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SALAMONDE II REPOWERING PROJECT: NATURAL FLOOD PROTECTION OF THE OUTLET STRUCTURE

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Abstract

The Salamonde Hydroelectric power scheme is located in the north of Portugal, within the Cávado river mountainous basin, and is one of the seven powerplants of Cávado-Rabagão-Homem hydropower system.

The original Salamonde scheme began industrial operation in 1953 and recently EDP took the decision to repower it by means of a new 209 MW reversible scheme (Salamonde II).

Several scale hydraulic model studies of the main hydraulic structures were performed. The paper presents the basic design studies and the description of the outlet structure and downstream channel scale model tests as well as the results obtained.

Keywords: Hydropower; channel; pump-turbine; hydraulics; sediments.

1. Introduction

1.1 Brief description of the Cávado-Rabagão-Homem hydroelectric system

With a length of about 100 km and a total head of about 1 000 m, dominating a watershed of roughly 1 600 km^2, with an average annual rainfall of approximately 2 200 mm, the Cávado river mountainous basin is the Portuguese region with the highest rainfall values (*e.g.* Plasencia *et al.*, 2008).

The Salamonde Hydroelectric power scheme is one of the seven powerplants within the Cávado river mountainous basin. Alto Cávado, Paradela, Salamonde, Caniçada and Penide, on the Cávado River, Alto Rabagão and Venda Nova on the Rabagão River and Vilarinho das Furnas on the Homem River compose the Cávado-Rabagão-Homem hydropower system (see Figure 1), whose hydroelectric potential began to be explored in 1945 with the construction of Venda Nova dam.

The water volume retained by Salamonde dam (net capacity of about 20 Mm^3) constitutes the lower reservoir for both Venda Nova II and Venda Nova III pumped-storage schemes.

The repowering of the Salamonde scheme (Salamonde II), by means of a new 209 MW reversible system, will enable the net volume of Caniçada reservoir to be mobilized to the Salamonde reservoir, consequently increasing the power storage capacity of the Venda Nova power schemes and of the Cávado-Rabagão-Homem hydropower system.

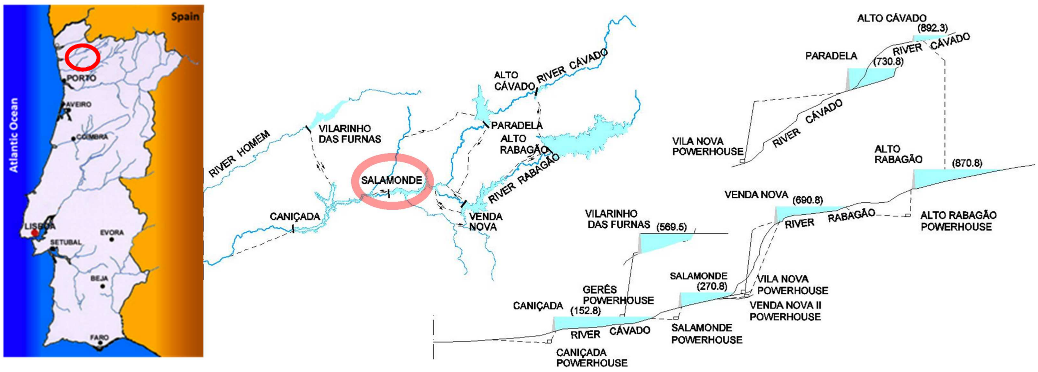


Figure 1. Salamonde II project location and Cávado – Rabagão - Homem Hydroelectric system.

1.2 Existing Salamonde hydroelectric scheme (1953)

The existing Salamonde scheme was built in the early 1950s. It consists of a 75 m high concrete arch dam, with top elevation at (271.00) - shown in Figure 2 - an underground hydraulic circuit, with a tower intake near the left abutment, and the outlet on the right bank of the downstream Caniçada reservoir. The average head available between Salamonde, NWL=(270.36), and Caniçada, NWL=(152.50), reservoirs is about 118 m.

Figure 2. Aerial view of Salamonde dam and spillway in operation.

Salamonde I powerhouse is located underground, on the left bank of the Cávado river, under the left abutment of the dam. It houses two Francis-type generating sets, with a nominal flow rate of 21 m^3/s per unit that results in a unit rated capacity of 21 MW (25 MVA). The water is returned to Cávado river through a 1.9 km long tunnel, with 30 m^2 cross section. Current annual average production is around 244 GWh.

