HYDRAULICS OF THE TAIL RACE SURGE TANK OF GOUVÃES PUMPED-STORAGE HYDROPOWER

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Abstract: The 880 MW pumped storage hydro power plant Gouvães, part of the Alto Tâmega hydro power scheme from Iberdrola is currently under construction in the north of Portugal. The energy storage and grid regulating plant is equipped with 4 reversible Francis pump turbines with nominal power of 220 MW and a gross head of 660 m, the discharge in turbine mode is 160 m³/s and in pumping mode 128 m³/s. The current paper underlines the layout, the design criteria and the results of the physical small-scale test of the tail race surge tank in the hydraulic laboratory. Most unfavourable load cases were studied such as synchronous pump trip in resonance and multiple loading and unloading followed by full load rejection in generating mode. A collaborated transient investigation for water hammer and mass oscillation capturing was conducted and gives cross checking opportunity.

1 Introduction

The 880 MW pumped storage power plant Gouvães, part of the Alto Tâmega hydro power scheme from Iberdrola is currently under construction in the north of Portugal. The cavern situation with complex civil works is shown in Fig. 1. The power plant is equipped with four reversible Francis pump turbines with nominal power of 220 MW and a gross head of 660 m, the discharge in turbine mode is 160 m³/s and in pumping mode 128 m³/s. The grid balancing and energy storing power plant utilizes the lower reservoir Daivões at the river Tâmega and the upper reservoir Gouvães at the river Torno.

This paper presents the specifics of the hydraulic layout and design issues regarding the tail race surge tank and the results of the physical model test. Especially the final hydraulic design load cases for the upper and the lower chamber are visualized. Fig. 1 shows the placement of the tailrace surge tank right behind the transformer cavern. All four draft tube pipes are directly connected to the surge tank to allow quick transient response.

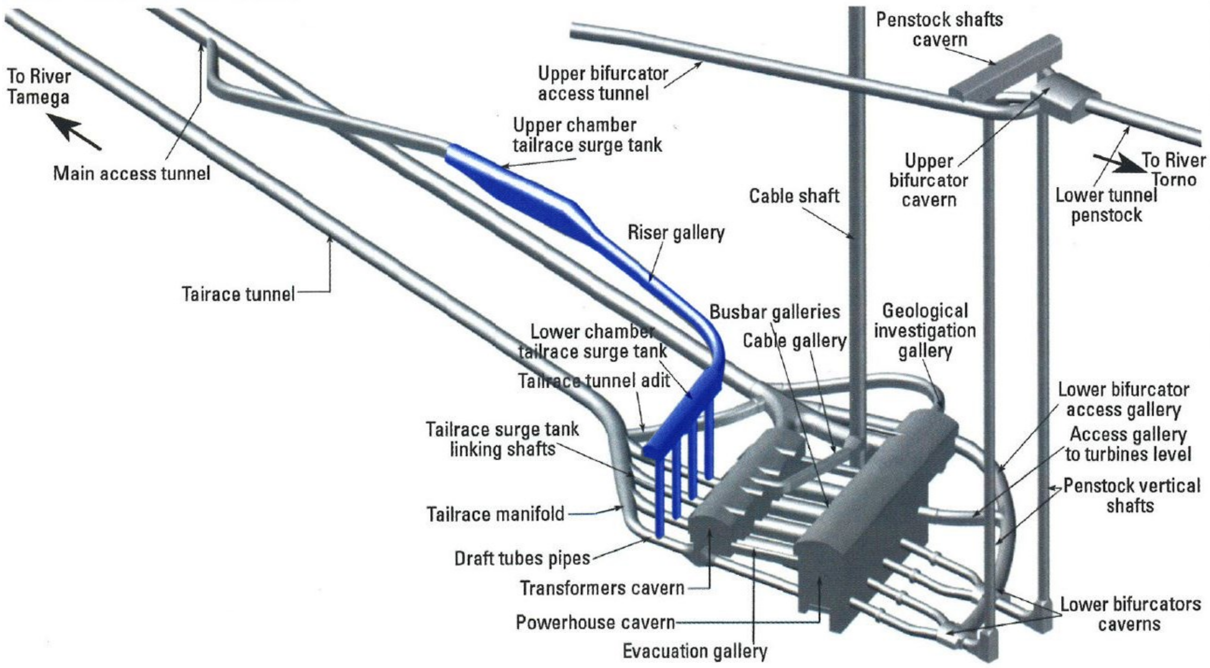

Fig. 1: Power cavern, civil works and tail race surge tank indicated [1]

