EXPERIMENTAL INVESTIGATION OF TRANSIENT BEHAVIOR IN THE SURGE TANK PHYSICAL MODEL OF A PUMPED-STORAGE POWER PLANT (PSPP)

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Abstract: During commissioning of a pumped storage power plant (PSPP) featuring an upstream surge tank, unexpected sub-atmospheric pressures were measured at the top of the penstock during pump emergency shutdown. This paper presents the experimental investigations performed in a physical model of the surge tank, to reproduce the mass oscillations and until a certain extent, to point out the pressure drop in the penstock. The proposed solution with an additional surge tank connected to the existing scheme was also tested by physical model to overcome the sub-atmospheric pressures.

1 Introduction

Pumped storage power plants featuring a layout with headrace tunnel, surge tank and penstock may be subjected to low pressure risk at the top of the penstock resulting from transients in pump mode operation. Indeed, water hammer caused by quick closing of the wicket gates due to a pump power failure induces negative pressure wave propagating in the penstock and consequently low pressure phase along the penstock. Besides, the risk of cavitation and water column separation, the low pressure phase may also cause the unexpected opening of air-vacuum valves located downstream the safety gate valve at the top of the penstock, producing a risk of entrapped air in the hydraulic circuit.

Such events were observed during the commissioning tests of the 185 MW Avče PSPP located on the Soča River, in Slovenia, equipped with one reversible Francis pump-turbine. Fig 1 left, shows the record of the pump start-up failure at 40% guide vane opening, followed by emergency shutdown (ESD). Fig 1 right shows the pressure measurement records at the top of penstock and at level of air-vacuum valves in the valve chamber (see Fig. 3), in which the pressures drop below atmospheric pressure. As the pressure transducers were not able to measure sub-atmospheric pressures, they featured saturation at 0 mWC. During this event, the air-vacuum valves of the valve chamber opened and amount of air was sucked into the waterway, then, during air expelling the small air-release valves were damaged and spill of water occurred through these small valves.

Therefore, in order to ensure full plant safety, extensive transient analysis and experimental studies in hydraulic scaled model of the surge tank, were carried out to understand the phenomenon roots and propose solutions to this unacceptable operation.

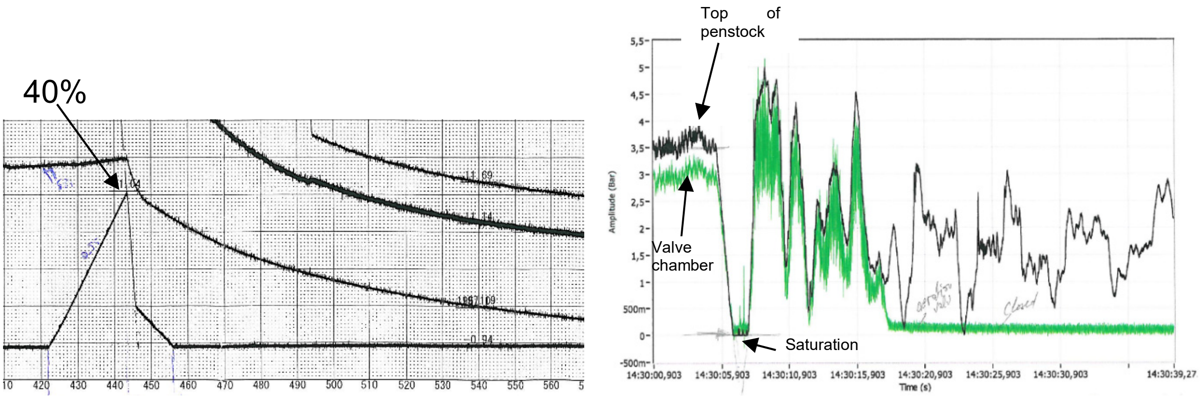


Fig. 1. Left: Sequence of the pump start-up failure at 40% guide vane opening, followed by ESD.
Right: pressure measurement at the top of penstock (black line) and valve chamber (green line)

2 Layout of the PSPP and Surge Tank

Fig 2 presents the general layout of the 185 MW Avče pumped storage power plant, comprising an artificial upper reservoir of storage capacity of 2.17 million m^3 between operating water levels of 597 masl and 625 masl, a headrace tunnel of 670 m length and 3.9 m diameter, a surge tank featuring an upper surge chamber and a lower expansion chamber (Fig 3), a penstock of 1585 m length and 2.6m diameter and a tailrace tunnel of 107 m length. The powerhouse is installed in a shaft 57 m below the lower reservoir and it is equipped with one reversible Francis pump-turbine of variable speed technology.

