Design of the tailrace surge tank for the Gouvães pumped-storage plant

Juan Carlos Vera
Civil Engineer
Iberdrola
Avda Manoteras, 20
Madrid, Spain

Wolfgang Richter
Civil Engineer
TU Graz Hydr. Inst.
Stremayrgasse 10 / II
Graz, Austria

Luis de la Torre
Civil Engineer
Iberdrola
Avda Manoteras, 20
Madrid, Spain

Christophe Nicolet
PhD Mechanical Eng.
Power Vision Eng.
Chemin des Champs-Courbes, 1
Ecublens, Switzerland

As it's well known, the Spanish company Iberdrola is constructing the Hydropower System Tâmega at present, in the mainland northern region of Alto Tâmega, in Portugal. In July 2008 Iberdrola won an international tender launched by the Portuguese Government to construct and operate a cascade scheme of four hydropower plants (Padroselos, Alto Tâmega, Daivões and Gouvães), that finally came to three plants, as Padroselos was suspended for environmental reasons. The total installed capacity of the whole project will be 1158 MW with an expected annual production of 1766 GWh, 1468 GWh corresponding to Gouvães.

The Gouvães pumped-storage plant, between the Torno and Tâmega rivers, is an underground scheme that involves the construction of a 7.50 km-long power circuit (6.70 km underground), a powerhouse cavern to be equipped with four reversible Francis pump-turbines and several other large excavation works such as the upstream and downstream surge tanks and transformers caverns. The construction of this ambitious project began in 2015, and completion is scheduled for 2022. The four reversible Francis pump-turbines are designed with nominal power of 220 MW and a gross head of 660 m and rotational speed of 600 rpm, the total discharge in turbine mode is 160 m^3/s and in pumping mode 128 m^3/s. The grid balancing and energy storing power plant utilizes the upper reservoir Gouvães at the Torno river, and the lower reservoir Daivões at the Tâmega river, right tributary of the Douro river.

As it has been mentioned before, upstream and downstream surge tanks are among the critical points of the project, not only for their excavation volumes, but also for their design complexity and their implications in the plant safety. This paper tries to describe the process of design of the tailrace surge tank of Gouvães Pumped Storage Hydropower Plant.

1 General layout of Gouvães

The layout is standard for this type of pumped-storage plant, with the following main features:

- A headrace concrete lined tunnel of about 4.7 km with 7.3 m inner diameter
- A cylindrical upstream surge tank, designed as a concentric Johnson differential surge tank, with a large shaft of 21 m diameter, an inside gate shaft of 8 m diameter and 71.8 m high, connected to the headrace tunnel with an asymmetric diaphragm of 2.5 m diameter.
- A steel lined penstock of 2.2 km with variable diameter between 6 m and 1.6 m in the four final feeders close to the turbines.
- The Powerhouse in the main underground cavern, where all the units and associated equipment are located, at a depth of approximately 300 m.
- The tailrace surge tank, connected to the four draft tubes from the turbines,
- And finally a tailrace concrete lined tunnel of 7,3 m diameter and about 700 m long, where all four draft tubes (3,8 m diameter) converge with a transition manifold.

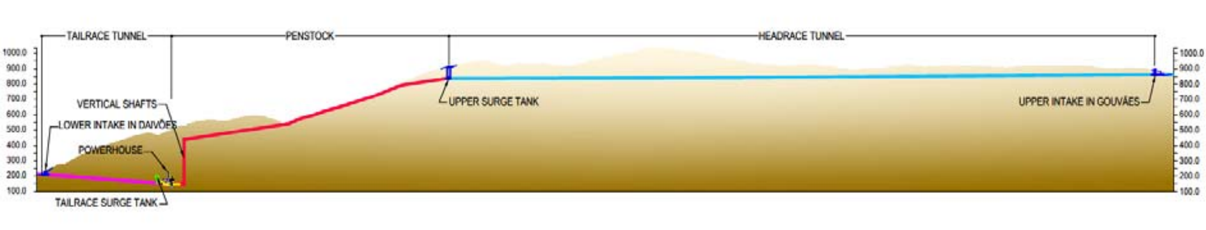


Fig. 1 General view of PSP Gouvães layout

2 First design of the tailrace surge tank

Due to the length of the tailrace tunnel, a surge tank is required to enable the controllability of the machine units, to reduce the overpressures and to prevent the system from macro cavitation. The size of the surge tank is derived by the effects of the water mass oscillation in the tunnel, when this water is accelerated and decelerated by opening, closing or uncontrollable events such as load rejection or pump trip during operation.

