



FIRST INFILLING OF THE UNDERGROUND STRUCTURES OF THE GOUVÃES HYDROELECTRIC SCHEME – MONITORING AND OBSERVED BEHAVIOUR



Renato Pereira¹
LNEC



José Muralha
LNEC



Luís Lamas
LNEC

ABSTRACT

The Gouvães pump-storage hydroelectric scheme includes a 7800m-long underground power conduit connecting the Gouvães and the Daivões reservoirs, with a hydraulic head of 657 m and a 49 m-high underground powerhouse located at the depth of 300 m. To monitor the behaviour of the main caverns during the construction stages, a monitoring plan was developed and implemented. For the first infilling of the power conduit, a detailed plan was prepared, and the monitoring plan was upgraded to account for the hydraulic actions and the water flow in the rock mass.

This paper describes the main structures of this scheme, presents the main geological and geotechnical information and introduces the main aspects of the monitoring system used for the construction stage of the underground structures. The paper outlines and justifies the proposed sequence and schedule for the first infilling phase, as well as the upgrades made to the monitoring system for this stage. It examines the observed behaviour during infilling, such as flow rates and water pressures, and how these factors influenced adjustments to the original infilling plan. Finally, it reviews the condition of the underground structures at the start of their service life.

Keywords: Gouvães hydroelectric scheme, Underground structures, Monitoring, Construction, First infilling

¹rpereira@lnec.pt, Portugal

1. INTRODUCTION

The first infilling corresponds to a critical phase of the life of an underground hydroelectric scheme, since it constitutes the first loading of the underground structures, with water pressures in the hydraulic tunnels, which influences the rock mass hydraulic conditions. Water inflow in the rock mass, originated from the hydraulic tunnels, introduces internal hydrostatic pressures, which are proportional to the hydraulic head. Such pressures, together with the hydromechanical properties of the rock mass and the existing confining conditions, influence the flow pattern in the rock mass.

During the first infilling of the power conduit, not only the internal water pressure is introduced but also temperature variations, due to the water flowing, from the reservoir, at lower temperatures than the tunnel. In addition, the first infilling initiates a process of groundwater level rise, as water flows into the rock mass, particularly through unlined or concrete-lined sections. This influences the external water pressure on the linings of the underground openings and may induce leakage into them.

It should be emphasised that concrete-lined sections considerably reduce the exchange of water with the rock mass but cannot be considered impervious because concrete inevitably fissures under the action of the internal pressure and of the temperature variations imposed by the water flow. In addition, external water pressure may be present which deserve control measures. Steel-lined sections, adopted in high-pressure zones and transition zones, can be considered impervious.

For these reasons, first infilling of the Gouvães reversible hydroelectric scheme required the definition of a detailed plan [1], which includes an upgrade of the monitoring system used for the construction phase, providing adequate information for assessing the safety throughout the infilling process and identifying potential risk situations in a timely manner.

This paper presents, in section 2, a summary of the main aspects of the Gouvães underground works structures, the geological and geotechnical aspects, the schedule of the construction phase and the monitoring plan implemented for observation of the behaviour of the main underground caverns and tunnels. Section 3 presents the aspects related to the first infilling of the power conduit, namely the necessary upgrade of the monitoring system, the first infilling plan and the main occurrences registered during this period. At the end, some conclusions on the benefit of developing a detailed plan and on its application to the Gouvães power conduit are presented.

2. PROJECT DESCRIPTION

2.1. Underground structures

The Gouvães reversible hydroelectric power scheme is intended for energy production, utilizing a gross head of 657.0 m, and enabling the pumping of water from the upper reaches of the Daivões dam reservoir on the Tâmega River to the Gouvães dam reservoir in the Torno River, a right bank tributary of the previous.

This scheme consists of a 34 m high concrete gravity dam (Gouvães dam), located on the Torno River, creating a reservoir with a storage capacity of 13.7 hm³ at the full supply level (FSL) of 885.0 m. The power conduit is located on the right bank of this river, with a total length of approximately 7800 m, and discharges into the Daivões reservoir on the Tâmega River. The underground powerhouse, located in a cavern at a depth of 300 m, is equipped with four Francis reversible pump-turbines with a total power of 880 MW, upstream of the transformers cavern.

The power conduit of the Gouvães hydroelectric power scheme has the following main elements:

- Upper water intake structure at the Gouvães reservoir, with a water level at elevation 885.0 m.
- Headrace tunnel, relatively shallow, with a gradient of less than 1%, a 7 m diameter circular cross-section and a length of 4770 m.
- Upper surge shaft.
- Penstock between the upper surge shaft and the upper manifold, approximately 1710 m in length, with circular cross-sections of 6.0 m and 5.4 m in diameter, consisting of an initial underground section, an intermediate section in a trench, followed by another underground section.
- Penstock between the upper manifold and the powerhouse cavern, including two vertical shafts with a circular cross-section of 3.6 m in diameter and a length of 65 m, at the end of which are located two lower manifolds that lead to the four turbines.
- Powerhouse complex and its associated underground structures comprising the main cavern, the transformers cavern, the lower surge chamber, several access adits and the access tunnel.
- Tailrace tunnel, with a circular cross-section of 7 m in diameter and 800 m in length.
- Lower water outlet structure in the Daivões reservoir, with a water level at elevation 228.0 m.

