Surge tank geometry modification for power increase

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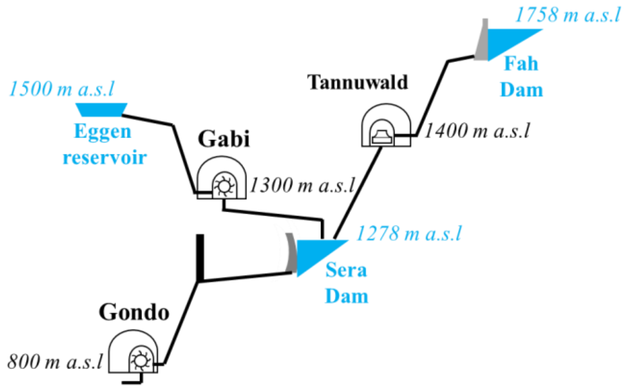
Introduction

"Energie électrique du Simplon SA" (below EES) manages the three hydroelectric power plants of Gondo, Gabi and Tannuwald. The location and the functioning of these plants are shown in Figure 1.

(a)



(b)

Fig. 1. (a) General location of the Gondo power plant (Source: http://www.swissdams.ch); (b) Schematic view of the working stage of EES

The hydroelectric power plant of Gondo was commissioned in 1952 with two 18.5-MW-Pelton turbines exploiting a 470-meters head, see Fig. 2. During the 80's, a third Pelton turbine was commissioned with an adding of 8 MW. At this period, the total turbined discharge was 12.1 m^3/s.
The project "Erneuerung Gruppe 3" proposes to replace the third turbine by a more powerful one. The discharge flowing through the plant will increase up to 14.7 m^3/s.
The present study is organized in this way: Firstly, a numerical transient analysis is carried out to determine the needed modification at the surge tank entrance. This first step allows to define target head loss value at the surge tank entrance. Secondly, as the surge tank geometry is complex, an experimental campaign is needed to design the placed orifice.

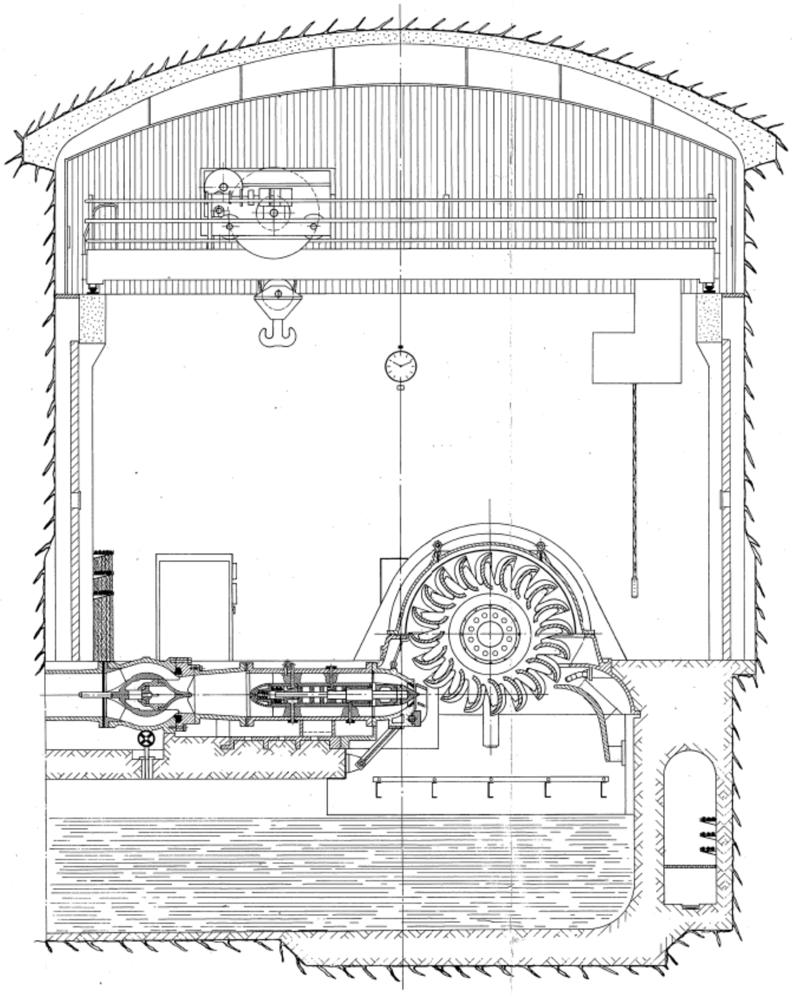


Fig. 2. Cross-section through underground powerhouse with Unit 2 of the Gondo power plant equipped with Pelton turbine of 18.5 MW

1. Numerical analysis : Transient phenomena

1.1. Modeling of hydraulic system

Assuming uniform pressure and velocity distributions in the cross section and neglecting the convective terms, the one-dimensional momentum and continuity balance for an elementary pipe of length dx, cross section A and wave speed a, see Fig. 3 left, yields to the following set of hyperbolic partial differential equations [11]:

$$\begin{cases} \dfrac{\partial h}{\partial t} + \dfrac{a^2}{gA} \cdot \dfrac{\partial Q}{\partial x} = 0 \\ \dfrac{\partial h}{\partial x} + \dfrac{1}{gA} \cdot \dfrac{\partial Q}{\partial t} + \dfrac{\lambda \left| Q \right|}{2gDA^2} \cdot Q = 0 \end{cases} \quad (1)$$

The system (1), where Q is the discharge and h is the piezometric head, is solved using the Finite Difference Method with a 1st order centered scheme discretization in space and a scheme of Lax for the discharge variable. This approach leads to a system of ordinary differential equations that can be represented as a T-shaped equivalent scheme [3], [8], [9] as presented in Fig. 3 (b). The RLC parameters of this equivalent scheme are given by:

$$R = \frac{\lambda \cdot |Q| \cdot dx}{2 \cdot g \cdot D \cdot A^2} \qquad L = \frac{dx}{g \cdot A} \qquad C = \frac{g \cdot A \cdot dx}{a^2} \tag{2}$$

where λ is the Darcy-Weisbach friction loss coefficient. The hydraulic resistance R, the hydraulic inductance L, and the hydraulic capacitance C correspond respectively to energy losses, inertia and storage effects. The model of a pipe of length L is made of a series of nb elements based on the equivalent scheme of Fig. 3 (b). The modelling approach based on equivalent schemes of hydraulic components is extended to all the standard hydraulic components such as valve, surge tanks, air vessels, cavitation development, Francis pump-turbines, Pelton turbines, Kaplan turbines, pumps, see [3], which are implemented in the EPFL simulation software SIMSEN. The system of equations relative to those models is set-up using Kirchoff laws and the time domain integration of the full system is achieved in SIMSEN by a Runge-Kutta 4th order procedure. The software developed for the simulation of the dynamic behavior of hydroelectric power plants also including electrical system [10], [3], [4], and was subject to several validations against measurements for various hydraulic systems [1], [5], [6], [7].

