Hydraulic model research of spillways and stilling basins on the reach of the lower Sava river in Slovenia

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1. Summary

The construction of the chain of hydro power plants (HPP) on the reach of the lower Sava River (figure 1) started in 1993. Although the initial phase of the HPP chain design process on the lower Sava suggested the construction of the single plan HPP chain, it has been proven later on, that each HPP required its very own design. Since the initial plan did not foresee the asymmetric operation of the spillways, the flushing of debris has given rise to important loads of the stilling basins and of the downstream riverbed reach. As a consequence major erosion problems occurred, which we wish to prevent at the current project of the HPP Brežice.

This article presents the results of the physical model research of the spillway shape and the dimensions of the stilling basin elements of the HPP Brežice. The research reveals that the initial type shape of the spillway on the HPP mentioned above is going to be realized in its third version, as the Creager type of spillway was applied on the first two HPP, while on the next two HPP, the spillway was carried out with improved discharge capacity. The first dam of the HPP chain, experiences problems of the hydraulic jump stability in the stilling basin, or, as the case may be, the problems of excessive loads on the river banks on the downstream riverbed reach of the Sava river. In order to avoid these difficulties, the research of several different spillway shapes with steeper spillway face has been conducted in the course of the design engineering of the HPP Brežice, since by applying this measure we can get a longer and more efficient stilling basin with the same dimensions of the spillway, dissipating a larger part of the kinetic energy of the water flow. Pressures along the spillway face were measured for different operating cases and different spillway shapes. The latter are essential for the decision on the adequacy of the spillway shape, since the design engineer has given only the upper permissible level of subpressures $p_{min} \geq -2.0$ m. The objective of the research was also the optimization of the number of spillways, which could be reduced, in case of the favorable result, from 5 to 4. Various variants of sizes and positions of the baffle piers in the stilling basin have been studied for the selected shape of the spillway. At the end of this research phase, the discharge capacity of the free overflow has been defined for the selected spillway shape.

2. Introduction

The HPP chain along the lower reach of the river Sava in Slovenia includes six low-head run-of-river power stations. Each of them consists of a dam with five spillways, 15 m wide, and of a turbine structure with three generator sets. The first two power plants were built with bulb turbines, while the rest of the chain is equipped with the Kaplan turbines. The installed power is P_i = 43 MW at the operating head of 10 m and the installed turbine discharge of Q_i = 500 m^3/s.

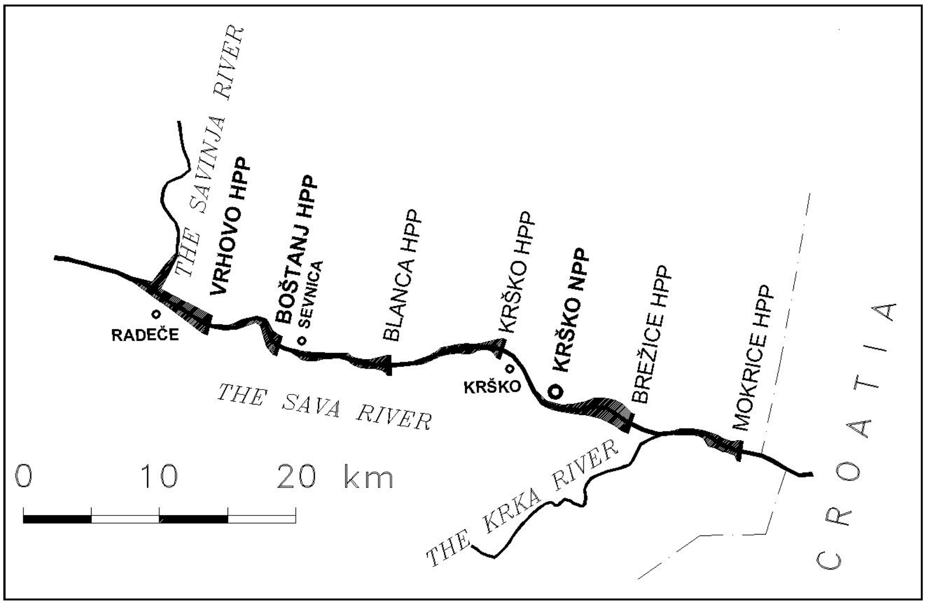

Figure 1: Lower Sava river basin. (Brenčič, 2008)