1.3 General description of Salamonde II

The Salamonde II repowering project will use the storage capacity of the existing Salamonde and Caniçada reservoirs, taking advantage of the average 118 m head available between these reservoirs (*e.g.* Liberal *et al.*, 2010). On Figure 3, the general plan of both Salamonde I and II schemes is shown.

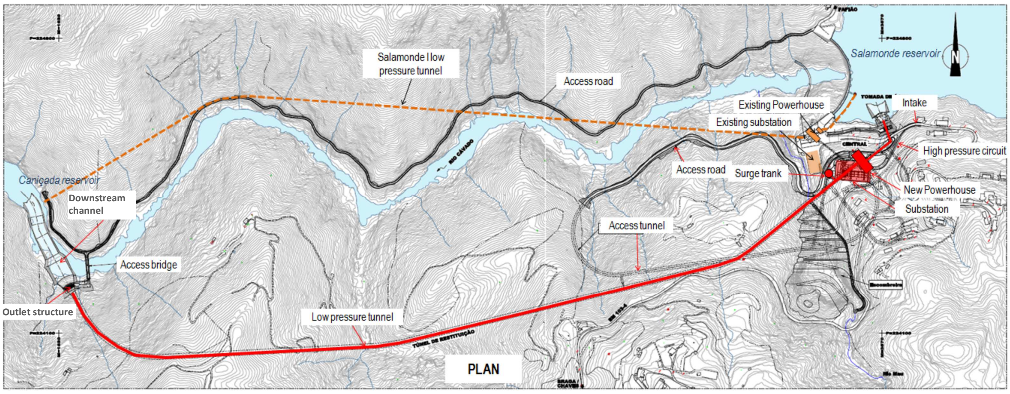


Figure 3. General plan of the Salamonde I and II schemes.

The Salamonde II scheme will be also essentially underground, excavated in a good quality granite massif, and includes the following main elements:

- An underground hydraulic circuit with 2.2 km total length, between the water intake in the Salamonde reservoir and the restitution in the Caniçada reservoir;
- The underground powerhouse, located under the left abutment of Salamonde dam, close to the existing Salamonde I powerhouse, equipped with a single reversible unit;
- The open air substation and its support building, built over the powerhouse and connected with it by means of a vertical busbar shaft.

The longitudinal profile of the Salamonde II scheme is presented in Figure 4.

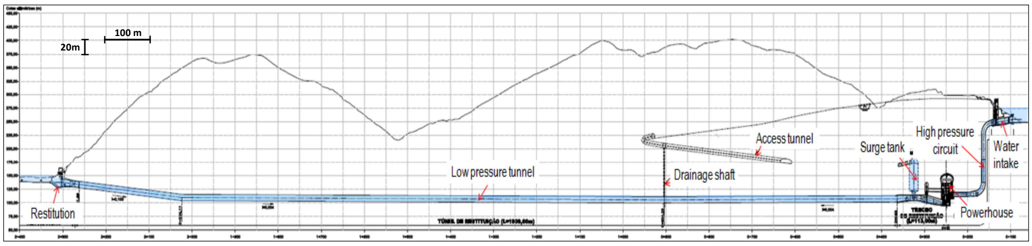


Figure 4. Longitudinal profile of the Salamonde II scheme.

2. Salamonde II scheme

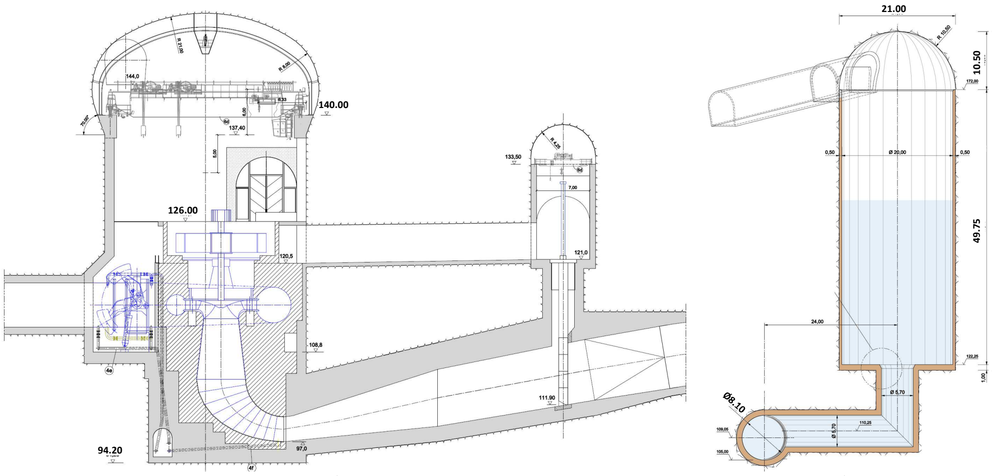
The underground hydraulic circuit includes a water intake in the Salamonde reservoir, a high pressure shaft and tunnel, the low pressure tailrace tunnel, protected by a surge tank, and the outlet structure at the Caniçada reservoir with a downstream channel excavated in the Cávado riverbed.

