dam world 2018
Third International Dam World Conference
BRAZIL • Foz do Iguaçu • September 17-21, 2018

SAFETY CONTROL OF RIBEIRADIO DAM SINCE THE FIRST FILLING OF THE RESERVOIR

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Keywords: Ribeiradio, Concrete Dam, Reservoir, First Filling, Safety, Behaviour

Abstract. *The Ribeiradio-Ermida multipurpose hydro scheme, built between July 2010 and the end of 2015, is the first major project in the Vouga River basin and is located in the centre of Portugal. Its main purposes are power generation, water supply and flood control. The Ribeiradio dam is a 83 m high concrete gravity dam, with a controlled gated spillway over the dam structure. This project encompasses a second lower dam, Ermida, located 5 km downstream, to regulate Ribeiradio flows. Both schemes are under operation since the first quarter of 2016.*
This paper presents the main features and results obtained during the first filling of the Ribeiradio dam reservoir and during the subsequent period of exploitation until the end of 2017. In accordance with the Portuguese legislation, the results of the detailed inspections of the dam and its foundation, as well as the integrated analysis of all results provided by the monitoring system, which are presented in the paper, have shown both the dam and its foundation present a satisfactory behaviour.

1 INTRODUCTION

The present paper describes the principal features of the Ribeiradio multipurpose hydro scheme and the main activities related to the safety and monitoring of that water infrastructure during the first filling of the reservoir. The Ribeiradio-Ermida hydro scheme, built between July 2010 and the end of 2015, is the first major project in the Vouga River basin in Portugal (Figure 1). Its main purpose are power generation, water supply and flood control. This project includes two hydropower plants and two large dams in the Vouga River, namely Ribeiradio dam and Ermida dam. To monitor the dam´s performance, the rate of the filling was controlled and a predetermined surveillance program, including the observation and analysis of instrumentation data, was carried out.

For this purpose, a reservoir filling program was defined for the two dams, which specifies the planning and the objectives to be achieved to comply with the safety control requirements for each specific type of dams. For each filling level of the Ribeiradio reservoir, and based in the analysis of the behaviour of the dams, Portuguese Authority for Dams Safety (APA – Portuguese Environment Agency), LNEC (National Laboratory

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for Civil Engineering), EDP – Gestão da Produção de Energia SA dam´s owner and design team COBA (Engineering and Environmental Consultants) took the necessary decisions envisaging the following stages of the reservoir filling.

Figure 1: Location and general view of Ribeiradio hydropower project

This paper summarizes the features of the project, the first filling plan of the reservoir and the main safety control results obtained during the first filling of Ribeiradio reservoir, that were coincident with the final construction phases of several important dam’s works.

2 GENERAL DESCRIPTION OF THE RIBEIRADIO PROJECT

Ribeiradio dam is located on a straight section of the Vouga river, 150 m upstream from a sharp river bend to the left near the village of Ribeiradio. Due to the reduced width of the valley, a circular alignment in plan was selected for the dam site, to allow for a wider intake section for the spillway while narrowing to the river bed width at the dam foot. The dam is a concrete gravity structure, the highest of this type in Portugal, with a circular surface alignment of 240 m radius, reaches a maximum height of 83 m and a crest length of 265 m, and involves a concrete volume amounting to about 300 000 m^3. The dam creates a reservoir with 136 hm^3 of total storage capacity at normal water level (NWL) at elevation (110,0), that corresponds to a flooded area of 561 ha. The dam includes a gated spillway with 2 750 m^3/s design capacity, located over the central blocks, as shown in Figures 1 and 2. The discharged flow is conveyed along the downstream surface of the dam unto a slotted roller bucket that restores the water to the river.

The dam is divided into 16 blocks, separated by 15 contraction joints, defined by vertical planes perpendicular to the reference surface of the dam (Figure 2).

The dam is provided with several galleries, including two drainage galleries near the foundation, one parallel to the upstream surface, along the whole dam length, and the second, next to the downstream surface, on the spillway blocks. Both galleries allow the installation of the monitoring system and the foundation treatment (Figure 3).

This scheme includes, on the left bank, a hydraulic circuit and an underground cylindrical power house equipped with one vertical axis Francis unit, with a nominal capacity of 74,5 MW, able to turbine up to 125 m^3/s, that generates 117 GWh average annual energy.

