Innertkirchen compensation basin outlets – Flap gate combined with small stilling basin

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Introduction

In the context of an update of their hydropower plants, the Hydroelectric Company KWO plans an adaption of their powerhouses Innertkirchen 1 and 2. One aim of the project is, among many others, an optimized restitution regime of the turbined water to the Aare River. Therefore, a compensation basin is planned to reduce the currently pronounced hydro-peaking. The basin is situated downstream of the *Hasliaare* and the *Gadmerwasser* confluence, next to the outlets of the two powerhouses. The spatial situation and the geology implicate strong restrictions regarding the volume of the compensation basin, allowing for a storage capacity of approximately 20'000 m^3. This volume is more than doubled by a voluminous tailrace tunnel between the turbines and the basin. The regulation of the basin is assured by a flap gate and a radial gate. The basin intents to limit hydro peaking, and thereby ameliorates the ecology of the Aare River between the basin and Lake of Brienz. It will facilitate to access the *Gadmerwasser* for the fishes, which is known as excellent spawning ground.

The efficiency and reliability of the basin regulation structures is a key item for the operation of the two powerhouses. The basin outlet gates were thus model-tested at the *Laboratory of Hydraulic Constructions* of EPFL, Switzerland, to assure an sufficient discharge capacity even for elevated water levels in the Aare River, to avoid unwanted erosion on the area, to avoid sedimentation of the structure by the bed load of the Aare River, and to generated acceptable conditions for fish passage along the Aare River. The modeled hydraulic perimeter covered the basin outlet structure, a length of some 250 m of the Aare River, as well as a part of the compensation basin. The model is set-up with a geometrical scale factor of 1:40 and operated under the similitude of Froude. In the experiments, the efficiency of the basin regulation gates is tested. Additionally, water levels, flow velocities and the erosion of the river bed are measured. The paper describes this particular case study with some optimization steps; finally leading to a solution with satisfies the principle requests. Given the importance of the ecological aspects and the Swiss legislation, the present compensation basin can provide ideas and concepts for similar structures to foresee in the near future.

1. Background

In the context of an update of their hydropower plants, the Hydroelectric Company Kraftwerke Oberhasli (KWO) plans an adaption of their powerhouses Innertkirchen 1 and 2 in the Bernese Alps, Switzerland. One aim of the project is, among many others, an optimized restitution regime of the turbined water to the Aare River. Therefore, a compensation basin is planned to reduce the currently pronounced hydro-peaking.

The basin (Fig. 1) is situated downstream of the Hasliaare and the Gadmerwasser confluence, next to the outlets of the two powerhouses. The spatial situation and the geology implicate strong restrictions regarding the volume of the compensation basin, allowing for a storage capacity of approximately 20'000 m^3. This volume is more than doubled by a voluminous tailrace tunnel between the turbines and the basin. The regulation of the basin is assured by a flap gate and a radial gate. The basin intents to limit hydro-peaking, and thereby ameliorates the ecology of the Aare River between the basin and Lake of Brienz. It will facilitate to access the Gadmerwasser for the fishes, which is known as excellent spawning ground.

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The paper describes this particular case study, focusing on the stilling basin. The latter was design under horizontal spatial restrictions implemented by Aare River and its confluence Gadmerwasser (flood passage), the train line of MIB and the steep topography surrounding the latter. The vertical space for the plunge pool was given by the water levels defined by the River and the turbines, and by the geotechnical conditions of the ground limiting the excavation depth. The soil consists of permeable alluvium with an elevated groundwater table, requiring under-water concrete and a complex excavation pit. These restrictions limited the dimensions of the stilling basins, so that an optimal hydraulic operation was not achieved. From a hydraulic point of view, the stilling basins are too small, so that a part of the flow energy is dissipated in a second hydraulic jump downstream of the end sill, on the riprap protecting the locally the river bed.

Figure 1: Animation of the future compensation basin (KWO)

2. Physical model

The physical model (Fig. 2) set up at the *Laboratory of Hydraulic Constructions* (LCH) of EPFL reproduced a section of about 270 m of the Aare River, the downstream portion of the compensation basin and its two control structures (sector gate and flap gate). The model was built with a geometrical scale factor of 1:40 and operated under the similitude of Froude. Beside the spur-dikes in the Aare River, a moving bed is provided to study potential erosion and deposition areas. In this paper, only some hydraulic features of the flap gate stilling basin are discussed.