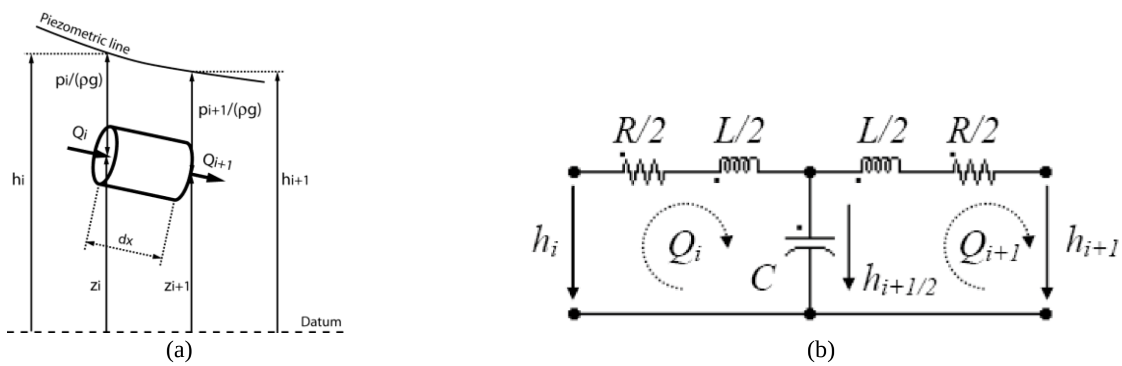


Fig. 3 : Elementary hydraulic pipe of length dx (a) and related equivalent circuit (b).

1.2. Modeling of Gondo power plant

Fig. 4 presents the SIMSEN simulation model of the Gondo power plant which main characteristics are summarized in Table 1. The simulation model takes into account:

- the headrace gallery of 3’236 meters long and 2.1 m of diameter;
- the surge tank featuring upper and lower expansion chamber, see Fig. 5;
- an inclined pressure shaft of 780 meters long with a diameter of 1.8 meters on the upper part which is not steel lined, while the lower part is steel lined and has a diameter of 1.6 meters;
- the repartitor feeding the three Pelton turbines with total installed capacity of 45 MW for the original configuration.

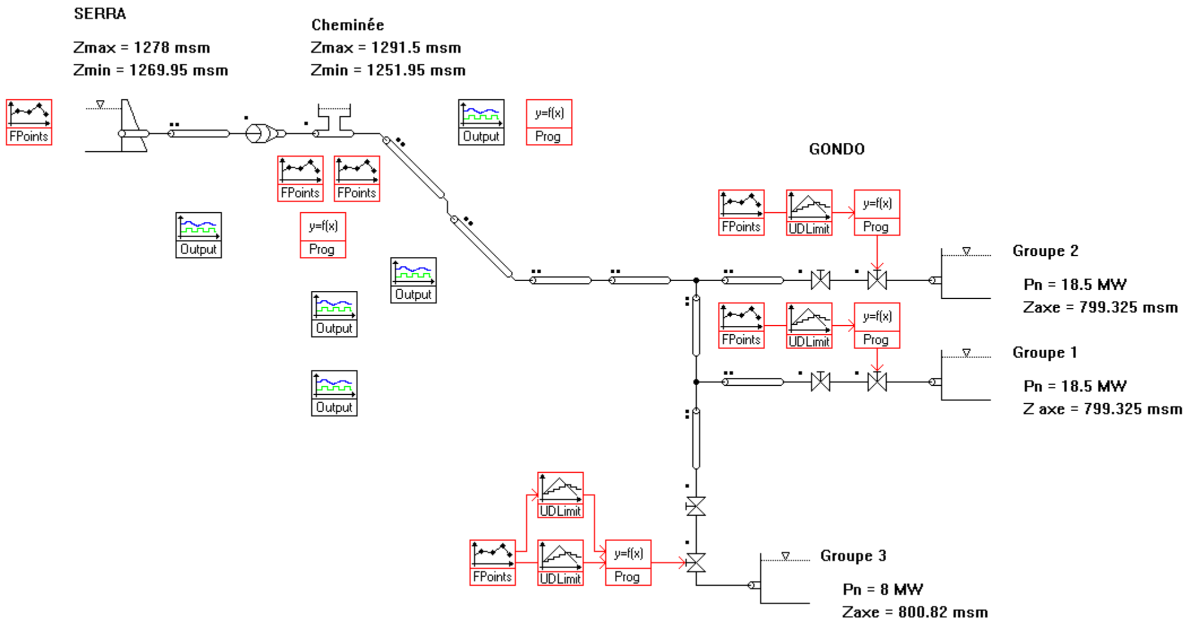


Fig. 4. SIMSEN simulation model of the Gondo 45 MW hydroelectric power in the existing configuration

Table 1: Gondo power plant original characteristics

Power plant	
Total discharge	12.1 m^3/s
Installed capacity	45 MW
Number of units	3
Maximum gross head	478.675 mWC
Units 1 and 2 with Pelton turbine horizontal axis	
Nominal power	18.5 MW
Nominal discharge	4.5 m^3/s
Maximum discharge	5 m^3/s
Nominal rotational speed	450 tr/min
Number of injector	1
Generator type	Synchrone
Apparent power	20 MVA
Unit 3 with Pelton turbine horizontal axis	
Nominal power	8 MW
Nominal discharge	2.1 m^3/s
Nominal rotational speed	600 tr/min
Number of injectors	2
Generator type	Asynchrone

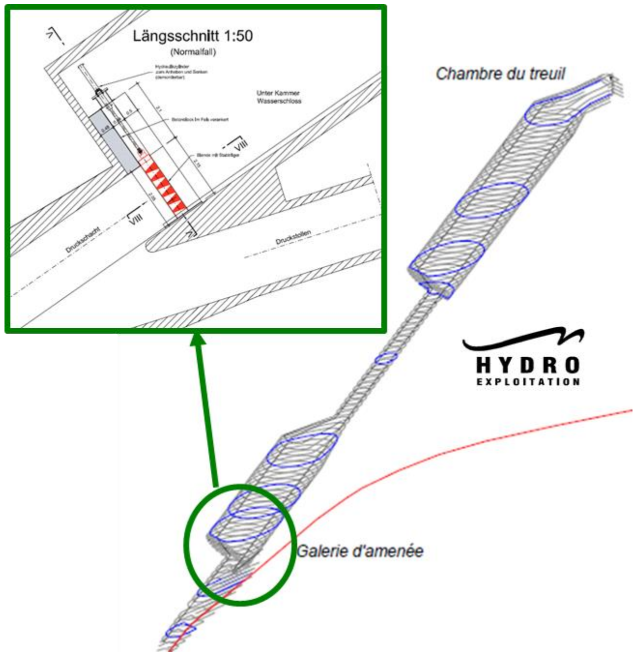


Fig. 5. Geometry of the Gondo power plant surge tank (source Hydro Exploitation SA) with the introduction of a new surge tank diaphragm to prevent from surge tank dewatering in case of unit unloading and reloading

