by the extensometers. Apart from those factors it was also made sure that near each extensometer both the BRAGG and the DTSS monitoring technologies would be present.

As a methodology for installing the fiber (Figure 2.4) along the structure of the dam the following steps were adopted: boring hole surface cleansing, fixing of the sensor's head on the base of the hole, fiber optics cable tensioning, filling of the hole with cement paste and protection of the fiber optics cables.

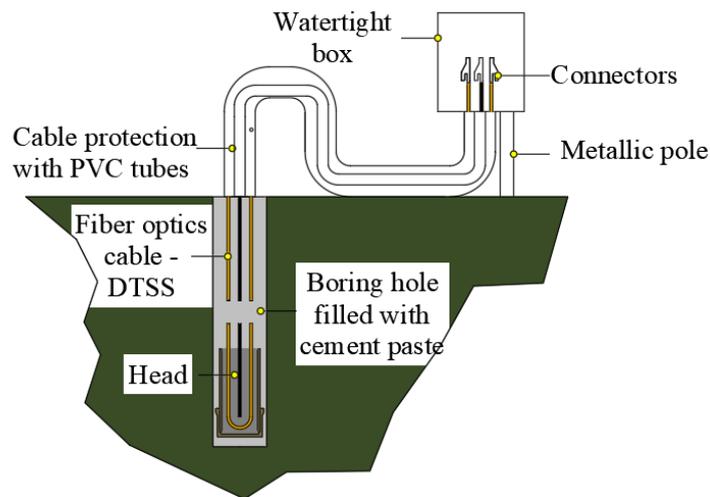


Figure 2.4: Placing of optical fiber inside boring hole.

The adopted sequence starts at the data collection unit, where the connectors are installed, from this point it follows to the boring holes 1B/1A/3A/F5/F6/SR1/2B Series/2A Series/SR2/F7, and finally returns to the data collection unit, according to the illustration in Figure 2.5.

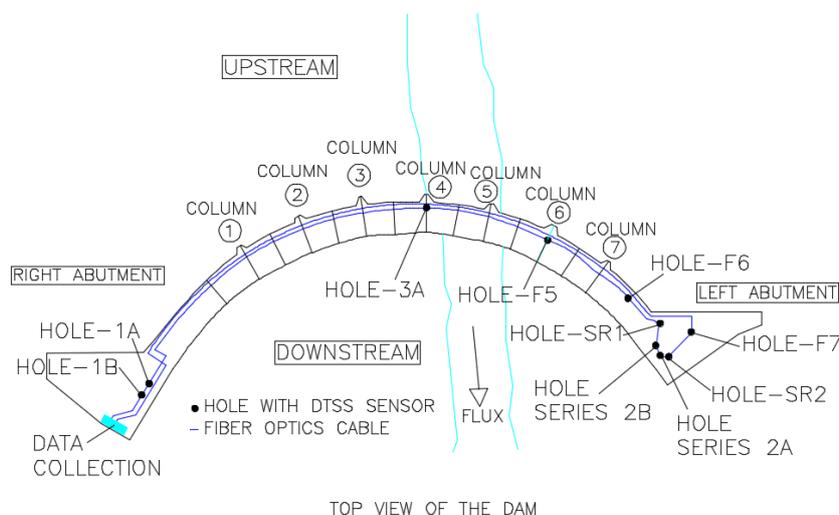


Figure 2.5: Top view of the dam with the DTSS fiber-optic cable distribution.

The fiber optics monitoring of the dam was split in three separate data collection campaigns, distributed along three seasons: spring, autumn and winter.

The first campaign took place after the sensors were installed, on the 27<sup>th</sup> of November of 2012, being set as a reference campaign, meaning that the absolute strain measurements of this campaign were set as zero for each sensor's scale. The second campaign happened 4 months after the reference campaign, on the 18<sup>th</sup> of March of 2013, and the third campaign took place on the 28<sup>th</sup> of July of 2013.