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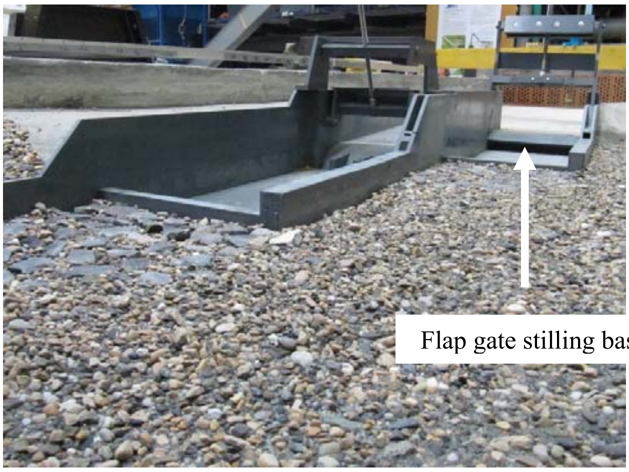


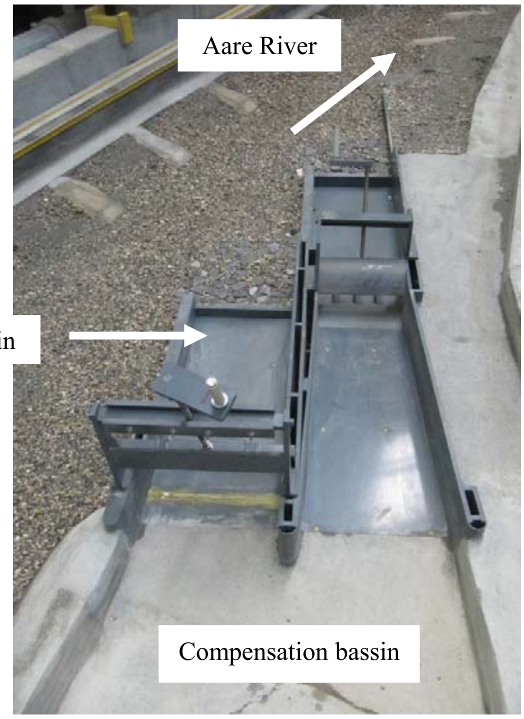


Figure 2: Physical model of the compensation basin outlet, (top) seen from the river Aare, (right) seen from the compensation basin (both G2).

3. Geometry of stilling basin

As previously mentioned, the dimensions of the flap gate stilling basin are strongly influenced by its location and by the geology of the ground. One of the main challenges of the basin is to design it in order to guarantee satisfying energy dissipation despite of its restrictions in length and depth. In parallel, discharges up to 120 m^3/s are spilled across the basin under extreme conditions, under typical summer discharge of the Aare River is between 5 to 10 m^3/s. This means that the flow depth in the Aare is small and thus critical for a dissipation of the residual energy leaving the stilling basin. As a consequence, this surplus of energy to dissipate will generate a second hydraulic jump located on the bed of the Aare River.

3.1 Optimal basin shape

The "optimal" shape of a stilling basin assures a complete dissipation of the flow energy. The downstream conditions of the river and a sufficiently high end-sill height (*vice versa*: a sufficiently low bottom of the stilling basin) generate then an adequate flow depth to keep the hydraulic jump in the basin. The herein considered basin width for the "optimal" shape is 12.5 m (given from the local space conditions). A rough estimation of the stilling basin length and depth under the maximum discharge indicates the minimally required dimensions as shown in Figure 3.

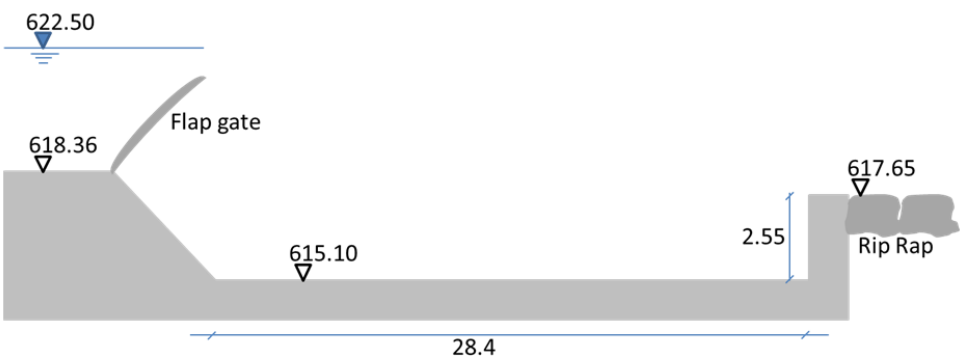


Figure 3: "Optimal" stilling basin for complete energy dissipation

3.2 Reduced basin length (G1a and G1b)

As stated above, various reasons hinder the construction of the basin with the required length of 28.4 m and a depth of 2.55 m at the Innertkirchen location respectively would generate excessive cost. Therefore, a smaller stilling basin (Figure 4) was foreseen by the designer and model-tested to evaluate its performance.