1.3. Simulation model validation

For existing power plants subjected to significant power extension, it is important to proceed to power plant detailed modeling and to perform simulation model validation in order to reduce as much as possible modeling uncertainties, see [1]. Therefore, early in the project of Gondo power extension, transient tests have been performed on-site to characterize the hydraulic system dynamic response and to validate the numerical SIMSEN simulation model. For Gondo power plant, the most uncertainties were related to the surge tank effective geometry and singular head losses related to inflow and outflow. Therefore, in-situ measurements have been carried out by Hydro Exploitation SA to determine the detailed 3D geometry of the surge tank, see Fig. 5, while the surge tank singular head losses have been calibrated by comparing simulation results against on-site measurements in case of emergency shutdown and unit loading respectively for surge tank inflow and outflow head losses.

Fig. 6 and Fig. 7 present the comparison between on-site measurements and simulation results obtained for the case of emergency shutdown of 3 unit operated at total output power of 45 MW for the time evolution of surge tank water level and pressure at the inlet of turbine 1. It could be noticed that very good agreement have been achieved thanks to all efforts from the power plant owner and power plant staff in charge of the operation to provide a reliable set of the input data for the system modeling.

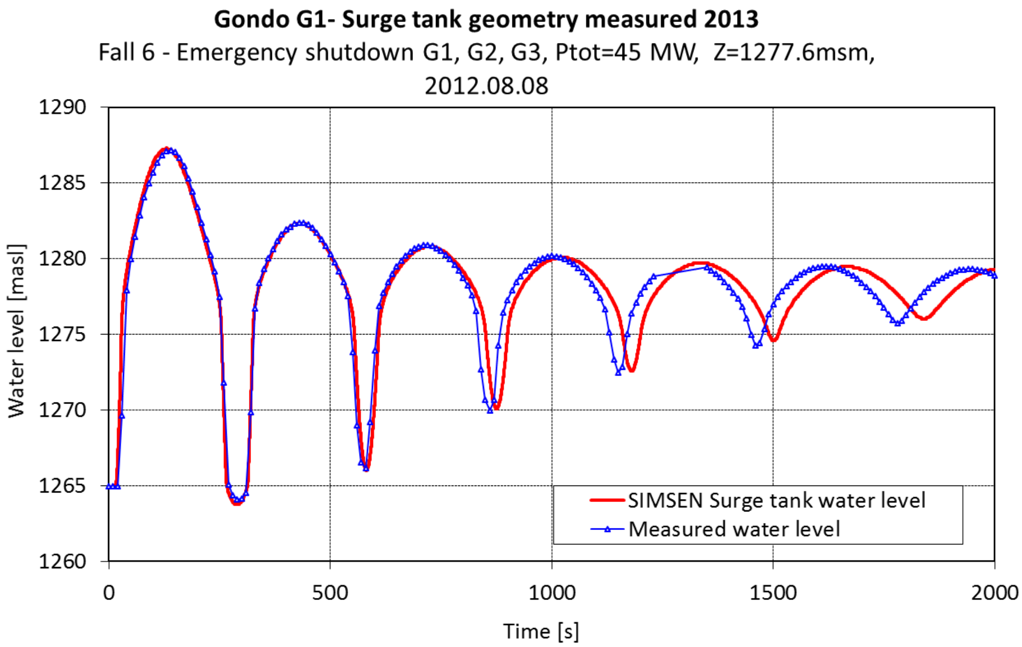


Fig. 6. Comparison between simulation results and on-site measurements of the surge tank water level evolution resulting from the emergency shutdown of 3 units performed in 2012

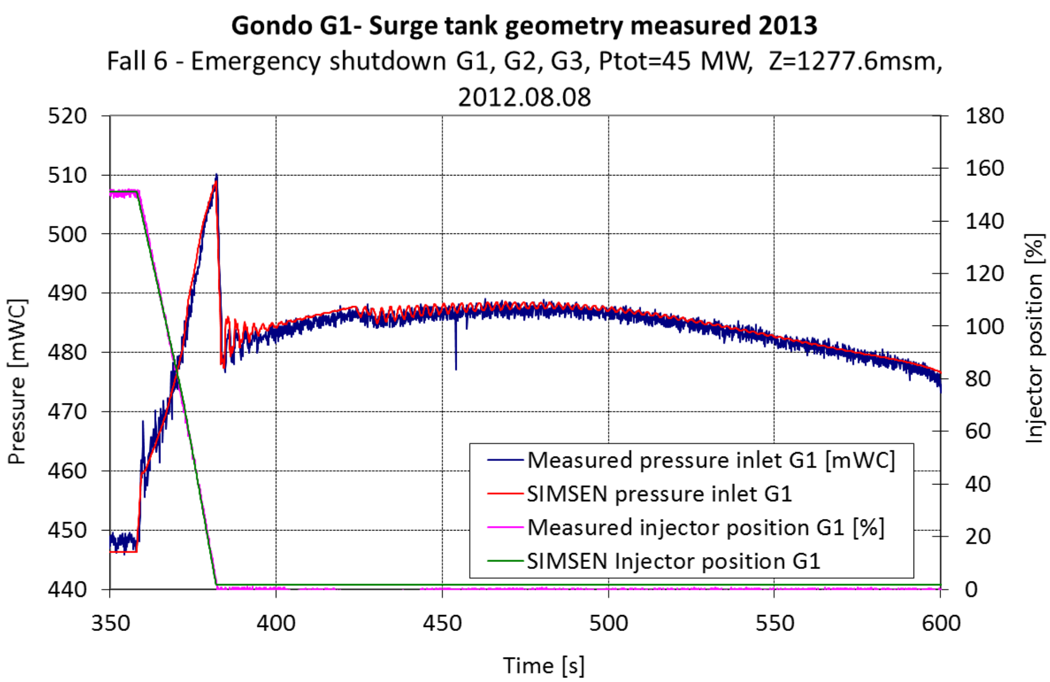


Fig. 7. Comparison between simulation results and on-site measurements of the pressure at turbine 1 inlet resulting from the emergency shutdown of 3 units performed in 2012

1.4. Transient analysis for power extension

Once the simulation was dully validated, a comprehensive transient analysis has been performed to identify possible problems induced by power plant capacity increase with respect to admissible values related to penstock maximum pressure, minimum pressure in the entire waterways and surge tank minimum and maximum water level.