The design of the lower surge tank had to take into consideration the difficulties of constructing a conventional shaft solution completely underground, in addition to the hydraulic criteria. The total volume calculated for this surge tank was about 11000 m^3 so it would have required the excavation of a huge cavern, with high costs and very long construction time. Therefore, it was decided to build two chambers of around 70 m long at the extreme elevations, and a connecting gallery between them. This approach places the biggest horizontal areas where is more necessary, at the lower and upper levels. That reduces the vertical speed of the water before the limits and reduces the necessary excavation volume, giving a quicker response to pressure mass oscillation. The two chambers were displaced horizontally in order to let them being connected by a riser gallery with a reasonable slope and a length of 115 m long. This solution made it possible to excavate the surge tank based on a conventional tunnel strategy, reducing construction time and costs.

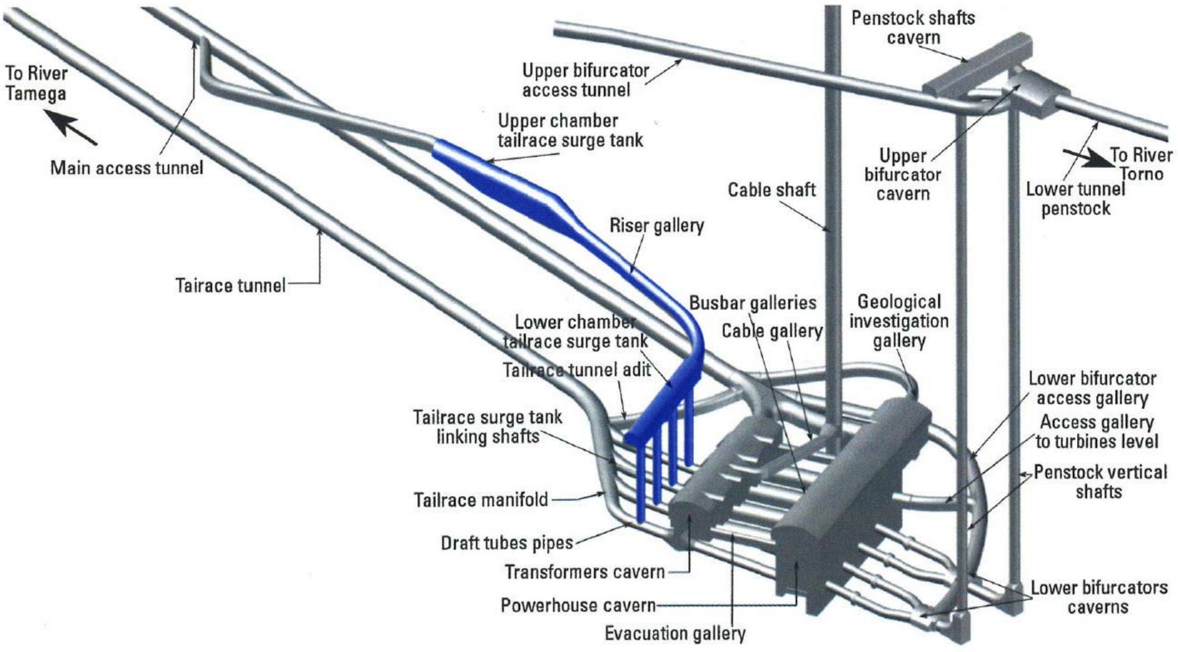


Fig 2 General 3D layout of the underground powerhouse with tailrace surge tank indicated

The excavation was initiated from the main access tunnel. This fact creates a connection between the upper chamber of the surge tank and the powerhouse, which must be kept open due to the aeration of the surge tank. The potential danger to eliminate is that no water reaches the powerhouse in case of a surge tank overflow. This makes an exhaustive verification of the surge tank design necessary, in order to avoid any spilling in worst case scenario since the water would lead directly into the transformer and power house caverns. Such a surge tank spilling was reported by Dahlbäck due to insufficient surge tank volume for resonance load cases [5].