The smaller basin had a reduced length of only 18.75 m and a width of 11.2 m. The geometry of this basin is shown in Figure 4 and Figure 5, and will be designated with the abbreviation G1. To augment the conjugated flow depth, and to enhance thereby the energy dissipation in the basin, a central baffle was installed at the end sill of the stilling basin. It was tested with two sub-configurations: (G1a) with a streamwise left sidewall crest at 618.40 m a.s.l. including two baffles (Figure 5a), and (G1b) without lateral baffles but with a higher sidewall crest level at 618.65 m a.s.l. (Figure 5b).

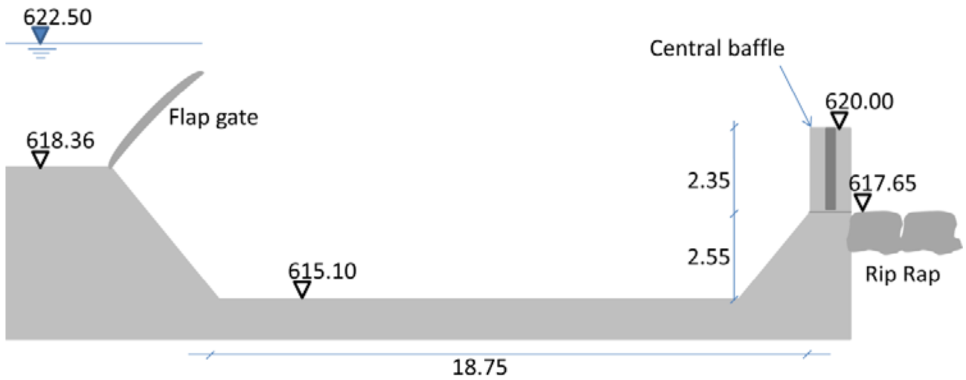


Figure 4: Reduced size stilling basin (G1)

(a)

(b)

Figure 5 Physical model of G1, (a) with lateral baffles, and (b) without

3.2 Elevated basin bottom (G2)

Continuing field investigations indicated that the reduced stilling basin of G1 was still too deep to guarantee good construction conditions. To reduce the construction costs, a more economical solution had to be developed (Figure 7 and Figure 6). The length was slightly increased but the depth was reduced to 615.50 m a.s.l.. The rip rap, used to protect the river bed at the downstream of the basin end sill was lowered by some 0.5 m, as the model tests indicated the efficiency of this measure to fix the hydraulic jump on the river bed near the sill, and particularly on the riprap (Figure 8). The performance of this configuration was evaluated by tests using the adapted physical model, as shown in Figure 7. The geometry shown in Figure 7 and Figure 6 will be designated by the abbreviation G2 (geometry 2) for the following discussions and analysis. All baffles were removed, as they increased the water level in the stilling basin. This is a priori positive as it augments the energy dissipation in the basin. Nevertheless, the hard drop between the basin and the Flow on the Aare River bed also increases there, causing a more pronounced second hydraulic jump on the river bed.

Besides, the entire structure was slightly rotated, and the spur dykes were removed. The concentration of the flow in the river bed for discharges with weak sediment transport is achieved by the outer sidewalls of the basins. These are overflown during floods, providing a sufficient flow section to safely convey extraordinary Aare discharges.