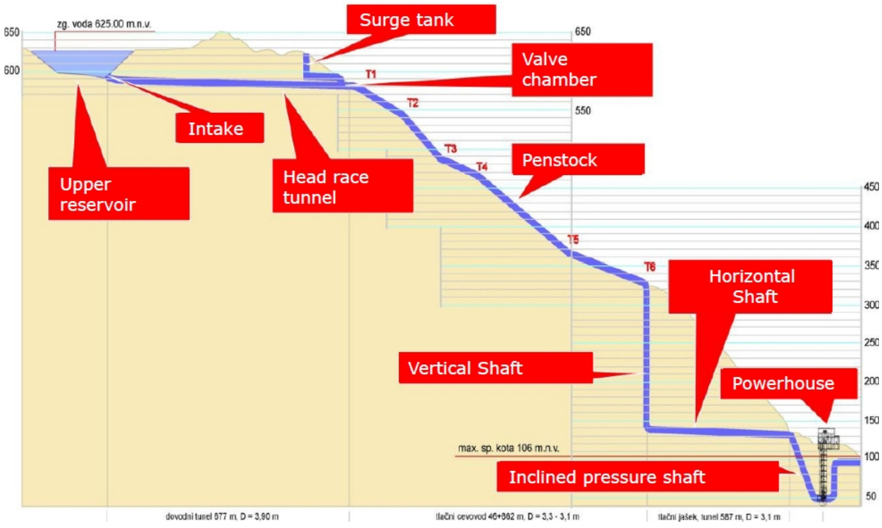


Fig. 2. Avče PSPP hydraulic layout

The vertical shaft of the surge tank has a diameter of 3.9 m and a height of 40 m, the lower expansion chamber has a circular cross section of 3.9 m of diameter and 104 m length. The connection to the head race tunnel is done through a 90° bend with variable diameter from 3.9 m to 2.8 m. This is throttled area of the surge tank.

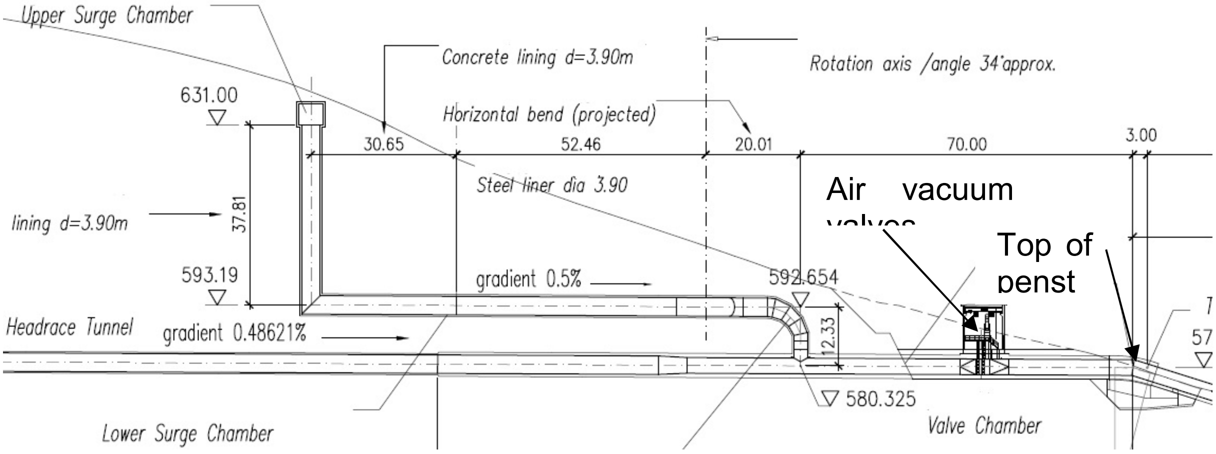


Fig. 3. Surge tank layout, chamber of safety gate valve and top of penstock

3 Transient simulations

As part of the investigation campaign to understand and solve the low pressure issue at the plant, extensive transient simulations with Simsen software and with appropriate modelling were carried out at first, see [1]. The outcome of this investigation led to the following conclusion: as the lower expansion chamber of the surge tank is always filled with water at standstill and at normal operation of the pump-turbine, this chamber acts as a pipe during transients caused by pump emergency shutdown. Indeed, the water in the surge tank has to be accelerated from standstill to a flow rate corresponding approximately to the pump discharge. The flow accelerating time is increased by the rather long length and small diameter of the lower expansion chamber inducing high water inertia. Thus, pressure drops very fast when considering the surge tank inertia which causes a delayed reaction of the surge tank to a very fast penstock discharge change induced by the pump tripping.

The pressure drop measured during pump ESD shown in Fig. 1 was reproduced by transient calculation, see Fig 4. The pressure calculations (red curve) showed that pressure dropped below atmospheric pressure due to the water inertia effect in the lower expansion chamber.

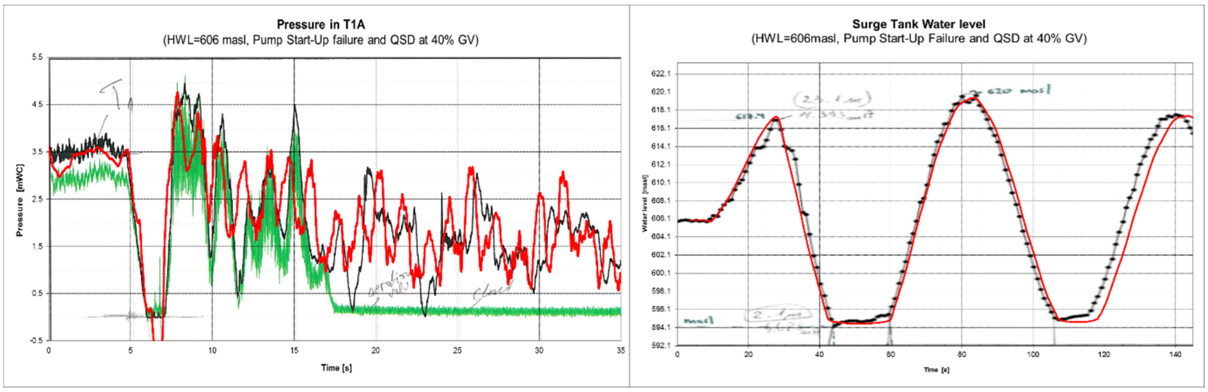


Fig. 4. Comparison between simulation results (red curves) and on-site measurements resulting from the pump ESD observed in Fig 1. At left, pressure at the top of the penstock and valve chamber. At right, surge tank water level oscillation.

