Case Study

Design of a Throttled Surge Tank for Refurbishment by Increase of Installed Capacity at a High-Head Power Plant

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Abstract: The Swiss confederation aims to phase out nuclear power production with its Energy Strategy 2050 program by increasing the renewable energy contribution to its overall energy generation. Hydroelectricity, which is the most important form of renewable energy in Switzerland, supplying almost 60% of the electricity in 2015, should increase its production capacity to achieve this goal. The case study presented in this paper focuses on the replacement of the third turbine in the Gondo high-head power plant with a turbine with a higher discharge capacity. The results of one-dimensional (1D) numerical simulations shown that throttling the surge tank is an efficient measure to adapt the existing hydraulic system for the increased discharge. Physical-scale modeling was performed to validate the design of the grid throttle placed at the bottom of the lower chamber of the existing surge tank. The grid throttle geometry and its head losses are compared with two existing similar throttles in Switzerland. Finally, prototype tests of the temporal evolution of water levels in the surge tank using the throttle coefficients obtained experimentally showed good agreement. Hybrid modeling using a combination of 1D numerical models, three-dimensional (3D) physical models, and prototype tests are highly recommended for checking the transient performance of the waterway after a refurbishment of turbines with increased design discharge. Furthermore, placing a throttle at the bottom of an existing surge tank is often an effective and economical solution in the case of small increases in installed capacity. **DOI: 10.1061/(ASCE)HY.1943-7900.0001404.**

Introduction

Most existing Swiss storage hydropower plants were built between 1945 and 1970. In the last few years, hydroelectricity has supplied almost two-thirds of the domestic electricity production and is the major source of renewable electricity (SFOE 2016). Hydropower storage plants account for half of the hydroelectricity production. With its Energy Strategy 2050 program, Switzerland aims to increase the yearly expected average production from approximately 36.0 to 38.6 TWh/year, although the technically feasible potential is approximately 41.0 TWh/year (International Journal on Hydropower and Dams 2016). This objective can be achieved mainly by refurbishing and extending existing plants and building new ones to a limited extent only.

In this respect, refurbishing the existing Gondo hydropower plants would allow an increase in the existing installed generation capacity with the renewal of the third turbine installed during the 1980s. This would lead to an increase in the discharge flowing in the headrace system from 12 to 14.7 m^3/s, with a 470-m head between the upstream reservoir and the Gondo power plant. The existing headrace system had to be carefully inspected with regard to the dynamic pressure by using a one-dimensional (1D) numerical transient model. Furthermore, water levels in the surge tank had to be studied as an increase in discharge results in an increase in the maximum water level and a decrease in the minimum water level for the same opening or closure time. Therefore, a pressurization or dewatering of the surge tank could occur.

Throttling the surge tank, and thus implementing distinct head losses, might help to handle these extreme water levels (Chaudhry 2014; De Martino and Fontana 2012; Jaeger 1977). According to Vereide et al. (2015) and Gabl et al. (2014), there are at least three tools, i.e., physical-scale models, 1D numerical simulations (Cao et al. 2013; Chaudhry 2011; Di Santo et al. 2002; Kim 2008), or three-dimensional (3D) numerical simulations, to investigate and study the effects of the throttle geometry on head losses. In other words, the required head losses of the throttle is often evaluated with 1D numerical simulations, whereas the geometry optimization is evaluated by physical-scale models, 3D numerical simulations, or both. Table 1 shows several studies performed in the last few years on the throttled surge tanks and throttle optimization. Majority of the studies used physical-scale models but few performed prototype measurements to check the validity of the physical model. For the numerical simulations, Table 1 shows that the authors used either 1D transient models or 3D computational fluid dynamics (CFD) models (only one single study used both modeling).

This paper presents a hybrid modeling approach involving 1D numerical simulations of the entire hydraulic system, physical

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Table 1. Existing Studies on Throttled Surge Tank: Goal of the Study and Means of Investigation

Source	Goal	Physical scale	1D numerical simulation	3D numerical simulation (CFD)	Prototype validation
Klasinc and Bilus (2009)	Geometry optimization and flow visualization	Done	Not done	Done	Not done
Kim (2010)	Throttle optimization	Not done	Done	Not done	Not done
Gabl et al. (2011)	Throttle optimization	Not done	Not done	Done	Not done
Nabi et al. (2011)	Throttle optimization	Not done	Done	Not done	Not done
Richter et al. (2012)	Flow visualization	Done	Not presented	Not done	Not done
An et al. (2013)	Geometry optimization	Not done	Not done	Done	Not done
Hachem et al. (2013)	Geometry optimization	Done	Done	Not done	Not done
Kendir and Ozdamar (2013)	Geometry optimization	Done	Done	Not done	Not done
Alligne et al. (2014)	Geometry optimization and flow visualization	Done	Done	Done	Not done
Schneider et al. (2014)	Geometry optimization and flow visualization	Done	Not done	Done	Not done
Meusburger (2015)	Geometry optimization and flow visualization	Done	Not done	Done	Not done
Present study	Geometry optimization	Done	Done	Not done	Done

modeling of the throttled surge tank, and prototype calibration and validation. The optimization process of the throttle device is highlighted, and the behavior of the prototype waterway system with the new throttle is assessed to validate the simulation with the scaled physical model.

Case Study: Gondo High-Head Power Plant

Energie électrique du Simplon SA (EES) manages the three hydroelectric power plants in Gondo, Gabi, and Tannuwald. The location and longitudinal profile are shown in Fig. 1, and the main characteristics are listed in Table 2. The three reservoirs store water collected from the southern Simplon Mountains on the Swiss-Italian border.