The underground powerhouse complex lies around 300 m below the surface. It includes two large caverns and several tunnels, adits and shafts for hydraulic and access purposes. The powerhouse cavern, with approximate dimensions of 20 m in width, 48 m in height, and 121 m in length, is oriented approximately N35°E. The transformers cavern is parallel to the powerhouse cavern, located downstream of it, and has approximate dimensions of 18 m in width, 18 m in height and 81 m in length. The horizontal distance between these two caverns is about 29 m.

Connecting these two caverns are four busbar galleries, approximately 8 m wide and 8 m high. The four draft galleries have a diameter of about 4.5 m and a slope of 15%, ending at the draft tube tunnel. Figs. 1 and 2 present a perspective view and a plan view of the powerhouse cavern complex.

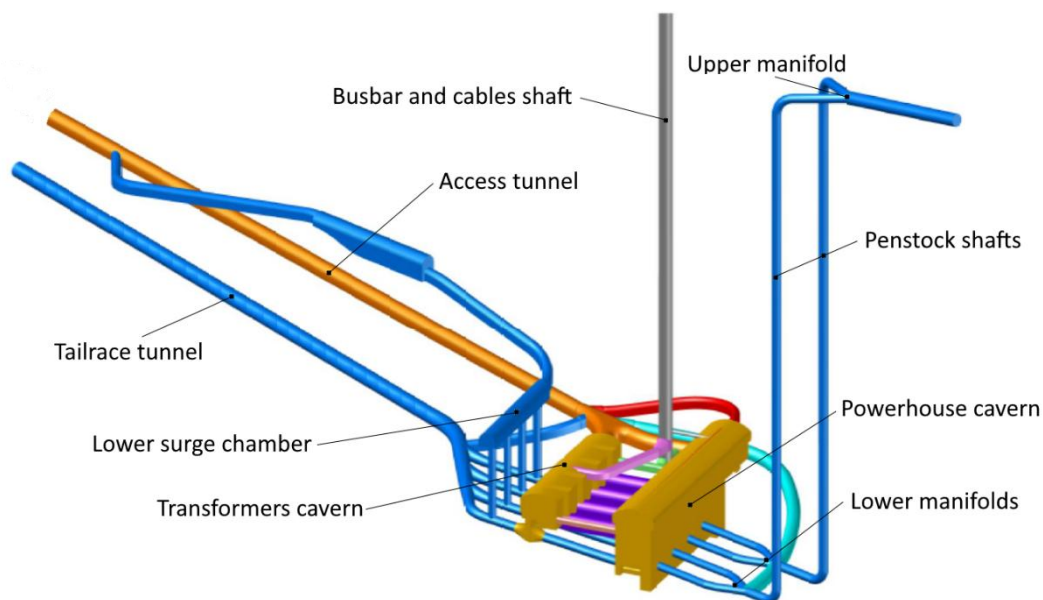


Fig. 1 – Perspective view of the underground powerhouse complex

2.2. Geological and geotechnical aspects

Three different geologic units occur in the zone of interest of the Gouvães hydroelectric power scheme. At the Gouvães dam site and along the upper third of the headrace tunnel, granite formations are of primary interest, referred to as the syntectonic granite massif of Santa Marta do Alvão (unit G1), which can generally be described as medium- to coarse-grained, porphyroid, two-mica granites. The remaining hydraulic circuit is developed within the schist formations of the Fragas Negras unit (unit X1). These formations are composed of fine-grained mica-schists and schists, as well as quartzitic and biotitic schists.