On all three data collection campaigns, the climate conditions and the reservoir water level were different, and also the number of opened sluices was different on all three campaigns, as shown in Table 2-1. Figure 2.6 illustrates the climate and sluices conditions on the data collection instant.

Table 2-1: Gathered information on all three data collection campaigns

Characteristics		Campaign		
		1	2	3
Date		11/27/2012	03/18/2013	07/28/2013
Climate		Sunny	Rainy	Sunny
Reservoir water level (m)		708,53	711,16	712,07
Ambient temperature (°C)		28,5	22	19
Number of opened sluices		3	0	1
Central span	strain PEBCEH 101 (με)	172	173	182
	strain PEBCEH 102 (με)	-	165	172
	strain PEBCEH 103 (με)	182	143	178
Left abutment	strain PEBCEH 201 (με)	700	713	722
	strain PEBCEH 202 (με)	706	737	745



Figure 2.6: Peti dam characteristics during data collection on all three campaigns.

### 3. RESULTS

#### 3.1 Laboratory specimens

Given the size differences between the standard specimens [11] and the prepared large ones with fiber optic sensors, it is expected that expansion does not occur in the same manner during the fixed period of 30 days. Penetration of the solution's reactive elements across the larger specimens is more time consuming and the longitudinal expansion is not homogeneous across the transversal section. Larger longitudinal strains are expected closer to the surface in direct contact with the heated solution. Therefore, strain measurements should be different not only between small and large specimens, but also within each large specimen between external pin and fiber optic measurements.

Figure 3.1 shows evidence of this behavior where the expansions of the large and small specimens, molded with the same material, are compared along 30 days. For readings on the specimens according to the standard [11], three metallic pins were placed in the lateral surface of each specimen in order to allow external expansion monitoring with a calliper rule. Each group of pins was fixed with at least 50 cm spacing.

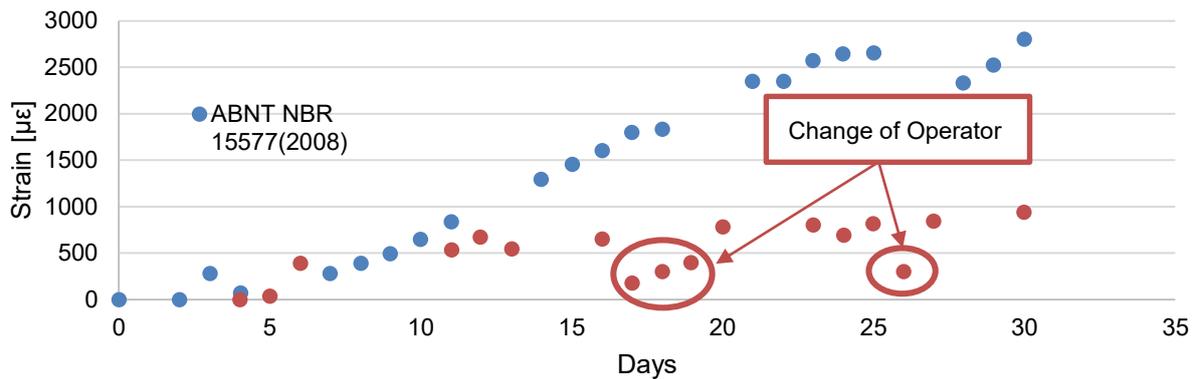


Figure 3.1: Comparison between standard and larger specimens.

The final expansion of the smaller specimen is close to 2800  $\mu\epsilon$ , while the average external pin measurements of the larger specimen reached 900  $\mu\epsilon$ , approximately. Due to intrinsic characteristic of the metallic pins and measuring procedure, larger measuring uncertainties were expected. This is clearly shown in Figure 3.1 when a second operator performed the same measuring procedure.