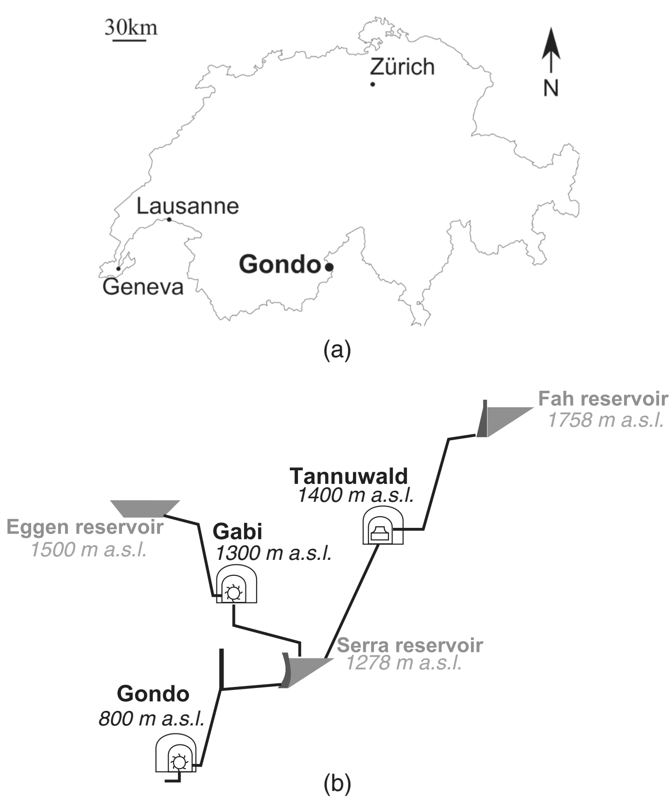

Fig. 1. (a) General location of the Gondo power plant; (b) schematic view of the working stage of EES

The hydroelectric power plant at Gondo was commissioned in 1952, with two 18.5 MW Pelton turbines exploiting a head of 470 m. The discharge flowing through the tailrace tunnel was increased from 11.0 to 12.1 m^3/s with the commissioning of a third 8-MW Pelton turbine during the 1980s. The project described in this paper, Renewal of Group 3, aims to replace this third turbine with a more efficient and powerful one, increasing the discharge by up to 14.7 m^3/s.

Fig. 2 shows a schematic of the waterway system and the hydroelectric power plant. Two upstream intakes, Krummbach and Lagginbach, feed the reservoir formed by the Serra arch dam and the Gabi and Tannuwald powerhouse outlets. The water level in the Serra reservoir varies between 1,269.9 and 1,278.0 m above sea level (a.s.l.), and the maximum head is 470 m. The overpressure and underpressure must be limited in the concrete-lined headrace tunnel. The steel-lined part of the pressure shaft starts at an altitude of 1,040 m a.s.l. The main characteristics are shown in Table 3.

To protect the pressure tunnel against the water hammer and enable fast operation cycles of the turbines, a surge tank is placed at the intersection of the pressure tunnel with the pressure shaft (Figs. 2 and 3). This inclined surge tank consists of two expansions, i.e., a lower and upper expansion chamber connected by an intermediate shaft, and was built as a prolongation of the pressure shaft in 1952.

This allows for an economical and cost-effective design (Chaudhry 2014; Giesecke and Mosonyi 2009; Jaeger 1977).

During the 1980s, the geometry of the original surge tank allowed for an increase in the discharge by more than 20% without any change. As the presented numerical transient simulation shows, a further increase in the turbine discharge would require some modification of the surge tank. Compared with extending the chambers, which is practically not feasible, implementing a throttle

Table 2. Head, Discharge, and Installed Generation Capacity for Gabi, Tannuwald, and Gondo Hydroelectric Power Plants

Power plant	Characteristics	Values
Gabi	Head	295 m
	Discharge	3.8 m^3/s
	Generation capacity	11 MW
Tannuwald	Head	363 m
	Discharge	2 m^3/s
	Generation capacity	5.2 MW
Gondo	Head	470 m
	Discharge	12.1 m^3/s
	Generation capacity	45.4 MW

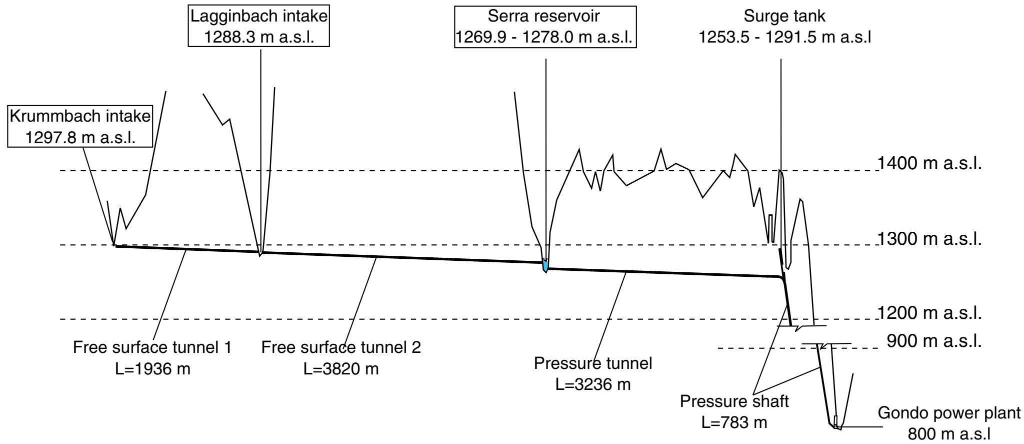

Fig. 2. Longitudinal profile of the hydropower scheme from the Serra Lake to the Gondo Valley

Table 3. Main Waterway Characteristics

Waterway	Characteristics	Dimensions	Lining
Free-surface tunnel 1	Length	1,936 m	—
	Mean slope	0.41%	
Free-surface tunnel 2	Length	3,820 m	
	Mean slope	3.2%	
Pressure tunnel	Length	3,236 m	Concrete
	Mean slope	0.29%	
	Diameter	2.1 m	
Pressure shaft, upper part	Length	259 m	Concrete
	Mean slope	55.7%	
	Diameter	1.8 m	
Pressure shaft, part below 1,040 m a.s.l.	Length	524 m	Steel
	Mean slope	55.7%	
	Diameter	1.6 m	

device at the bottom of the surge tank is an alternative cost-efficient solution.