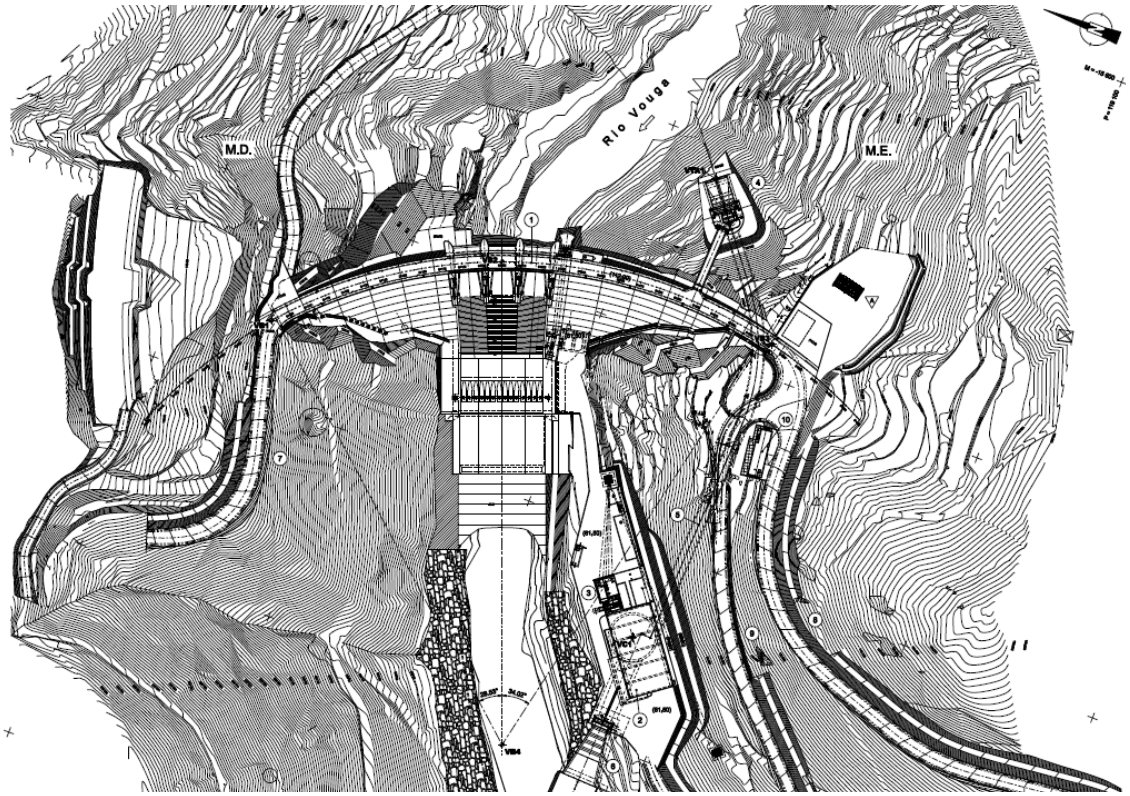

Figure 2: General plan of Ribeiradio hydropower scheme

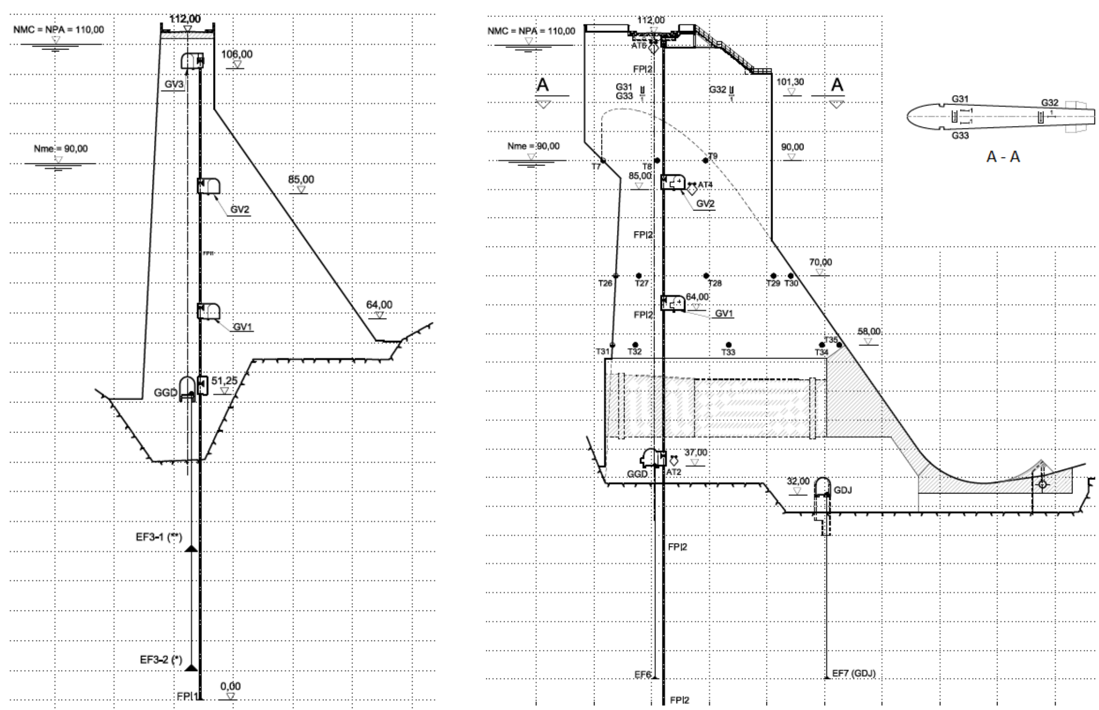

Figure 3: Two instrumented cross sections of Ribeiradio dam (block 5 on right bank and block 8 on the river valley)

3 DAM CONSTRUCTION AND MAIN ENCOUNTERED DIFFICULTIES

Due to the main hydraulic and geotechnical constraints encountered during the final design and the excavation works, associated to several important faults and to intense fracturing, weathering and heterogeneity of the rock foundation mass, the former design of the dam has to be subject to adaptations. Significant changes in the foundation and configurations of dam blocks were implemented and, for the Ribeiradio dam, the spillway type was modified.