The tailrace surge tank is located as close as possible to the machine cavern. The lower chamber connects with four shafts into each draft tube pipe. This approach has specific advantages for very quick water hammer response and mitigates asymmetric and thus unfavourable water hammer interferences at delayed load rejection events. This design significantly reduces the risk of water column separation in the pump-turbine's draft tubes, inherent to low specific speed pump-turbine featuring very pronounced S-Shape characteristics, see [8]. This also is an advantage for predicting the worst case in the simulation. The positioning of the four shaft connections mitigates the influence of the water inertia acting between the units and the surge tank itself [2].

3 Hydraulic investigations

3.1 Numerical modelling for Transient Analysis

In the preliminary engineering of the project, Iberdrola defined the layout described above performing numerical simulation of the transient behaviour of the power plant, designing the upstream and downstream surge tanks and checking the minimum and maximum pressures in the hydraulic circuit, using a simplified model of the pump-turbines.

In 2016, Power Vision Engineering (PVE) performed the first optimization of the surge tanks. Simulations of hydraulic transient behaviours of the Gouvães Pumped Storage power plant were performed with the SIMSEN software, developed by the EPFL (Ecole Polytechnique Fédérale de Lausanne) [6].

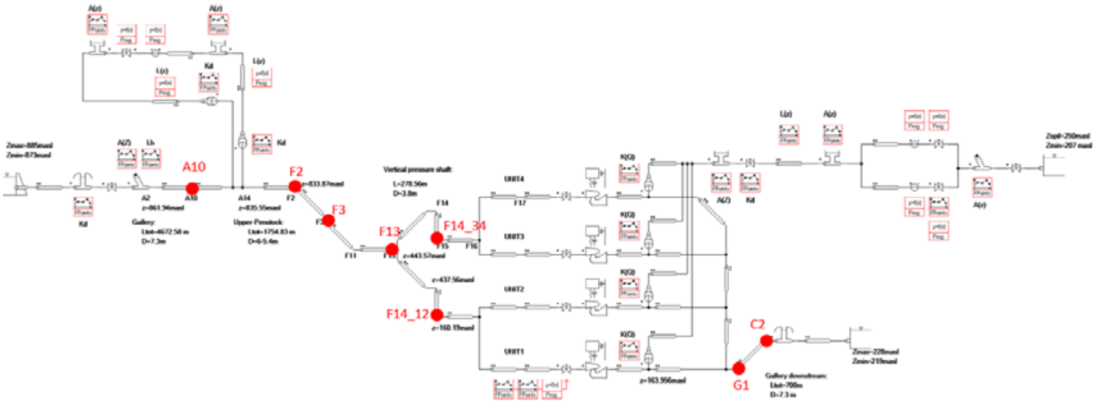


Fig 3 SIMSEN model of the Gouvães pumped storage power plant.

Overflow and dewatering for the upstream and downstream surge tanks for normal load cases induced an increase of the loading and unloading time of the units. The vertical elevation of the chambers was increased 4 m, and the section of the chambers was modified, maintaining the volume, but getting narrower. These were important changes for achieving the necessary safety margin.

After this first optimization, physical model testing of the downstream surge tank was performed at the Institute of Hydraulic Engineering and Water Resources Management of Graz University of Technology (TUG) in 2017, which led to significative improvements. The comprehensive mass oscillation simulations were carried out in redundancy with Wanda V4.5 considering the reversible pump-turbine discharge time evolution based on the manufacturers diagrams of the machine transients. The results of these mass oscillation simulations were the transient physical model test inputs. Furthermore, two-phase flow 3D-CFD pre-investigations were undertaken (by different parties involved in the project) to identify challenges in specific 3D flow occurrence. These simulations revealed that the upper chamber was filled with a significant wave that asked for further improvements. The local losses in every connection of the surge tank where calculated via 3D CFD model in order to increase the accuracy of the 1D transient analysis.

Moreover, the stability criterion was checked via the approach of Svee (1970) [9] and was found that the main riser section could be reduced.

3.2 Physical model test

A physical reduced-scale model test was constructed and elaborated at Graz University of Technology for the downstream surge tank. The hydraulic model test was operated in Froude similitude law and a geometric scale factor of 1:25. The chambers, the main raiser, the four shafts and the manifold substitution were constructed. The procedure of the hydraulic transient model test is the following: The results of the 1D transient mass oscillation simulations with Wanda software were first converted to Froude scaled discharges and then imposed as surge tank inflow/outflow boundary condition. The transient flow behaviour was controlled via air pressure valves that are governed via a calibrated PID governor, valves (1) and (2) in Fig 4. The discharge is then checked by an IDM and it returns the information to a PID governing control software. Basically all discharges (pump/turbines and mass oscillation) in the tailrace tunnel are operated via these two valves. The mass flow in the pressure tunnel is the most important flow and drives the excitation of the water level in the surge tank.