4 Physical Model of the existing Surge Tank ST1

The physical hydraulic model was built in the laboratory of the Institute of Hydraulic Research in Ljubljana and was designed to perform dynamic simulations of the behaviour of the surge tank in terms of mass oscillation.

Although the elastic waves phenomena (i.e. water hammer) cannot be transposed from model to prototype as it is strongly influenced by pipe hydroacoustic characteristics, the model was instrumented with taps for piezometric heads as well as pressure sensors to try to point out the water inertia effect in the head race tunnel and to reproduce the pressure drop in the penstock and lower expansion chamber of the existing surge tank. With such information potential solutions could be sensed.

The scale of the model 1:13.2 was selected on the basis of the available space in the laboratory and to meet similarity criteria for scaled water-mass inertia. Indeed, Froude similarity between model-prototype is fulfilled, and the Reynolds number in the model is large enough to represent same resistance as in the prototype. The physical model constructed of clear PVC was composed of the upper reservoir, the headrace tunnel, the original surge tank and a short part of the penstock, ended with a valve which was used to quickly close the discharge during pump mode, see Fig. 5.

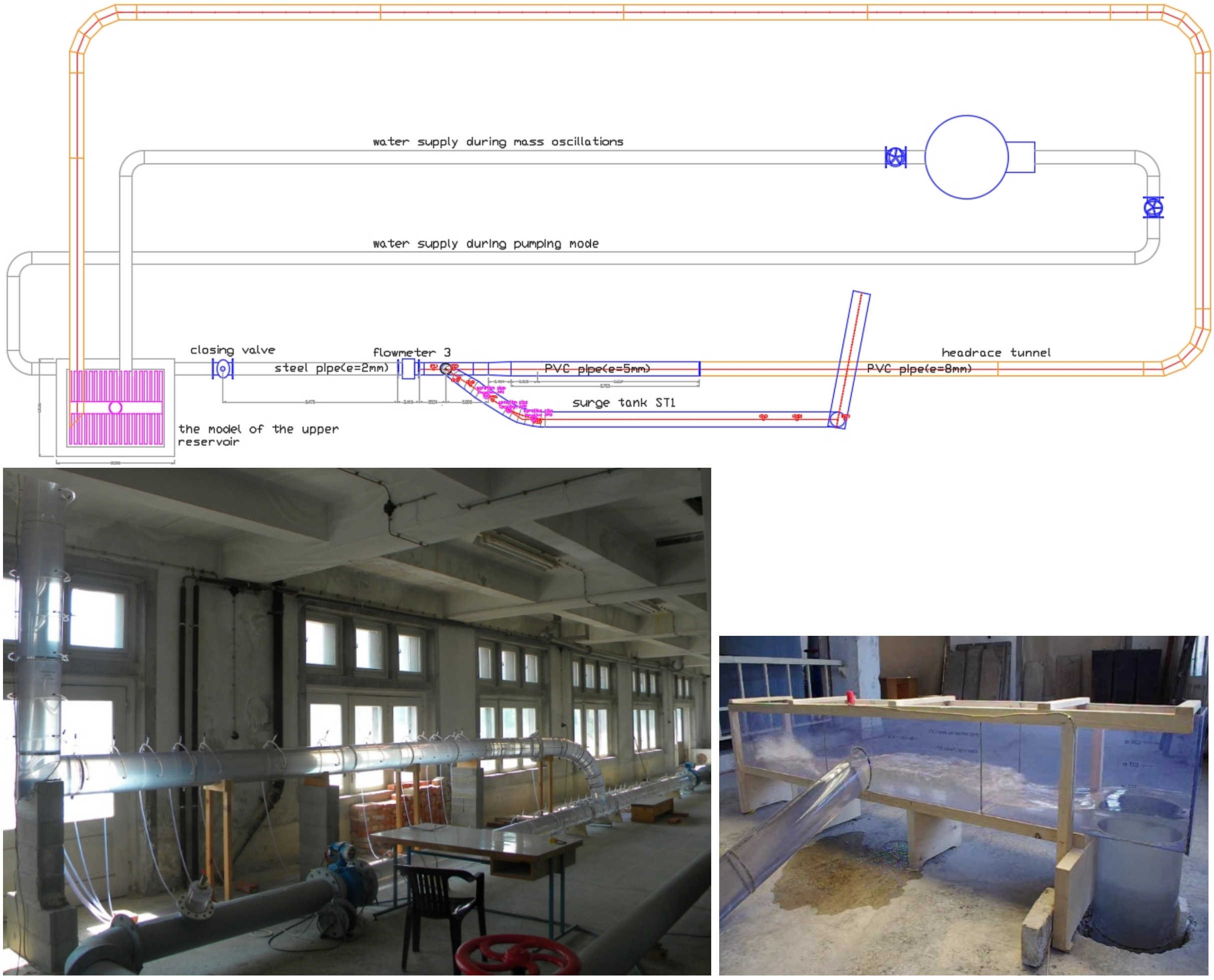


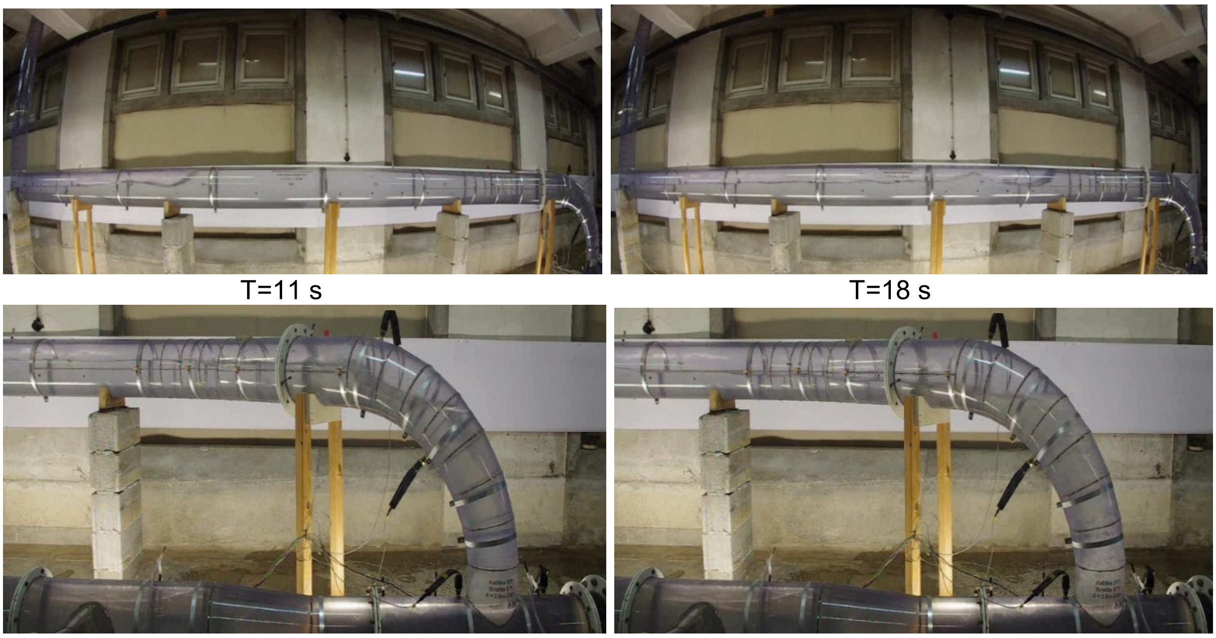
Fig. 5. Top: Laboratory test rig. Bottom Left: scaled hydraulic model of original surge tank ST1. Bottom right: scaled model of surge tank upper tank

In order to determine the inflow-outflow head loss coefficient of the throttle of the surge tank ST1, for different combinations of flow between the surge tank, headrace tunnel and penstock, measurement of piezometric heads was performed. Locations of piezometers (three holes around the perimeter in each cross section) can be observed in Fig. 5 left. The objective of these measurements was also to validate the throttling head loss coefficient used in the transient model.