Due to the aggressiveness of the high temperature NaOH solution, cable and tight buffer degradation were observed. This condition is not a problem in field installations, but it is relevant in the laboratory test analysis since it affects the bonding condition between sensors and the surrounding expanding mortar. The DTSS retrieves results that are an average condition of the cable (or tight buffer) along 1.02 m. If this condition is changed within this range, the system cannot interpret the optic signals properly. This effect is evident in Figure 3.2. Data results from the tight buffer are not reliable after 10 measuring days, while the cable, which is a more protected element, shows coherent results up to the 15th day of measurements. After these periods in each case, the obtained information is not relevant. However, it must be emphasized that the expansion detected within the coherent period is in agreement with the external pin measurements. Its magnitude is lower as expected, due to the strain gradient from the external surface to the centre of the specimen. However, the important results are the evidence of its capacity of detecting AAR evolution.

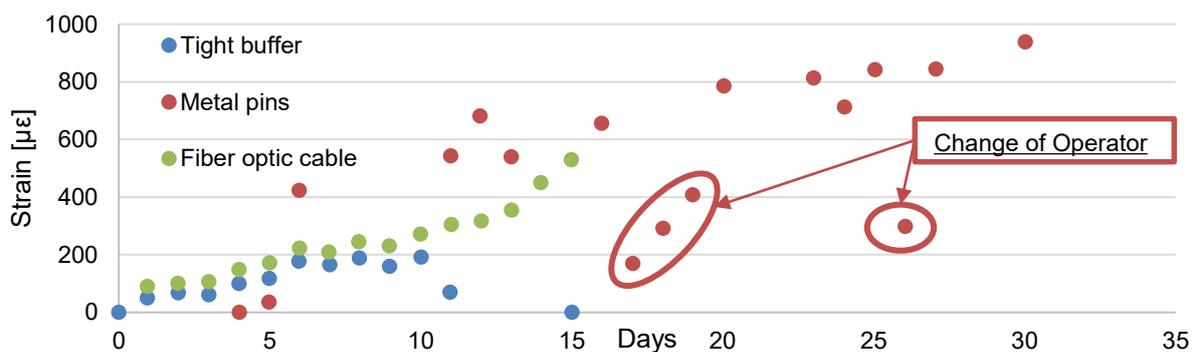


Figure 3.2: Comparison of measurements of a large specimen – external metallic pins and optic sensors.

### 3.2 Experimental on-site tests of Peti dam

The experimental results were processed taking into account the influence of temperature, with that, in this paper, only the results of boring holes 3A and SR2 will be discussed. Besides that, the obtained results are plotted along the length of each boring hole, the ordinate axis receives the data of the hole's depth and the abscissa axis the strain measured on each campaign. The reference values, gathered during the first campaign, represent the strain on the fiber-optic cable after the first 24 hours of the hole's filling.

Values to the left of the reference line correspond to negative strain, representing a compression process, and when placed to the right of the reference line the values correspond to positive strains, representing a tensioning process.

Attention is brought to the graphs (Figure 3.3 and Figure 3.4), where it is possible to notice that between the dates of the reference and the second campaign, negative strain was observed on all the instrumented sensors. This behavior is due mainly to the shrinkage of the cement paste that occurred after the collection of reference data during the first campaign. According to Rodrigues and Bauer [12], shrinkage on cement-based structures occurs in an accelerated manner on the first 10 days and its effect may exceed 60 days, reaching magnitudes of circa  $300 \mu\epsilon$ , which justifies the observed results.

The comparison between the DTSS data gathered on the third campaign with the results of the second campaign show an increase on the strain values. These increases stay in the range of error of the DTSS equipment, being that  $\pm 50 \mu\epsilon$ , the observed increases were always positive. This behavior was also observed on the multi-point rod extensometer installed in 1997, as shown in Table 2-1.

It is also possible to observe that the positive strains that occurred on the points vary for each meter increase, which may be justified by the heterogeneity of the conditions (materials, temperature, confinement) along each hole.