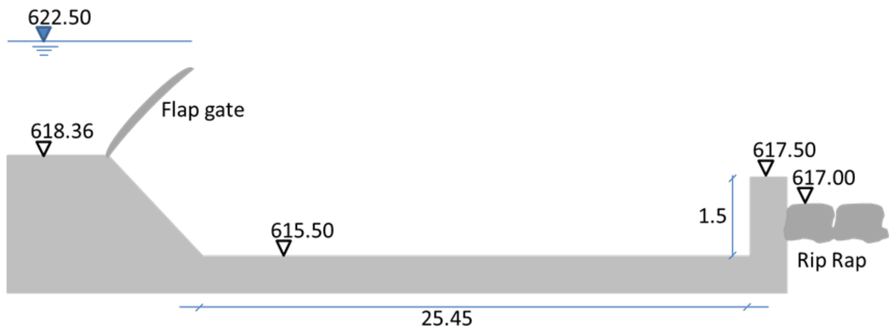


Figure 6: Ameliorated stilling basin size

Figure 7: Physical model of G2

4. Model tests

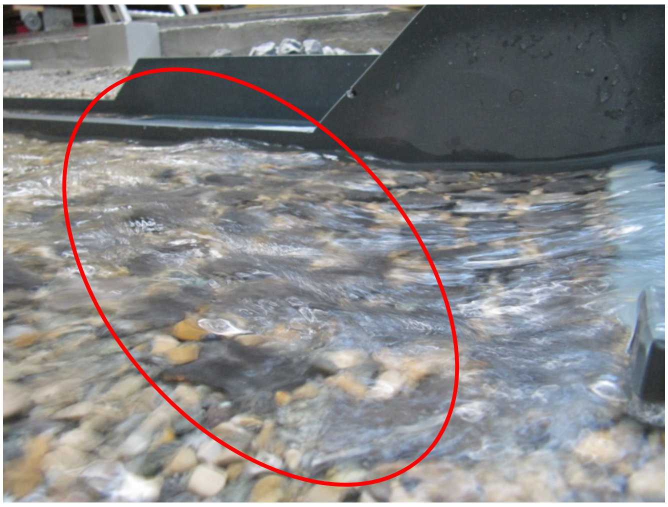
Given that the boundary conditions make it impossible to provide an economically perfect energy dissipation within the stilling basin, exclusively the “reduced” size configurations have been tested (G1 and G2). Different discharge scenarios were taken into account. The tested discharges for the different geometries are given in Table 1.

Table 1 Overview of the tested discharge scenarios

Aare River discharge Q_A [m^3/s]	Flap gate discharge Q_B [m^3/s]	Water level in compensation basin N_B [m a.s.l.]
Geometry 1a (G1a)		
5	40	622.5
80	80	622.5
80	120	622.5
Geometry 1b (G1b)		
80	120	622.5
Geometry 2 (G2)		
10	20	622.5
5	40	622.5
5	80	622.5
5	100	622.5

The physical model indicated that the local limitations (leading to the tested basins as shown in Figure 4 and Figure 6) do not allow for a complete dissipation of the flow energy. For both "reduced" size stilling basins, a hydraulic jump *outside* of the stilling basin was observed, being necessary to dissipate the residual energy. As a consequence, the second energy dissipation process outside of the basin (second hydraulic jump) was included in the design scenario. *The dissipation of the energy generated by the outflow of the compensation basin is thus mainly dissipated in the stilling basin, but also downstream of it on a well defend area protected by riprap.*

Therefore, model tests were conducted to avoid excessive erosion on the riprap, caused by the dissipation of the remaining energy downstream the stilling basin. Figure 8 gives an example of the influence of a lowered riprap. Lowering the riprap after the basin end sill generates locally a higher flow depth, fixing a compact and stable hydraulic jump. This means that lowering the riprap zone creates a hydraulically active flow depth downstream the stilling basin, and not further down in the Aare River. Thus, the prediction of the position of the hydraulic jump is more reliable for a lowered riprap. As the riprap protection can be shorter, costs and uncontrolled energy dissipation, due to less stable hydraulic jumps, are avoided.

(a)


(b) 

Figure 8: Hydraulic jump downstream of the the stilling basin end sill due to insufficient energy dissipation in the stilling basin. Observed hydraulic jump for an outlet discharge of Q_B=60 m³/s and a river discharge of Q_A=5 m³/s, for (a) a riprap located at the same level as the end sill, and (b) a 0.5 m lowered riprap elevation

As the lower riprap fixes the position of the hydraulic jump, exclusively this configuration is considered for the following discussion.

A quantification of the dissipated energy, inside and downstream of the stilling basin (resulting in a description of the relative efficiency of the stilling basin), can be elaborated based on the flow depth measurements. Figure 9 shows as an example the water levels in the stilling basin for G2.

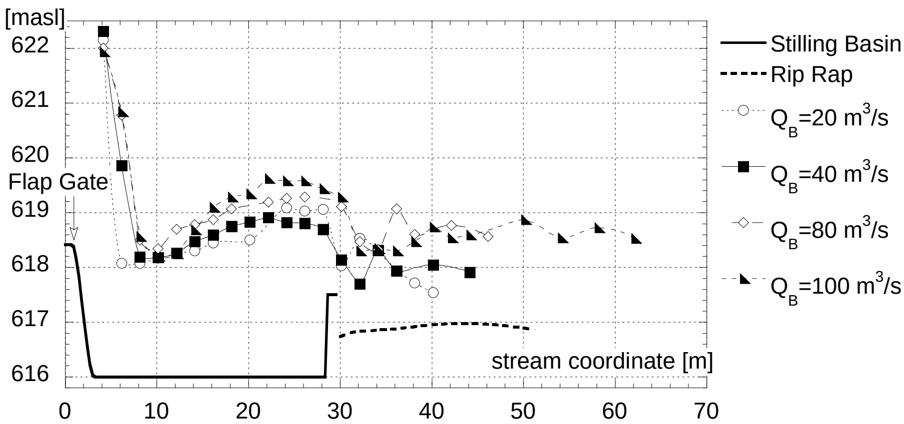


Figure 9 Comparison of water levels in the stilling basin G2 for different discharges on the flap gate

Knowing the initial potential energy (water level in the compensation basin denoted as H_B [m a.s.l.]), the energy dissipation in and downstream of the stilling basin can be estimated as follows.