The reference section (Fig. 3) for the evaluation of head losses in the throttling device is the opening at the bottom of the surge tank with a cross section of 3.937 m^2.

Methods

Complementarity between the Numerical and Experimental Models

Following the decision to refurbish the hydropower plant, the behavior of the waterway was verified by carrying out a transient analysis using a 1D numerical model. Pressure fluctuations caused by the water hammer should be below critical values regarding the stability of the linings of the pressure shaft and tunnel. Extreme water levels in the surge tank also have to be limited to avoid air entrainment and cavitation.

Before this verification, the 1D transient model was calibrated with on-site measurements. All possible load cases were simulated, including emergency shutdown, simultaneous loading, and loading after an emergency shutdown at the most critical moment for the surge tank.

The main aim of this step is to identify a pair of head-loss coefficients produced by a throttle in each flow direction at the entrance of the surge tank. Throttles can limit the mass oscillations between the upper reservoir and the surge tank (Adam et al. 2016b). Experimental formulas give head-loss coefficients relative to the

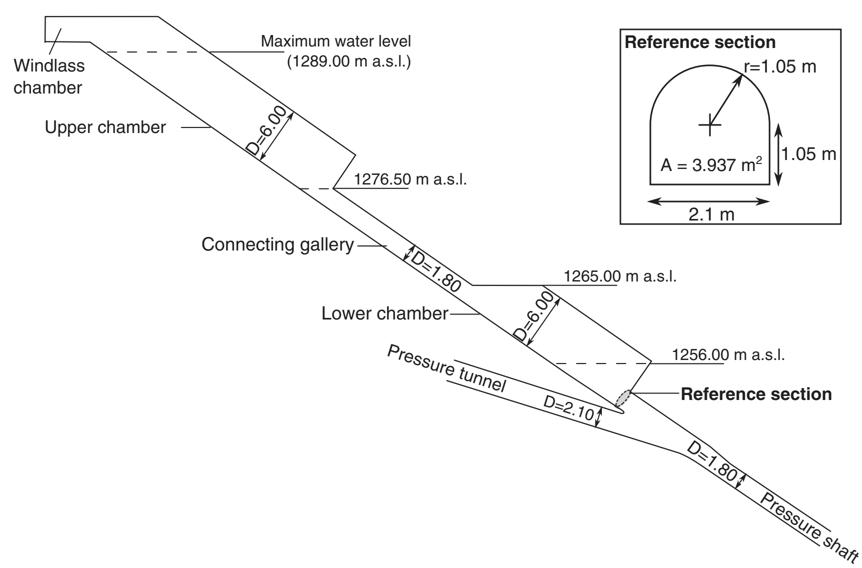

Fig. 3. Longitudinal profile of the surge tank with upper and lower expansion chambers with the reference section ($A = 3.937$ m^2)

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geometries of the throttle (Blevins 1984; Idel'cik 1969). However, local waterway geometry is often far from their hypotheses, for example, assuming turbulent velocity flow fields or long straight conduits. Physical modeling allows for consideration of the local geometry of the waterway in the evaluation of the throttle head losses.

Numerical Model

Numerical simulations have been performed with *SIMSEN*, which solves one-dimensional momentum and continuity by using the finite-difference method and an analogy with electrical schemes (Nicolet 2007). The *SIMSEN* software was developed to simulate the transient behavior of hydroelectric power plants and was validated by Nicolet et al. (2007).

Experimental Setup

The physical model in Froude similarity (Fig. 4) was built at the Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique de Lausanne (EPFL), with a geometric scale of $1/12$ to reduce scale effects. Even if Froude similitude is more common in free-surface flow-modeling and Reynolds similarity for pressure flow, the lowest Reynolds number R ensures a fully turbulent behavior, as recommended in Blevins (1984). Such fully turbulent behavior allows for Froude similarity because head losses do not depend on R. Seven discharges were tested from 5.5 (prototype, 2.7 m^3/s) to 33.0 L/s (prototype, 16.5 m^3/s). According to Idel'cik (1969), head losses in turbulent flow are linearly proportional to the kinetic energy of the flow.

All conduits are made of acrylic glass, and the throttle is PVC. Fig. 5 shows two different views of the physical model.

The tests were performed with different throttle configurations. The relevant flow directions were as follows: turbine flow (C-B), turbine start (A-B), flow leaving the surge tank during mass oscillations (C-A), and flow entering the surge tank during mass oscillations (A-C). The sections used for the evaluation of head losses in each direction according to Table 4 are shown in Fig. 4. Each measurement section is connected to pressure sensors (Keller Series 25, Keller AG für Druckmesstechnik, Winterthur, Switzerland), and two flowmeters in Pipes B and C record the discharge (Proline Promag 50W, Endress+Hauser, Greenwood, Indiana).

For each discharge, the pressure sensors record the average piezometric head (altitude and pressure), while flowmeters give the discharge flowing through each of the pipes. The acquisition rate is 100 Hz for a total duration of data acquisition of 15 s. All experiments are performed in steady state. According to Chaudhry (2014), transient head losses can be taken as equal to head losses produced in a steady flow.

Modeling of the Existing System Before Extension

Calibration of the Numerical Model

Fig. 6 shows the calibration with local head-loss coefficients at the reference section (Fig. 3), with (k_{IN}, k_{OUT}) values of (5, 5) and (9, 9) in both flow directions. The two different values of the head-loss coefficients do not largely influence water-level variations in the surge tank during the mass oscillations. A head-loss coefficient of 5 better approaches the oscillation period, whereas a head-loss coefficient of 9 better approaches the maximum and minimum water levels.