Although the initial phase of the design engineering of the HPP chain on the lower Sava River foresaw a construction of the single type hydro power plants, it has been established later on, primarily due to the erosion problems behind the stilling basins, that the design engineering of each of them required a different, individual approach. Thus, the new spillway shapes have been studied on the physical model of the HPP Brežice, with the goal to extend the stilling basin within the extent of the whole spillway dimensions.

3. Spillway shape

Shorter shapes of the spillway have been studied in order to provide more effective stilling basins (higher energy dissipation). The spillway crest elevation, the beginning point of the spillway, and the downstream end of the spillway remained unchanged. The spillway face shall meet the criterion of the minimum, still permissible pressures. The limit, agreed with the design engineer, was $p_{min} \geq -2.0$ m. Pressures were measured along the 1:25 physical model of the spillway, inserted into the glass measuring flume. The research was conducted in the Institute for Hydraulic Research.

Figure 2 demonstrates individual variants of spillways. The initial design shape of the spillway has a markedly gently sloping spillway crest (slope 1:2). To achieve stilling basin efficiency it has been suggested, that the stilling basin base shall be deepened for 1.10 m in regard to the design variant.

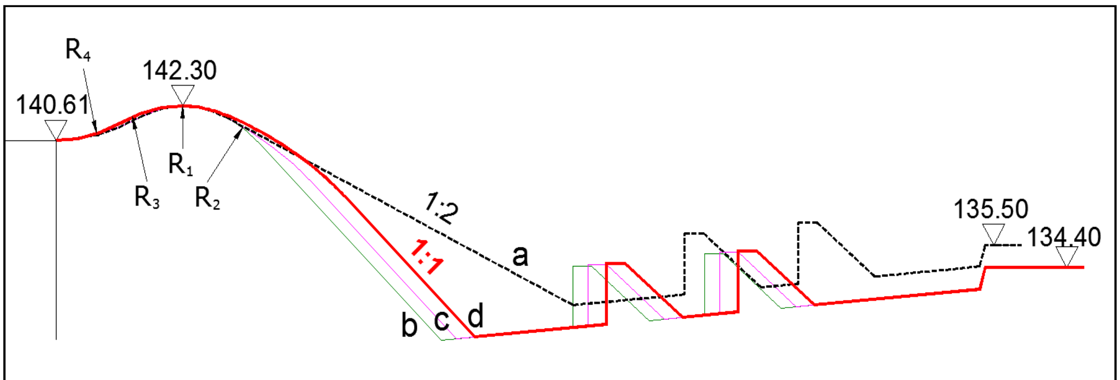

Figure 2: Variants of the spillways on the HPP Brežice. The variant a (design variant), variant b, variant c, variant d (final variant).

The first studied variant b of the spillway differs from the initial one in the downstream part from the radius R_1 = 5.0 m on the top of the spillway (equal in both cases), followed by the transition into the radius R_2 = 7.0 m, and the latter followed by the downstream face in the inclination 1:1. With this shape of the spillway and with the simultaneous lowering of the stilling basin base for 1.10 m, the initial stilling basin extends for 7.02 m.

The pressures along the spillway were measured for the case of the free flow over the spillway irrespective of any influence of the tail water level. Results for the selected discharge are shown in figure 3. The lowest pressure values were p = -5.54 m, and they significantly exceeded the limit of p_{min} = -2.0 m defined by the design engineer. Therefore a different shape of a spillway was suggested.