The intake is located on the left bank of Salamonde reservoir, 120 m upstream from the left abutment of the existing dam, and it has the invert at elevation (248.00) and will have an outside platform at elevation (274.00).

The high pressure hydraulic circuit has a total length of 200 m. After an initial short sub-horizontal stretch, a 90° vertical bend conducts the water to a 100 m high, concrete lined, vertical shaft with 8.3 m inside diameter. At the bottom of the shaft, another vertical bend connects to a final sub-horizontal steel lined stretch that leads to the powerhouse.

The Salamonde II powerhouse is located underground, close to the existing powerhouse of Salamonde I, and houses a single reversible unit, with a motor-generator, rated at 244.0 MVA, directly connected to the 231.4 MW maximum power pump-turbine. The cavern has a rectangular shape in plan, with 65.65 x 26.50 m², and a total height that varies between 27.50 m, at the southern atrium, and 44.70 m in the group area (see Figure 5 a)).

The low pressure circuit consists of a 11.80 m diameter tunnel, that begins immediately downstream from the surge chamber, and extends for about 1910 m to the restitution at Caniçada reservoir. Just downstream the powerhouse, this tunnel connects to a cylindrical surge tank with 50 m high and 20 m of diameter and restricted admission (see Figure 5 b)).



a) b)

Figure 5. a) Power house main cross section; b) Surge tank cross section.

3. Studies at basic design stage

At a preliminary stage, studies were carried out in order to define the basic design solution for the Salamonde II restitution works in Caniçada reservoir. These works consist of an outlet structure and a downstream channel excavated in the Cávado riverbed, aiming to ensure the operation of the new scheme without constraints, especially in pump mode and having in mind its proper performance during natural flood events.

3.1 Outlet structure

The design of this structure took into account the possibility of its operation either in turbine or in pump modes. A mean approach flow velocity of about 1 m/s, calculated with the maximum flow in permanent turbine mode (200 m³/s), was considered to define the net flow area of the outlet cross-section. This section consists of three rectangular openings with 12 x 6 m² each and a total area of 220 m², protected by movable steel trash racks.

In order to determine the elevation of the outlet structure, two main issues were addressed, assuming the operation of the new power scheme in pump mode with the lowest level at Caniçada reservoir: minimum submergence to guarantee no vortex formation in order to avoid air entrainment in the power scheme and undesirable vibrations in the trash racks; ensure appropriate approach flow conditions to the outlet structure for the whole range of Caniçada reservoir operation levels, both over the crest of the control sill as on the river stretch downstream.

The approach proposed by Gordon (*e.g.* Gordon, 1970) was applied for minimum submergence definition in pump operation mode, leading to an outlet section with the invert placed at elevation (131.00), see Figure 6, and ceiling at elevation (143.00), 1 m below the minimum Water Level (mWL).

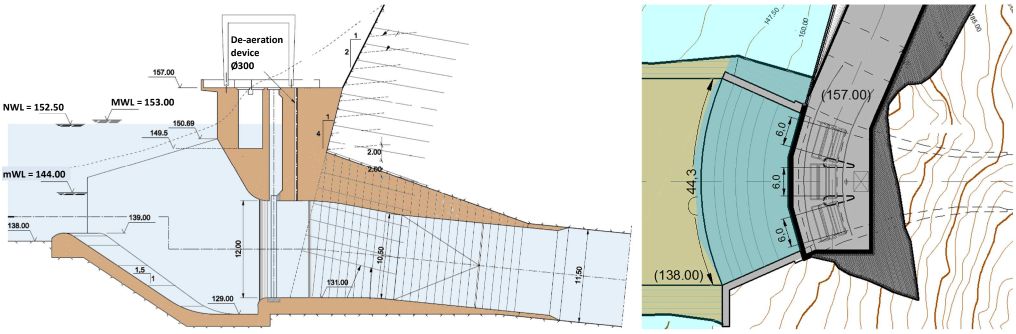


Figure 6. Longitudinal profile of the outlet structure.