Experimental Results

The measured head-loss coefficients obtained from the physical model tests at the entrance of the surge tank with no throttle during mass oscillations are equal to 5.7 for water flowing out and 3.9 for water flowing into the surge tank. These results are in good agreement with the numerical calibration, as shown in Fig. 6.

Throttle Design

Numerical Analysis

Load Cases

After calibration of the numerical model, different load cases are studied to evaluate new transient behaviors attributed to the

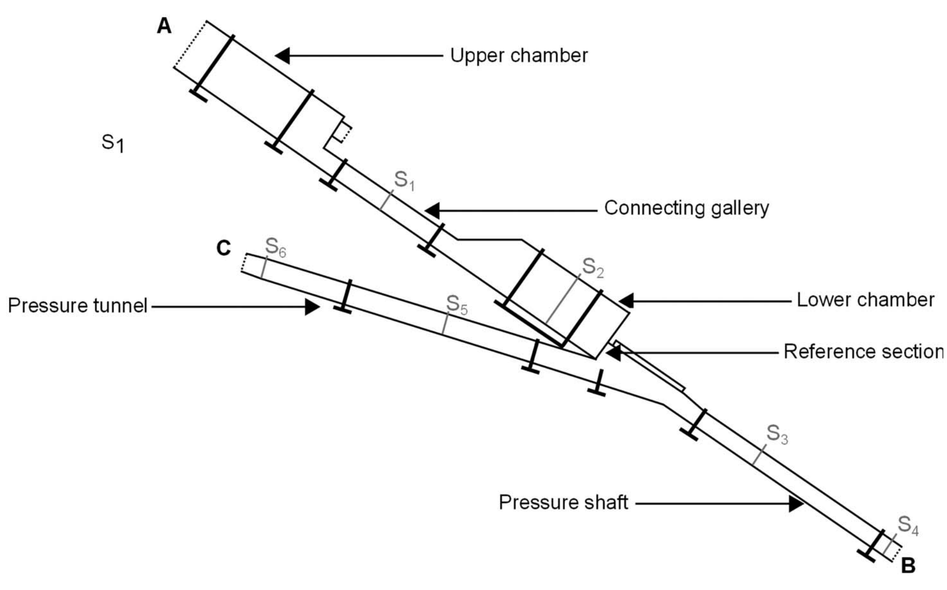

Fig. 4. Schematic view of the physical model and position of the pressure measurements (A = surge tank branch; B = pressure shaft; and C = pressure tunnel)

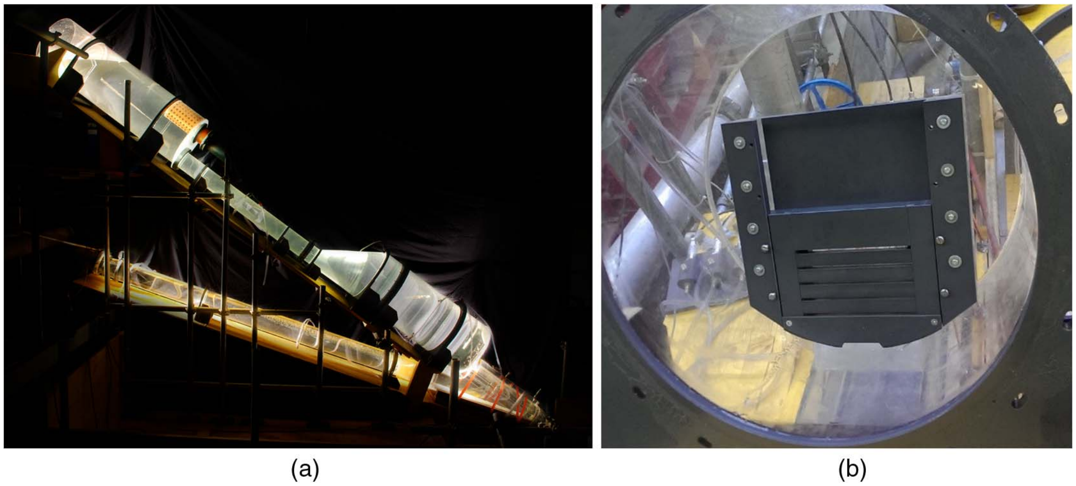

Fig. 5. View of the physical model at LCH EPFL (images by A. J. Schleiss): (a) view of the entire physical model; (b) upstream view of the final throttle

Table 4. Section Used to Evaluate Head Losses in All Relevant Flow Directions (Fig. 4)

Flow direction	Upstream control section	Downstream control section
A-C	S_1	S_6
C-A	S_5	S_1
A-B	S_1	S_4
C-B	S_5	S_4

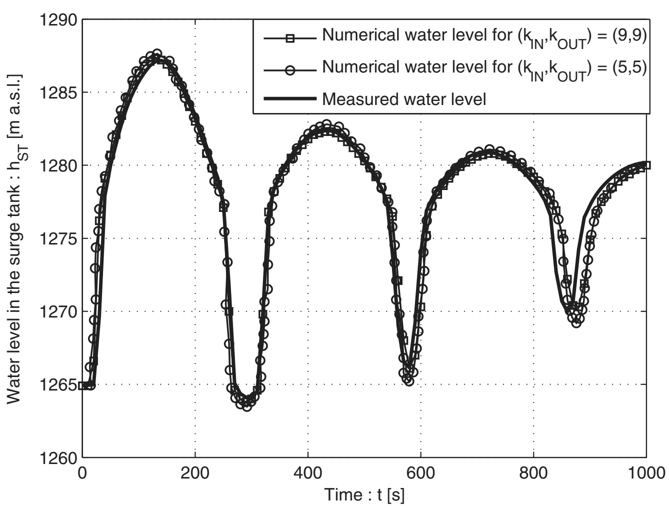

Fig. 6. Water levels in the surge tank; calibration of the numerical model for local head-loss coefficient of 5 and 9 in both directions; prototype measurements for Case A with an upper reservoir at 1,277.6 m a.s.l. (August 8, 2012)

increased generation capacity, which may also cause problems. Maximum and minimum water levels in the surge tank, as well as maximum and minimum pressures in the penstock, have to be within admissible values.