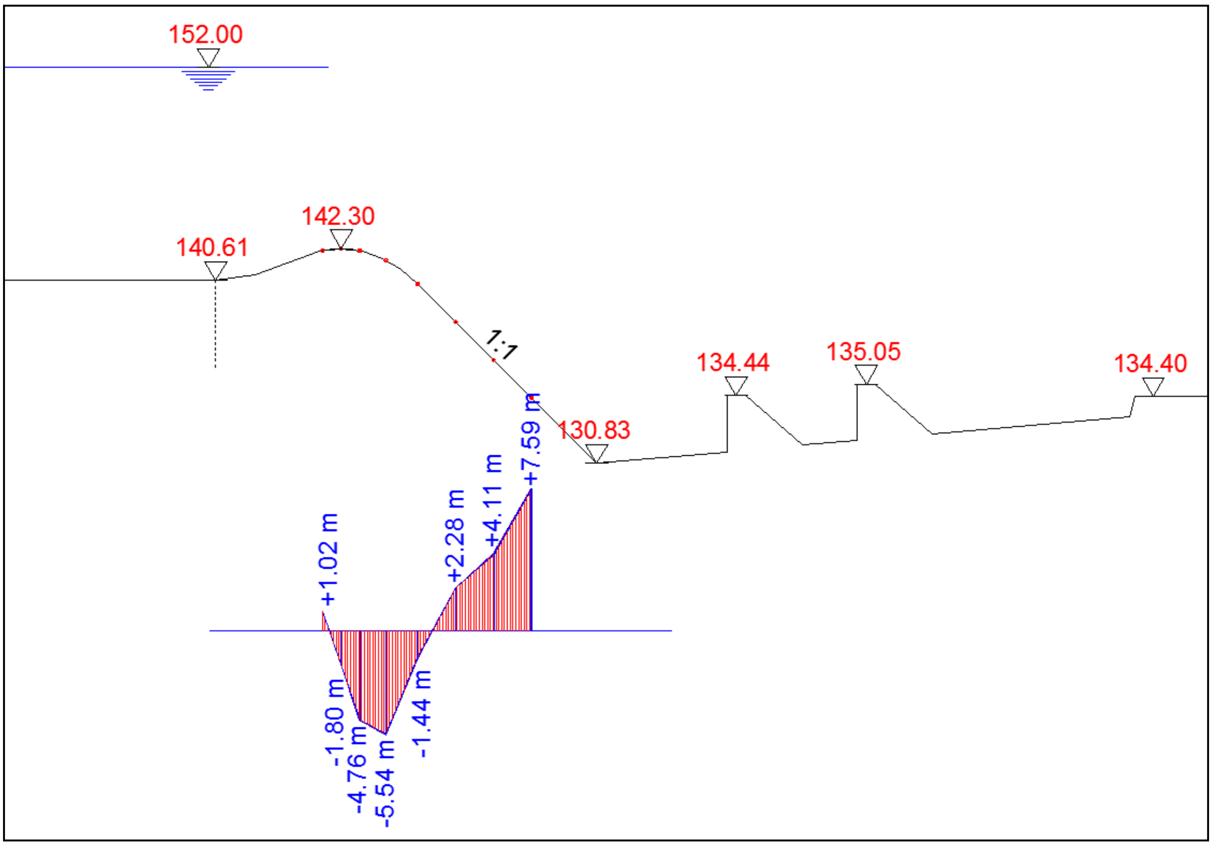

Figure 3: Pressures, measured at free flow case for the first studied variant b of the spillway of the HPP Brežice.

In comparison to the variant b, variant c employs a different radius R_1. In this variant the spillway continues with the Creager shape. By applying this spillway shape the initial stilling basin (variant a) extends for 6.20 m (compared to 7.02 m of the variant b). The lowest measured pressures were p = -3.29 m, which is better than in the variant b, but still exceeding the p_{min} = -2.0 m limit.