To ensure the necessary flow conveyance over the control sill, both in turbine and pump mode, its length and crest elevation were defined bearing in mind its function as protection from potential sediment entrainment and its hydraulic performance, assuming appropriate shape transitions.

For the river reach downstream the outlet, the first hydraulic studies showed that a channel in the riverbed needed to be excavated in order to meet the established criteria for operation of the Caniçada reservoir in pumping operation which are addressed in the following point.

3.2 Downstream channel

Due to the site constraints and other criteria related to economic, socio-economic and hydraulic/geotechnical stability conditions two main operating conditions are to be guaranteed in reversible schemes.

Firstly, the total volume stored in the reservoir between the NWL and the mWL should be used, meaning to ensure the ability to feed the reversible units during pumping operation, until the level reaches the mWL.

Secondly, one may ensure the possibility of pump start-up at the minimum water retention level in the reservoir (*e.g.* Ribeiro and Pinto, 2013).

The numerical simulations carried out took into account the unsteady flow regimes, adopting a set of conditions concerning time for flow variation (operation hydrographs) and the downstream characteristic exploitation levels mentioned above.

Aiming to seek the downstream channel solution that minimizes the sum of the economic value of energy losses during operation life time and of construction costs (mainly excavation) associated, a technical and economic analysis was conducted, considering several alternative solutions, with different geometric definitions and bottom elevations, resulting in different excavation volumes, all of them meeting the operating conditions mentioned in the above paragraphs.

That analysis concluded that Cávado riverbed downstream from the outlet structure has to be excavated along about 200 m, forming a trapezoidal canal with the bottom elevation at (139.00) and the width dimensions varying from 43.1 m, near the outlet, to 30.0 m at the downstream end (see Figure 7). The excavation volume was estimated at about 38 000 m^3.

Figure 7. Cávado river nearby and upstream the outlet structure.

Given the significant slope of the Cávado river upstream from the Salamonde II restitution works and the location of such structure in the extrados of the pronounced curve that exists in this section of the river (see Figure 7), further studies were carried out to determine the flow conditions in the Cávado river, nearby the access bridge and outlet structure, during natural flood events. For this purpose, the previously used numerical model was completed with the Cávado river stretch between the Salamonde dam and the outlet structure (≈ 2 km).

The results achieved have estimated a maximum water level of approximately (154,5) and the occurrence of flow velocities exceeding 7 m/s in the section immediately upstream from the access bridge (see Figure 7), with 2850 m^3/s, the maximum discharge capacity of Salamonde dam flood spillways (*e.g.* Oliveira *et al.*, 2011), which indicates a highly turbulent and difficult to predict flow behavior that could lead to unsatisfactory operating conditions and, even, safety hazard to personal and equipment, among which stands out the access bridge to the outlet.

In order to check the flow conditions in this area, both for normal operating conditions of the Salamonde II powerplant, and for natural flood events, it was decided to perform several tests using a hydraulic scale model.

4. Physical modeling purposes

In many practical cases, physical models still proof as useful tools for simulation of complex hydraulic problems that can hardly be solved solely by means of analytical or numerical modelling. Considering the complexity of the whole hydraulic system it was decided to test the hydraulic structures of the repowering scheme in a hydraulic physical model.

The verification and optimization of the outlet structures hydraulic behavior under a wide range of operation conditions was the physical model tests main goal, namely in what concerns the submergence levels in both turbine and pump modes. However, conditions leading to river banks potential damage and river bed sediment behavior in the vicinity of the structures, under normal operating conditions (turbine and pump modes) and in natural flood situations, were also analyzed in the physical model. More specifically, the physical model tests included:

- Evaluation of vortex formation with air entrainment tendency, i.e., involving risk of floating material being driven into repowering circuit (submergence analysis);
- Verification/optimization of outlet structure and downstream channel hydraulic performance;
- Velocity field characterization in several sections of the outlet structure under different operating conditions;
- Mean pressures measurements along the internal solid boundaries of the outlet structure for different operating conditions;
- Hydraulic performance analysis of the downstream channel under several flow conditions, with attention paid to any undesirable flow conditions such as concentration of flow and/or recirculation areas in the vicinity of the outlet and testing of corrective measures;
- Analysis of global performance of the outlet structure for extreme flow conditions, considering maximum and minimum exploitation water levels in Caniçada reservoir;
- Identification of potential areas for erosion or deposit of sediments leading to possible interference between entrained/deposited sediments and the outlet structure operation.