The transient analysis focuses on the five following cases:

- Case A: Emergency shutdown of all the units;
- Case B: Simultaneous loading of all units;
- Case C: Loading followed by emergency shutdown at the worst moment for the upsurge in the surge tank;
- Case D: Load rejection followed by a reloading while all units remain connected to the grid; and
- Case E: Emergency shutdown and loading and emergency shutdown leading to the closure of injectors in the penstock reflection time, i.e., the so-called peak of Michaud (Nicolet et al. 2012).

On the basis of the simulation results, the increase in discharge from 12.1 to 14.7 m^3/s can be achieved safely if the following conditions are met:

- The duration of the closure is increased to restrict the maximum stress in the steel-lined pressure shaft below its yield point; and
- The surge tank is throttled to prevent dewatering in the case of unloading followed by a reloading (Fig. 7).

Throttle Design Using Data from Numerical Simulations

Numerical simulations allow the introduction of head losses at the bottom of the surge tank in both directions, i.e., water flowing in and out of the surge tank. Fig. 8 shows the evolution of the water level in the surge tank with the throttle. The throttle prevents dewatering of the surge tank (compared with Fig. 7). Furthermore, the maximum pressure in the pressure tunnel increases while the maximum water level is reduced. The numerical simulation reveals that a head-loss coefficient of 30–31 is required for inflow into the surge tank, whereas the head-loss coefficient for the outflow is between 40 and 76.

Model Test Results

To ensure target head losses in both directions found by the numerical analysis, several iterations of the hydraulic model were performed. Two different types of geometry were tested: The first is a gate with a profile of its bottom to ensure asymmetry, and the second is a grid or a bar screen with horizontal asymmetric beams.

For the first type, three different alternatives of gate geometry are tested, as shown in Fig. 9 and Table 5. The second type is rack geometry as defined by Adam et al. (2016c). These grids consist only of horizontal beams. The beam number remains unchanged, and only the beam geometry and the opening space (between two beams) are modified. However, all beams have practically trapezoidal cross sections (Fig. 10). Fig. 10(a) shows different spacing sizes

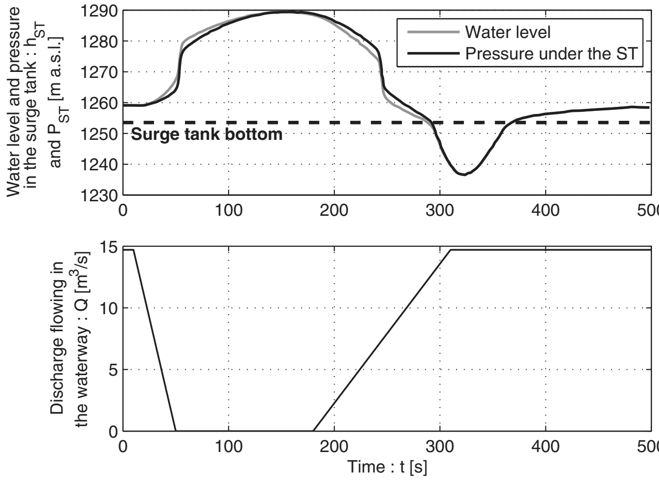

Fig. 7. Water level and pressure in the surge tank without a throttle; numerical simulation for Case D with the new discharge of $14.7\ \mathrm{m^3/s}$

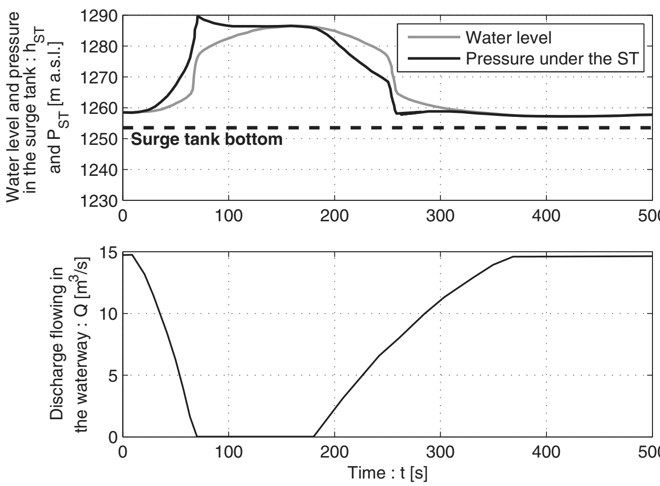

Fig. 8. Water level and pressure in the surge tank after the introduction of head-loss coefficients 50/30 at the entrance of the surge tank; numerical simulation for Case D with the new turbine discharge of $14.7\ \mathrm{m^3/s}$

along the grid height, ensuring a constant opening area along the height.

To evaluate head losses for the different throttle geometries, steady-state experiments are performed for 10 discharges. According to Prenner (1999), physical models are still efficient to evaluate steady head losses up to $k \approx 150$. The relation between the head losses and the velocity head combined with the head-loss coefficient is given by

$$\Delta H = k\frac{v^2}{2g} \tag{1}$$

where ΔH = steady-state head loss (m); v = flow velocity at the reference cross section (Fig. 3) (m/s); g = gravity acceleration ($\mathrm{m/s^2}$); and k = nondimensional head-loss coefficient, whose value is determined by the least-squares method in the current study, related to the reference cross section.