During the excavation works in Ribeiradio, a fault with geotechnical significance importance was identified on the right bank, which crosses the dam foundation surface along 4 blocks. This situation, unforeseen during tender design phase, required an unorthodox engineering solution considering fundamentally a deeper excavation exclusively on the upstream zone of the foundation (Figure 4). By maintaining the geometry of the downstream area intact, it was possible to significantly reduce the quantity of excavation and, consequently, of concrete. The dam geometry was then adapted to solve the strength and deformability constraints revealed by the rock mass. A major fault was also identified in the river bed that affected three other dam blocks.

When the results of the geological survey were introduced in the physical model, discharge carried out by LNEC [4], on the form of loose blocks simulating the rock mass discontinuities, the erosion pattern resulting from the jet impact proved to be deep and wide, putting the stability of the valley sides in risk. Physical model tests also showed considerable turbulence downstream, as expected. Since the physical model results were available, it was decided to replace the ski jump by a submerged roller bucket with a slotted lip (Figure 5), although the head and flow concentration were both outside the usual current practiced. As the high flow velocity over the toothed weir of the roller bucket (30 m/s) increases the risk of cavitation and erosion, the teeth edges were rounded and several different configurations were tried in order to select optimum width and spacing distances.

Figure 4: View of the site works and excavations on right bank in 2013

Figure 5: View of the dam site works and roller-bucket construction in 2014

4 FIRST FILLING OF THE RIBEIRADIO RESERVOIR

According to the Portuguese Regulation on Dams Safety (RSB) [2], during the first filling and until the water reaches the maximum level in the reservoirs for the first time, attention must be given to the safety conditions of the dam and its foundation, including the monitoring and analysis of its structural behaviour and also the behavior and the safety of the water release facilities. The first filling of the Ribeiradio dam reservoir was thoroughly accompanied and analyzed to confirm the adequately behaviour. In each filling stage (Table 1) specified in the monitoring plan, the main loads and measurements of the representative parameters of the structural responses have been analyzed, envisaging the full reservoir filling under safe conditions.

Stage	Water level (m)	Water height (m)	P (%)	Level stabilization period (days)
P0	Bottom discharge (53,25)	24,25	---	---
P1	(80,0)	51,0	40	5
NE1	(90,0) mOWL	61,0	57	3
P2	(99,0)	70,0	75	5
P3	(110,0) FSWL	81,0	100	5

mOWL - minimum operational water level; FSWL - full supply water level;
P - percentage of the effort transmitted to the dam foundation

Table 1: Water levels during the first filling of the Ribeiradio reservoir

During the final construction phase, the Vouga river was diverted through the bottom outlet, to allow the execution of all works related to the roller bucket, the spillway, the and the monitoring system. The first filling began in May 2014 and finished in June 2015 (Figure 6).

During the first months of the filling observation, some works in the dam were finalized, mainly the foundation treatment of some blocks which bases were above the water level, the execution of the drainage and piezometric systems and the installation of the spillway hydromechanical equipment.

Bearing in mind that, when the water level in the reservoir is below the spillway level, it isn’t possible to control the rate of water level rise in flowing rivers, because the limited flow capacity of the bottom outlet discharges, measures have been taken to control the reservoir filling which was conducted at a possible slow rate in order to allow the gradual adaptation of the dam-foundation system to the new load conditions. Although it has been possible to control the filling during the following four months, floods occurred in the last quarter of 2014 caused a sharp increase in the level of the reservoir, period during which the structural behavior of the dam was continuously monitored.

In order to fulfill the initial plan filling, the reservoir was partially emptied until the water reached level P1 (level 80,0 m). Afterwards, the filling of the reservoir continued under controlled way, in compliance with the plan. Figure 6 presents the evolution of the reservoir level and the dates on which the levels and stabilization levels took place.

When the last stage of filling ended, the foundation treatment was already completed and, regarding the monitoring system, the drainage system of the foundation and the devices for the measurement of total flow rates were in final phase of installation. Observation campaigns, visual inspections, geodetic observation campaigns and analyses of the water of the reservoir and of the drains, foreseen the first filling plan, were carried out. Observation campaigns, visual inspections, geodetic observation and analysis of the water of the reservoir and of the drains were carried out during all the filling period.