4.1 Mass oscillation in the Surge Tank ST1

Tests of pump ESD at minimum water level of the upper reservoir (HWL=597 masl), i.e.at the lowest pressure in the head race tunnel, were performed. The maximum prototype flow discharge is 34 m^3/s, however to magnify the phenomenology, tests with prototype flow discharge of 40 m^3/s is presented in this section.

Fig. 6 shows different instants, in prototype scale, after pump tripping (T=0 s) where strong pressure drop starts. The strongest pressure drop is measured at time 4.7 s as can be seen in Fig. 7. One can observe that a negative free surface wave is travelling through the surge tank lower chamber (T=11 s and T=18 s). Between T=25 sec and T=33 sec, when the lower chamber is emptying, one can observe air bubbles entering into the head race tunnel. However, the surge tank is not completely emptied and most of air bubbles seems to come back to the lower expansion chamber.



T=11 s T=18 s

T=25 s T=33 s

Fig. 6. Mass oscillation in the scaled model of surge tank ST1 after a pump trip at HWL=597 masl and Qp=40 m^3/s

4.2 Reproducing the pressure drop in the surge tank ST1

Fig. 7 shows the results of pressure measurements transposed to prototype at HWL=597 masl and Qp=34 m^3/s for a pump tripping. One can observe that just after the closure of the closing valve, high pressure drop due to the inertia of the moving water mass in the head race tunnel appeared. The sensor placed at the top of the elbow of the lower chamber P4, shows a pressure drop of 10 m, bringing the pressure to underpressure of -6 m that appears for few seconds.

Air was trapped in the lower chamber when the vertical shaft of the surge tank starts to fill, thus air evacuation to the vertical shaft led to pressure fluctuations which can be seen from 80 sec to 190 sec.