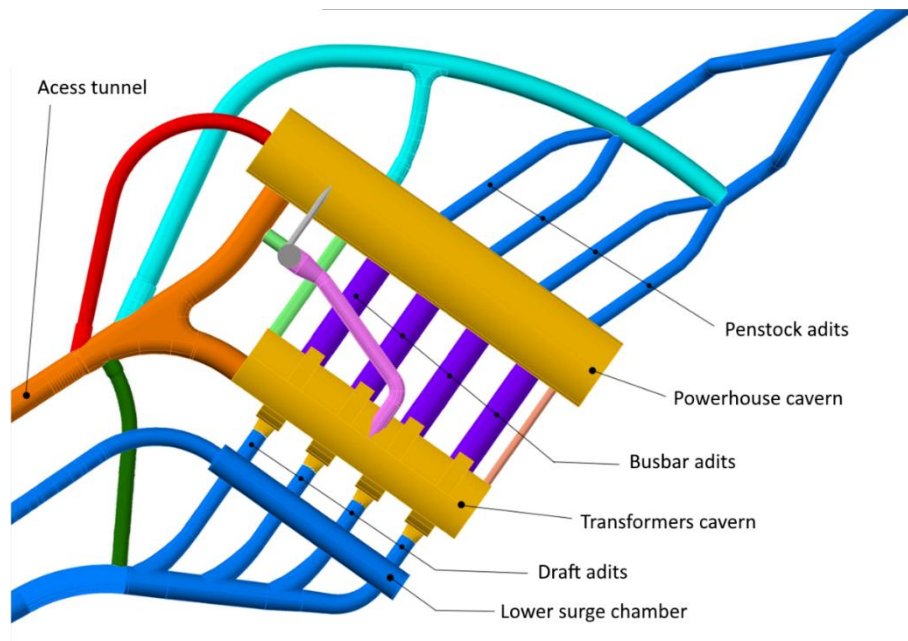


Fig. 2 – Plan view of the underground powerhouse complex

Two different rock lithologies with an undulating, sub-horizontal contact occurs in the rock mass surrounding the powerhouse complex: the intrusive, gray-colored, medium- to coarse-grained two-mica granites (unit G2), and the overlying fine-grained mica schists with frequent occurrences of exudation quartz (unit X1). The contact between these two lithologies is gradual and includes intercalations of aplites, dolerites, and pegmatites (Fig. 3). Although this contact between the two lithologies (granites and mica-schists) is welded and even in general difficult to ascertain, during the excavation of the access galleries, particularly the exploratory adit in the crown of the powerhouse cavern, the occurrence of faults and the presence of water in the rock mass were observed.

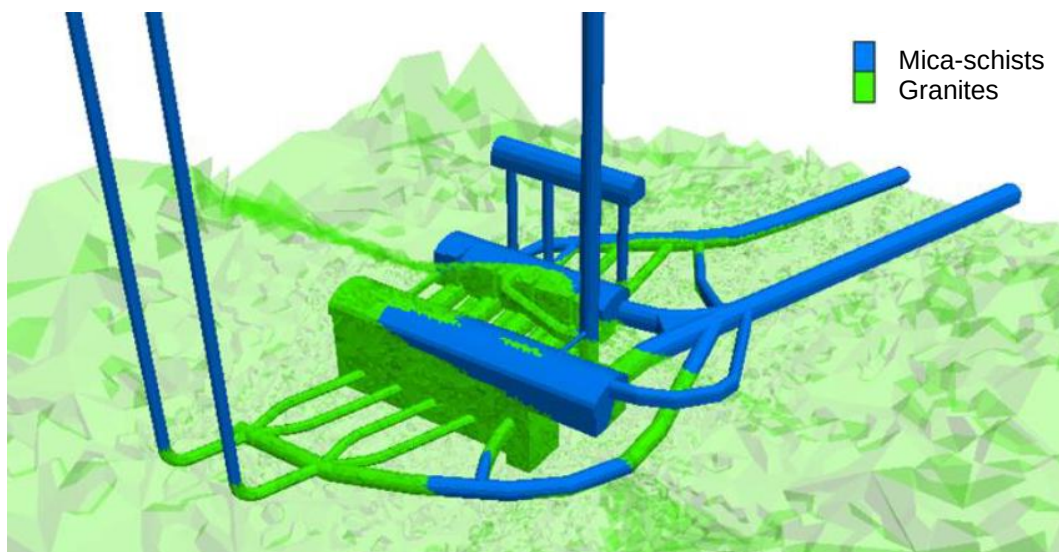


Fig. 3 – Perspective view of the contact between the mica schist and the granites

In the design phase, the designers consisting of Eptisa, Granell Ingenieros Consultores, and Intecsa Industrial carried out a study [2] of the characteristics of the geological units crossed along the hydraulic circuit alignment (units X1, G1, G2), classifying them according to the degree of weathering (W) and fracturing (F) and the values of Rock Quality Designation (RQD) and Rock Mass Rating (RMR). Table 1 summarizes the geomechanical properties of the rocks in each geological unit, specifically the unit weight, porosity, compressional wave propagation velocity (V_P), uniaxial compressive strength (UCS), Young's modulus, and Poisson's ratio.

Table 1 – Geomechanical properties for the intact rock of the geological units

Geologic unit	Unit weight (kN/m ³)	Porosity (%)	V_P (m/s)	UCS (MPa)	Young's modulus (GPa)	Poisson's ratio (-)
Granite G1	24.5–26.5	0.5–1.5	4200–5000 (W1–W2) 2500–3500 (W3–W4)	70–100 (W1–W2) 35–60 (W2/3–W3) 5–15 (W4)	40–55 (W1–W2) 25–35 (W2/3–W3) 5–20 (W4)	0,15–0,3
Mica-schist X1	27.5–28.2	0.2–0.9	3900–4500 (W1) 3000–4000 (W2)	15–25 (W1–W2) 3–5 (W2/3–W4)	20–30 (W1–W2) 10 (W2/3–W4)	0.2–0.25 (W1–W2) 0.25–0.3 (W2/3–W4)
Granite G2	26.0–27.0	0.3–0.6	4500–5500	70–85 (W1–W2) 40–50 (W3–W4)	40–60 (W1–W2) 25–40 (W3–W4)	0,2–0,3

It is relevant to note that the values presented in Table 1 are for intact rock. Estimates for rock mass values, based on results from *in situ* tests and considering the Hoek-Brown failure criterion and the GSI classification system, revealed that the mica schist is two times more deformable than the granite.