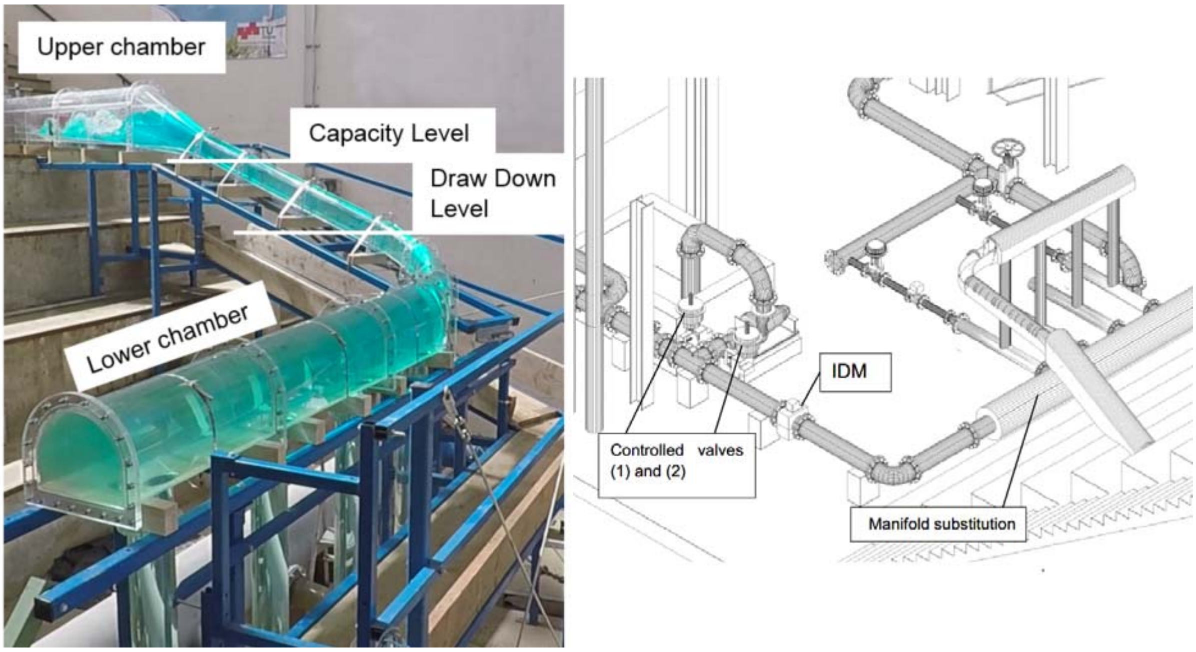


Fig 4 Physical model test

The advantage is in particular that only one controlled valve at the same time is responsible to govern the full transient flow. This avoids interference from operating more controlled valves at the same time and allows high accuracy regarding the discharge at specific time points.

Fig 5 shows the direct comparison of the defined transient discharge with the measured discharge of the model test operation. The y-axis is the discharge in l/s and the x-axis the time. Figure also shows the comparison of the target inflow/outflow and measured inflow/outflow for the most severe pump trip case. At point of interest, only a deviation of 0% - 5% was established. This 5% were over inflow and thus on the save side.

The figure describes the start-up of the pumps with an outflow of the surge tank due to down surge and acceleration of the water mass in the tunnel. After the peak acceleration of the flow in the pressure tunnel, the flow to the surge tank reverses and starts filling it. At the time point of the peak acceleration in the tail race tunnel, all pumps face a full trip and the flow direction of the pumps reverse very quickly and leads to the peak discharge of 68 l/s (220 m³/s in prototype) into the surge tank creating the massive design surge in the upper chamber.