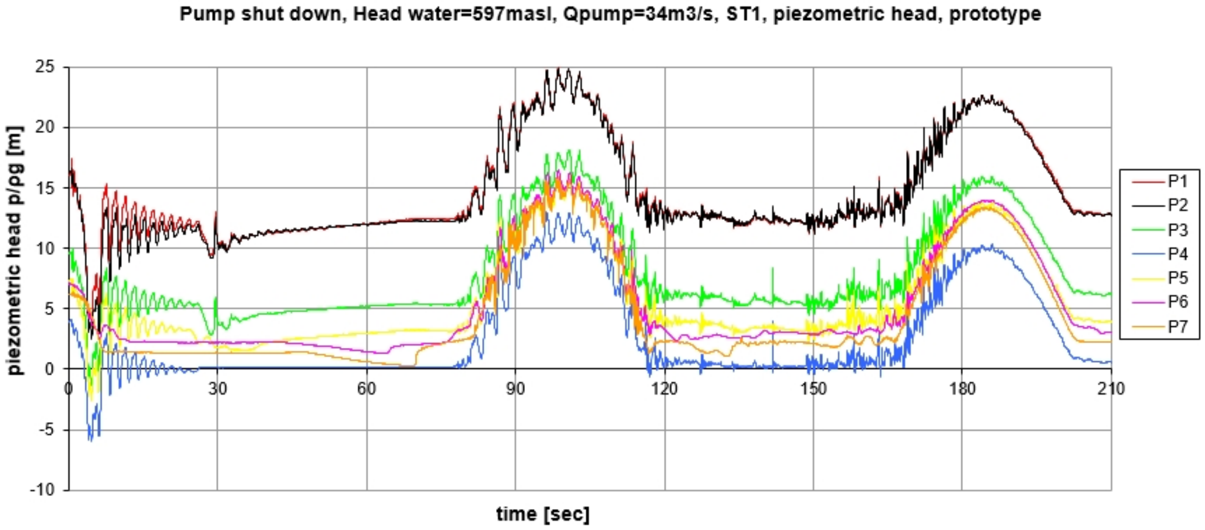


Fig. 7. Pressure measurements at different positions in hydraulic model of original surge tank ST1. P4 is the measurement at the top of the bend of the lower expansion chamber of ST1.

5 Additional Surge Tank ST2 as proposed solution

With the help of the validated transient model of the PSPP discussed in Section 3, different solutions were studied by numerical simulation with Simsen software to find the solution which would consider as best feasibility and full plant safety. The proposed solution consisted to connect an additional Surge Tank ST2 designed as a parallel surge tank to the existing surge tank ST1, see Fig. 9.

Fig. 8 shows the transient calculation results due to pump tripping at HWL=597 masl at the bend of the lower expansion chamber of ST1 and at the top of penstock, before and after addition of the Surge Tank ST2. Full vacuum is predicted at the bend of the lower expansion chamber of the existing surge tank without ST2 (Fig 8 left). The efficient work of the additional surge tank to break the inertia effect in the head race tunnel can be seen in Fig 8 right, the strong pressure drop is eliminated and minimum pressure remains almost at atmospheric pressure.

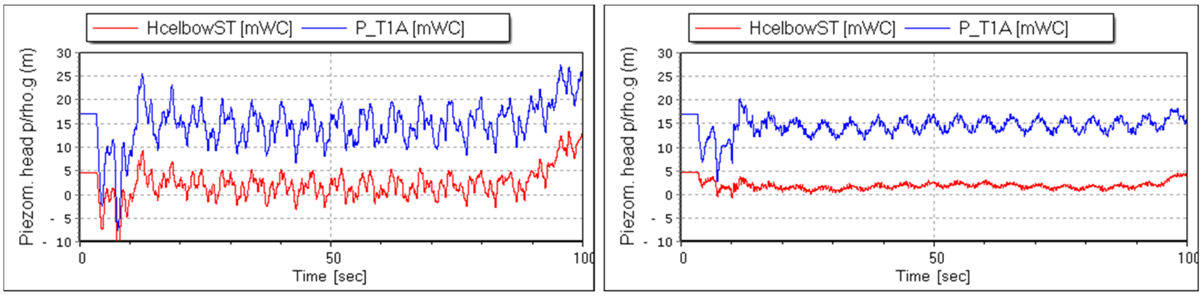


Fig. 8. Pump load rejection simulation. Left: Pressure at the bend of lower expansion chamber (HcelbowST) before additional ST2. Right: Pressures after addition of ST2

The transient calculations also allowed to determine the loss coefficient values of the throttling for the surge tank ST2. Design of throttle was done by Hidroinstitut (Ljubljana) and the loss coefficients (inflow and outflow) were confirmed through steady tests in the scaled model of the surge tank ST2.

In the prototype, the additional surge tank ST2 is composed of a connecting pipe to the headrace tunnel of 2.8 m diameter and 13 m length, of a surge shaft of 9.4m diameter and 30.3m height and of an inclined pipe of 2 m diameter and 69.7m length between the surge shaft and the existing upper surge chamber. The surge tank ST2 is connected to the headrace tunnel at a distance of 24 m upstream from the connection of the existing surge tank ST1.