2.3. Construction

The construction works of the Gouvães hydroelectric power scheme started with a contract for the excavation of the access adits to the underground power complex, which ran from December 2015 to August 2016. It comprised the excavation of several access tunnels, namely the main access tunnel starting close to the location of the water outlet structure near the Daivões reservoir and reaching the confluence of several other shorter access adits. One of them, the access adit to the crown of the vault, running along the whole length of the powerhouse cavern, was used for geotechnical surveys, in particular to establish the contact between the granite and the mica-schist formations. The general contract for the civil works

followed shortly, as it started in January 2017 and ended in October 2021, and the commissioning of the power units took place between March and June 2022.

The period between the contract for the access adits and the main contract was used to carry out *in situ* overcoring and flat jack tests for the estimation of the *in situ* stress field and other geotechnical surveys [3], which were needed for the design of the underground structures.

2.4. Monitoring plan

The monitoring plan for the underground works of the Gouvães hydroelectric scheme [4] was established considering the geotechnical and geological characteristics of the surrounding rock masses, the specific conditions of the designed structures, and their construction processes. The plan included monitoring of the actions, characterization of the material properties and observation of the structural, hydraulic and thermal response of the structures and the surrounding rock mass.

It comprised a set of measurement instruments that were installed primarily for monitoring the excavation and construction stages. They remained in place during the first filling and operation stages and were supplemented by additional instruments specifically for the monitoring of these stages of the project lifecycle.

Details on the monitoring of the structural behaviour and actions during the excavation and construction of the underground works, as well as during the first infilling of the power conduit are presented in Table 2.

Table 2 –Monitoring equipment

Physical quantity	Equipment	Location	Quantity
Relative displacement	Rod extensometer	Powerhouse cavern	18
		Transformers cavern	12
Force on anchors	Load cell	Powerhouse cavern	3
Hydrostatic pressure	Piezometer	Powerhouse cavern	2
Ambient temperature	Thermometer	Powerhouse cavern	1
Water temperature	Thermometer	Gouvães and Daivões reservoirs	2
Internal hydraulic pressure	Pressure transducer	Draft gates	1
Inflow discharge	Weir	Access tunnel to the powerhouse	5
		Cables shaft	2
		Busbar adits	2
		Powerhouse cavern	6

Additionally, displacements of the excavated surfaces, both in the underground caverns and tunnels, and on slopes at the ground surface, were measured all around the various working faces using topographic equipment during the construction stage.

Monitoring of the behaviour of the rock caverns during constructions relied strongly on the measurement of displacements inside the rock mass provided by the rod extensometers installed in the powerhouse and transformers caverns. This equipment measures relative displacement between the anchoring points and the head at the surface of the excavation. In this case, triple extensometers were used with anchoring points located approximately at depths of 3 m, 6 m and 25 m inside the rock mass, with the exception of the extensometers installed in the rock mass between the two caverns, where they are located approximately at depths of 3 m, 6 m and 15 meters.

The extensometers were installed in the crown, at the springing points of the arch and in the sidewalls, at four cross-sections of the powerhouse cavern (at 8 m, 32 m, 75 m and 102 m along the longitudinal axis) and at four cross-sections of the transformers cavern (at 8 m, 42 m, 52 m and 77 m along the longitudinal axis). Figs. 4 and 5 show, respectively, the locations of the rod extensometers in the powerhouse and the transformers caverns.

