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OBSERVATION OF THE BEHAVIOUR OF FOZ TUA DAM DURING THE FIRST FILLING OF THE RESERVOIR

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Abstract: *The Foz Tua Project is the latest accomplished hydroelectric investment of EDP - Energias de Portugal, located in a tributary of Douro River, close to its mouth, in the northeast of Portugal, which includes a concrete double curvature arch dam 108 m high with a total crest length of 275 m, closing a narrow granitic valley.*
After a brief presentation of the project, the monitoring system is introduced, reporting namely the automatically controlled remote observations.
The overall characterization of the behaviour evolution is presented, noticing the perceived agreement between observations in redundant systems, as well as the sought correlation between related physical quantities.
Furthermore, some minor inelastic behaviours related to local adjustments of the dam/foundation structure, as well as the improvements in the designed foundation drainage and piezometric networks which were implemented accordingly to the foundation hydraulic behaviour observed in the last impoundment stages, are also commented.
Bearing in mind the adequate behaviour during the first filling of the reservoir and the good fitness of a nonlinear finite element model it was concluded that the dam is apt to the following serviceability state.

1 DESCRIPTION OF THE FOZ TUA DAM

Foz Tua dam, located in the Tua River, 1100m far from its confluence into Douro River, in the North of Portugal[1], is a double curvature concrete arch dam 108 m high, 275m long at the crest, which has a theoretical width of 5m (Figure 1). The structure is divided into 18 blocks whose widths varies from 13.50m to 15.5m, except for 3 blocks in the valley bottom with 17m. The total concrete volume of the dam is 317,000m³. It was engineered and constructed by “EDP Produção” a company of “EDP – Energias de Portugal” Group, being the detailed design performed by COBA – Consultores de Engenharia e Ambiente, S.A..

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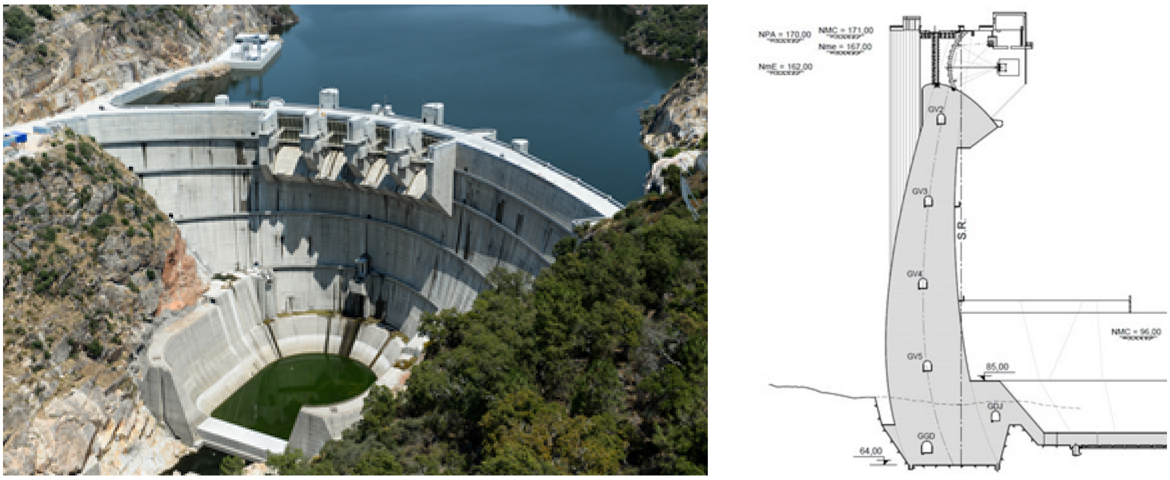
The dam is provided of five horizontal inspection galleries (GV1 to GV5) and of a drainage gallery along the dam-foundation contact, near the upstream face (GGD). In the bottom of the valley there is a downstream drainage gallery (GDJ). The inspection galleries have geodetic observation systems installed and allow the data collection of several dam monitoring devices. Drainage and piezometric systems are installed along the drainage gallery.

The spillway, located in the central part of the dam, comprises four 15.7m long bays, equipped with radial gates, separated by 5.85m wide piers. The spillway has a maximum discharge capacity of 5,500m³/s at maximum flood level. The energy of the discharged water is dissipated in the downstream stilling basin.