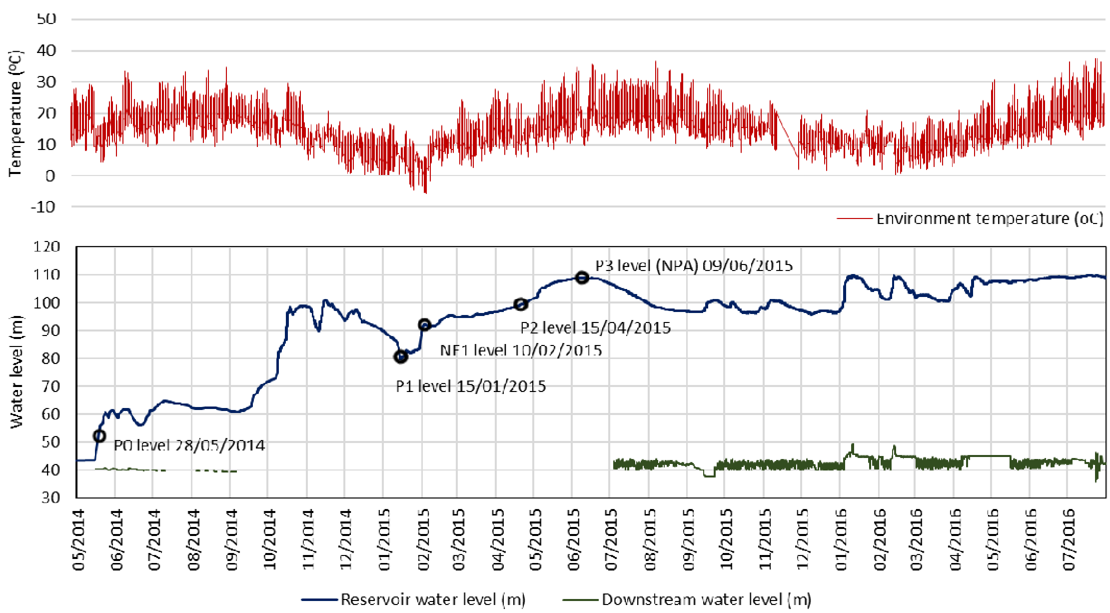

Figure 6: Water level and environment temperature evolution during the first filling

6 ANALYSIS AND INTERPRETATION OF THE DAM BEHAVIOR

During the first filling of Ribeiradio reservoir the behaviour of the dam and its foundation were thoroughly evaluated to access their safety conditions. For each filling stage of the reservoir, and based in the monitoring plan, that considers the measurements of the main loads and of the representative parameters of the structural responses, with the analysis of the behaviour of the dam, the Authority (APA), LNEC, dam´s Owner and design team took the necessary decisions envisaging the continuation of the reservoir filling.

The interpretation of dam behavior during the first filling of the reservoir was based on thermal and structural FEM models developed at LNEC [7]. The temperature distribution inside the dam was estimated using a finite element model which considered the effects associated with air temperature, water temperature, solar radiation and cement hydration heat. These temperatures variations together with the hydrostatic pressure of the impounded water were the input of the periodic mechanical analysis. Figure 7 shows the results obtained in the numerical model simulation. The analysis of the values of displacements observed by the plumb lines demonstrated that, in general, during the first filling phase, there was a good agreement between the computed results and the observed displacements values.

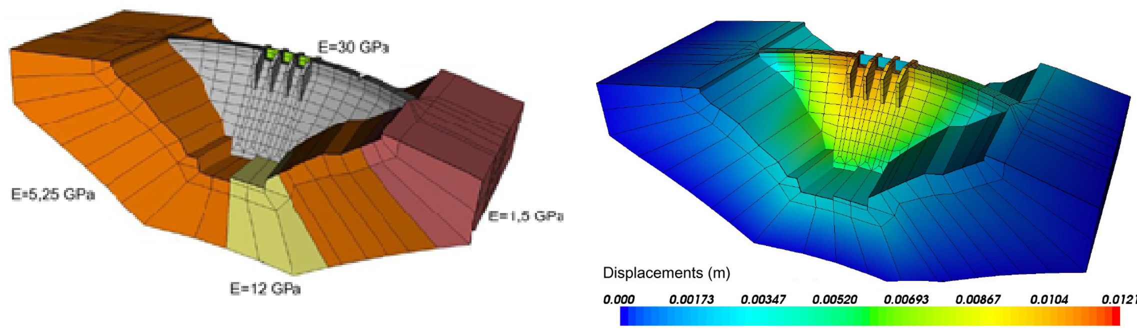

Figure 7: Finite element mesh and displacements calculated at the end of the first filling of the reservoir [7]

The analysis of the dam behavior was performed on the basis of the results provided by the monitoring system, comprising a qualitative assessment prepared from the time evolution diagrams of the observed quantities, and a quantitative evaluation based on a statistical separation effects model analysis.

In the statistical model used, the measured values were decomposed in order to obtain the best possible adjustment with the observed values, in the elastic sum of parts related to the effects of the evolution of the hydrostatic pressure action (C_{hi}), assimilated to the variation of the water level in the reservoir, the seasonal variation of ambient temperature (C_{Tj}) and the irreversible effect, considered to be exclusively associated with the dimension of the elapsed time in the studied period (C_{tk}).