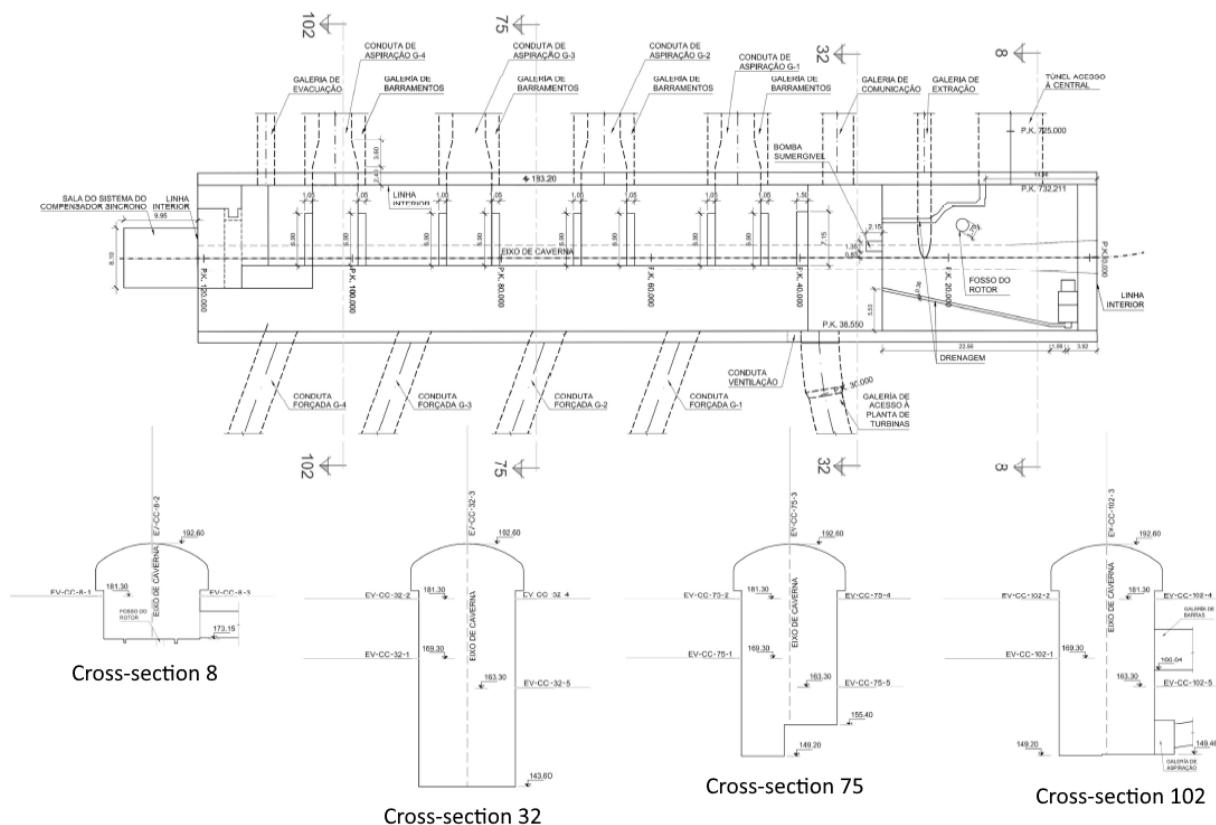


Fig. 4 – Extensometers in the powerhouse cavern

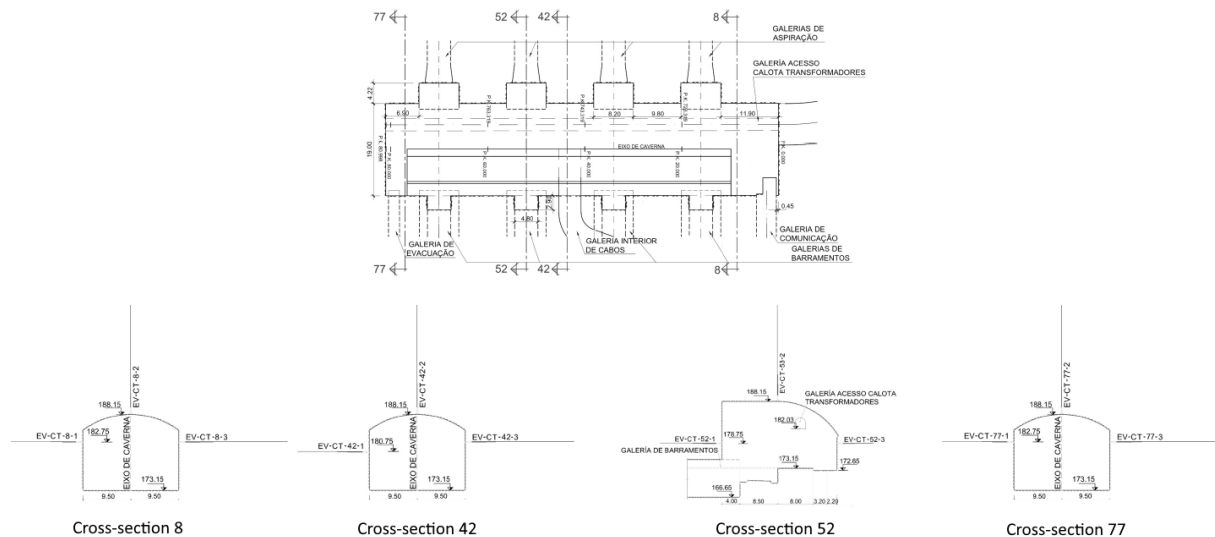


Fig. 5 – Extensometers in the transformers cavern

3. FIRST INFILLING OF THE POWER CONDUIT

3.1. Upgraded monitoring system

The monitoring system, initially designed to monitor the structural behaviour during construction, considered for the geological-geotechnical characteristics of the site and the construction sequence. It included a set of instruments, presented in Table 2, that remained functional during the first infilling but needed to be supplemented by additional instruments, specifically designed for this phase of the project. Therefore, in addition to the thermometer installed in the powerhouse cavern, and the rod extensometers and load cells installed in the powerhouse and transformers caverns, a set of piezometers and flow weirs, were included to measure hydrostatic pressures and flow rates in underground tunnels, adits and caverns, respectively, as well as a pressure transducer to measure the internal pressures in the circuit.