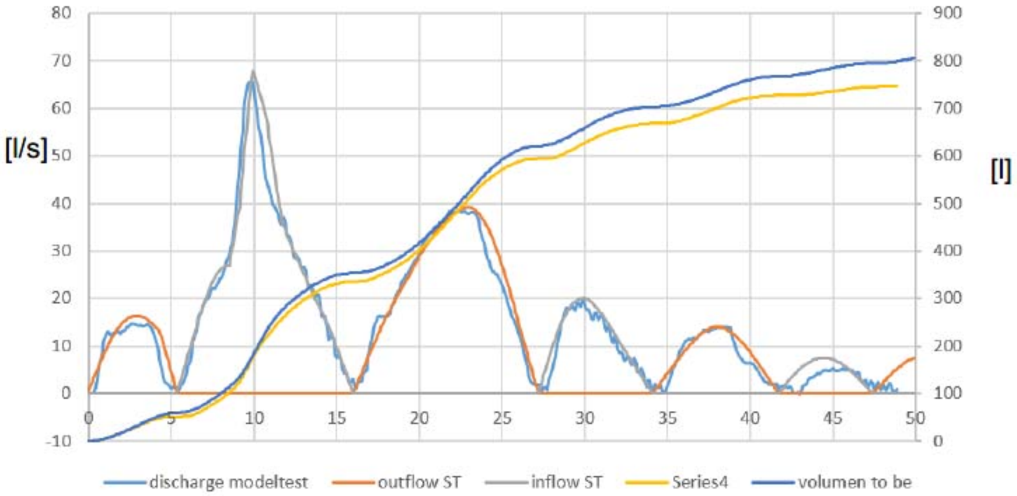


Fig 5 Comparison 1D transient analysis outflow/inflow and physical model test discharge

Video analysis was used to study and check the behaviour of the mass oscillation in the model test, and eight pressures sensors were placed in the model test to measure both the water level and the occurring pressures.

3.3 Design load cases

Simulations of several load cases of mass oscillation and water hammer were done by different teams, such as the machine supplier, PVE and TUG, during the hybrid modelling for the surge tank investigations. The surge tank is designed for the normal use and for the most severe load cases both in turbine and pumping direction, allowing safe and quick power regulation and avoiding any dangerous water hammer over- and under pressure peaks:

a. Normal load cases:
   - Start-up, loading, unloading and normal shutdown;
   - Emergency shutdown (ESD);
   - Delayed load rejection;
   - Any combination of normal load cases;

b. Exceptional load cases involving failure of components
   - ESD with 1 guide vane failing to close;
   - ESD with 1 main inlet valve (MIV) failing to close;
   - ESD with GVO closing on the security diaphragm;

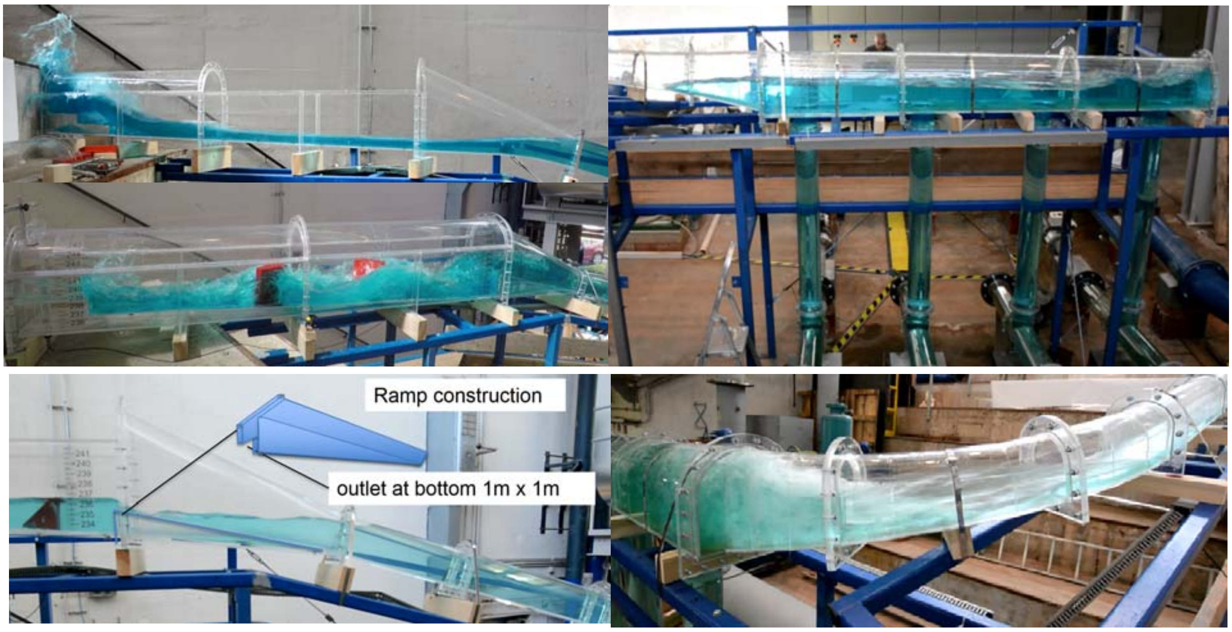
Exceptional load cases also include resonance and unlikely events nowadays, as simultaneous loading of the 4 pumps that have resulted to be the most unfavourable cases. That prepares the installation for the operational challenges of the future, with faster cycles of turbine and pumping.