The reservoir has a capacity of 106Mm³ and a surface area of 420.9ha at the normal water level (NWL=170) being the crest at elevation 172m. At the maximum flood water level (MWL=171), the reservoir capacity rises to 110Mm³ and its surface area increases to 436ha.



a) b)

Figure 1: Foz Tua dam, a) aerial view after the first filling of the reservoir, b) cross section through the central block

The bottom outlet is in the mid-section of the dam below the central pier of the spillway and it is equipped with an upstream fixed wheel gate and a downstream radial gate.

The powerhouse is an underground structure located on the right bank, provided with two reversible generating units, each one with a capacity of 131MW. The two independent hydraulic tunnels located on the right bank are 700m long.

2 MONITORING SYSTEM

2.1 General Requirements of the Portuguese Dam Regulations

The Dam Safety Monitoring Plan, was elaborated in accordance with the regulations dealing with dam safety in Portugal, namely the Dam Safety Regulation[2] and the Guidelines for the Observation and Inspection of Dams[3], which take into account the size of the dam, the volume of its reservoir, the safety factors considered in the design, the characteristics of the dam foundation and the associated potential risks in the downstream valley.

The Dam Safety Monitoring Plan includes the definition of the different visual inspections required and their frequencies, the definition of the monitoring system, the placement of the measuring instruments, the reading frequency of the instruments, the gathering and processing of the monitoring data, the reporting and communication scheme in the event of exceptional occurrences or the detection of abnormal behaviours, the installation and operation reports, the qualifications of the staff responsible for the installation and operation, the analysis of the behaviour, and the assessment of the structure's safety.

2.2 Static monitoring system

Due to its dimensions and consequent importance of the dam, the structure has a complete monitoring system[1],[4]. The quantities monitored, by regulatory imposition, are: i) displacements; ii) joint and crack movements; iii) drainage flows; iv) uplift pressures; v) air temperature and air moisture; vi) concrete temperatures; vii) strains; viii) stresses; and ix) seismic induced vibrations. The different loads acting on the structure, such as the hydrostatic pressure on the upstream and downstream faces, air and water temperatures and seismic loads either at the dam site or on the perimeter of the reservoir are also monitored. Table 1 lists all the measurement instruments of the monitoring system.

In addition to the regulatory impositions, geodetic methods are used to measure slopes' convergence, upstream and downstream of the dam, as well as displacements in survey points at dam's downstream face, using a 3D continuous geodetic monitoring system. At the crest level, a Global Navigation Satellite System (GNSS) antenna was used during the first filling of the reservoir[5][6]. A dynamic response monitoring system was also implemented.

The horizontal displacements are monitored at 28 points by five plumb lines, at 32 points by precise traversing inside two inspection galleries, at 11 points by precise traversing at dam's crest, at 25 points by the 3D continuous geodetic monitoring system and, during the first filling of the reservoir, 1 object point at dam's crest by the Global Navigation Satellite System (GNSS) (Figure 2).

The vertical displacements are monitored at 21 points by levelling at crest, at 44 points inside four inspection galleries and at 25 points by the 3D continuous geodetic monitoring system. Vertical and horizontal displacements at the dam insertion surface are measured by 17 rod extensometers installed in the drainage gallery, 9 of which are single rod and the remaining 4 are double rod extensometers.