The two piezometers, PZ170 and PZ192, were installed close to power units G2 and G3, respectively (Fig. 6). Although providing only localized information regarding the hydrostatic pressures installed in the rock mass surrounding the main caverns, this setup allowed to evaluate the impact of the infilling of the power conduit onto the water flowing through the rock mass.

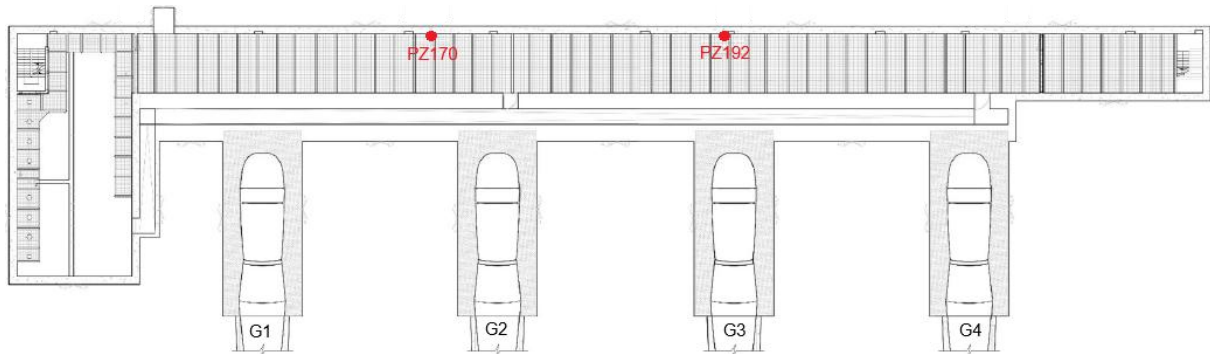


Fig. 6 – Spatial disposition of the piezometers

Initially, five flow weirs were located in pre-defined locations to isolate different portions of the access tunnels, namely water coming from the entrance of the access tunnel (flow weirs F-TO-CEN-01 and F-TO-CEN-03), water flowing to the access adit to the lower surge shaft (F-TO-CEN-02), water coming from the cables shaft (F-CEN-01) and a totalizing weir at the entrance of the powerhouse cavern (F-TO-CEN-04), which could isolate the volume of water flowing to the powerhouse cavern, based on the total water volume pumped from the pumping shaft. However, after the infilling began, this setup needed to be expanded and a total of 15 flow weirs were installed. Additional flow weirs were located in the cables shaft (F-CEN-02), at the entrance of the powerhouse cavern (F-TO-CEN-05), at the powerhouse cavern to isolate water coming from each rod extensometer (F-TO-CEN-06 to F-TO-CEN-11) and at the busbar adit (F-TO-CEN-12 and F-TO-CEN-13). Fig. 7 shows the spatial distribution of flow weirs.