The transient analysis was first focused on the following normal load cases:

1) Emergency shutdown of all the units;
2) Simultaneous loading of all units;
3) Loading followed by emergency shutdown at the worst moment for the upsurge in the surge tank;
4) Load rejection followed by a reloading while all units remain connected to the grid;
5) Emergency shutdown as well as loading and emergency shutdown leading to the closure of injectors in the penstock reflection time, the so-called Peak of Michaud, see [5].

For the Gondo power plant, it was found that the total power plant discharge could be increased safely from 12.1 m^3/s to 14.7 m^3/s, provided that:

- the closure time of the injector is increased to fullfil admissible maximum pressure in the penstock in case of Peak of Michaud load cases;
- a solution was found to prevent surge tank dewatering in case of unloading followed by a unit reloading.

Indeed, the case of unit unloading followed by a reloading cannot be excluded since the power plant might experience some power network stability issues as the power plant is located in a remote Valley of the Swiss Alps at the Italy border and is therefore subjected to possible antenna and isolated grid operation in case of disturbances on the 125 kV transmission line between Switzerland and Italy. Moreover, unit unloading and reloading might also results from unit protection activations, followed by clearance for recovering the load.
Fig. 8 presents the simulation results in case of units unloading and reloading when total power plant discharge is increased to 14.7 m^3/s and evidencing a risk of surge tank dewatering.
To avoid surge tank dewatering and ensure appropriate margin for minimum water level in the surge tank (Fig. 9) as well as minimum pressure in the headrace gallery, the following solutions, sorted by investment cost, have been considered:

1) Increase of ramping rate of the units;
2) Introduction of surge tank diaphragm;
3) Introduction of turbine governor algorithm to restrict the loading rate when the surge tank water level is low;
4) Extension of the lower expansion chamber.

Due to access difficulties to the surge tank also related to extreme climate conditions during winter time, solutions 3) and 4) have been found not cost effective. The solution 1) required considerable increase of injector maneuvers time not compatible with control service requirements. Therefore, solution 2) related to the introduction of a new surge tank diaphragm optimized for the particular load case of unloading and reloading of the unit was chosen as illustrated in Fig. 9.
Fig. 11 presents the simulations results obtained after surge tank diaphragm optimization for the load case of unloading followed by reloading of the 3 units which fulfil the system admissible values with discharge increased to 14.7 m^3/s. The head loss coefficient referring to the original surge tank inlet cross section found by multi-criteria iterative optimization process is K=30/40 respectively for inflow and outflow, while an average value of K=9 was determined by calibration for the original surge tank without diaphragm. The singular head losses being defined as follows:

$$dH_r = \frac{K}{2gA_{ref}^2} Q^2 = K \frac{V_{ref}^2}{2g} \qquad (3)$$

Where A_{ref} is the reference cross section area [m^2], dHr is the singular head losses [mWC] and K is singular loss coefficient [-]. The diaphragm loss coefficient was optimised to obtain optimal transient response over the entire upper reservoir water level range considering discharge limitation for the reduced water levels as illustrated in Fig. 11. The most restricting factor for diaphragm optimisation was finally found to be the minimum pressure in the headrace gallery.

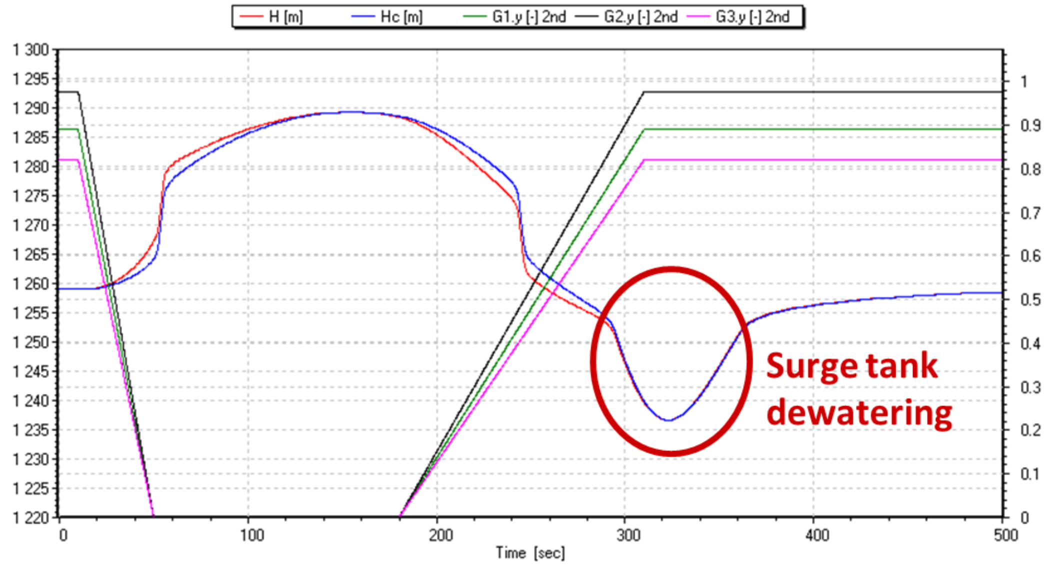


Fig. 8. Simulation results of time evolution of the surge tank water level and Pelton Unit injector openings in case of units unloading followed by a reloading in case of discharge increase to 14.7 m^3/s, where "H" is the surge tank head in the headrace tunnel, "Hc" is the surge tank water level and "y" is the injector openings