Two major types of tests were considered:

1. *Hydraulic performance tests*: to evaluate the hydraulic performance of the initial design and assess alternative solutions if undesired hydraulic behaviors were observed.
2. *Sediment tests*: global sediment tests (including calibration of the model based on existing operational elements) to analyze sediments erosion and deposition near the outlet structure.

5. Physical model description

The hydraulic physical model studies of the outlet structure and the downstream channel were performed by LNEC, the adopted scale having been 1/58.4507. The model general layout is represented in Figure 8.

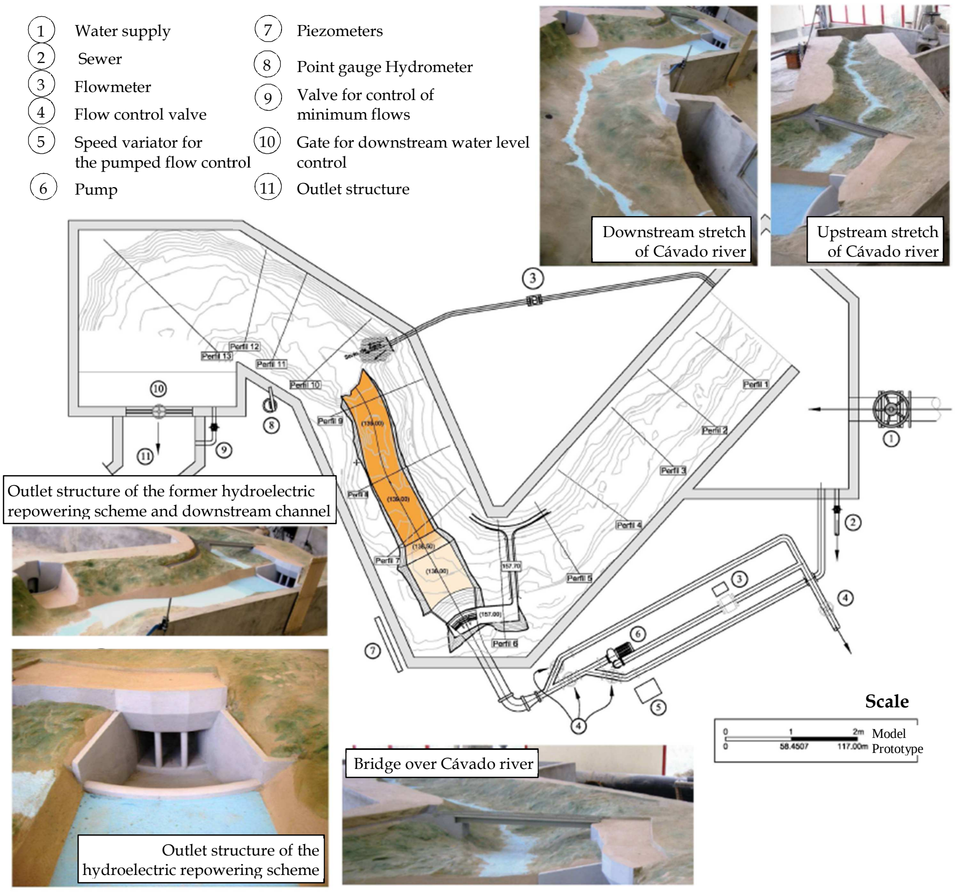


Figure 8. Hydraulic physical model of the outlet structure and the downstream channel.

The main features of the model are as follows:

- Main water supply allowing to simulate the river discharges;
- A secondary supply circuit incorporating a pump and an appropriate set of valves and by-passes allowing to simulate both turbine and pumping operations;
- Outlet structure of the former hydroelectric power scheme;
- Cávado river stretches reproduced upstream and downstream of the outlet structure with about 350 and 425 m long;
- A 200 m long channel excavated in the riverbed, located downstream the outlet structure of the hydroelectric repowering scheme;
- A 52 m span bridge over Cávado river, located immediately upstream the outlet structure of the hydroelectric repowering scheme.