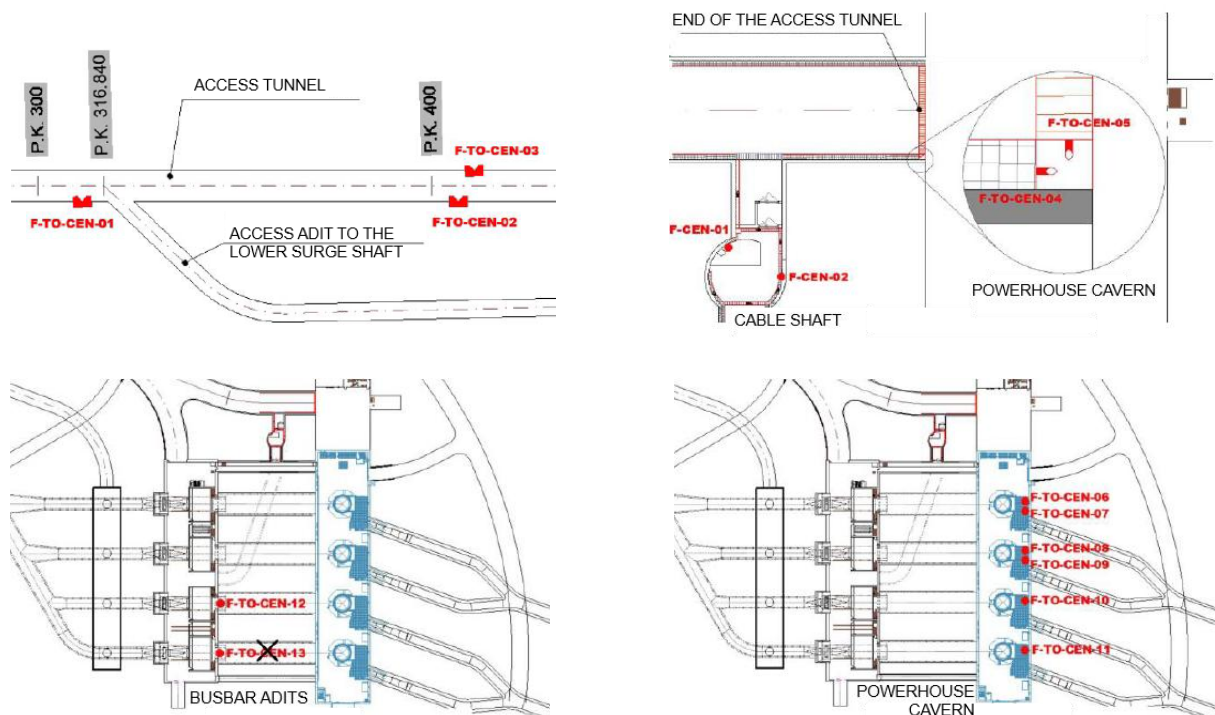


Fig. 7 – Spatial disposition of the flow weirs

3.2. First infilling plan

The “First infilling plan” [1] establishes the safety control measures to be carried out with the aim of:

- a) preventing accidents or incidents, or minimizing their significance and effects;
- b) ensuring the structural capability of withstanding service loads and the operability of the equipment;
- c) assessing the effectiveness of the monitoring system. It accounts for the specific characteristics of the Gouvães power conduit, namely the magnitude of internal pressures, type of linings adopted, geological-geotechnical conditions and the dimension of underground works.

The plan defines a cautious approach, based on LNEC’s experience and technical recommendations [5, 6, 7], characterized by a staged infilling procedure, where the inflow is interrupted at pre-defined levels. Furthermore, it ensures a slow infilling procedure, specially in the case of unlined or concrete-lined elements, avoiding a transient flow state and any damage that may occur, mainly around the powerhouse and the upper and lower plug sections. In those cases, a maximum increase in elevation of the water level of 5.0 m/h was adopted. This is particularly relevant for the tailrace tunnel, but also for the headrace tunnel, where the still-lined penstock is the most loaded structure of the power conduit but is considered impervious.

The first infilling plan establishes that it should begin by the tailrace tunnel. The water inflow was controlled by managing the balancing valves in the sluice gate at the lower water outlet. Five infilling stages were prescribed, specifically when the water level in the tailrace tunnel reached elevations of 166.0 m, 193.0 m and the Daivões reservoir level, followed by opening the draft gates, filling the draft adits and, finally, the spherical valves of the power units, filling the portion of the penstock below the Daivões reservoir level. Between each stage, a stoppage period of 24 to 48 hours is prescribed, to assess pressure losses in the circuit and to detect any resurgence in underground tunnels, galleries and caverns. Fig. 8 illustrates this process.

The filling of the lower portion of the penstock creates a water cushion that allows the infilling of the headrace circuit to take place, while protecting the spherical valves. The infilling of the headrace can be initiated after this condition be met and the plan prescribes eight infilling stages, achieved by opening and closing the sluice gate at the upper water intake. The first five stages regard the filling of the penstock which, due to its steel-lining, can be carried out very fast. The stoppages between each of these stages are short, allowing for a short inspection. In a second phase, the upper surge shaft and headrace tunnel are filled, with 24-hour stops at elevations 831.5 m, 865.6 m and the Gouvães reservoir level. The structural

behaviour during this phase is assessed by measuring the water level drop in the upper surge shaft.