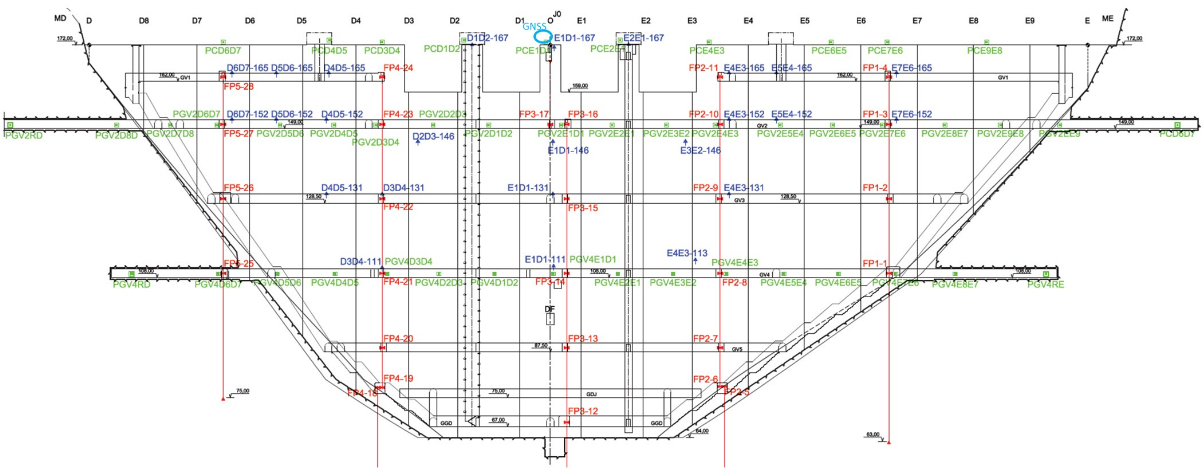


Figure 2: Horizontal displacements measuring instruments in Foz Tua dam. Five plumb lines (red), three precise traverse in the crest and in two galleries (green), 3D continuous geodetic monitoring system (dark blue) and GNSS (light blue).

The relative movements of the contraction joints are measured manually by electrical resistance jointmeters at 98 points and by three-dimensional baselines placed in 5 galleries and in both drainage galleries in a total of 68 monitored points.

The strain field in the dam's body is monitored in 30 points, covering the zones of maximum stresses, by groups of Carlson strainmeters, being 8 one-dimensional, 16 two-dimensional and 6 tri-dimensional, placed in 11 radial sections. The stress state is evaluated by the knowledge of the state of strain considering the creep function. Additionally, there are 12 stressmeters placed in 5 radial sections, near the strainmeters groups to get an acceptable calibration of the concrete stress-strain relationships.

The temperature of the concrete is measured by 41 electric resistance thermometers, 29 of them on the upstream and downstream dam surfaces, but also by the jointmeters, strainmeters, stressmeters and creep cells which makes a total of 331 electric instruments measuring the temperature.

The percolation through the foundation is monitored by 97 foundation drains, 4 drains per block, measuring the drainage flows in the drainage gallery and the infiltrated flows. There are 7 flow measuring weirs to control the partial flows by structural areas and the total flow.

The creep of the concrete is evaluated in situ by sets of 2 cells, in two different blocks, several meters apart. Each set has one full-mixed creep cell and one full-mixed non-stress cell, one wet-screened #38 mm creep cell and one wet-screened #38 mm non-stress cell.

	Values	Monitoring devices	Number of measuring points
1	Air parameters	Meteorological station	
		Air temperature sensor	1
		Air humidity sensor	1
		Solar radiation sensor	1
		Rain gauge to measure the precipitation	1
2	Water level	Upstream water level indicator	2
		Downstream water level indicator	1
3	Uplift pressure	Piezometers	26
5	Displacements	Coordinometer bases at 5 plumb lines	28
		Geodetic survey points at crest with GNSS during first filling of the reservoir	1
		Geodetic survey points at dam's downstream face with 3D continuous geodetic monitoring system	25
		Levelling at crest	1
		Levelling inside the inspection galleries	4
		Precise traversing at crest	1
		Precise traversing inside the inspection galleries	2
		Rod extensometers	17
		Electrical resistance joint meters	98
		Three-dimensional baselines	68
6	Drainage	Foundation drains	97
		Flow measuring weirs	7
7	Concrete temperature	Electric resistance thermometers	41
8	Strains	Carlson strain meters	172
9	Stresses	Stress meters	12

Table 1 Static monitoring system of the Foz Tua dam

An automatic data acquisition system (ADAS) is currently being installed covering all the physical quantities contemplated by the dam monitoring system, reading in automatic mode about 380 different values. It is a system of significant size involving the automation of about 34% of the readings performed in manual mode.

An Emergency Plan and a Warning and Alert System, enabling the population immediately downstream of the dam to be warned in case of an incident or accident, were also implemented.

2.3 Dynamic monitoring system

To ensure a good characterization of the dynamic behaviour of the dam and its response to seismic loads, 12 uniaxial accelerometers were installed, in the radial direction, along the two upper galleries, 4 in the GV1 gallery and the remaining 8 in the GV2, as well as 7 triaxial accelerometers, 2 in the GV1 gallery, 1 in the central pier, 3 in the GV2 gallery and 1 in the drainage gallery. Figure 3 characterizes the position of the accelerometers, with the uniaxial sensors marked in red whilst the triaxial sensors are marked in blue.

The accelerometers, as well as other equipment installed, such as the three existing digitizer units in the GV2 gallery, are connected by optic fibre or copper networks and the synchronization of all the data recorded is assured with GPS antennas. The main field computer is connected to the fiber optic network between the dam and the Observation and Control Building (OCB), allowing remote access to the acquired data.

The dynamic monitoring system is configured to continuously record acceleration time series at all uniaxial accelerometers, whilst the triaxial accelerometers data is registered on an event basis, depending on predefined parameters.