6. Physical model tests main results

6.1 Hydraulic performance tests

6.1.1 Methodology and characteristics of the tests

For the *hydraulic performance tests* the main concerns were: i) possible occurrence of return currents near the outlet structure inducing excessive agitation; and ii) safety of the bridge located upstream the outlet structure under flood conditions.

The following sequence of tests was considered:

- Verification of the initial forms defined in the Project;
- Tests of alternative forms;
- Tests of optimized proposed forms.

Tests were performed with flow values between 140 e 3200 m^3/s and considering extreme water levels in Cávado river – NWL *Normal Water Level* and mWL *minimum Water Level* of Caniçada reservoir, as this reservoir influences the water levels of Cávado river up to a section immediately upstream the outlet structure of the repowering scheme.

6.1.2 Tests main results

Observed strong flow currents impacting on the bridge deck and significant flow disturbances near the outlet structure confirmed that the hydraulic performance for the *Initial Forms* defined in the Project were not acceptable for high flow conditions - Figure 9.

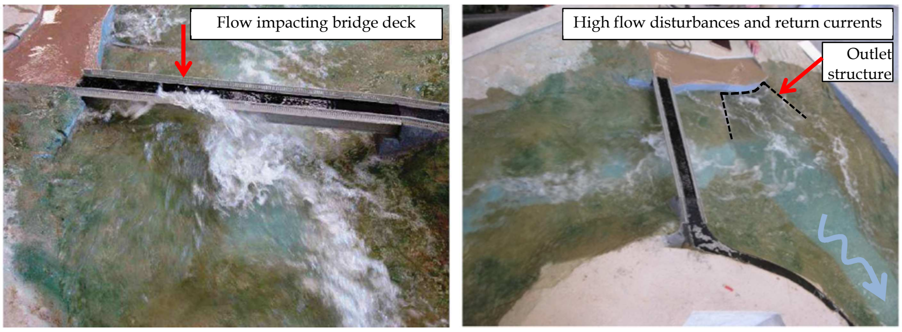


Figure 9. *Initial Forms*. $Q_{T=100years}$ = 2170 m^3/s; $Level_{Caniçada}$ = NWL. Left – Detail of flow impacting the bridge deck near the left bank; Right – General view of the flow near the outlet structure.

The first set of tests with *Alternative Forms* consisted mainly in changing the following work components: i) the general excavation plan defined in the Project; ii) the outlet structure, namely its lateral walls; and iii) the geometry of the downstream channel. In general, this first set of alternative forms still presented inadequate flow conditions, since the flow impact on the bridge deck was not prevented and the flow disturbances near the outlet structure were not reduced - Figure 10.

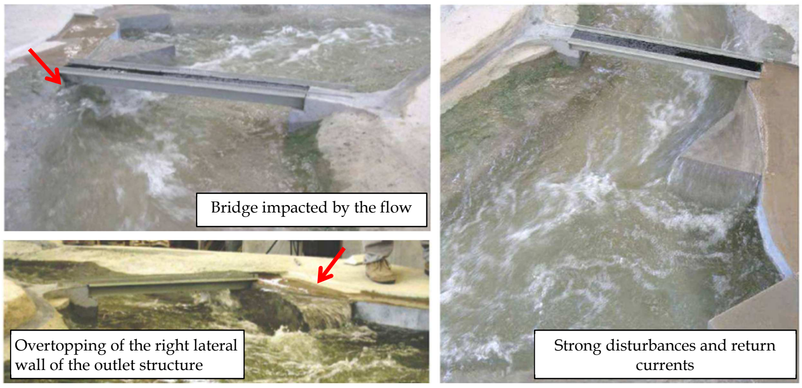


Figure 10. *First Alternative Forms*. $Q_{T=100years}$ = 2170 m^3/s; $Level_{Caniçada}$ = NWL. Left - Upstream and downstream view. Right - General view of the flow near the outlet structure.

The last set of tests with *Alternative Forms* focused on mitigation of problematic flow conditions in certain areas. These refer mainly to the introduction of a weir upstream the bridge to create conditions to soothe the predominantly torrential flows of Cávado river. The several alternatives studied in this last set of tests allowed the optimization of the weir geometry and its plan positioning.