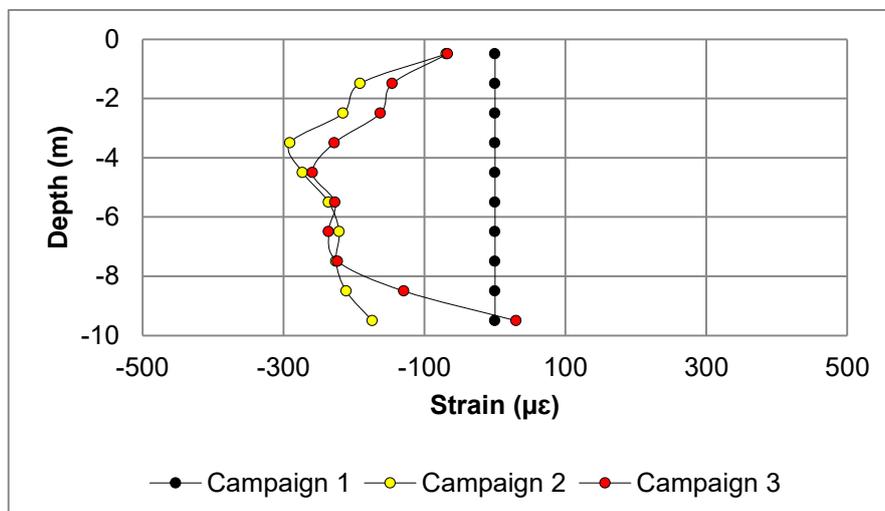


Figure 3.3: Strain profile gathered via DTSS for hole 3A.

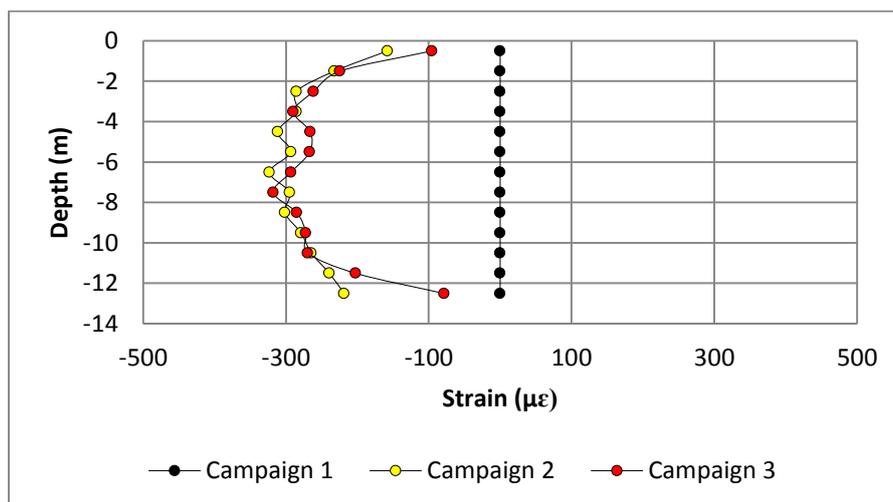


Figure 3.4: Strain profile gathered via DTSS for hole SR2.

#### 4. CONCLUSION

Laboratory tests demonstrated the viability of using DTSS sensors for AAR expansion monitoring. One of the main advantages of distributed monitoring technology is the high spatial coverage and the density of information, because with only one end it is possible to obtain the deformations present in all holes

sequentially. The Peti dam is still showing evidence of a slow and continuous expansion due to ARR. The installation of DTSS sensors in this structure is a great opportunity for validation of these technologies for this type of assessment.

The final result of the on-site instrumentation was positive, since all sensors were capable of bringing results on all three campaigns. Focus is brought to the installation, to the practical way in which data is gathered and to the number of points spread along a single hole, which allows for the assessment of strain for increments of 1 meter along the length of the hole.

The first experimental readings are consistent and point to the expected behavior of cement paste shrinkage.

When the second and the third campaign's results are compared, it is possible to notice the coherence between behaviors observed when comparing results with data gathered via the multi-point rod extensometer.

## 5. ACKNOWLEDGEMENTS

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