4 Physical model test improvements

This chapter describes the main technical structures that were recommended for the final geometry of the lower surge tank in order to improve the hydraulic behaviour after the physical model test.

4.1 Baffles in upper chamber

Exceptional synchronous pump trips in resonance with mass oscillation in tailrace tunnel can lead to massive filling of the upper chamber. In such a case the water would spill out of the aeration construction and would cause severe damages without measures to dissipate the surge. In order to prevent overflow and sloshing in the chamber, the energy of the surge must be efficiently dampened by large and horizontally inclined baffles, a steeper inclined bottom and a stepped ramp at the rear of the chamber, as shown in Fig 6 (a)



(a) (b)

Fig 6 Physical model test improvements

4.2 Weir in upper chamber

Air should not be intruded into the pressure tunnel system. Additionally, the Froude scaled physical model test does underestimate the air intrusion so it decided to fully avoid air bubbles in the physical model to be intruded into the connection shafts. Therefore, first the system was intensively studied to understand the intrusion phenomena and then numerous measures were tested to find the proper solution.

Basically air is intruded into the water body when a jet from the upper chamber mixes air under the water surface. This air then needs to rise and leave the water body. In nature the vertical terminating velocity of the chosen design bubble of 6 mm diameter can be found between 0.2 m/s and 0.25 m/s [10].

In numerical models the bottom of the lower chamber is not reached as the outflow is reaching its maximum after full load rejection in superposition of mass oscillation. This simulations do not account for the free surface wave behaviour and the air intrusion. The aim of the physical investigations for this case is to check 3D flow behaviours and water-air interaction:

- the outflow into the four shafts to avoid air core swirls;
- prevention of air bubble in the pressure tunnel system;
- free surface wave behaviour in the lower chamber;
- de-aeration of the lower chamber without blow outs;
- behaviour of the upper chamber in this case.

Fig 6 (b lower) shows how the jet of the upper chamber outflowing intrudes large amount of air into the water body with free surface flow in the lower chamber, if no structural measures are taken to mitigate the unwanted air intrusion. This behaviour is typical for chamber surge tank systems with upper chamber [7]. In the case of the present geometry the intruding jet is double unfavourable because of:

- the curved riser geometry, that concentrates the jet
- the very close situation of the first vertical connection shaft

After testing several structural measures in the lower chamber to prevent air intrusion, a weir structure in the upper chamber was found to efficiently trap the surge that would otherwise create a heavy discharge into the water cushion of the lower chamber in a subsequent down surge. It was also found that the lower chamber hydraulically works best without direct structural measures. Also swirls flows can be best mitigated with the natural free surface wave behaviour in the lower chamber itself Fig 6 (b upper). The outlet of 1 m by 1m size creates a defined outflow that is dissipated by some small deflectors in the main riser floor Fig 6 (b lower)..

4.3 Smooth transition from lower chamber to main riser

It was found that the transition from the lower chamber to the main riser needs to be smoothened. Thus, a conical section is designed to connect the lower chamber with the riser gallery.

5 Conclusions

The selected option for the tailrace surge tank design, with two long chambers connected by an inclined riser gallery, is suitable both from the hydraulic and the economical point of view, because:

- it’s possible to be excavated based on a conventional tunnel strategy
- the design reduces the excavation volume
- it avoids the excavation of a large cavern

On the contrary, the necessary aeration creates a direct connection with the power house, and in case of overflow, staff and installation could be in danger. This made it necessary to compressively check and design the surge tank for the most unfavorable load case to eliminate the risk of overflow.