2 Layout of the surge tank

The tailrace surge tank is located as close as possible to the machine cavern. The tailrace tunnel has a length of about 700 m with an internal diameter of 7.3 m. This water mass has to be accelerated and decelerated in case of opening, closing or uncontrollable events such as load rejection or pump trip. The surge tank consists of four connection shafts into a lower chamber a main riser and an upper chamber. It was chosen to design four connection shafts into each draft tube pipe. This approach has specific advantage for very quick water hammer response and mitigates asymmetric and thus unfavourable water hammer interferences at delayed load rejection events [2]. This also is an advantage to predict 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 [3].

The air ventilation is provided via an opening in the crown at the rear of the upper chamber into the access tunnel system. This location of the aeration makes it necessary to avoid any spilling in worst case scenario since the water would lead directly into the transformer and machine cavern. Such a surge tank spilling was reported by Dahlbäck due to insufficient surge tank volume for resonance load cases [4]. A main challenge for all surge tanks is that pressurized flow is transferred to free surface flow at upswing and inversely at downswing. This may additionally happen in a complex geometry if not simple shaft surge tanks are used. The advantage of complex surge tanks such as differential chamber surge tanks is the significant lower volume demand compared to shaft surge tanks because of quicker response to pressure mass oscillation. Also for large hydropower and pumped storage plants complex surges may be also more economically to be constructed. Fig. 2 shows the model test with four connection shafts, lower chamber, riser and upper chamber. The water level in the lower reservoir varies 9 m between level 228 masl and 219 masl. The horizontal section of the main riser has to fulfil the stability criterion.