The third studied variant (d) of the spillway equals the Creager spillway downstream from the crest (that is in accordance with the initial type project of the HPP), while the radius upstream from the crest is R_3 = 7.0 m, and further upstream the contra-radius is R_4 = 7.2 m. By applying this spillway shape the initial stilling basin extends for 5.24 m.

In all examined cases of the free overflow the lowest pressure values appeared 1.0 m downstream from the crest. The lowest value was measured in the case of the discharge Q_{100} through 3 spillways without the effect of the tail water level, and amounted to p = -1,15 m. In the cases of the flow under the gate, the lowest pressure values were measured 2.5 m downstream from the spillway crest. As shown in figure 4, for the case of the opening of the gate for Y = 3.0 m this value amounted to p = -1.13 m. In these cases the measured pressures were within the specified limits, and therefore this shape was suggested as the most suitable.

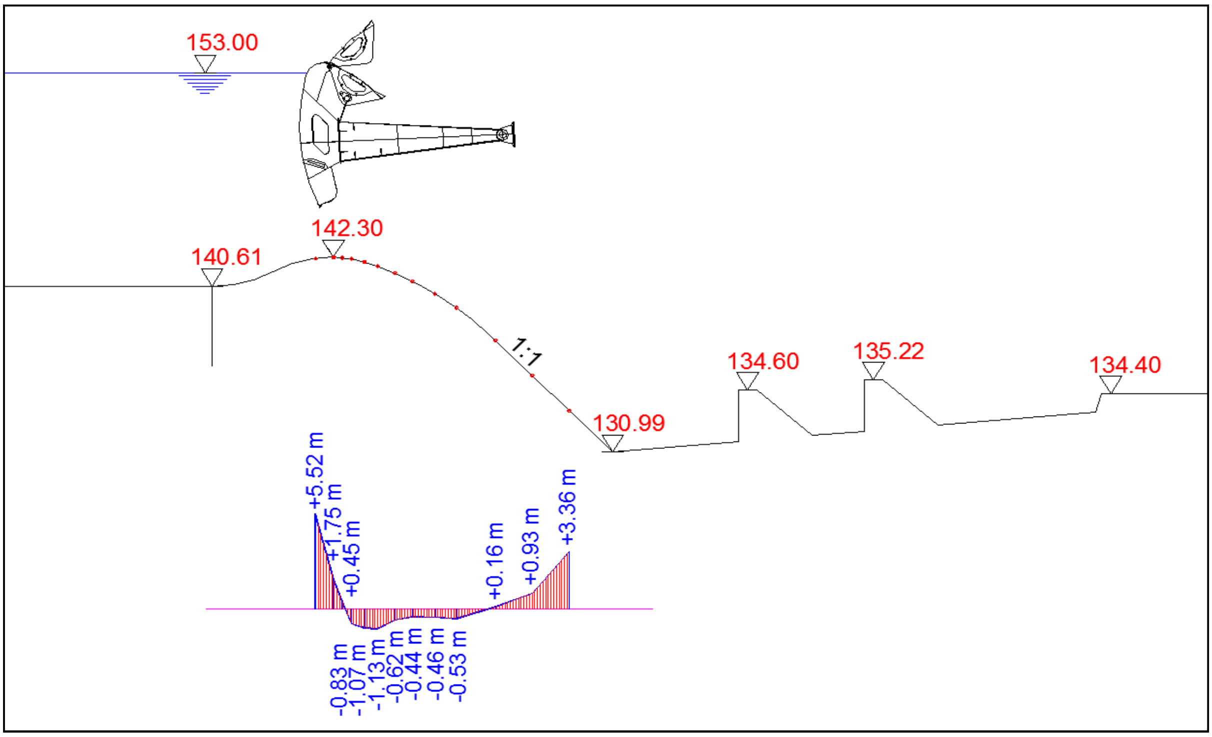

Figure 4: The measured pressures at the flow under the gate for the proposed final variant of the spillway shape of the HPP Brežice. Gate opening Y=3.0 m, case without tail water.