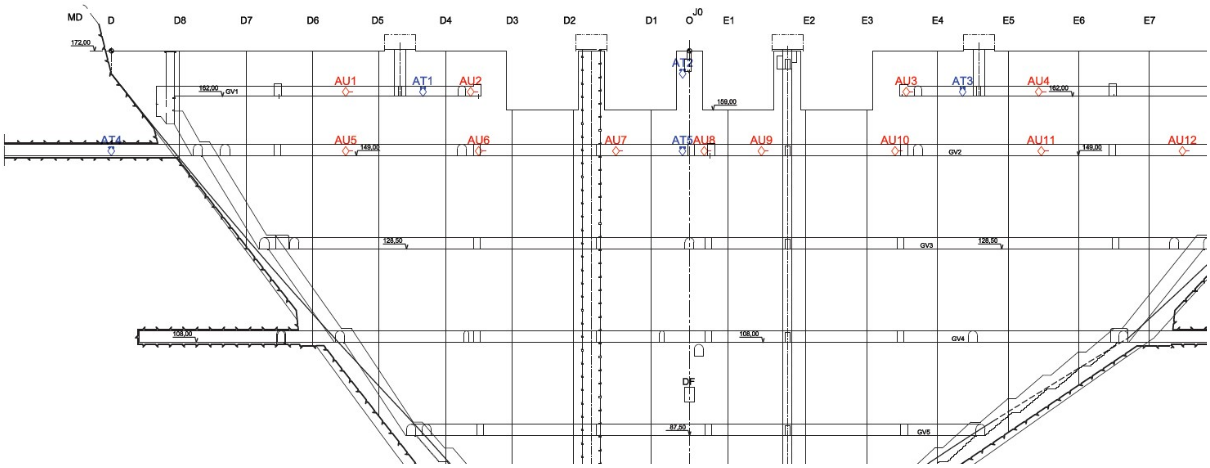


Figure 3: Position of measuring points on Foz Tua dynamic monitoring system.

3 THE FIRST FILLING OF THE RESERVOIR

The first filling of the reservoir, as a load test for the real operational conditions of the dam-foundation-reservoir system, is a special period of the dam's lifetime. During this period, safety control activities are very important, not only to avoid accidents and incidents but also to acquire knowledge about the structural behaviour of the dam, which will be a reference during its lifetime. For these reasons, special monitoring plans are developed, including, among other aspects, the definition of the evolution of the water level and of a set of stages at which the filling is suspended to do general observation campaigns and to perform dam's behaviour evaluation and the requirements for the development of a structural model to support the interpretation of the behaviour of the dam during this period. In this context, a thermal and mechanical model was developed at LNEC, which results supported the decisions about the evolution of the filling. In the next paragraphs only a general qualitative analysis of the monitoring data is presented.

3.1 Reservoir filling phases

The first filling of Foz Tua reservoir began in June 2016 and finished in June 2017, when the water in the reservoir reached the normal water level (NWL=170 m), allowing the beginning of the operation phase. Figure 4 presents the time evolution of the reservoir level during the first filling, including the indication of the filling stages and the correspondent dates at which the dam's behaviour was evaluated.