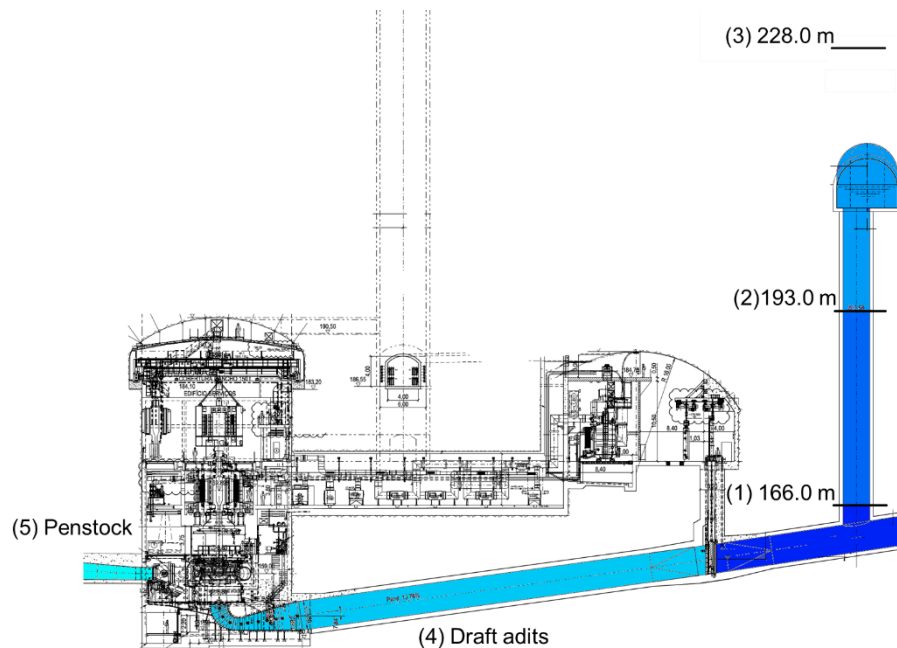


Fig. 8 – Infilling stages of the tailrace tunnel

The plan also indicates the observations that should be performed during the infilling, as well as their frequency, and the visual inspection details. It distinguishes six different observation periods. The first three correspond to the infilling of the tailrace tunnel, starting from one month prior to the infilling, during the infilling and during one month after. The other three for the infilling of the headrace circuit with the same rationale. Finally, the plan also includes a list of possible risk scenarios and the corresponding contingency and mitigation measures.

3.3. Occurrences during the first infilling

The predicted duration of the first infilling was one week for the tailrace circuit and five days for the headrace circuit. However, several constraints and delays made the first infilling of the underground structures of the Gouvães hydroelectric scheme take longer than expected.

A new stop at 178.0 m was included in the infilling procedure of the tailrace tunnel, as requested by the owner. This way the security of the underground works could be assessed before opening the draft gate of power unit G4, allowing testing the operation of the respective turbine under pressures smaller than planned. Afterwards, the infilling would proceed, as planned, with the infilling of the draft adits of power units G3, G2 and G1 after the tailrace tunnel reached a pressure corresponding to the elevation of the Daivões reservoir. This adaptation would make the infilling of the tailrace circuit to take two weeks.

However, the planned sequential procedure could not be fulfilled because, on one hand, delays in the installation of mechanical equipment occurred, making it impossible to perform tests on the turbines. This way the stop at 178.0 m would not be needed. On the other hand, the balancing valves in the sluice gate at the lower water outlet could not be managed properly after the first stop (166.0 m), making it impossible to completely stop the inflow. This way, the infilling of the tailrace tunnel had to proceed continuously, without stops, but at a lower rate (0.2 m/h), until the elevation of the Daivões reservoir was reached. From this point, the infilling of the draft adits was conditioned on the installation of the mechanical equipment in each power unit.

The infilling started on 7 June 2021 and an internal pressure corresponding to the Daivões reservoir elevation was reached, in the tailrace tunnel, on 16 June. The infilling of the draft adits took place on 21 June, 17 July, 4 August and 15 October for power units G4, G3, G2 and G1, respectively. During the infilling the observation schedule was fulfilled. The most important occurrences to be mentioned are the water inflow through some of the rod extensometers installed, which may have intersected flow paths, namely conductive discontinuities, the seepage through the floor slab of the transformer cavern (Fig. 9), and the infiltration through the lower plug (Fig. 10). These situations were promptly mitigated by installing new drains and carrying out waterproofing works and monitored by installing new flow weirs. The observation system performed appropriately, except the pressure transducer which lost functionality during the procedure and, therefore, could not track the evolution of the internal pressure.



Fig. 9 – Floor slab of the transformers cavern before (left) and after (right) waterproofing works and collecting water



Fig. 10 – Lower plug before (left) and after (right) pumping the inflow water to the access tunnel

After the infilling of power units G4 and G2, it was possible, by opening the respective spherical valves, to fill the lower portion of the penstock, ensuring this way the creation of a water cushion that protect the spherical valves. The infilling of the headrace circuit started on 9 August and ended, following the plan, on 16 August. Seepage through the upper plug and fissures in the concrete blocks surrounding the penstock close to the upper and lower bifurcation were observed. No significant changes were observed in the access tunnel to the powerhouse cavern. A detailed account of the first infilling was presented in a specific report [8].

4. CONCLUSIONS

The Gouvães reversible hydroelectric scheme has very large and deep underground structures—caverns, tunnels and shafts—most of them with a concrete lining. The most important ones, namely all the large caverns and most adits and shafts, are located downstream of the powerhouse. Having in mind the importance of these underground structures and the impact that the increase in the water pressures may have on the leakage that may occur into them, the first infilling of the power conduit is usually done in a planned way, in steps, and relatively slowly so that the flow in the rock mass can be established and stabilised.

The paper presented the first infilling plan and the upgraded monitoring system, and demonstrated the importance of performing the first infilling of the Gouvães power conduit in accordance with a plan, which was agreed beforehand between the LNEC, the owner and the

designer. The established procedure proved to be very useful to understand the hydraulic behaviour of the rock mass around the underground structures, to detect unforeseen occurrences, namely leakage into the openings, and to implement the necessary corrective measures.

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