The general expression that defines the model is:

$$V\,(m, h(t), T(t - t_0\,(m)), t) = C_{hi}\,(m)\,.\,h^i\,(t) + C_{Tj}\,(m).\,T^j\,(t - t_0\,(m)) + C_{tk}\,(m).\,t^k + V_0\,(m) \qquad (1)$$

For each quantity (m) that was analyzed, the calibration of the separation effects model, in relation to the corresponding observed values, consisted in determining the values of its parameters that minimize the quadratic function (in these parameters) defined as the sum of squares of differences between the values observed and the values calculated by the model. The degree of the polynomials adopted to represent the effects of variation of water level, the environmental thermal action and the time were, 4, 3 and 4 respectively.

Figure 8 presents radial and tangential displacements observed until the end of 2017 and measured at different elevations in plumb line FPI2, located on the dam’s central block.

The radial displacements show a behaviour that is compatible with the loads that the dam has supported during its short lifespan. All plumb line readings show a displacement towards downstream associated to the filling of the reservoir. Temperature decrements also induce displacements towards downstream. In the begin of 2015, when the minimum temperature was reached, and the reservoir water level was relatively low, the observed displacements were lower than those observed in 2016 and 2017.

As expected, tangential displacements of the central block present extremely low values. After a initial six months' period, with a slight tendency towards the right bank, the measured tangential displacements remain within a 1 mm bandwidth.

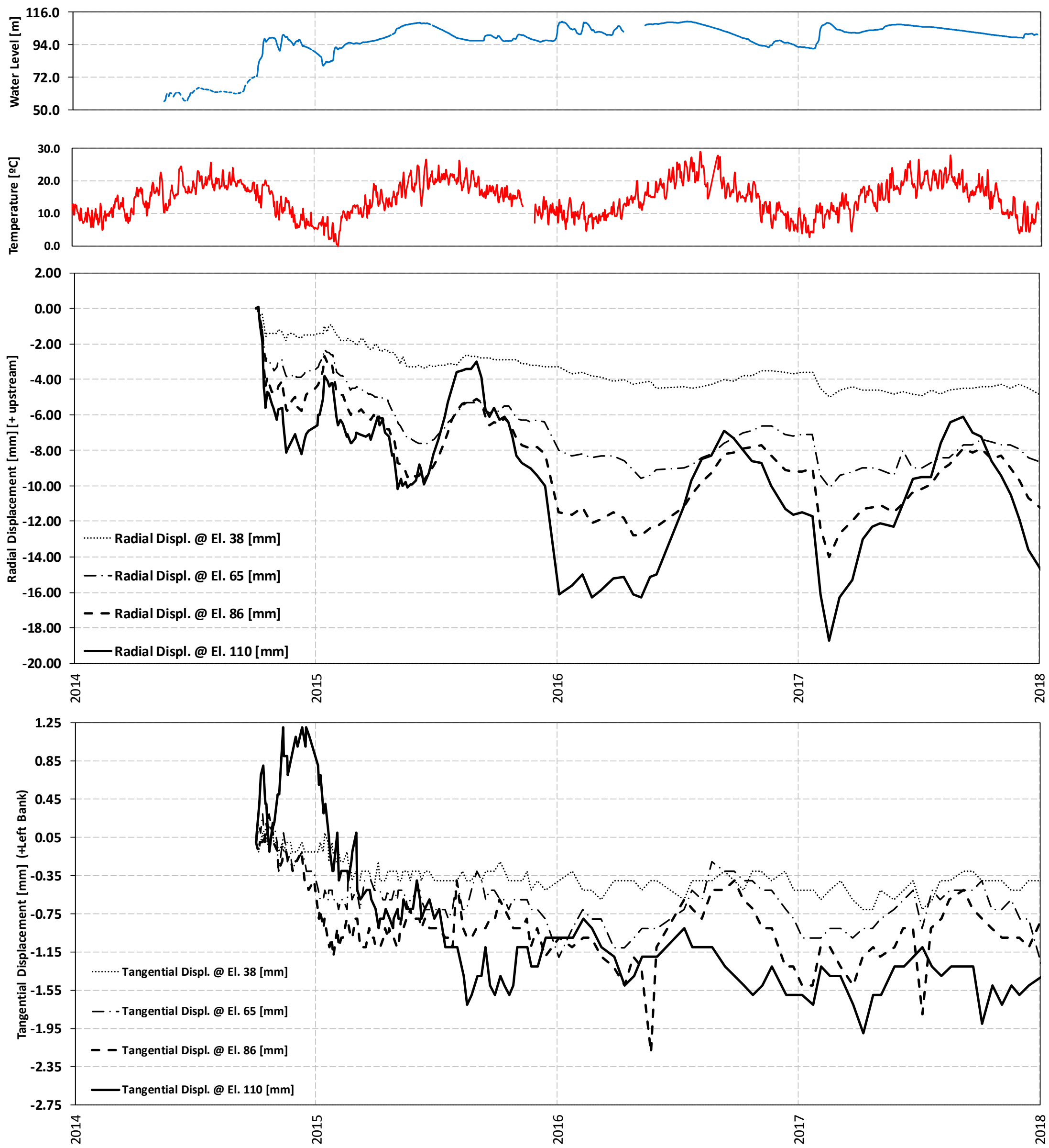

Figure 8: Measured radial and tangential displacements in the plumb lines FPI2

Figure 9 presents the results of the separation analysis effects model for radial displacements of plumb lines FPI1 (left bank block), FPI2 (central block) and FPI3 (right bank block). Results demonstrate the behavior above described, with the most relevant influence of the water level, inducing displacements towards downstream. Temperature increase induces displacements towards upstream. Even though there was a slight induced tendency towards downstream of the irreversible time displacements, but the available data are still relatively scarce, but that will be an evolution to be analyzed in the future.