The streamlines along the spillway were observed, too, for all the cases of the selected variant of the spillway. It has been established that the flow at the spillway face is stable, i.e., that there are no occurrences of detachment of the water flow from the spillway face. Minor detachment of the streamlines from the bottom was observed on the downstream part of the spillway only in cases of the high tail water level. Flow conditions along the spillway for free overflow case are shown in figure 5.

Figure 5a: The streamlines along the spillway.

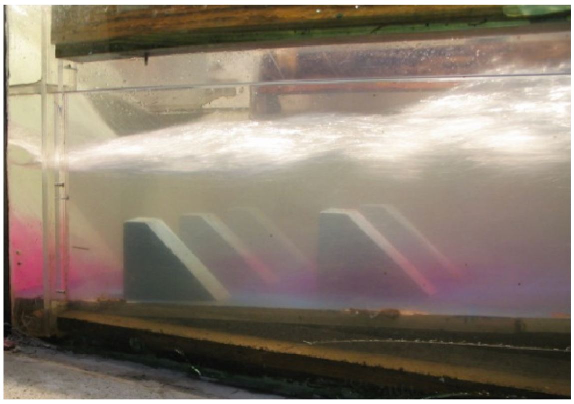

Figure 5b: The streamlines in the stilling basin.

The figure 5a demonstrates streamlines for the final variant of the spillway with the discharge Q_{100} = 3750 m^3/s through 3 spillways. It is evident that injected tracer does not detach from the base along the spillway. Figure 5b displays streamlines in the stilling basin for the same case.

4. Stage-discharge curve of spillways without the influence of the tailwater level

The discharge capacity for the selected shape of the spillway was determined for the case of free overflow without the influence of the tailwater level. Operation without the influence of the tailwater level takes place, when the ratio of the pressure heads of the tailwater (H') and the upper basin (H) is H'/H < 0.5, with heads H' and H measured from the spillway top to the water level. In such a case the effect of the submergence of the spillway can be expressed with a coefficient $\sigma = 1$.

The discharge capacity was measured in the 1:45 physical model of the HPP Brežice. The range of measured discharges covered practically all the values of the discharge, which could appear in the nature.

For the discharge Q over the transverse weir with the width B and the overflow depth H it applies generally:

$$Q = m \cdot \sigma \cdot B \cdot \sqrt{2 \cdot g} \cdot H^{3/2}$$

where m is a discharge coefficient of the weir. In the present study this coefficient was equal to:

$$m = a + b \cdot H + c \cdot H^2$$

with coefficients a, b and c, amounting to: a = 0.43331716, b = 0.003922573 and c = -0.00036066702.

The stage-discharge curve for a single spillway of the HPP Brežice is shown in figure 6, together with the stage-discharge curves of the existing hydro power plants on the lower Sava.