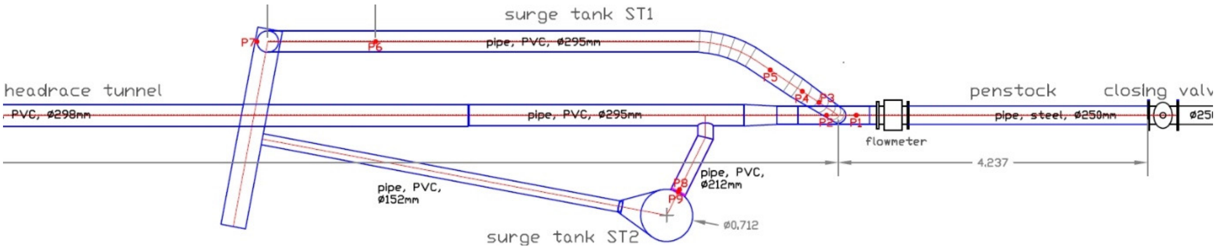
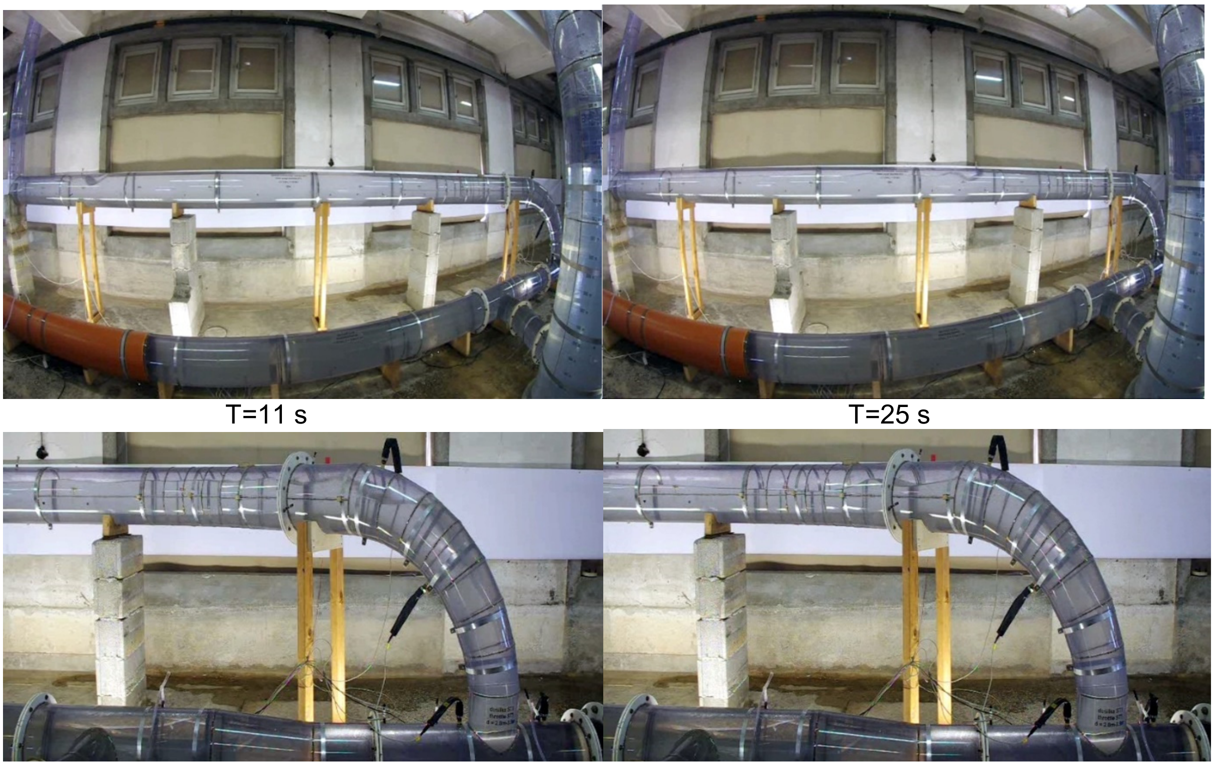


Fig. 9. Scaled hydraulic model of the surge tank ST2 connected to head race tunnel model

5.1 Mass oscillation in Surge Tanks ST1 and ST2

Tests of pump ESD at minimum water level of the upper reservoir (HWL=597 masl) were performed at prototype flow discharge of 34 m^3/s.

Fig.10 shows the positive influence of the surge tank ST2 on the system after pump tripping starts (T=0 s). A negative free surface wave starts to travel through the lower expansion chamber of ST1 (T=11 s and T=25 s). At T=33 sec when minimum water level is reached, the bend of the lower expansion chamber is not emptied as it is observed in Fig. 6. At T=40 sec one can observe that there are some air bubbles which remains in the bend and does not enter at all into the head race tunnel. The water oscillation in the surge tank ST2 remains in the vertical shaft and does not present any abnormal behavior.



T=11 s T=25 s

T=33 s T=40 s

Fig. 10. Mass oscillation in the scaled model of surge tank ST1 and ST2 after a pump trip at HWL=597 masl and Qp=34 m³/s