Due to the low magnitude of the tangential displacements, interpretations from the separation effects model could be not conclusive, but it is possible to see the relatively symmetrical behaviour of the dam between the plumb lines FPI1 and FPI3.

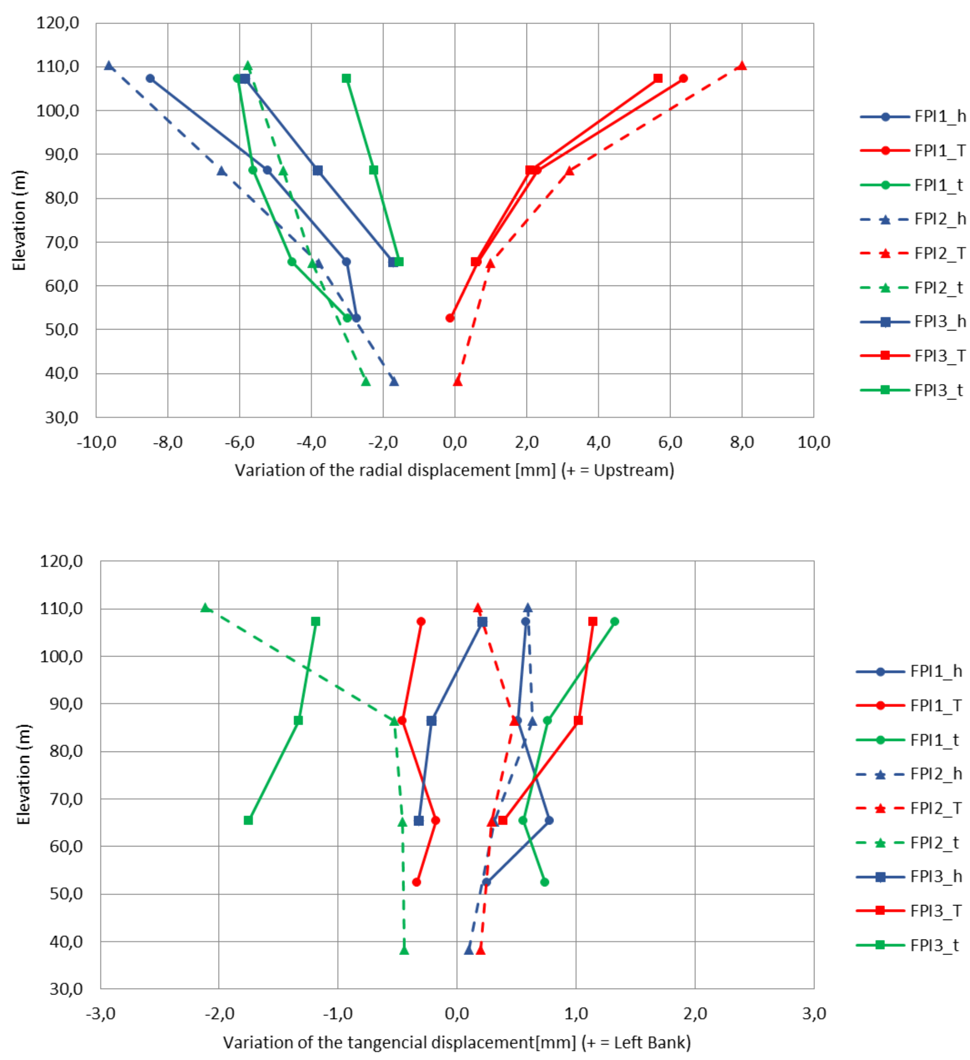

Figure 9: Results of the separation analysis model effects for plumb lines FPI1, FPI2 and FPI3 (absolute movements)

The displacements evolution observed in the rod extensometers was coherent with the variation of the main loads. The water level increase in the reservoir implied, as expected, an increment in the downstream settlement and upward displacement on the upstream zone. The upstream and downstream displacements observed in the central block (block 8) of the dam are shown in Figure 10. In spite of the limited magnitude of the observed displacements, sudden rises of the water level in 2016 and 2017 have produced minor displacements that have been observed.