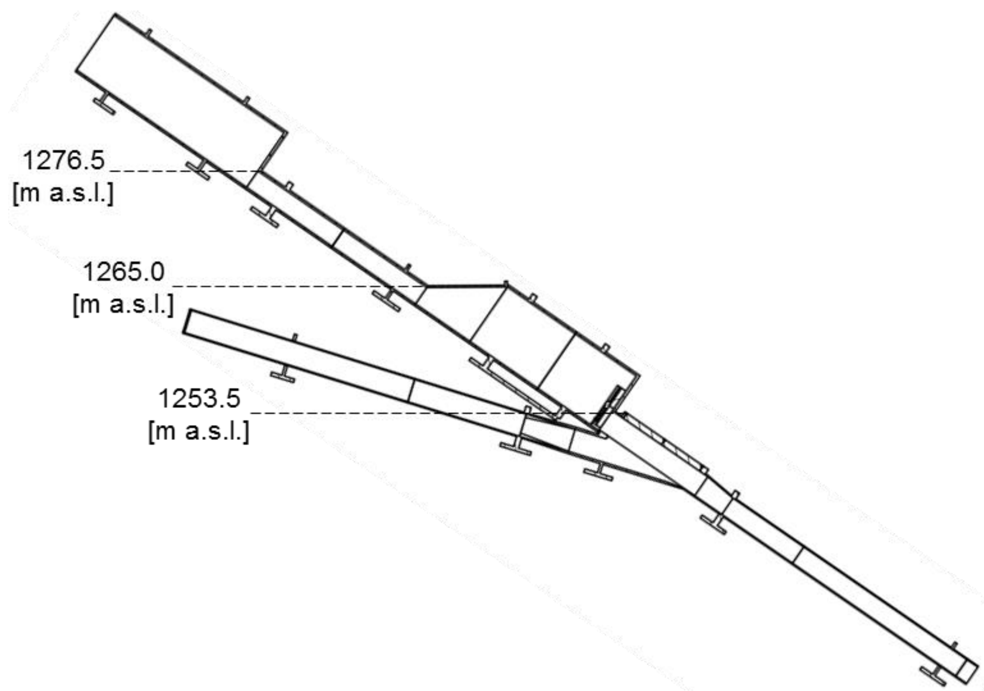


Fig. 9. Schematic view of the surge tank and relevant altitudes

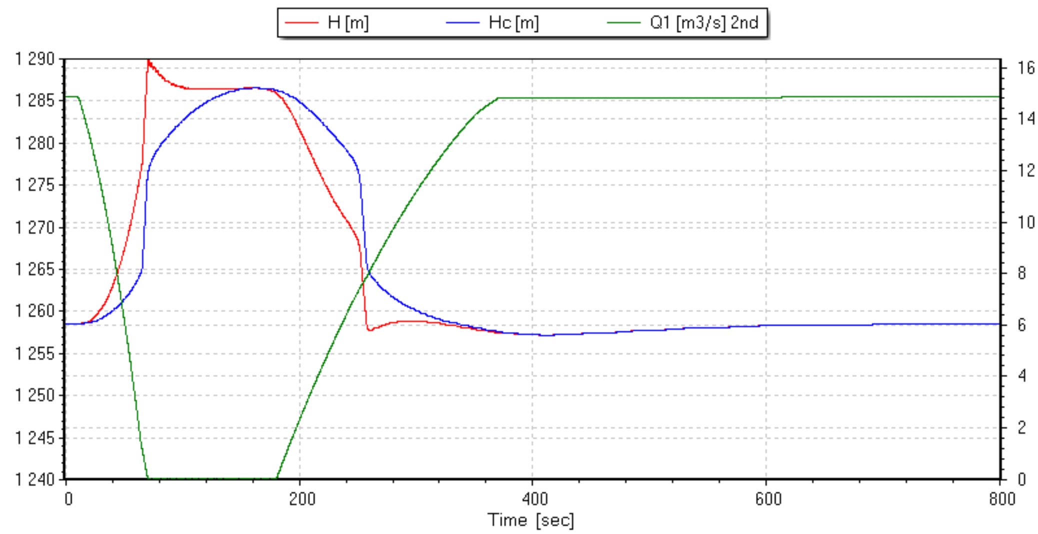


Fig. 10. Simulation results in case of units unloading followed by a reloading at maximum upper reservoir water level with discharge increase to 14.7 m3/s and introduction of optimized surge tank diaphragm; where "H" is the surge tank head in the headrace tunnel, "Hc" is the surge tank water level and "Q1" is the penstock discharge

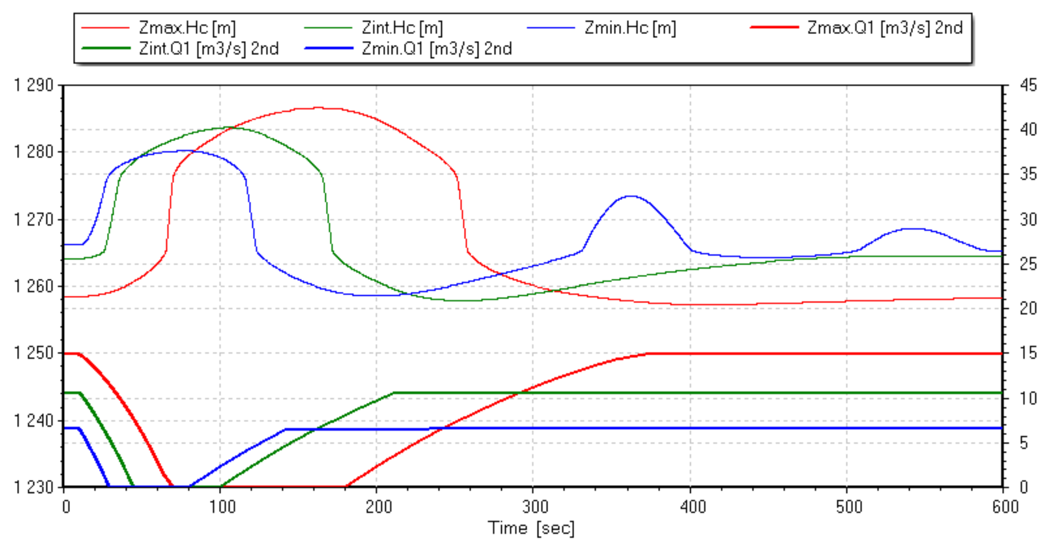


Fig. 11. Simulation results in case of units unloading followed by a reloading for different upper reservoir water levels with discharge increase and introduction of optimized surge tank diaphragm; where "Hc" is the surge tank water level and "Q1" is the penstock discharge

2. Physical model : Surge tank modification

Head losses are proportional to the square of the opening area [13]. As, in this case study, the section restriction and head losses are quite high, a small geometry change could induce a big head loss variation.

2.1. Experimental set-up

The 1/12-scale physical model was built in the LCH using Froude similarity. This type of similarity can be used as the lowest Reynolds number in the larger pipe is higher than 10^4 to insure a fully turbulent flow [12,13]. All pipes are made of Plexiglas (PMMA). Figure 12 shows a schematic view of the model. Fig. 13 shows an upstream view of the final diaphragm on the physical model.

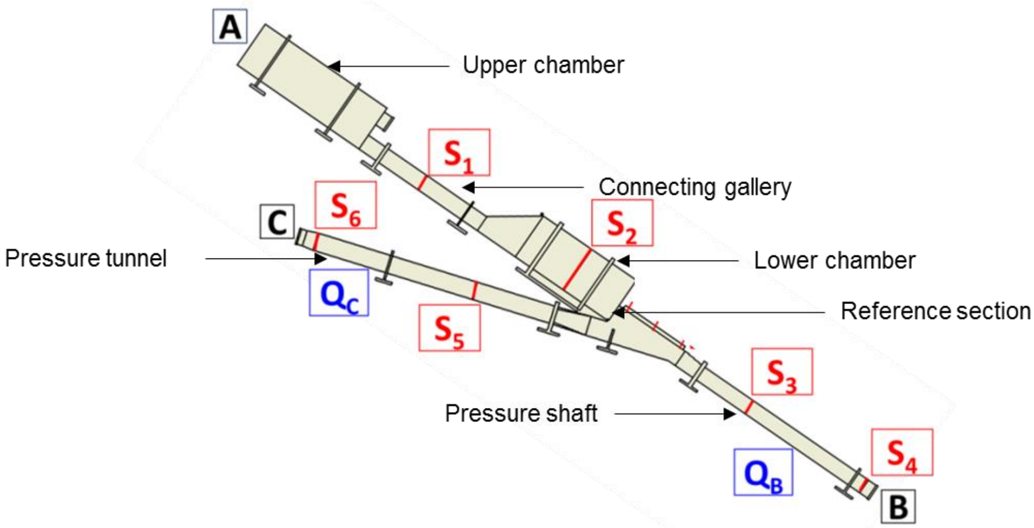


Figure 12 : Schematic view of the physical model

For each diaphragm type, three relevant flow directions are tested i.e. Generation turbining flow (C – B), turbine start (A – B), flow going in the surge tank during mass oscillations (C – A) and level decrease of mass oscillations (A – C).