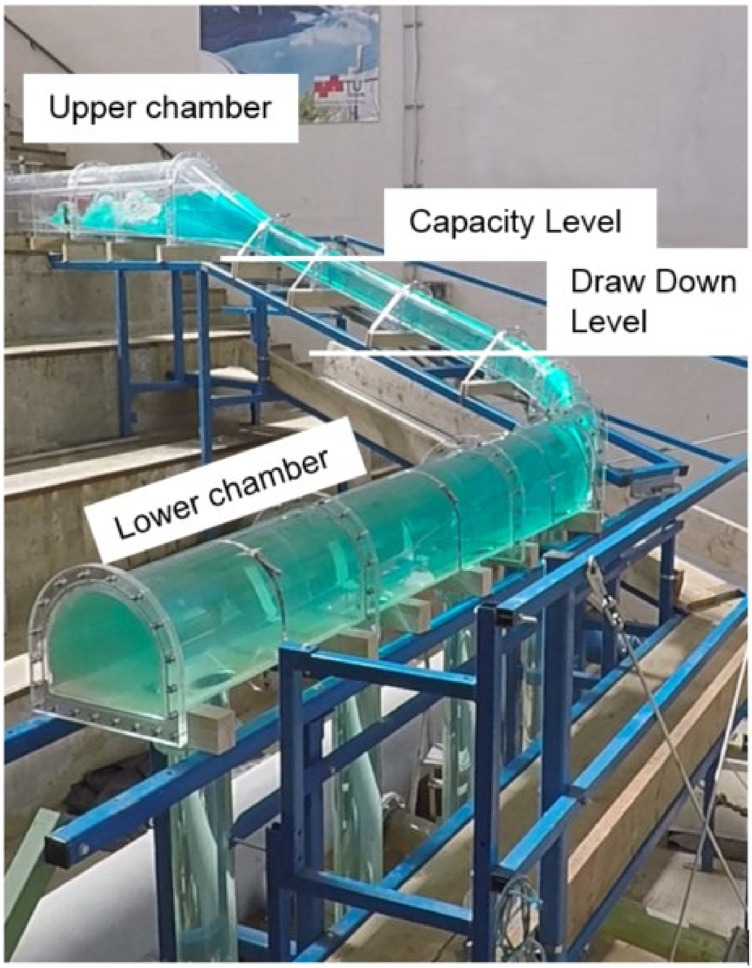

Fig. 2: Tail race surge tank model test

3 Design load cases for tail race surge tank

An extensive amount of load cases were evaluated for the machine design and the design of the power water way such as mass oscillation and water hammer mitigation in the headrace tunnel and the headrace surge tank. Subsequently numerous load cases are needed to be checked for the tail race tunnel design and thus the tailrace surge tank. Those simulations were done by different teams, such as the machine supplier, the external transient simulation expert group and at TU Graz during the hybrid modelling for the surge tank investigations. For the mass oscillation resonance load cases were taken into account to capture the most severe events that are possible in lifetime. Opening gradients are defined but load rejections and pump trips may occur unexpectedly and are uncontrollable to a certain amount since the hydraulic behaviour is very quick.

The surge tank is designed to capture severe load cases both in turbine direction and pump direction.

Criteria of the surge tank layout in respect with most economical layout:

a) Allow safe and quick power regulation
   This point defines the need of the surge tank itself.
b) Avoid any dangerous water hammer over- and under pressure peaks

This aspect defines the distance to the machines and influences diameters of the connection shafts.

c) Generating mode: capture most unfavorable load ramping in resonance both at lowest reservoir level and highest reservoir level. Turbine loading to full load, followed by unloading to no load at most unfavorable time point, then re-loading to full load at maximum backflow discharge with followed emergency shutdown due to load rejection again at most unfavorable time point.
This load case defines the chamber sizes, especially the lower chamber.

d) Pumping mode: capture of an emergency shut down after pump trip that follows full pump start up at most unfavorable time point at maximum level of the lower reservoir. This event defines the most severe load case for the upper chamber

4 Hydraulic investigations

The tail race surge tank was investigated with two different 1D numerical approaches to capture and evaluate best the most unfavourable water hammer and mass oscillation transients. The comprehensive water hammer simulations were carried out with SIMSEN [5] and in redundancy the mass oscillation simulations for the model test input with Wanda V4.5. 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 have revealed that the upper chamber is filled with a significant surge that would ask for further improvements. A physical small-scale model test was constructed and elaborated at the Hydraulic Laboratory at Graz University of Technology. The hydraulic model test was operated in Froude similitude law and a geometric scale factor of 1:25. Once a physical model is in operation variations can be made very efficiently and even quicker as in 3D CFD. The procedure of the hydraulic transient model test is described as following. The results of the transient simulations are first converted to Froude scaled discharges that are imposed as surge tank inflow/outflow boundary condition. The transient flow behaviour is controlled via air pressure vents that are governed via a calibrated PID governor.
The final main load cases for the physical model test evaluation were found to be:

A) The most severe filling case of the upper chamber caused by a synchronous pump trip in resonance after start up at capacity level in the lower reservoir (Fig. 7)

B) The most unfavourable emptying case of the lower chamber caused by resonance load case with full loading, subsequent un-loading to 50% power in 6.7% of full loading time, following a re-loading to 100% power again in 6.7% of full loading time span that is followed by a full load rejection at most unfavourable time point. Whole load case at constant drawn down level

Load case A) most severe upper chamber filling at capacity level:
Fig. 3 shows the filling surge of the upper chamber without measures to dissipate the surge. In such a case the water would spill out of the aeration construction and would cause severe damages. The energy of the surge can be efficiently dampened by large and horizontally inclined baffles a steeper inclined bottom and a stepped ramp at the rear of the chamber. Fig. 4 shows the surge at the pump trip in the upper chamber with dissipating structures.