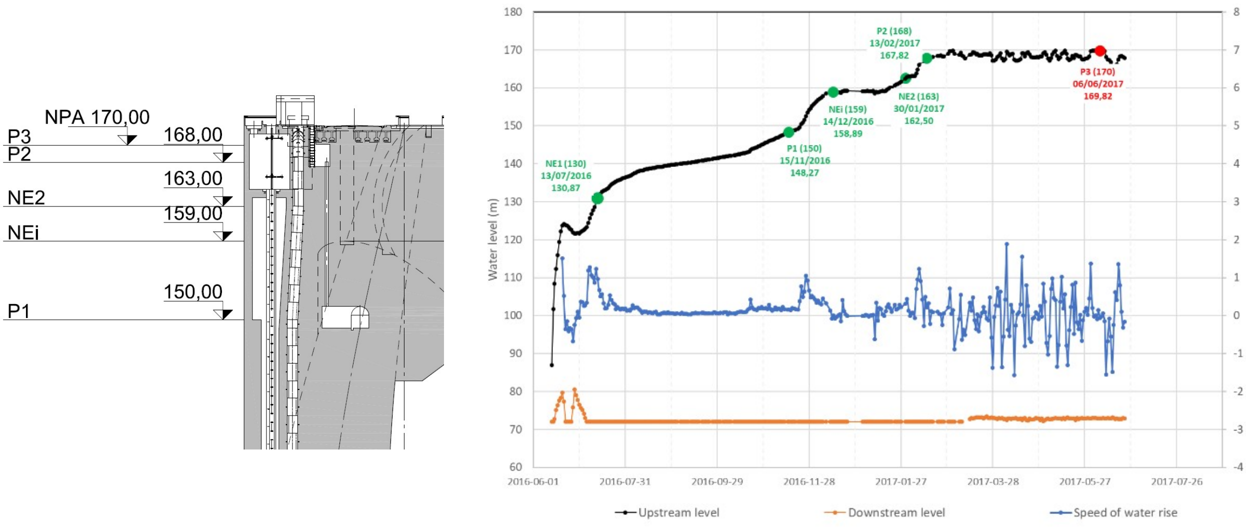


Figure 4: Filling stages and water level variation during the first filling of the reservoir

3.2 Observed behaviour

During the first filling, the evolution of the thermal state of the concrete was determined by the late effects of the release of concrete hydration heat and the evolution of the temperature of the air and of the water in the reservoir (Figure 5 and Figure 6).

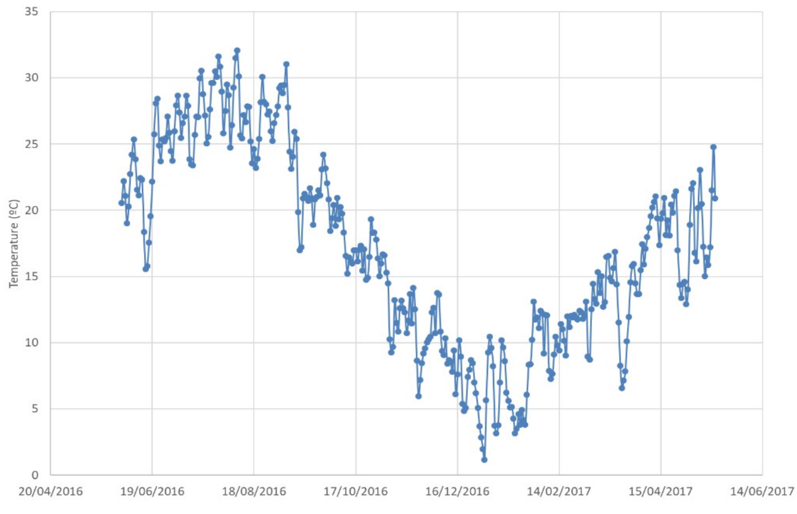


Figure 5: Daily mean values of air temperature during the first filling of the reservoir

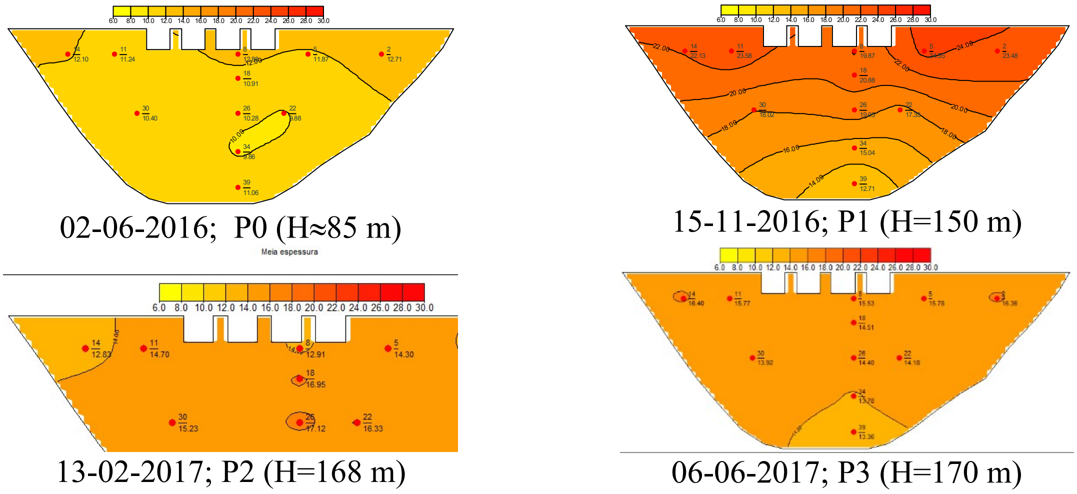


Figure 6: Concrete temperatures measured in thermometers located at half thickness

The dam presented a continuous behaviour, characterized by small movements in all structural joints, with the exception of small sections located at levels almost all the time above water level (Figure 7).