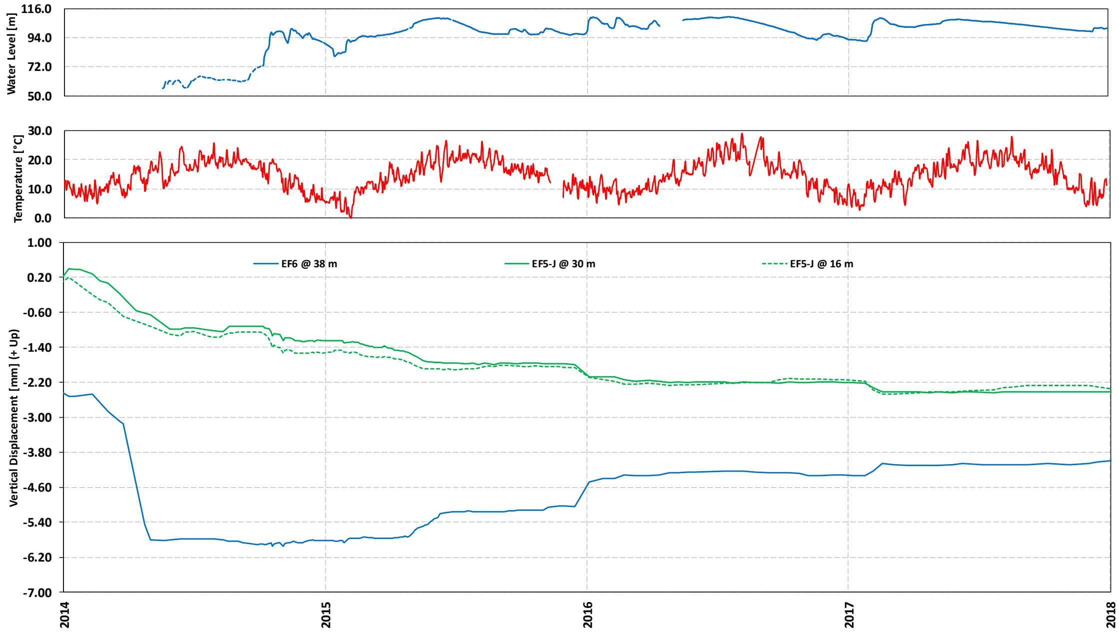

Figure 10: Vertical displacements in the foundation. Upstream and downstream displacements.

Figure 11 presents infiltrated and drained flow rates. As expected, considering geotechnical data, drained flow rates on the right bank are larger than on the left bank, nevertheless flow rates are within the usual values for this type of dam and foundation properties. Sudden water level rises have induced significant increases in the observed flow rates.

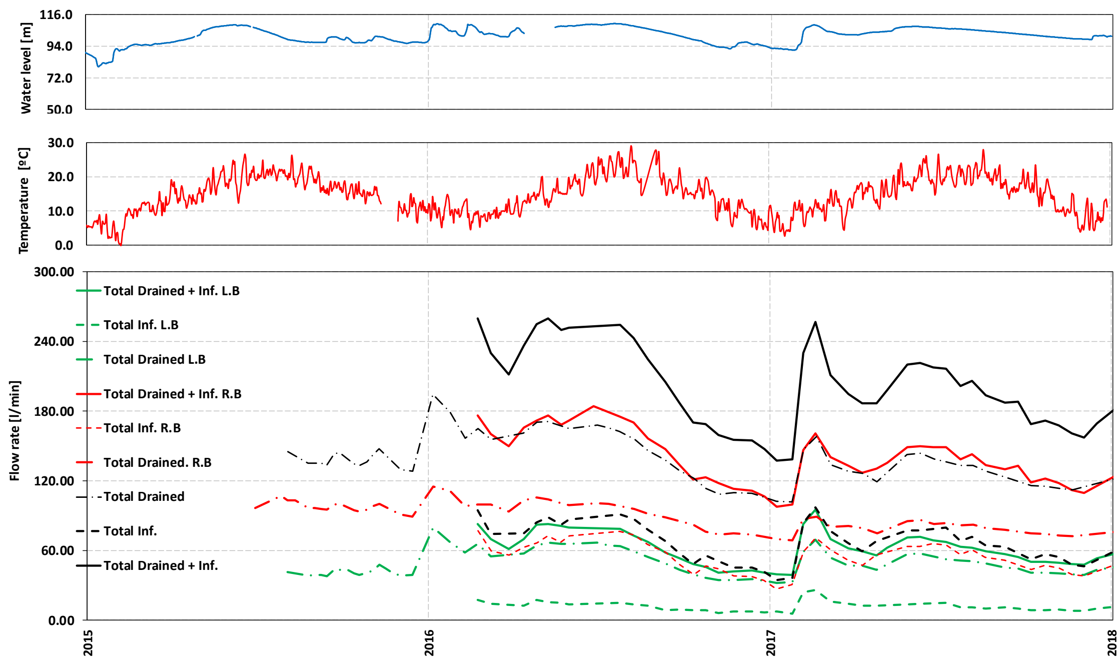

Figure 11: Flows seepage rates throughout Ribeiradio dam foundation

A slight tendency towards lower flow rates over time has been observed. Results from the separation effects analysis, presented in Figure 12, confirms this interpretation. The reduction of flow rates is greater in the right bank.