Fig. 3: Upper chamber surge without dissipation structures before optimization

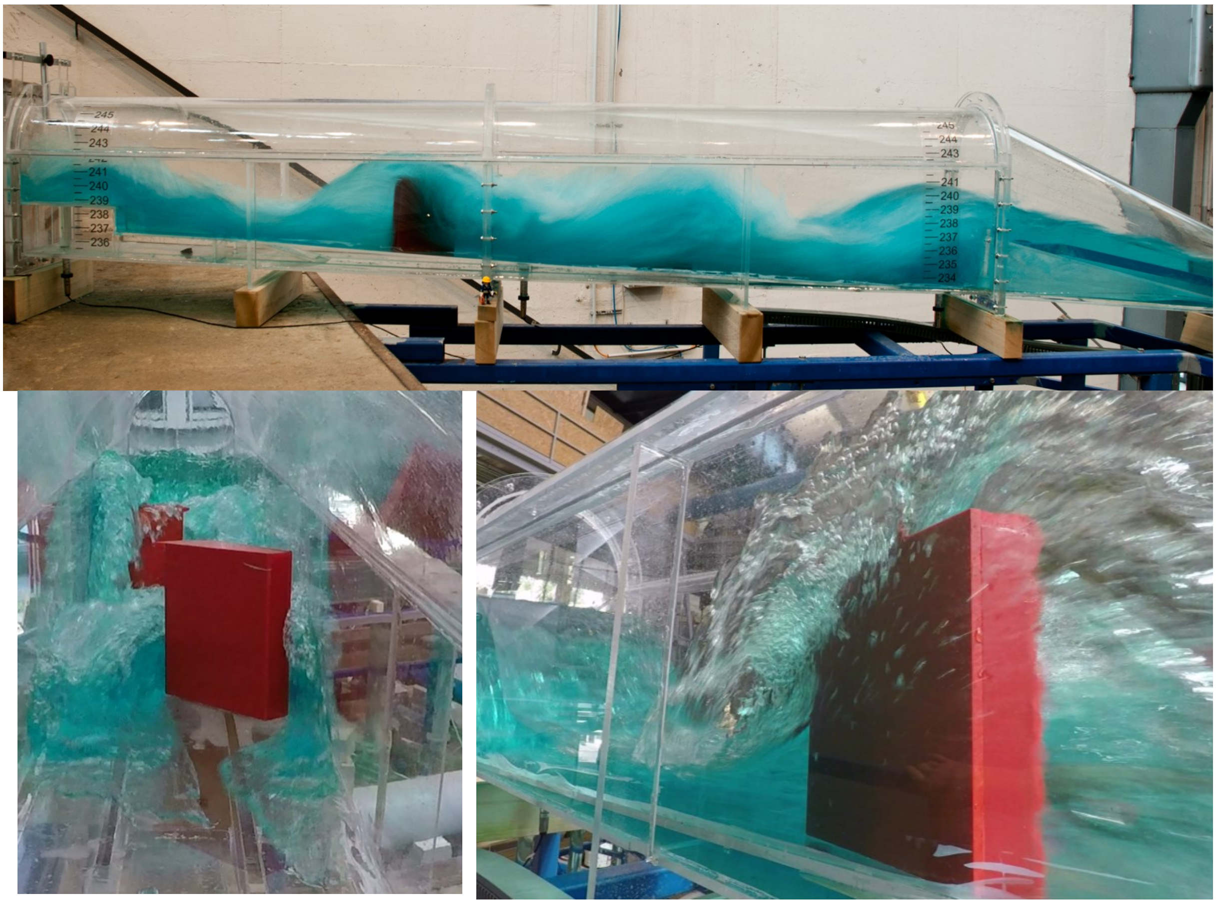

Fig. 4: Upper chamber surge final solution with dissipating structure

Fig. 5 shows the comparison of the imposed discharges of the 1D simulation and the model test discharges for load case A – most severe pump trip). The figure describes the start-up of the pumps in 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 it reverses and starts filling the surge. At time point (marked with line in Fig. 5) the peak acceleration in the tail race tunnel all pumps have faced a full trip and the flow direction of the pumps is reversed very quickly and leads to the peak discharge of 68 l/s (220 m^3/s in prototype) into the surge tank creating the massive design surge. At this time point the accuracy has a deviation of about 5%. This is the key time point for crucial filling event and the accuracy is found to be sufficient since it reflects also the highest absolute value. This accuracy is computed as difference between volume derived by integration of imposed discharge and integration of measured discharge.