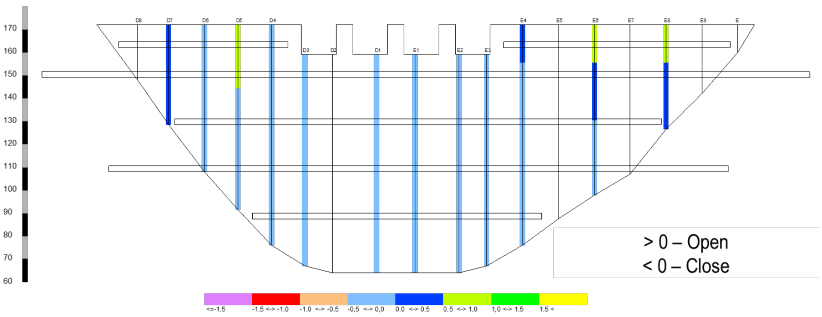


Figure 7: Joint movements, in millimetres, measured between the beginning of the first filling and stage P2 in electrical resistance jointmeters placed at half thickness

The horizontal displacements monitored in the five plumb lines show a good structural behaviour, explained by the evolution of the main actions, according to the model results. The temperature variations had the more important influence until the end of 2016 (Figure 8).

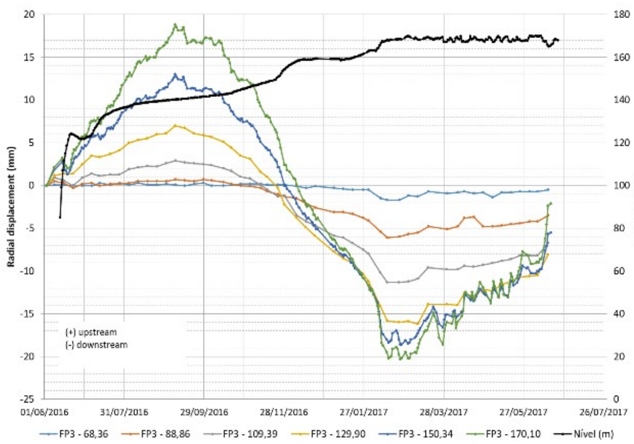


Figure 8: Radial displacements measured during the first filling in all measuring points along FP3 plumb line.

The horizontal components of the displacements determined in the precision traverse lines GV2 and GV4 galleries were also coherent with the expected structural behaviour and with the results obtained in the plumb lines (Figure 9).

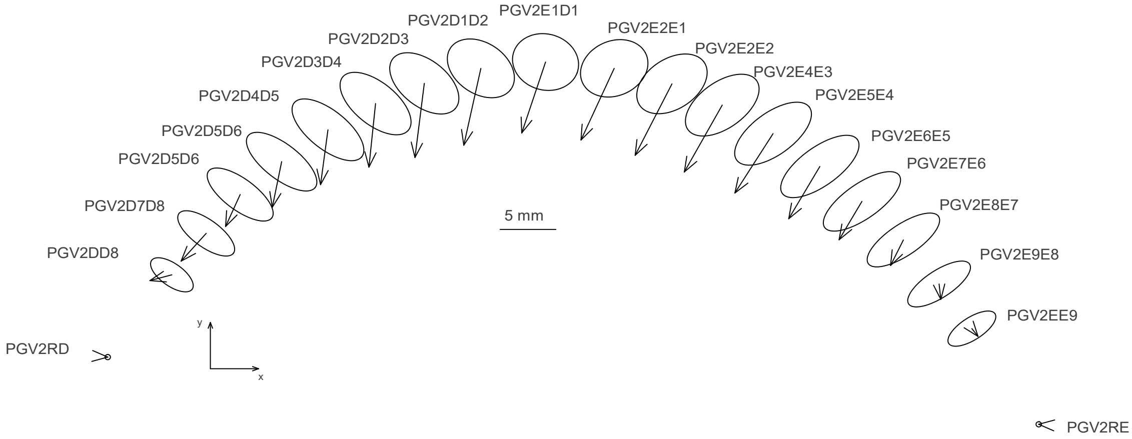


Figure 9: Horizontal displacements measured in the traverse line installed in GV2 gallery between May 2016, with the reservoir empty, and June 2017, at the end of the filling

Figure 10 shows the comparison between the horizontal displacements measured in the higher measuring point of the plumb line FP3 with the results obtained with the GNSS antenna and with the 3D continuous geodetic monitoring system. The results of the comparisons are good, particularly in the radial component.