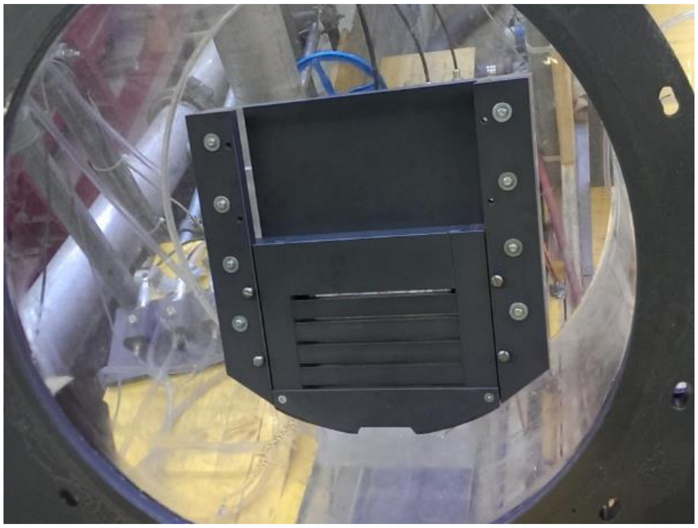


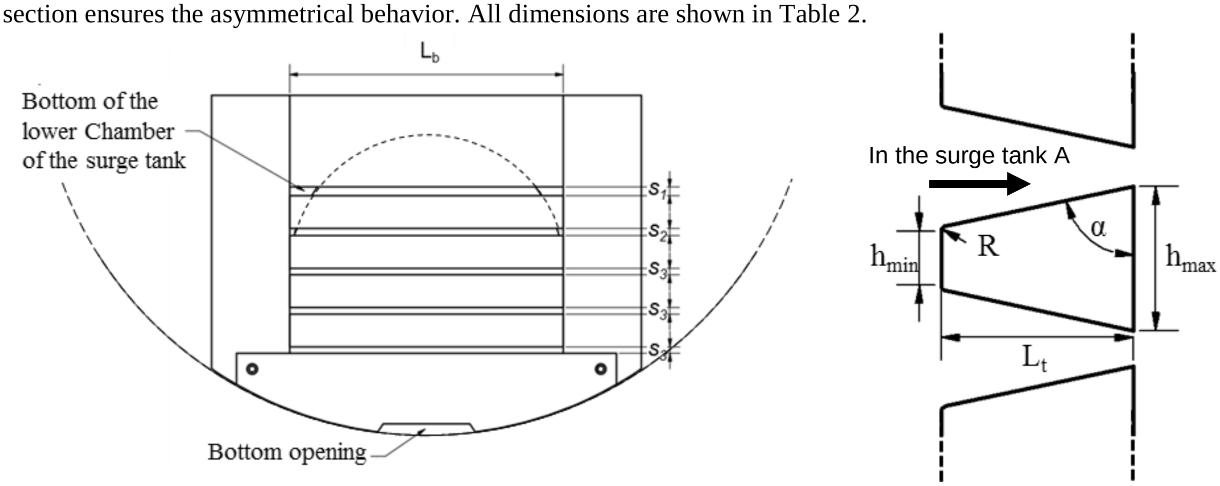
Figure 13 : Upstream surge tank view of the final diaphragm geometry on the physical model

2.2. Instrumentation

To determine head losses and head loss coefficients, different types of measurement equipments are used, i.e. six piezoresistive pressure sensors and two flowmeters. The pressure sensors are type Keller series 25 and are connected to 4 outputs distributed around the pipe section. Both flowmeters are type Endress-Hauser PROMAG 50 W. They are located at the end of B-pipe and at the entrance of C-pipe.
The total duration of data acquisition is 15 seconds for a recording frequency of 100 Hz. Only average piezometric head (altitude and pressure) and average discharge are used for the head loss coefficient evaluation.
Only steady state experiments were carried out as it is a usual hypothesis to assume that unsteady head losses are the same as steady losses [14].

2.3. Diaphragm geometry

Both the high values of the head loss coefficients and the significant ratio between inflow and outflow head loss required a special design of the diaphragm geometry. In Switzerland good experience was gained using diaphragms with horizontal bars as e.g. at the surge tank inlet of Grimsel 2 PSP and Amsteg HPP (see [15]). These experiences were used to determine roughly the design parameters as blockage ratio and other shape parameters. Further optimization of the diaphragm geometry was carried out by the help of the physical model tests presented here.
The target head losses are defined in Section 2 and evaluated in (A – C) and (C – A) flow directions. Several geometries were tested to ensure these losses. Fig. 14 shows the final diaphragm geometry. The trapezoidal bar beam section ensures the asymmetrical behavior. All dimensions are shown in Table 2.



(a) *(b)*

Fig. 14. (a) Up view of the grid, the bottom opening is due to the presence of the inspection wagon rails; (b) Schematic view of beam cross section

Table 2: Dimensions of the final diaphragm geometry (in prototype scale)

Diaphragm				
L_b [m]	S_1 [m]	S_2 [m]	S_3 [m]	
2.1	0.07	0.065	0.06	
Beam cross section				
L_t [m]	h_{max} [m]	h_{min} [m]	R [m]	α [°]
0.32	0.24	0.089	0.01	78

2.4. Results

Fig. 15 show the linear regressions between head losses and kinetic energy for all flow directions. Firstly, the diaphram's beam shape produces target losses in each direction. Secondly, the 15-percent difference between (A – C) and (A – B) is due to the almost 180 degrees bifurcation during the mass oscillations. Thirdly, losses in normal turbine flow remain small even with the diaphragm placement.