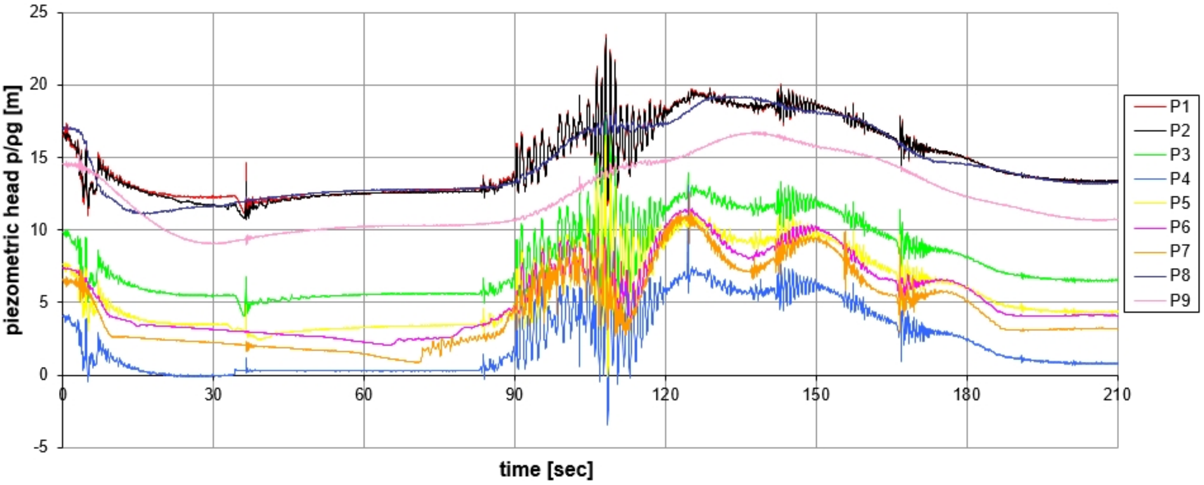
5.2 Reproducing the pressure drop in the system ST1 and ST2

The pressure measurements on the scaled model reproduce the same effect pointed out by transient calculations shown in Fig. 8. One can observe in Fig 11 (HWL=597 masl) that the strong pressure drop at the first seconds of pump tripping almost disappear by comparing with Fig 7 (about 50% reduction of the pressure drop). Intensive pressure pulsations due to evacuation of the large amount of air from the lower expansion chamber to the vertical shaft that appeared during the first positive surge can be observed between 90 and 120 sec.

Tests at higher upper reservoir (HWL=601 masl) were also performed, see Fig 11. The results show no more underpressure in the lower expansion chamber of ST1. As the lower chamber was under pressure all the time during pump tripping, no pressure fluctuations due to air evacuation into the vertical shaft was observed.

To have an insight of the pressure distribution and of the underpressure zone in the lower surge chamber of the surge tank ST1, Fig. 12 and 13 shows the absolute piezometric head lines at time t=5s for HWL=597 masl and HWL=601 masl.

With these results it was recommended to increase the minimum water level in the upper reservoir to 601 masl, so that minimum pressure at the bend of lower chamber can always remain above atmospheric pressure during transients, ensuring full plant safety. By increasing of the HWL, additional safety margin for non-considered cases in the model test can be taken into account, as well as to avoid high pressure fluctuations due to air evacuation through the vertical shaft.


Pump shut down, Head water=597m asl, Qpump=34m3/s, ST1+ST2, piezometric head, prototype

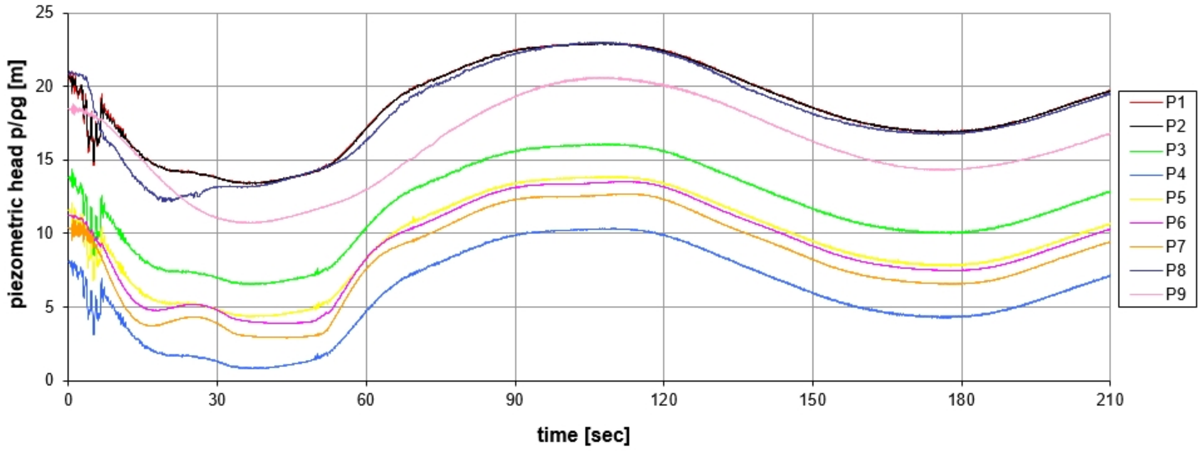

Pump shut down, Head water=601masl, Qpump=34m3/s, ST1+ST2, piezometric head, prototype

Fig. 11. Model results at HWL=597 masl and at HWL=601 masl with the surge tank ST1 and ST2