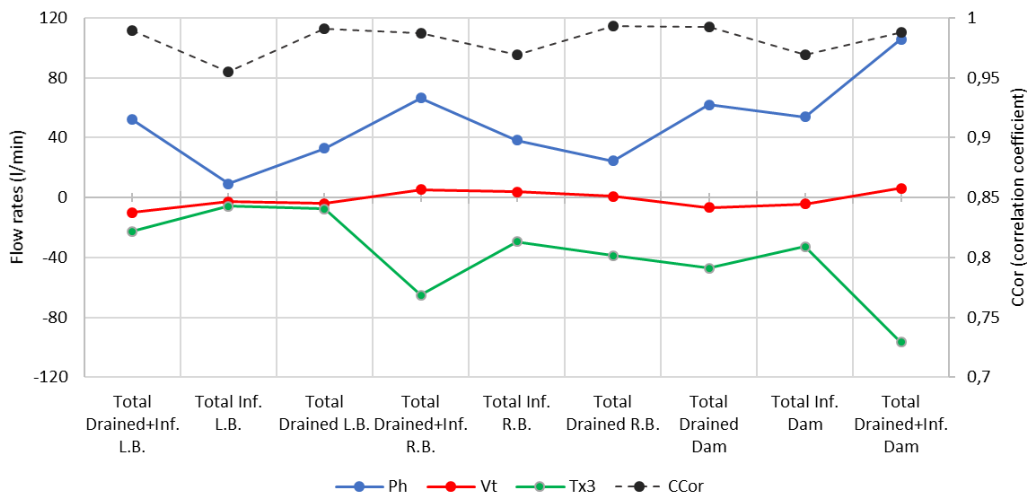

Figure 12: Results of the separation analysis model effects for total drained and infiltrated flows rates on dam foundation

In general the uplift pressures are small, corresponding to percentages of hydraulic load always lower than 20% in all the piezometers. Figure 13 presents maximum and minimum water levels in piezometers of each block. Maximum uplift pressures have been observed in central blocks 7 (upstream) and 8 (downstream).

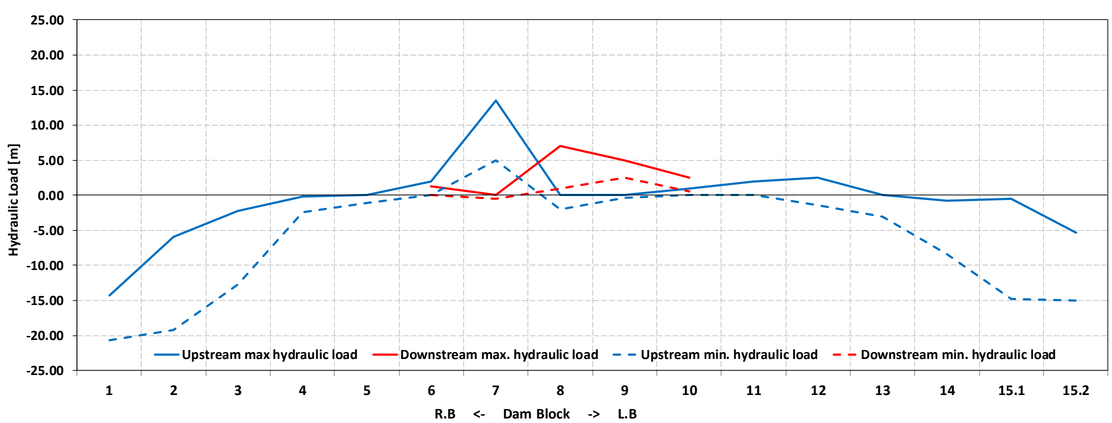

Figure 13: Uplift pressures throughout Ribeiradio dam foundation.

7 CONCLUSIONS

Ribeiradio dam site has complex geotechnical conditions mainly due to lithological heterogeneity and anisotropic behaviour because of the intense tectonization of the rock mass.

Some situations identified during the construction of Ribeiradio dam, mainly associated with some faults and fractures with unexpected expression, very intense weathering and heterogeneity encountered in the foundations rock mass, implied specific adaptations to the dam design and construction, and special attention was given to the preparation and implementation of the monitoring plans during the first filling of their reservoirs. The structural behavior of Ribeiradio dam during the first filling was analyzed using a thermo-mechanical FEM model, leading to a better understanding of the observed behavior of the dam. In view of the obtained results, it was considered that the Ribeiradio schemes could start the first normal period of reservoir operation concerning power generation.

The technical resources and procedures used in the control of the first filling of Ribeiradio reservoir proved to be adequate and efficient, allowing the permanent monitoring and interpretation of the dam's behavior. The records of the monitoring data and the results of the detailed visual inspection of the structures since the first filling showed that the dam behaviour as well as of the respective rock mass foundation are satisfactory.

Based on an integrated analysis of all monitoring data it was possible to understand and evaluate the behaviour of the dam, allowing to control the structural behaviour of Ribeiradio dam. The scheme is currently on its normal period of operation for power generation production. Careful monitoring of the dam and respective foundation behaviour will prevail along the entire service life of the project.

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