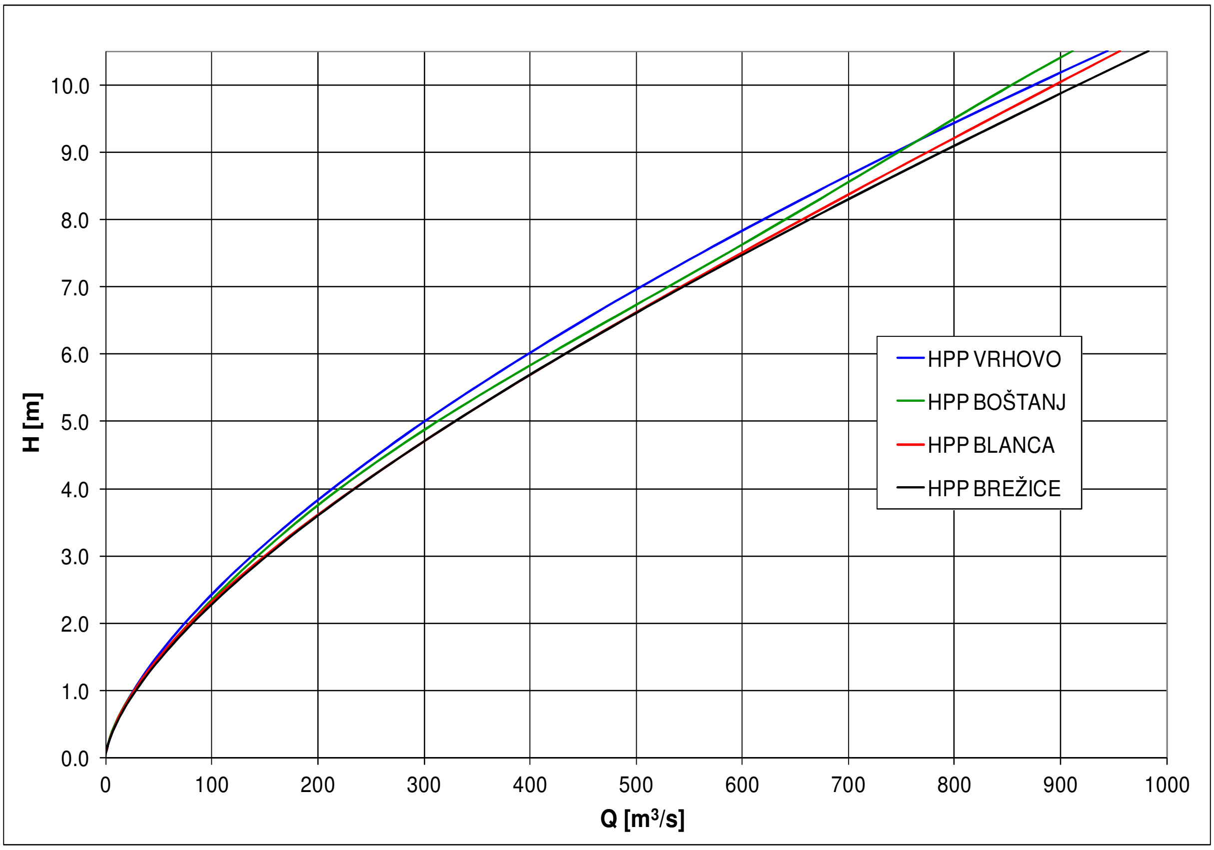

Figure 6: The stage-discharge curves of the hydro power stations on the lower Sava at the free overflowing, summarized from the preceding studies by the Institute for Hydraulic Research.

Figure 6 demonstrates that the new shape of the spillway (HPP Brežice) results in the 20 to 50 cm lower stage at higher discharge values in comparison to the spillways of the upstream hydro power stations.

5. Stilling basin efficiency

The stilling basin shall be dimensioned so that under any operating conditions the hydraulic jump within it remains stable. The shape of the stilling basin for the HPP Brežice is similar to the stilling basins of the upstream HPP, which were optimized with the physical hydraulic models. However due to the different local conditions the study of different shapes and positions of the baffle piers was performed within the research of the HPP Brežice again. The main focus was placed on the baffle pier shapes. Three baffle pier shapes were studied for the design shape of the spillway of the HPP Brežice. Results can be expressed as lines of stability, each of them defining the required tailwater level that provides stable hydraulic jump (figure 7). The discharge Q_{TW} in the downstream channel shall be, at a certain opening Y, above the boundary line, otherwise the hydraulic jump is not stable.