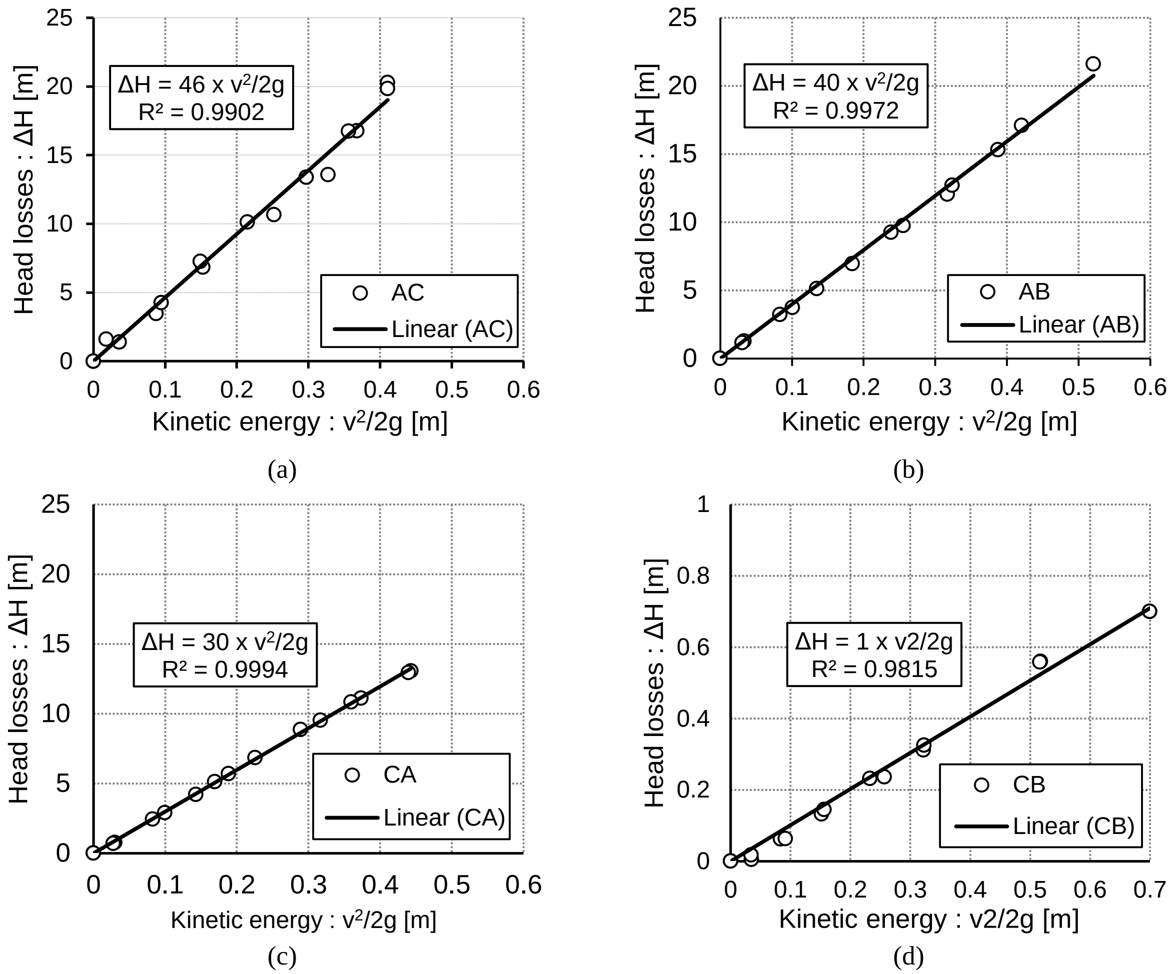


Fig. 15. Determination of head loss coefficient with the least square method for each flow direction: (a) Flowing out the surge tank during mass oscillation, (b) Flowing out the surge tank following an turbine opening, (c) Flowing in the surge tank during the surge tank during mass oscillation and (d) Steady flow during turbine generation

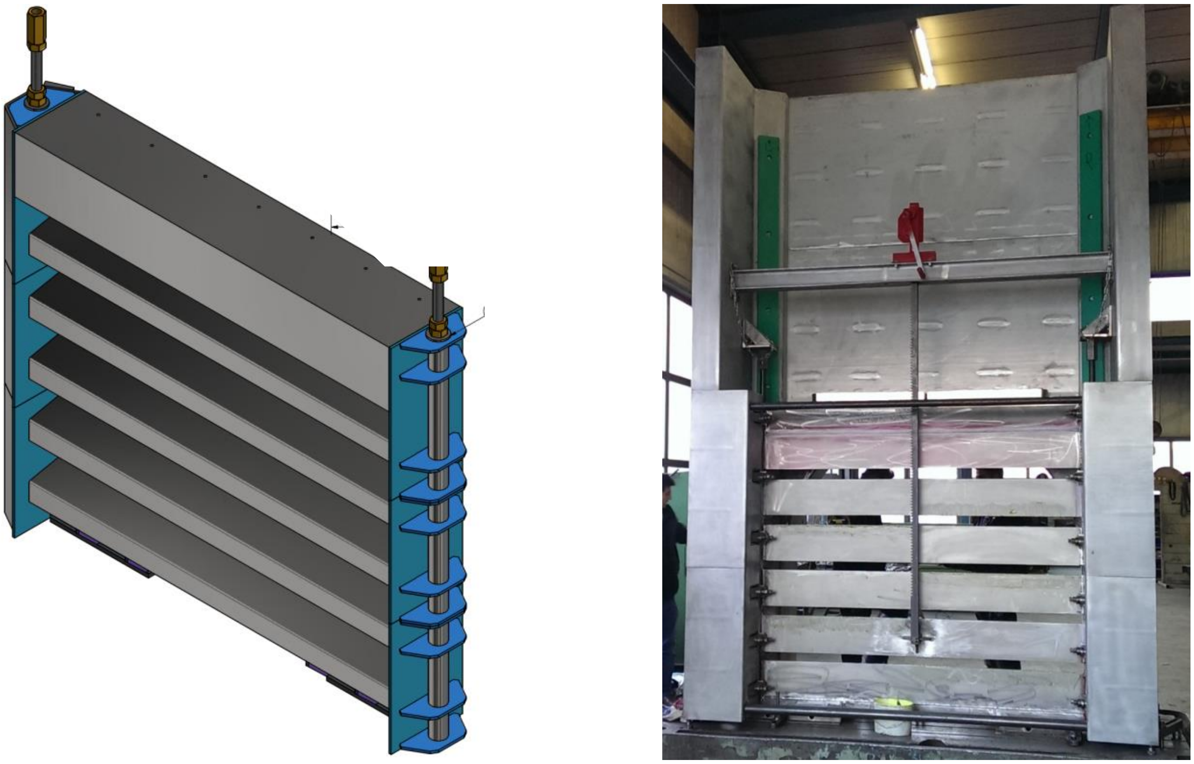
3. Prototype diaphragm

3.1. Construction and errection

The hydrodynamic forces (i.e. drag and lift forces) acting on the diaphragm depend to some extent on the head loss of the flow through the diaphragm. Since no pressure or force measurements could be carried out in the model test the operational loads acting on the bars of the diaphragm were computed in analogy to findings for the Amsteg diaphragm [15]. Maximum drag forces for both the inflow to and the outflow from the surge tank at maximum flow through the diaphragm amount to significant 95 kN/m and 50 kN/m, respectively, with maximum lift force of +/-40 kN/m.