Fig. 11 shows the head-loss coefficient obtained by using the least-squares method in all relevant flow directions for the throttle design with Grid F (Table 6). The difference of 15% between the losses when the water is flowing out of the surge tank (A-C and A-B) is caused by flow bifurcation during the mass oscillation. For all throttle geometries, this difference varies between 5 and 15%. The head-loss coefficient during turbine use logically remains constant around unity as there are no throttling influences.

The main issue is to optimize the design of the throttle to achieve the required head losses as obtained by the numerical model. The head-loss coefficient for inflow has to be approximately 30, whereas it has to be between 40 and 76 for the outflow. Fig. 12 shows the head-loss coefficients in both directions for all tested throttle geometries.

Even if the open area of the throttle is almost equal for both types, the losses are higher for grid throttles. This can be

Table 5. Characteristics of Gate Throttles with Corresponding Head-Loss Coefficients When Water Flows In or Out of Surge Tanks

Geometry	Gate A	Gate B	Gate C
Top opening	0.1	0.1	0
Bottom opening	0.4	0.33	0.33
k_{OUT}	18.4	25.2	25.2
k_{IN}	8.5	12.2	17.8

Note: Values are in meters at the prototype scale.

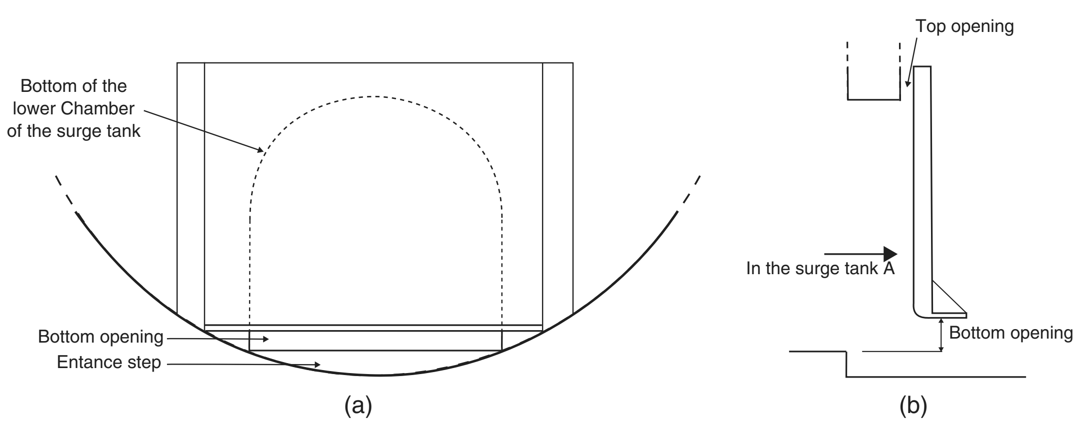

Fig. 9. Geometry of gate throttle: (a) front view of the gate; (b) section view of the gate

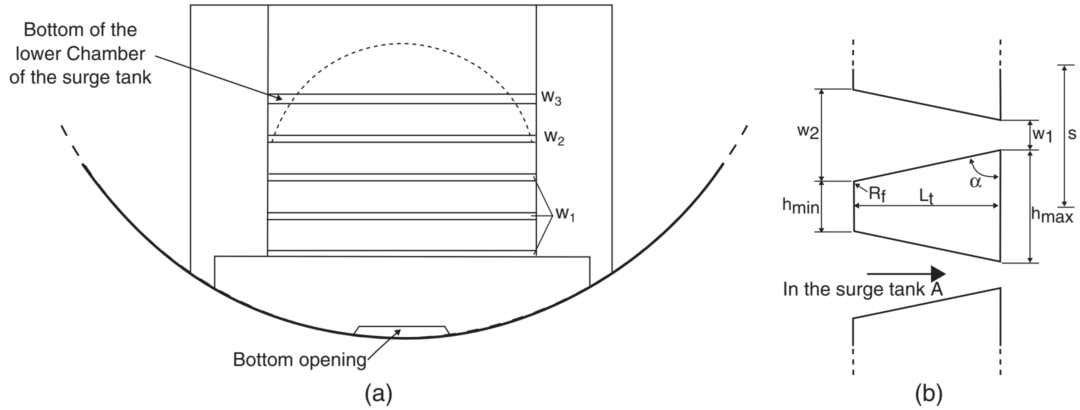

Fig. 10. Geometry of rack throttle: (a) front view of the grid (the bottom opening is attributed to the presence of the inspection wagon rails); (b) sectional view of beam

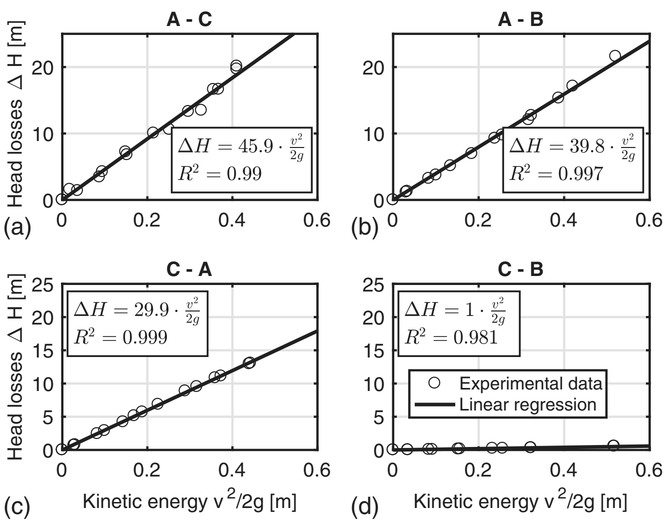

Fig. 11. Determination of the head-loss coefficient with the least square method for each flow direction in steady-state flow for throttle design: (a) flow out of the surge tank during mass oscillation; (b) flow out of the surge tank following a turbine opening; (c) flow into the surge tank during mass oscillation; (d) steady flow during turbine generation