The *Proposed Forms* revealed a suitable hydraulic behavior in what concerns: i) the improvement of flow distribution on the stretch of Cávado river downstream the weir; ii) mitigation of flow impacting the bridge deck; iii) and reducing the return currents and associated disturbances near the outlet structure and downstream channel - Figure 11.

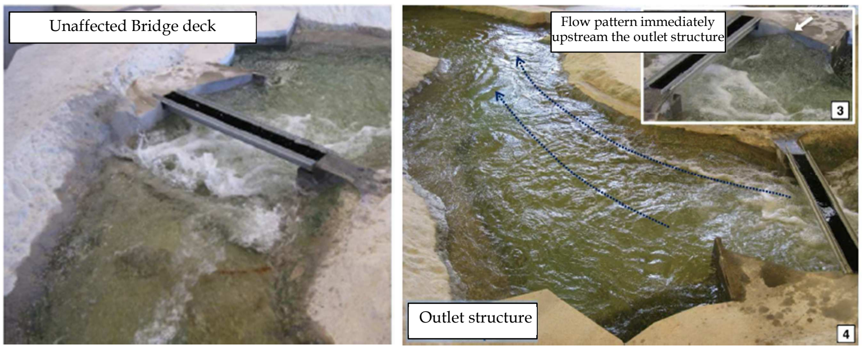


Figure 11. *Proposed Forms*. $Q_{T=100years}$ = 2170 m^3/s; $Level_{Caniçada}$ = NWL. Left - Upstream view. Right - General view of the flow direction near the outlet structure and on the downstream channel.

6.2 Sediment tests

The tests with sediment transport are aimed at identifying the areas of erosion and deposit of sediments in the downstream channel of the outlet structure. This aspect is particularly important during an operation of the bottom outlet of the upstream Salamonde dam.

Preliminary tests were carried out (i) to select the most suitable material, (ii) to determine the amount of sediment that should be added to the circuit and (iii) to know the best sediment feeding pattern. After some experiences with sand (d_{50} = 0,25 mm) and bakelite (d_{50} = 0,94 mm) it was decided to proceed the experiments with the latter due to its dimension and visualization issues. The sediments were gradually added to the circuit during 2 hours.

The experimental plan comprises nine different operating scenarios, combining water levels in the Caniçada reservoir, type of operation of the outlet structure (turbine or pump) and river flow discharge. The experiments with pump or turbine operation included three different parts namely (i) the sediment feeding, (ii) the evolution of the sediment transport, (iii) the equilibrium.

An example of one of these experiments is presented in Figure 12 showing the evolution of the sediment pattern and also the equilibrium phase in the downstream channel after six hours of model feeding.

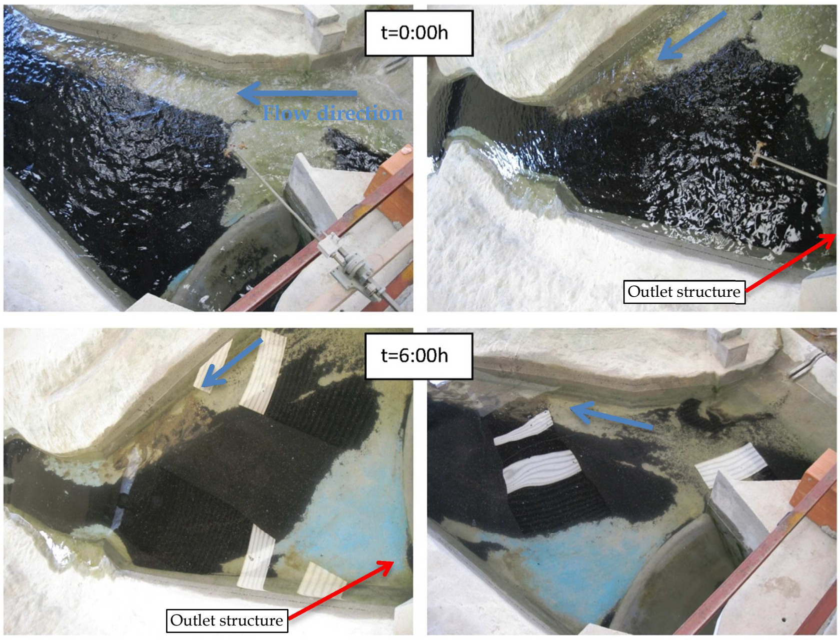


Figure 12. Evolution of the sediment deposition after 6 hours.