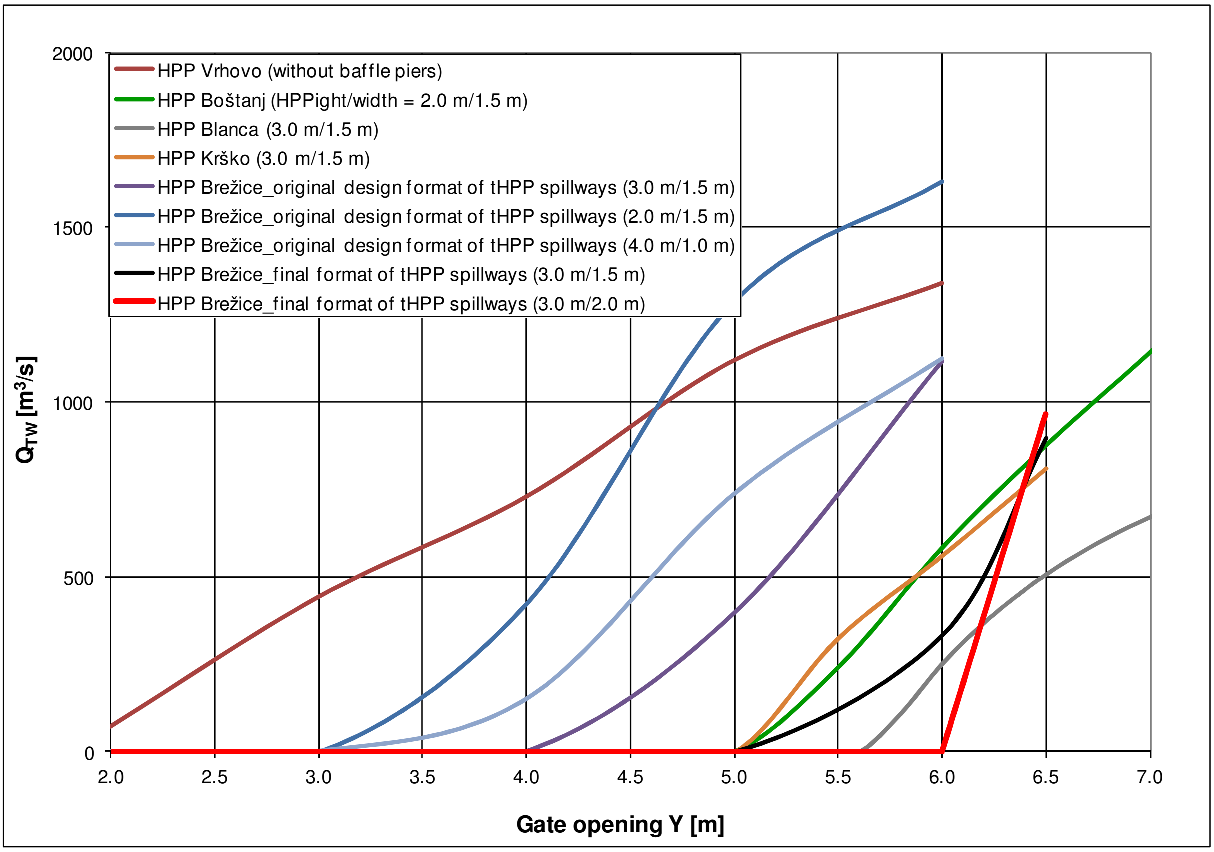

Figure 7: The stability boundary line of the stilling basin as a function of the opening of the segment gate Y, shown with regard to the discharge in the downstream channel (discharge Q_{TW} = 0 m^3/s corresponds to the water elevation of the downstream HPP).

Results demonstrate that the most optimal baffle piers are 3.0 m high, as already constructed on the upstream HPP Blanca and the HPP Krško. Figure 7 demonstrates that the hydraulic jump on the HPP Brežice at the Y = 6.0 m opening of the gate and with the incorporated baffle piers, 3.0 m high and 1.5 m wide, is stable already at the tailwater level, which corresponds to the discharge Q_{TW} = 1120 m^3/s. Discharge for the same case of operation with the 1.0 m lower baffle piers is Q_{TW} = 1630 m^3/s.