With B [m] as width of the basin and Q_B [m³/s] as discharge across the flap gate, the specific discharge is given as $q_B=Q_B/B$. The critical flow depth h_c [m] is given by $h_c=(qB^2/g)^{1/3}$, and occurs on the end sill, as confirmed by measurements (at the stream coordinate of 30 m in Figure 9). Based on the latter, the absolute head H_S [m a.s.l.] at the end sill can be estimated as (assuming a negligible flow velocity in the basin) $H_S=N+1.5h_c$, with N as elevation of the end sill crest. As the water level in the compensation basin gives the initial energy head H_B, the **dissipated energy in the stilling** basin is dH_S [m] as $dH_S=H_B-H_S$.

The **energy dissipated downstream of the stilling basin** (in the second hydraulic jump) is given by the head difference of the end sill crest and on the Aare riverbed as dH_D [m] with $dH_D=H_S-H_A$. The flow head in the Aare River at a streamwise coordinate of 40 m is computed based on the local flow depths. The cinematic head is locally derived as $V=q_B/h$, so that the Aare River flow head results as $H_A=h+V^2/2g$.

Thus the **relative energy dissipation** ratio is finally defined as efficiency [%] of the stilling basin, in terms of E=dH_S/dH_D. The efficiency of the stilling basins was calculated for the geometries G1a, G1b, and G2, as presented above. An analysis allows concluding on the amount of energy that is dissipated inside and downstream of the stilling basin. It was shown that (despite of the restricted depth of the basin) some 75 to 85% of the total energy is dissipated in the basin (Figure 10). The remaining energy of 15 to 25% has to be dissipated in the hydraulic jump downstream of the stilling basin on the riprap zone. Consequently, the riprap must to be sufficiently resistant to support the flow related to the dissipation. It should be reinforce with a concrete slab.

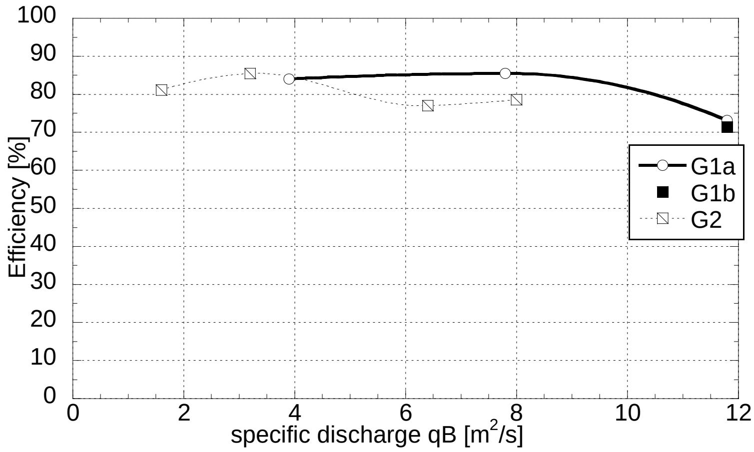


Figure 10 Efficiency [%] of the energy basin dissipation for the three tested stilling basins versus the specific flap gate discharge

5. Conclusions

The projected compensation basin, that will be used to store the turbined water in order to guarantee a controlled restitution of the water by the outlets to the Aare-River, is subjected to numerous constraints. Restricted space and disadvantageous geological conditions are strongly limiting the available space for the construction. Especially the stilling basins are concerned, due to their lower bottom level. It is impossible to construct stilling basins with the theoretically necessary dimensions. Consequently, the basins will be relatively small. Thus, only partial energy dissipation can be guaranteed.

Physical model tests on the flap gate could show that the river bed elevation downstream of the end sill had to be lowered in order to fix the consequent hydraulic jump near the sill. Furthermore, the model showed that the riprap is to artificially stabilize to avoid erosion, and thus its destabilisation.

Finally, the tested configuration indicated that some 80% of the total energy was dissipated in the stilling basin, and some 20% in the hydraulic jump on the riprap.

The Authors

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