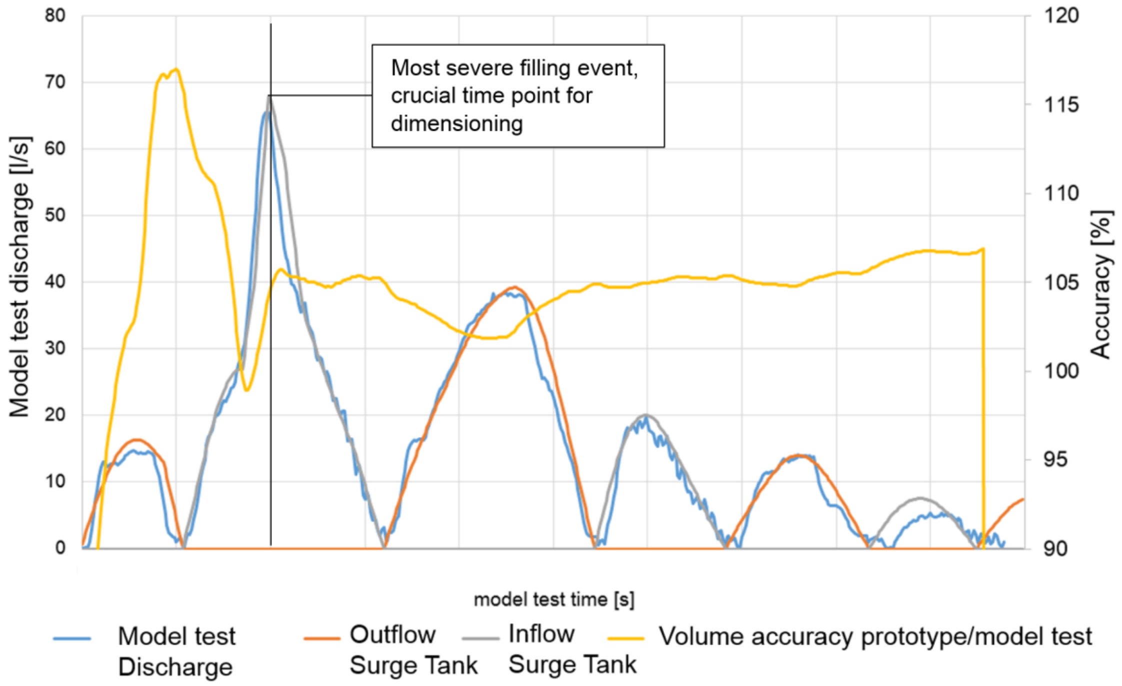

Fig. 5: Comparison model test inflow of model test, scale factor of time 5 [-]

Safety aspects in the 1D numerical simulation as input for the physical model test:
Even though the hydraulic simulations can provide precise simulation results the input conditions are needed to be carefully evaluated. The resonance load case simulation includes several aspects that can be noted at the safe side such as:

- lowest realistic friction loss in the tunnel
- simultaneous pump start-up of all four units
- quickest possible guide vane opening at pump start-up
- steady level for the simulations at either capacity level or draw down level

Load case B) most unfavourable lower chamber emptying at draw down level:
This load case describes a resonance cyclic operation of the four units in generating operation at draw down level 219 m a.s.l. First all units are loaded to full load, then 50% of the load is reduced in 6.7% time span of the full loading time at most unfavourable time and subsequently reloaded again at most unfavourable time and following this all units are facing a full load rejection at worst time point. Fig. 6 shows the results of the 1D numerical simulation for the mass oscillation of load case B to be used as input for the physical model test operation. The bottom of the chamber with level 205 m a.s.l. is not reached as the outflow is reaching its maximum after full load rejection in superposition of mass oscillation. The simulation does not account for the free surface wave behaviour.