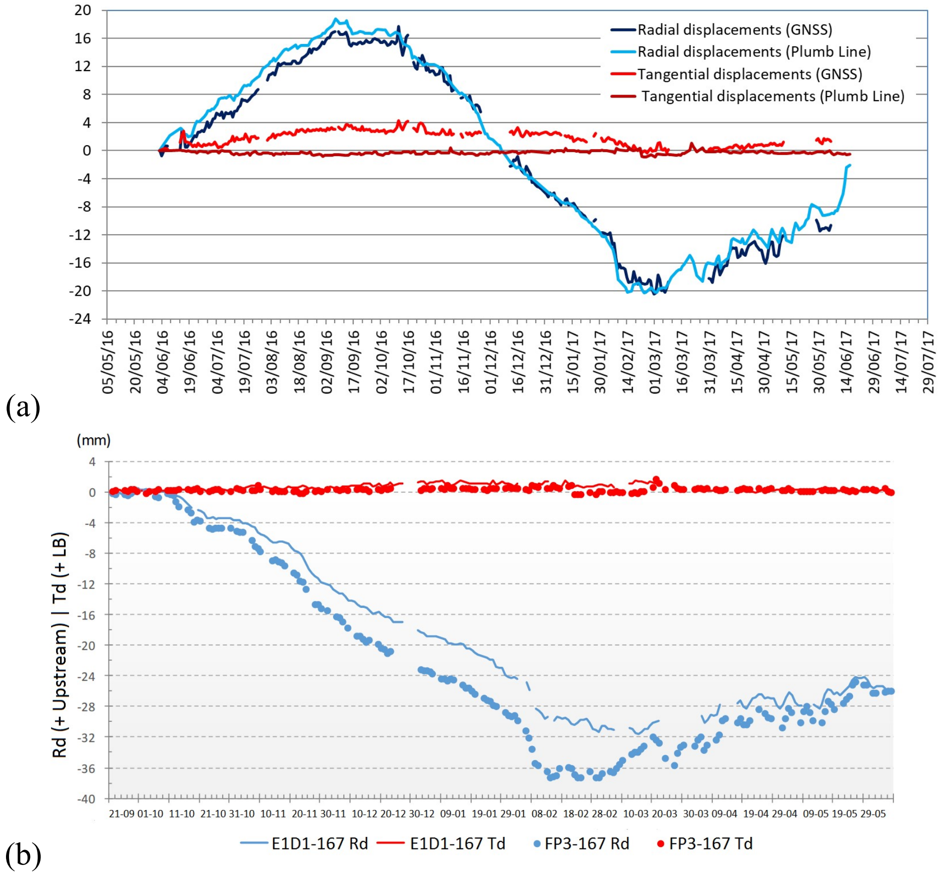


Figure 10: Comparison of the horizontal displacements measured during the first filling in the higher measuring point of plumb line FP3 with (a) GNSS results and (b) continuous geodetical monitoring system

The vertical displacements measured by rod extensometers along the dam/foundation interface were also coherent with the loads variation. In Figure 11 the effect of the level rise in the end of 2016 is notorious, when were observed upward displacement in the upstream gallery and downward displacements in the downstream gallery.

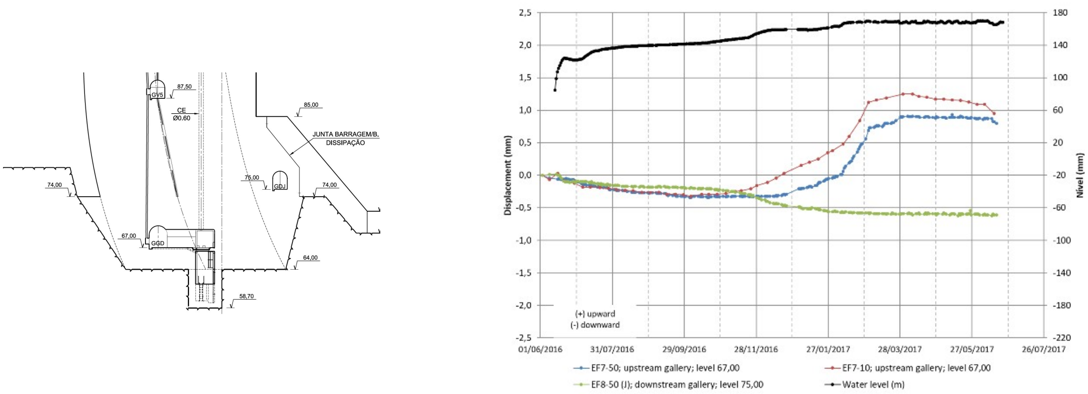


Figure 11: Vertical displacements measured in rockmeters placed in the central block.