In terms of numerical modelling the design volumes were optimized first, separating vertically the chambers and reducing their width, in order to reach an adequate safety margin without cost increase. Nevertheless, 1D numerical modelling doesn’t reflect waves or air intrusion. The 3D CFD, revealed that with exceptional synchronous pump trip in resonance after start-up, a wave could overflow the upper chamber. But only with the physical model all these adverse effects were made visible, as the wave in the upper chamber, or air bubble intrusion into the pressure tunnel with cyclic operation in resonance with subsequent full load rejection, and then adequate structural solutions could be investigated. Variant tests to improve the hydraulic behaviour of the physical model test can be made very quickly and effectively, just as quickly as in the 3D CFD, and it has led to the correction of serious safety faults in the design.

The present paper concludes that hybrid modelling, both a global transient 1D model and a local 3D CFD model, as well as physical investigations were essential for reaching a cost-optimized, safe and flexible tailrace surge tank design, that allows the Gouvães pumped storage power plant to provide ancillary services and fast response to grid demands next to the efficient energy shift utilizing the large energy content of 19 GWh of storage .

References

1. **Luis De La Torre Abietar**, “Construction of the Gouvães pumped-storage plant in Portugal,” Hydropower & Dams, vol. 24, no. 5, pp. 44-48, 2017
2. **W. Richter, G. Zenz, Ch. Nicolet, Ch. Landry, J.C. Vera, L. de la Torre**, “Hydraulics of the tail race surge tank of Gouvães pumped-storage hydropower”, Viennahydro 2018.
3. **W. Richter, G. Zenz**, “Gouvães Pumped Storage Hydropower Tailrace surge tank Hydraulic investigation and Physical model test Report”, 2018
4. **Ch. Nicolet, Ch. Landry**, “Transient Analysis of Gouvães (Portugal) Pumped Storage Power Plant after Surge Tank Optimization Report”, 2019
5. **N. Dahlbäck**, “Flooding from surge in underground plants, a severe safety risk,” in Proceedings of Hydro conference, Montreux, 2015

6. **C. Nicolet, F. Avellan, P. Allenbach, A. Sapin and J.-J. Simond**, “New Tool for the Simulation of Transient Phenomena In Francis Turbine Power Plants”, Lausanne: Proceedings of the Hydraulic Machinery and Systems 21st IAHR Symposium, 2002.
7. **W. Richter, G. Zenz and K. Vereide**, “Hydraulic design and modelling of large surge tanks,” in BHR Pressure Surges, Dublin, 2015.
8. **S. Pejovic,** “High Head Pump Turbine “S” Instability Huge Risk for Draft Tube Water Column Separation”, HydroVision, Charlotte, USA, 2010.
9. **Svee, R.** *Untersuchungen über die Stabilität bei Wasserkraftanlagen mit idealer Regelung.* Mitteilungen Nr. 15 Institut für Wasserbau Technische Universität Graz : s.n., 1970.
10. **Ervine, D., & Falvey, H**. (1987). *Behaviour of turbulent water jets in the atmosphere and in plunge pools.* Proc. Instn Civ. Engrs, Part 2, 295-314.

The Authors

Juan Carlos Vera Rodríguez received his master’s degree in civil engineering in the Escuela de Ingenieros de Caminos Canales y Puertos of the Polytechnic University of Madrid in 2005. He began his career in the same year with FCC Construcción where he developed structural engineering. He joined Iberdrola in 2008 and he has been working on electric power plants, EPC project tenders, renewable-energy power plant engineering and since 2011, on the civil engineering of the hydro project Gouvães.

Wolfgang Richter is a PhD candidate and hydraulic researcher at TU Graz working on large surge tank design for hydropower plants and pumped storage schemes. His main field of research is physical and numerical modelling of surge tanks. He made his diploma degree at the University of Innsbruck.

Luis de la Torre Abietar received his Master’s degree in civil engineering in the Escuela de Ingenieros de Caminos Canales y Puertos of the Polytechnic University of Madrid in 2000. In 2006 he completed his Master’s degree in tunnels and underground works in the same institution. He joined Iberdrola in 2007 and since then he is working as manager for civil engineering structures on several pumped storage and conventional hydro power projects as La Muela II, Xacbal Delta, Daivões, Alto Tâmega and Gouvães.

Christophe Nicolet graduated from the Ecole polytechnique fédérale de Lausanne, EPFL, in Switzerland, and received his Master degree in Mechanical Engineering in 2001. He obtained his PhD in 2007 from the EPFL Laboratory for Hydraulic Machines. Since, he is managing director and principal consultant of Power Vision Engineering Sàrl in Ecublens, Switzerland, a company addressing optimization of hydropower transients and operation. He is also external lecturer at EPFL in the field of “Transient Flow”.