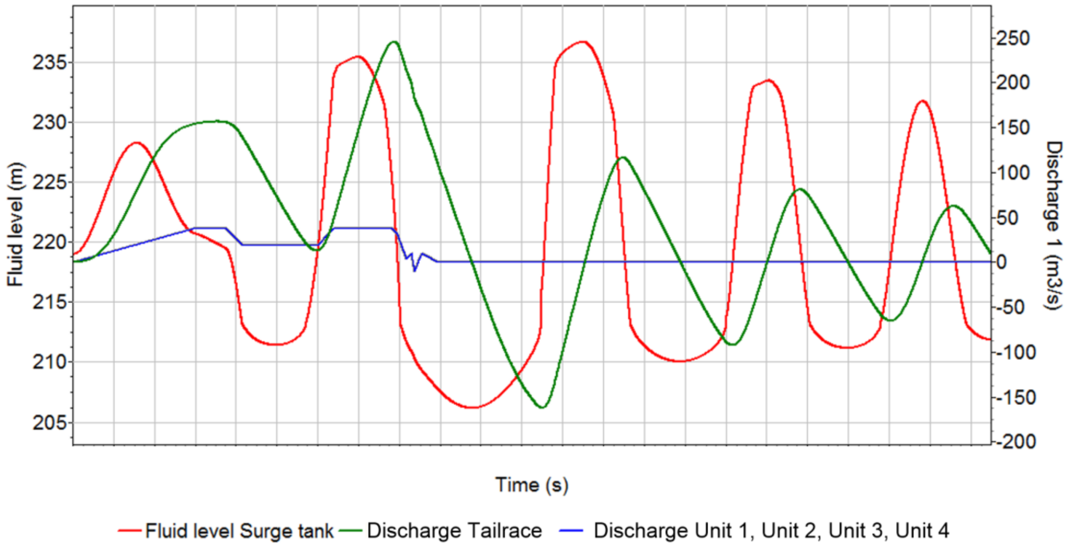

Fig. 6: Load case B, 1D numerical mass oscillation simulation for lowest level in lower chamber, level 205 m a.s.l. is the bottom of the lower chamber (WANDA 1D software)