During the first filling of the reservoir, some piezometers indicated higher values of uplift than expected (Figure 12). A maximum value of about 70% of the reservoir hydrostatic pressure was attained approximately at the central section of the right bank, in block D4/D5. The piezometer located in block D3/D4 also indicated a relatively high value of uplift of about 50% of the reservoir hydrostatic pressure. Another zone with relatively high values of uplift of about 35% to 50% of the reservoir hydrostatic pressure was detected in the upper portion of the left bank, in blocks E/E9 and E9/E8, but a tendency of reduction was observed.

The drains located in the zones of higher uplift did not yield significant flows. Nevertheless, relatively significant values of flow were measured in several drains, mostly located in the five central blocks (E3/E2 to D2/D3). A maximum value of 38 l/min was measured in a single drain, and a total of six drains exceeded a flow of 10 l/min during the first filling of the reservoir. The values of uplift in the central blocks were well below the reference of one third of the reservoir hydrostatic pressure.

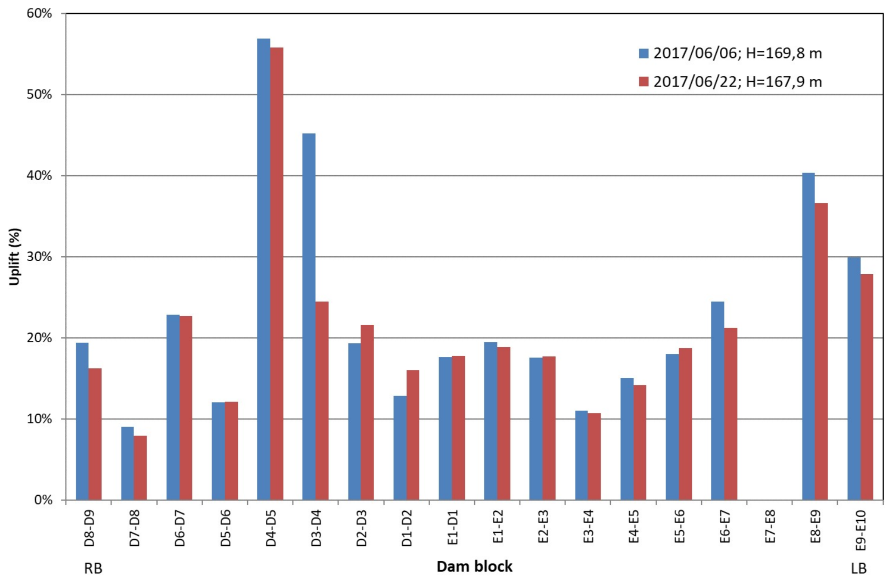


Figure 12: Uplift percentage measured in piezometers.

A more detailed analysis of these situations and an evaluation of additional actions to be taken was considered necessary, leading to the definition and execution of a set of tests to gather further information and to investigate if the flow or pressure were higher at certain depths or if they were relatively homogeneous along the tested drain and piezometer holes. Subsequently, a set of eight supplementary drains and one piezometer was implemented in the central section of the right bank, in blocks D3/D4 and D4/D5, resulting in a satisfactory reduction of uplift values, generally assuming values below the reference of one third of the reservoir hydrostatic pressure.

4 CONCLUSIONS

Foz Tua dam is a high arch dam recently built in the north of Portugal mainly for energy generation. According to Portuguese safety regulations on dams, its design included a monitoring plan where a complete instrumentation plan allowing, the safety control and the interpretation of the structural behaviour of the dam, is defined.

The continuous evaluation of the safety conditions of the structure during the first filling of the reservoir, based on the analysis of collected monitoring data and on the results of visual inspections, revealed a good structural behaviour, in accordance with the design previsions and with the results of a numerical model specifically developed for the safety control of the dam during this phase. The temperature variations were relevant during the most part of the filling and, as expected, the hydrostatic pressure effects were important when the water in the reservoir reached higher levels.

The observation campaigns allowed the detection of some small zones of the foundation with high uplift values. The drilling of more eight drains and the installation of one more piezometer corrected the situation, confirming the foundation’s good hydraulic behaviour.

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