The diaphragm, consisting of the bar grillage and the bracing frame, was constructed in stainless steel. Since the pressure shaft must be accessed with a trolley for inspection and repair the grillage needed both a lifting mechanism and a stable fixation at the bearings.

The prototype diaphragm was constructed according to the final design in Fig. 14. An isometric drawing and a picture of the gate at factory acceptance are shown in Fig. 16.



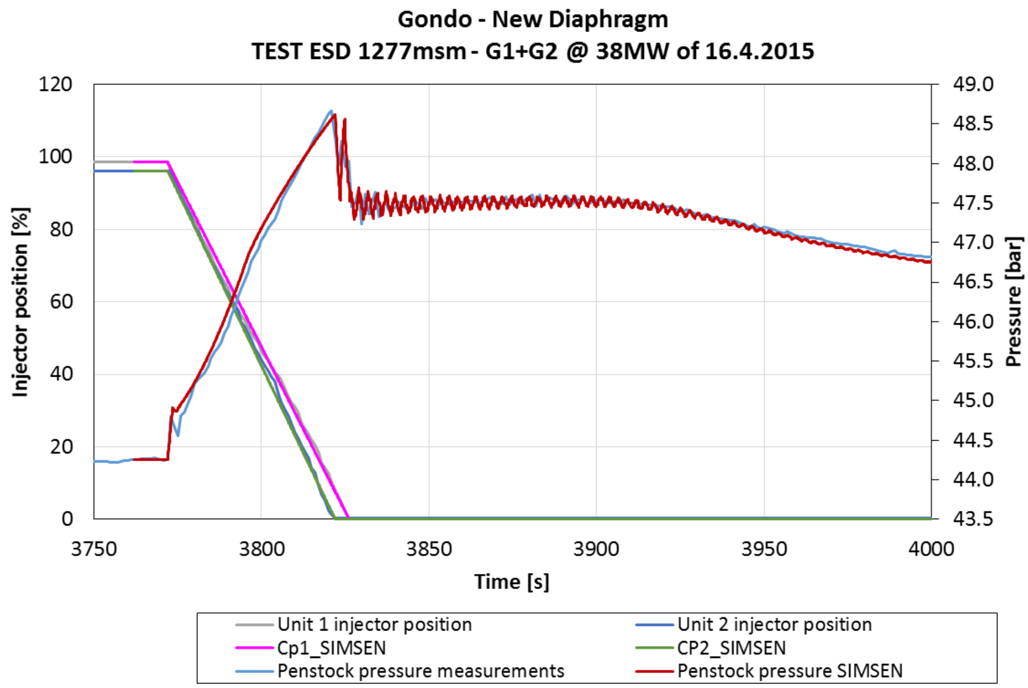
(a) (b)

Fig. 16. (a) isometric drawing of the diaphragm (drawing by Stahleinbau GmbH, CH-Stalden); (b); erected diaphragm at factory acceptance

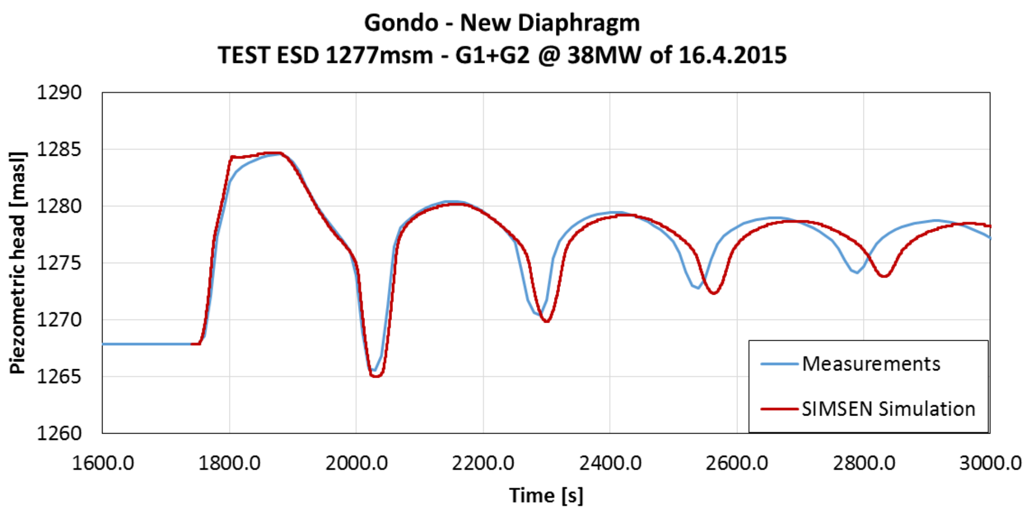
After factory acceptance the diaphragm was disassembled and transported to the site by truck and helicopter to the surge chamber that lies in a remote valley on about 1200 m a.s.l. Since the erection time window was limited to an acceptable plant shutdown of only 3 weeks, site erection during winter conditions in the steeply inclined and narrow pressure chamber required meticulous planning and strict safety precautions.

3.2. On site tests

Site acceptance test under in-situ conditions confirmed the behavior of the diaphragm and the whole tailrace system as expected by the numerical simulation. Fig. 17 shows the comparison between in situ measurements and SIMSEN computation for a fast turbine shut-off. As it can be seen measurement and computational data match very well.



(a)



(b)

Fig. 17. Comparison of in situ measurement (blue lines) and numerical simulation by SIMSEN (red lines) for turbine emergency shutdown (ESD): (a) needle position and pressure upstream of the turbine; (b) water level in the upper surge chamber.

4. Conclusions and outlook

The power extension of the Gondo hydroelectric power plant implied several modification of the hydraulic devices to insure a minimum safety level.

After a numerical model validation on on-site prototype measurements, the 1-D transient analysis showed the necessity of a diaphragm placement at the entrance and exist of the existing surge tank to avoid surge tank dewatering. The diaphragm head loss coefficients are defined for critical hydraulic and electrical loads.

Due to the high complexity of the junction between the surge tanks, headrace tunnel and pressure shaft, an experimental campaign was carried out in the Laboratory of hydraulic constructions. The final diaphragm geometry was a horizontal grid with trapezoidal grids. The main difficulties were to find the right ratio between losses in both directions.

Finally, the diaphragm was built in stainless steel and erected in the surge tank during only 3 weeks during winter condition.

5. Acknowledgments

The authors would like to express their gratitude to the company Etaeval who performed measurements during the first transient test campaign for model calibration, and also to the staff of Hydro Exploitation SA involved in the power plant operation and supervision during transient tests and performed the second transient test campaign and also performed the measurements of the detailed 3D geometry of the surge tank.

6. References

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