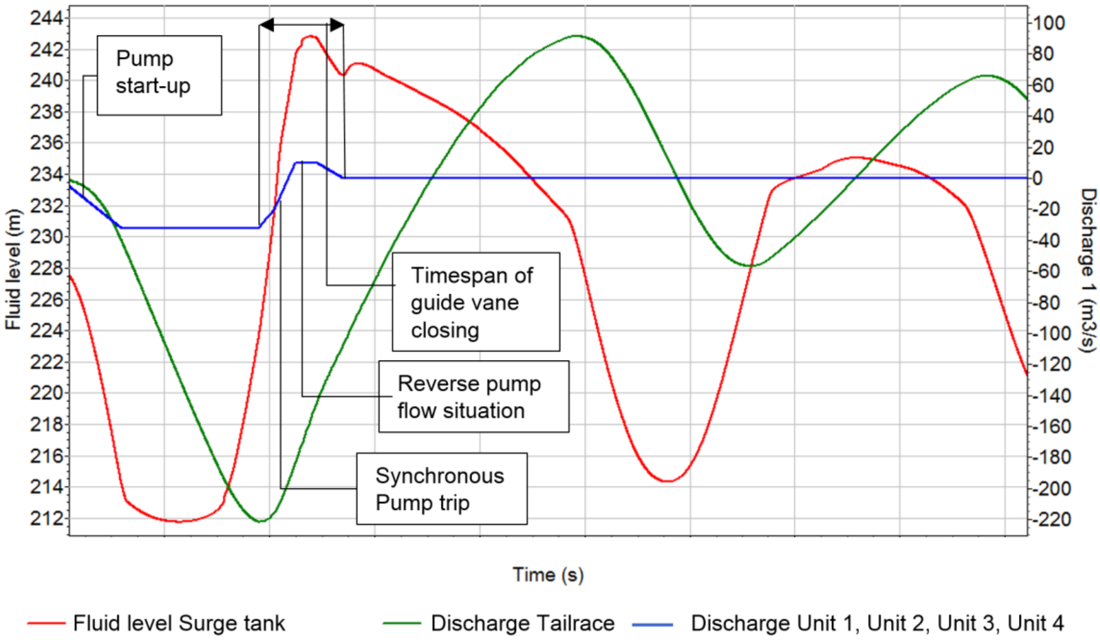

Fig. 7: Load case A, 1D numerical mass oscillation for most unfavourable synchronous pump trip, discharge imposed boundary condition (WANDA 1D software)

The aim of the physical investigation 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. 8 shows how the jet of the outflowing upper chamber 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 [6]. At the same time this outflow jet, which forms a waterfall in vertical shafts is positively dampening the mass oscillation due to flow separation that causes also a pressure separation. In case of the present geometry the intruding jet is double unfavourable because of:

a) the curved riser geometry that concentrates the jet
b) the very close situation of the first vertical connection shaft

To mitigate the air intrusion many variants were tested such as wall structures in the lower chamber, but those mainly triggered new issues such as vortices and secondary air intrusions. For the final solution a weir structure in the upper chamber was found to efficiently trap the surge that would otherwise have 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.

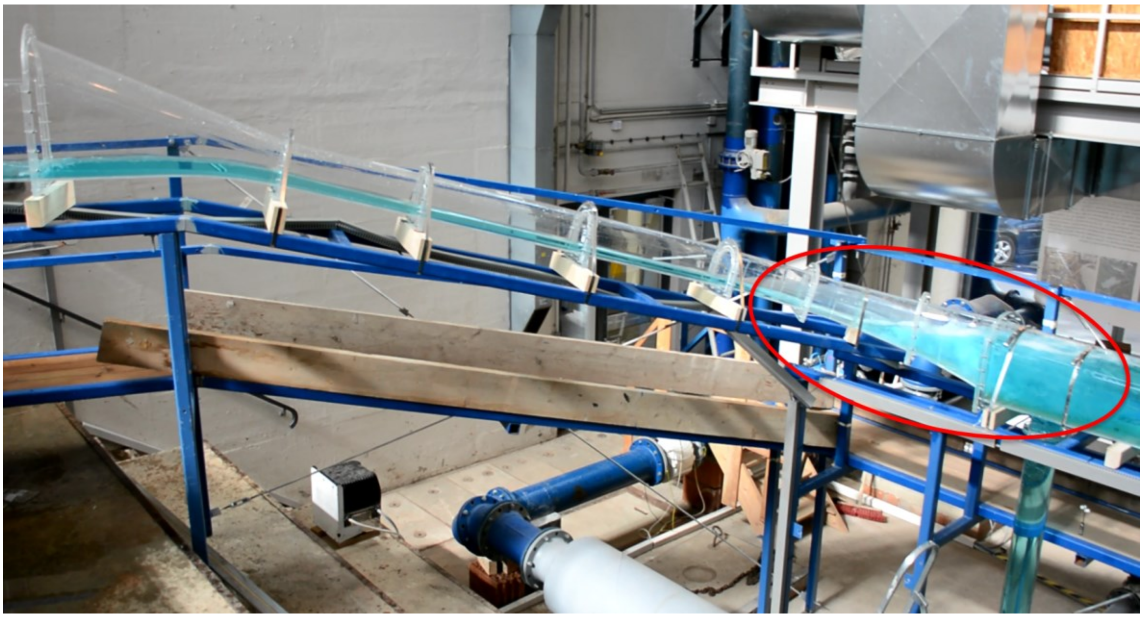

Fig. 8: Massive air intrusion in the lower chamber without measures before optimization