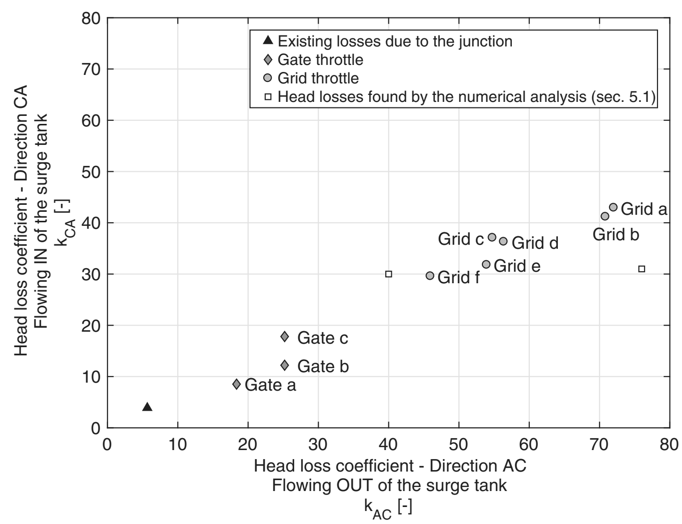

Fig. 12. Evolution of the head-loss coefficient in both mass oscillation flow directions

Table 6. Characteristics of the Tested Grid Throttles with Corresponding Head-Loss Coefficients When Water Flows In or Out of Surge Tanks

Geometry	Grid A	Grid B	Grid C	Grid D	Grid E	Grid F
w_1	0.05	0.05	0.05	0.05	0.058	0.06
w_2	0.055	0.055	0.055	0.055	0.063	0.065
w_3	0.065	0.065	0.065	0.065	0.069	0.07
L_b	2.1	2.1	2.1	2.1	2.1	2.1
$h_{\max}$	0.25	0.25	0.25	0.25	0.242	0.24
$h_{\min}$	0.069	0	0.05	0.088	0.087	0.089
L	0.4	0.36	0.4	0.3	0.3	0.32
R_f	0	0.055	0.03	0.03	0.03	0.01
α	77	77	79	79	80	78
k_{out}	83.1	72.0	54.8	56.4	53.9	45.9
k_{in}	47.4	42.9	37.1	36.3	31.8	29.9

Note: Values are in meters at the prototype scale.

explained as follows by the two phenomena as illustrated in Fig. 13:

- For the gate throttle, the streamlines are only contracted and expanded once when they flow through the gate opening. Furthermore, there is only one large recirculation cell in the lower chamber.
- For the grid throttle, the streamlines are contracted and expanded when they flow through each opening. There is a wake downstream of every single bar, with the separation zone and free shear layers producing losses. In this case, the head losses are distributed along the throttle height.

Comparison with Previous Studies

Fig. 14 shows the results of former studies performed at LCH-EPFL and at the Versuchsanstalt für Wasserbau, Hydrologie une Glaziologie (VAW) of Eidgenössische Technische Hochschule Zürich (ETHZ) (Billeter et al. 1996; De Cesare et al. 2015). Head-loss coefficients are given as a function of the dimensionless parameter characterizing the opening area, w_1/s (with w_1 as defined in Fig. 10 and s as the length between the two bars). Furthermore, the head-loss coefficient may be computed according to Eq. (2)

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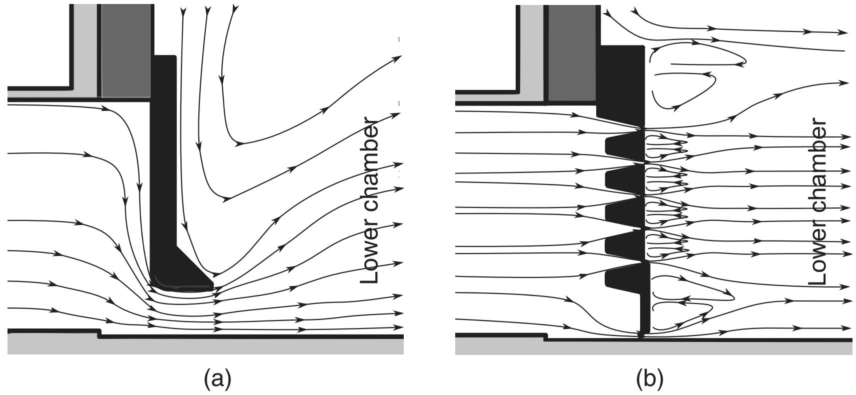

Fig. 13. Schematic view of streamlines: (a) through the gate throttle; (b) through the grid throttle

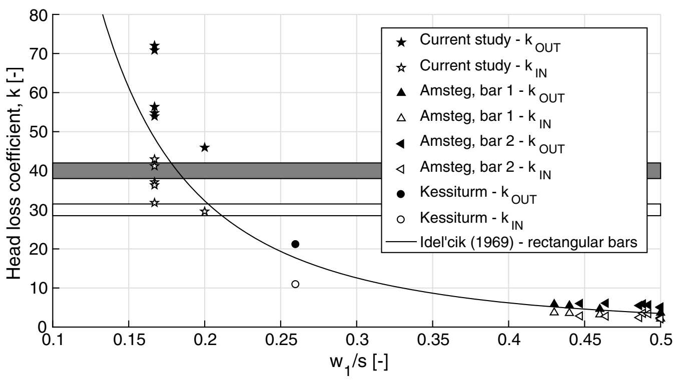

Fig. 14. Comparison of head-loss coefficients defined in the current study with previous studies and formulas given by Idel'cik (1969); the shaded bar is the ±10% zone for k_{OUT}, and the unshaded bar is for k_{IN}