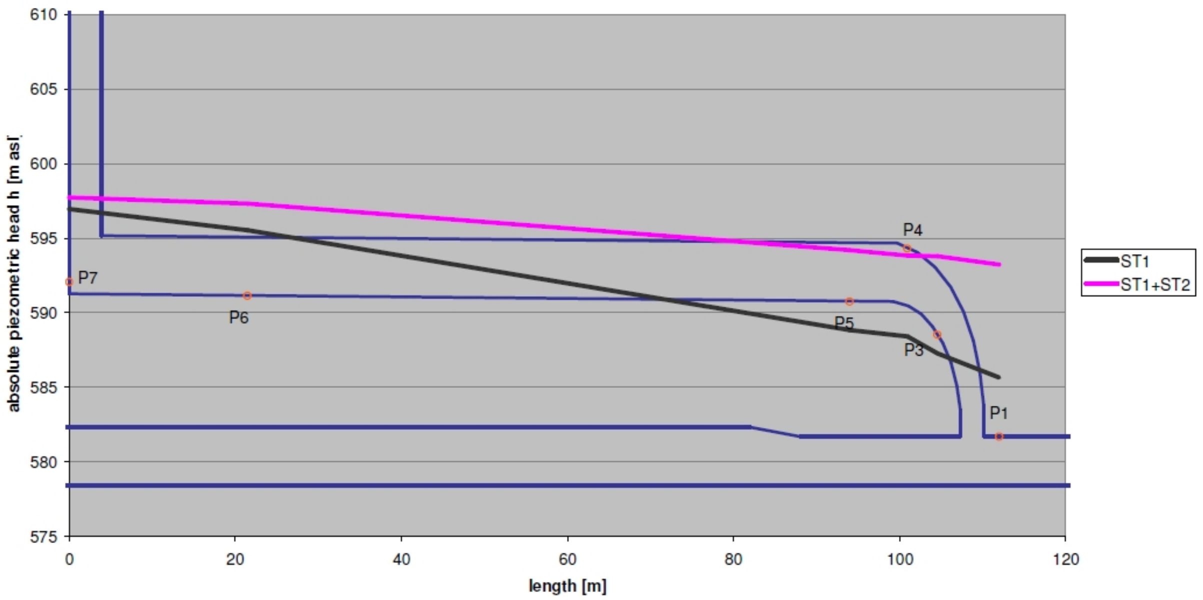


Fig. 12. Absolute piezometric head lines at time t=5s for HWL=597 masl

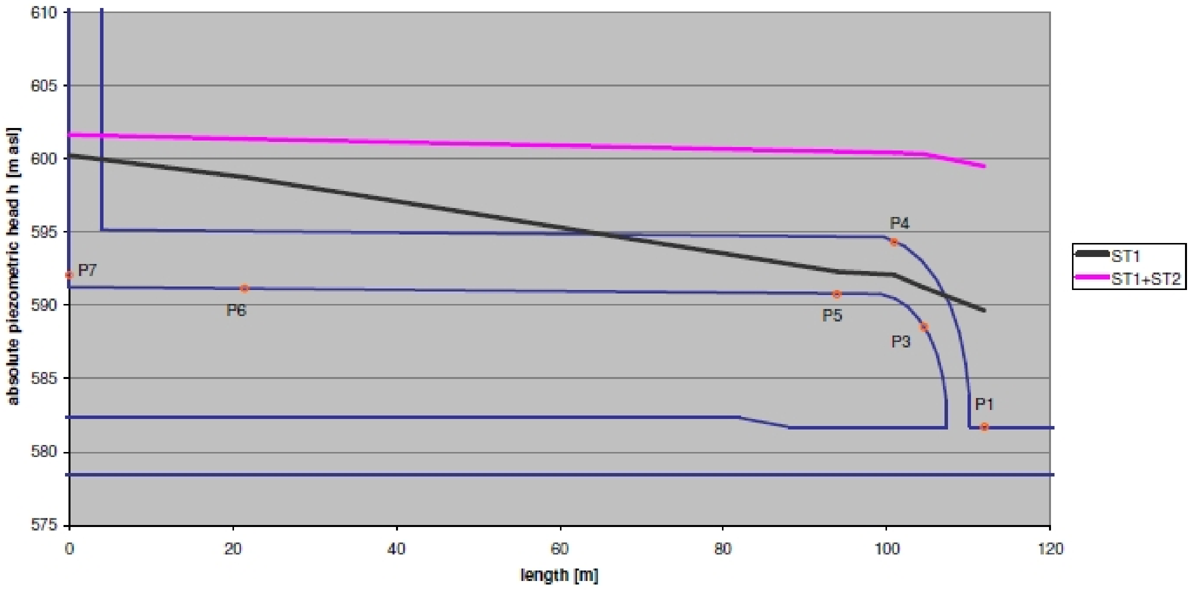


Fig. 13. Absolute piezometric head lines at time t=5s for HWL=601 masl

6 Conclusions

The pressure drop due to pump ESD observed in the lower expansion chamber of the existing surge tank ST1 of the PSPP, was pointed out by measurements in a physical scaled model at the lowest head water level (HWL=597 masl). To limit the pressure drop, a solution with an additional surge tank ST2 to the system was also checked in the scaled model. The results showed about 50% reduction of the pressure drops at the beginning of the pump shut down and few underpressure at the top of elbow of the lower expansion chamber. At HWL=601 masl, the results in scaled model showed that the issues of sub-atmospheric pressures in surge tank and top of penstock are eliminated. Although pressures cannot be transposed to prototype, the measurements in scaled model, together with transient calculations provided sufficient information and confidence to propose a solution.

References

[1] C. Nicolet, J. Arpe, A. Rejec, Influence of the surge tank water inertia on pumped storage power plant transients in case of pump emergency shutdown, *6th IAHR International Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems (2015),* Ljubljana, Slovenia.

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