From the experiments, it was concluded that the single effect of the flow turbines is not enough to do an acceptable sweeping of the sediment deposition verified on the downstream channel. Besides that, it was found that to avoid the sediment entrance to the outlet one should turbine at the same time as the opening of the bottom outlet of the Salamonde dam. On the other hand, special precautions may be taken if one wants to avoid the entrance of sediments during pumping operation.

6.3 Summary and recommendations

The physical model test with the *Initial Forms defined in the Project* revealed inadequate hydraulic behavior under flood flows with return periods as low as one hundred year.

The model tests allowed the improvement of flow conditions initially observed, resulting in the recommended *Proposed Forms* which consisted essentially in (see Figure 13):

- A weir and guide wall in the left margin of Cávado river upstream the outlet structure;
- A further upstream extension of the excavated channel from the outlet structure section up to the bridge section;
- 1 m crest heighten of both lateral walls of the outlet structure;
- Several other minor changes to the *Initial Excavations Plan*.

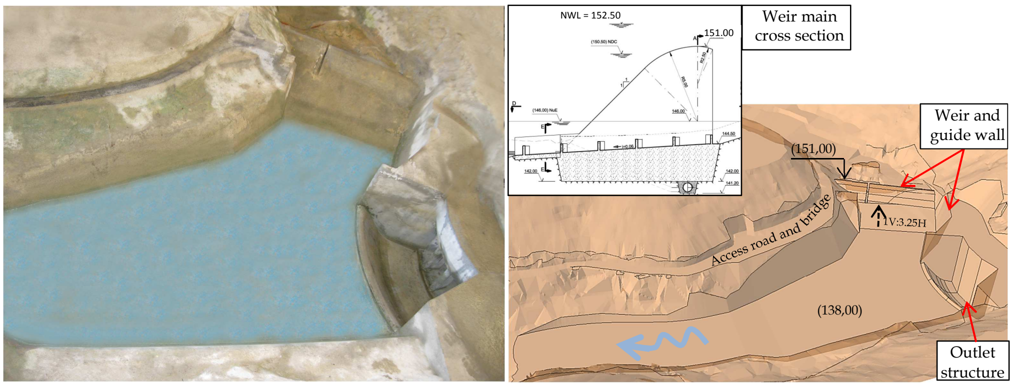


Figure 13. *Proposed Forms*: physical model photo, 3D preview and weir main cross section.

In general, appropriate flow conditions were verified with the *Proposed Forms*, particularly for the one hundred year return period flood, though rather acceptable hydraulic behavior was achieved for higher floods.

The major change resulting from the physical model tests turned out to be the introduction of a weir upstream the bridge section, correcting the dangerous flow pattern impacting the bridge deck for quite frequent flood events (20 year flood). Additionally, this weir also contributes positively to the mitigation of sediments entry into the outlet structure, once the weir works as a sort of sediment trap.

Model studies also allowed assessment of recommendable operation modes of the hydraulic circuit in order to avoid sediments from being dragged into the circuit when operation occurs simultaneously with the opening of Salamonde dam bottom outlet.

7. Conclusions

The studies carried out for the Project of Salamonde II repowering project, namely those related with the natural flood protection of the outlet structure, clearly evidences the importance of careful design, involving the best practices and supported by advanced analytical and numerical tools.

For the preliminary project stage these tools proved quite useful to properly conceive the repowering project general layout and identify localized areas where additional analysis and detail was required.

The physical hydraulic model was then an invaluable tool, allowing to properly reproduce many aspects of the complex flows and their interaction with fixed boundaries and to simulate macroturbulent flows and sediment transport. These were issues that could hardly be assessed by the designer using numeric tools, as far as flow conditions and the consequences in the operation and safety of the projected works are concerned. So, through the testing of different corrective measures in the physical model, the initial design was progressively fine-tuned.

From the above, one may conclude that through an adequate combination of analytical, numerical and physical modelling, efficient results can be achieved in terms of project costs versus improvement in operational reliability and hydraulic safety of large hydraulic structures.

Acknowledgments

The authors are thankful to Adelaide Gonçalves and Raquel Moreira for their essential help and commitment during the experiments.

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