Two widths of the baffle piers have been examined for the final shape of the spillway: In figure 7 we can see that the differences between the curves for the baffle piers with the widths of 1.5 m and 2.0 m are insignificant, therefore the proposed baffle piers were 3.0 m high and 1.5 m wide (as at the HPP Blanca and HPP Krško). It is also evident from figure 7, that from the point of the hydraulic jump stability, the final shape of the spillway is much better than the originally designed one. Hydraulic jump is stable at the tailwater level corresponding to the discharge of Q_{TW} = 1120 m^3/s, at the Y = 6.0 m opening, and with the 3.0 m high and 1.5 m wide baffle piers incorporated into the design spillway. For the same case of the operation and the same baffle pier shapes in the final shape of the spillway, this discharge is only Q_{TW} = 330 m^3/s.

6. Conclusions

Variants of spillways of the HPP Brežice were studied in the physical hydraulic models in the scale 1:45 and 1:25. The new shapes of the spillway were studied for the reason of the difficulties, observed in the stilling basins, and the related stabilities of the downstream channel banks on the site (i.e., on the existing hydro power plants), which were proven also in the physical model of the HPP Brežice. The changes of the spillway shapes were developed in the direction of the steeper spillway face, which resulted in extended stilling basin lengths without changing the original extent of the spillway.

As a result of optimization, the stilling basin was lengthened for 5.24 m, and it also results in better discharge capacity than the design variant. In case of conveying Q_{100} through 3 spillways, which is the most critical operating case for HPP Brežice, the decrease of the upper basin water elevation between the basic spillway shapes (incorporated in the HPP Blanca and the HPP Krško) and the proposed spillway shape of the HPP Brežice is 0.23 m.

The present study of various shapes and positions of the baffle piers was performed in the physical model. It has been established that the most optimal baffle piers in the stilling basin of the HPP Brežice were 3.0 m high and 1.5 m wide. Change of the spillway shape has significantly enhanced the efficiency of the spillway behavior in the light of the hydraulic jump stability in the stilling basin.

7. Literature

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The Authors

Martin Bombac was born in Ljubljana, Slovenia, in 1980. He graduated in 2005 at the Hydraulics Division of the Faculty of Civil and Geodetic Engineering of the University of Ljubljana with the graduation project Hydraulic Optimization of the Intake Part of the Run of-river Power Plants. He started working as a researcher in the hydraulic laboratory of the Institute for Hydraulic Research in 2005, where he is mostly engaged in combining the mathematical and physical hydraulic modeling. During his postgraduate studies he is examining different kinds of turbulence models, some of which will be built in the 2D mathematical model PCFLOW2D, developed by the researchers from the Chair of Fluid Mechanics with Laboratory, UL FGG. Memberships: SDHR.

Jurij Mlacnik finished his undergraduate studies in 1987 at the Hydraulics Division of the Faculty of Civil and Geodetic Engineering of the University of Ljubljana. He started working as a researcher in the hydraulic laboratory of the Institute for Hydraulic Research (at that time Water Management Institute) in 1988. Since 2000 he has been working as a manager of Institute for Hydraulic Research. His experience covers most of all physical modeling of the hydraulic phenomena and the field measurements in the domain of hydraulics, hydrology and hydro graphical surveys, as: pipe systems under pressure, river diversion tunnels, weirs, spillways, stilling basins, power or water supply intakes, bottom outlets, gates, valves, hydraulic dissipaters, harbors and marine structures, sediments transport in open channel flow, river engineering and regulations, cavitation and aeration, vortex formation, etc. He is also engaged in mathematical modeling in the domain of hydraulics and in the most recent period he has been making a great effort in introducing hybrid models into the Slovenian hydraulic research practice. Memberships: IAHR, ICOLD, SDHR, SLOCOLD