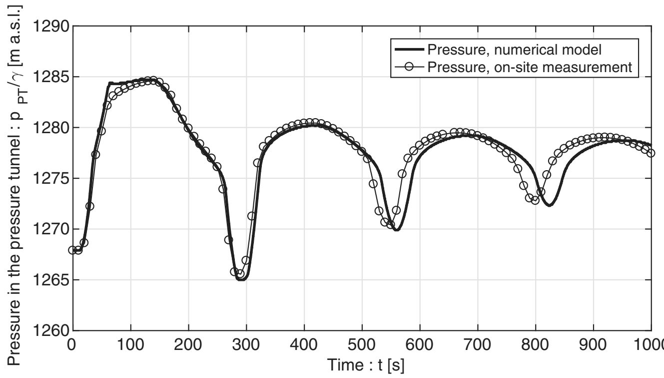

Fig. 15. Comparison between the numerical result and in situ measurements; prototype measurements for Case A with an upper reservoir at 1,277.6 m a.s.l. (April 16, 2015)

(Idel'cik 1969), which yields a good estimate of an intermediate head-loss coefficient (i.e., the average head loss between the coefficients in both directions of flow)

$$k = \beta_2 \sin\theta \cdot \left[\left(0.5 + \tau\sqrt{1 - \frac{w_1}{s}}\right)\left(1 - \frac{w_1}{s}\right) + \left(1 - \frac{w_1}{s}\right)^2\right]\left(\frac{s}{w_1}\right)^2 \tag{2}$$

where β_2 characterizes the shape of the beams (for a rectangular beam, $\beta_2 = 1.0$); θ = angle between the conduit wall and the throttle ($\theta = 90°$); and τ = coefficient depending on the ratio between one opening and the throttle thickness.

According to Fig. 14, the following observations can be made:

- The head-loss coefficient for water flowing out of the surge tank is always higher than for water flowing into the surge tank. This observation is consistent with the results of the performed numerical simulations (Fig. 7), in which the main issue is the dewatering of the surge tank.
- The average asymmetry ratio $\lambda = k_{\mathrm{IN}}/k_{\mathrm{OUT}}$ for all cases is relatively constant, approximately 0.5–0.6 (0.64 for Amsteg bar 1 and 0.50 for Amsteg bar 2; 0.52 for Kessiturm; and 0.62 for the current study). These values are consistent with those found for orifices (Adam et al. 2016a, c).
- The ratio w_1/s seems to be the most influential geometrical parameter for rack throttles. The measured data agree well with the computation from Eq. (2) over a wide range of w_1/s values.

On-Site Measurements with Installed Throttle

To ensure that the numerical and physical model represents the appropriate throttle behaviors, measurements have been performed with a prototype after the placement of the grid throttle. Strong agreement between numerical results and the in situ measurements for the final design of the throttle was obtained, as shown in Fig. 15. The measurements were performed several months after the installation of the new throttle, and the corresponding head-loss coefficient is given from the numerical model.

Conclusions

The Gondo hydropower plant exploits a head of 470 m. The renewal of a turbine with a higher capacity induces an additional increase in discharge in the waterway system. During the 1980s, the first increase in power capacity did not require adaptation of the existing surge tank. However, this renewal of the third turbines requires a throttle to be installed at the bottom of the surge tank.

Numerical simulations allow the analysis of the whole system, including the waterways and electromechanical equipment. The numerical model has to be calibrated with in situ measurements. With the 1D numerical model, the optimized head losses at the inlet of the surge tank for the inflow and outflow can be defined to obtain optimized transient behavior of the power plant. Moreover, the design of the throttle geometry for achieving the desired head losses depends on the existing geometry of the junction between the pressure tunnel and the surge tank. For the Gondo power plant, the complex geometry of this junction did not allow the use of an analytical approach for the throttle design because of lack of accuracy. Therefore, physical model testing was conducted to define the optimum throttle geometry.

The experimental model used for the steady-state tests performed many iterations to identify the best design of throttle geometry. Simple gate throttles do not produce sufficient head losses because of flow expansion in only one direction. Thus, a grid throttle with horizontal beams was chosen even though it will not be adjustable in the future. In situ measurements were performed to assess the throttle behavior of the prototype as predicted by numerical and physical modeling and the performance with regard to the steady and transient head losses.

Finally, this case study reveals all of the issues that engineers must address during the refurbishment process of a high-head power plant. The design of a throttle requires a hybrid modeling approach that uses an iteration between simplified numerical simulations of the whole power plant and waterway and the physical model to perform steady-state experiments for identifying the appropriate head losses for all flow directions.

Notation

The following symbols are used in this paper:

A = surge tank in physical-scale model (Fig. 4);
B = pressure shaft in physical-scale model (Fig. 4);
C = pressure tunnel in physical-scale model (Fig. 4);
g = gravitational acceleration;
h_1 = higher height of beam section (Fig. 10);
h_2 = lower height of beam section (Fig. 10);
k = head-loss coefficient;
k_{IN} = head-loss coefficient for water flowing into surge tank;
k_{OUT} = head-loss coefficient for water flowing out of surge tank;
L = length of beam section (Fig. 10);
L_b = length of beam;
R = Reynolds number;
R_f = radius fillet in beam section (Fig. 10);
s = length between median planes of two throttle beams (Fig. 10);
Si = sections where pressure is recorded in physical-scale model ($i = 1 \ldots 6$);
v = flow velocity;
w_1 = smaller space between two throttle beams (Fig. 10);
w_2 = larger space between two throttle beams (Fig. 10);
α = angle of beam section (Fig. 10);
β_2 = coefficient characterizing shape of throttle beam [Eq. (2)];
ΔH = head losses;
θ = angle between throttle and pipe wall;
λ = asymmetry factor, which is ratio between head-loss coefficient for water flowing in and out of surge tank; and
τ = coefficient depending on opening ratio of throttle w_1/s.

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