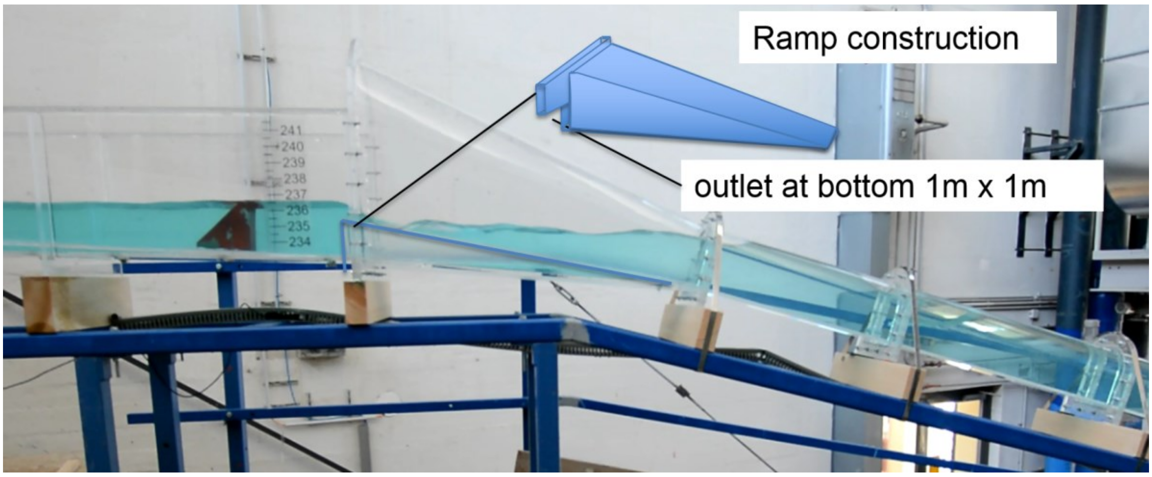

Fig. 9: Ramp construction that traps the water as solution to effectively separate and dampen the outflow of the upper chamber to prevent large air intrusion

Fig. 9 shows the structural measure of an additional ramp that forms a weir to trap the water inside the upper chamber to mitigate the backflow. A 1m by 1m rectangular opening controls the outflow of the upper chamber. This flow is additionally dissipated by baffles in the main riser bottom. Due to the maximum event at pump trip there is no accumulation of water in the upper chamber possible since a waiting time after rejection or trip is usually applied.

5 Conclusions

Hybrid numerical and physical investigations of the 880 MW pumped storage hydropower plant Gouvães in Portugal were undertaken to simulate and optimize the design load cases of the tail race surge tank. This paper reveals mainly the hydraulic effects of the mass oscillation and its impact on the surge tank design. The surge tank consists of a lower and an upper chamber and is very closely connected to the draft tube pipes via four shafts. The most severe load case of filling the upper chamber is the synchronous pump trip in resonance after start-up. For the lower chamber a cyclic operation in resonance with subsequent full load rejection was found to be the design case with minimum water level. In addition to 1D - and 3D numerical simulations a physical model test with scale 1:25 was found to be vital to detect issues of water-air interaction in order to prevent air bubble intrusion into the pressure tunnel. Applying structural measures by means of large baffles in the upper chamber sufficient dissipation can be provided to prevent undesired spilling. In addition, a weir structure with bottom opening at the transition to the main riser was designed to trap the water in the upper chamber after pump trip or load rejection. This avoids air intrusion into the water cushion of the lower chamber. The physical model test gives quick and full understanding of the complex transient hydraulics for severe cases that have to work safely. Once the model test is in operation, variant tests to improve the hydraulic behaviour can be made very quickly and effectively. An interdisciplinary team approach between external experts and the operators engineering group, allowing intense communication and discussion was found beneficial for best technical and economic convergence of the design process developing the unique hydraulic surge tank structure.

6 References

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