Hydraulic Modelling of Riverbed Embankment Under the Hričov Weir

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Abstract. The weir of the Hričov water structure has an untypical shortened stilling basin, which affects significant scour development in the downstream riverbed. A rockfill embankment structure adjacent to the stilling basin was constructed to prevent the formation of scours in the riverbed. However, increased flows at the weir erode this fortification and it is necessary to replenish the material back to the embankment after the flow situations. A 2D hydraulic model constructed in a flume of the Hydraulic laboratory was used for the research of new downstream fortification, which would be better resist the scouring effects. The model was created according to Froude's modelling similarity as a 2D model of the weir structure with control gates and part the downstream riverbed consisting of gravel. Different designs of the embankment were not allowed to interfere with the existing construction of the water structure. The construction of the embankment was designed as a concrete “secondary” stilling basin adjacent to the existing one. Tested variants of the embankment were of different length and depth of the stilling basin. The length varied from 11 to 24 m and the depths varied from 0 to 1,8 m. Overall 11 different design of the embankment were investigated. Each design was tested for three different flow rates on the model simulating common and extreme flow situations at the weir. The flows were selected to simulate also different hydraulic phenomena at the weir – overflow, outflow, and free overflow. After each flow simulation the scour in the riverbed was measured. The measured scour parameters were depth of the scour, the distance of the deepest point from the existing water structure and the amount of the material carried away. The resulting parameters were assessed with respect to each other for the corresponding flow rates. The best results in scour reduction were achieved for horizontal embankment with the depth of 0 m. The designs with increased depth were causing secondary hydraulic jump in the riverbed which increased the scours. The tested designs of the embankments were able to reduce scour size by up to 45% for the outflow, by less than 20% for free overflow and by more than 80% at the overflow.

1. Introduction

The Hričov Water Structure was built on the Váh River with shortened stilling basin and put into the operation in 1962. Design of water structure was investigated by the means of a hydraulic research for its construction. Afterwards, due to the cost reduction on the water structure, the dimensions of the weir were remarkably reduced relative to the original design (Figure 1). For scour reduction in the riverbed under the weir, a temporary fortification of rockfill embankment was designed (Figure 2). The operation of the Hričov Water Structure revealed that the rockfill fortification is not sufficiently durable to protect the riverbed against scour development. Increasing flows at the weir carry away the material from the fortification and it is needed to refill the material back after every increased flow.
situation. The erosion in riverbed leads to explosion of the foundations of the weir, what threatens with the collapse of the structure.

Each dam or weir should have a stilling basin constructed, where the energy of the flowing water will be dissipated. Stilling basins can be divided into four groups: rock basins, simple hydraulic jump basins, baffle basins and free trajectory jet. The majority of basins are of concrete construction which has the ability to withstand the effects of the flow velocity and dissipate its kinetic energy. The riverbed is thus protected from the scouring. The design of a stilling basin depends on many factors. First, it is determined by the hydraulic conditions (specific discharge, power flow and outflow hydraulic parameters, submergence, etc.). The design depends also on tailwater rating curve which has an impact in dissipating the energy. An important element are the geological conditions in the riverbed. There are also many other factors like economic comparisons, personal preferences, etc. [1]. The design of the stilling basin can be affected by expansion or creating drops, steps, blocks, baffles, and sills. Expansion of the basin or its depression is usually examined to increase Froude number that converts potential energy to the kinetic. To shortening and minimizing the length of the basin may be used baffles, blocks, or sills. These tools interfere with the hydraulic jump and raise the turbulence and energy dissipation. Even though it can increase the cavitation [2]. The impact of baffle blocks in different submerged jumps was investigated by Habibzabeh [3]. Ranga Raju concentrated on the design of stilling basin where an apron was at the river-bed level and obstacles like baffle blocks and end sill were used to force hydraulic jump to the toe of the spillway [4]. To dissipate energy and minimize downstream scour Hossam Mohamed Ali studied the effect of using different spaced corrugated aprons, that means at the stilling basin were installed triangular sheets [5]. The calculation method used the generic method for basin design, which has been investigated by many researchers, more recently by Rajaratnam [6] and Hager, Bremen and Kawagoshi [7], who also extended this investigation to a jump with a control sill by Hager and Li [8]. The implications of the hydraulics of the jump for the submerged jump stilling basin have been studied by Novak [9]. Due to complex flow conditions in a stilling basin and the adjacent streamed, methods of the hydraulic research are used for a proper design. The most reliable is the physical hydraulic modelling method, although the numerical flow modelling is being used to solve similar problems as well. Pagliara and Cheng assessed the effect of length and width of the downstream stilling basin on scour features in clear water conditions [10], [11]. Another type of dissipating energy at the stilling basin is by e.g. designing various block ramps like Pagliara [12] used at the research. Proposal can be changed by slope of the basins [13] or injecting air into the downstream, which is to reduce the creation of scouring in the riverbed [14]. In the past Smith [15] designed the unusual two-stage stilling basin, that means basin required tailwater depth for the basin. The jump in the second basin is forced by natural tailwater depth.

2. Hričov weir issue
Hričov’s weir is divided into four gated fields. The twin radial gates are placed in each field through which the flow is being released. At the bottom of spillway, the stilling basin where should be the kinetic energy dissipated is located. Original design of the stilling basin was 41 m in length with 1,85 m in depth. Due to the cost reduction on the water structure, the design was changed. The crest, spillway, pillars, and the stilling basin was shortened (Figure 1). The size of the stilling basin was reduced up to 10 m in length with 1,5 m in depth. At the end of the stilling basin a sill was created, which creates a backwards circular motion in the flowing water, that pushes the sediment material back to the weir partially filling the scour and covering the foundations of the weir [16].
The first flood after the construction caused very deep scours in the riverbed just below the weir. Subsequently, a remediation measure was made behind the stilling basin. In 1971 a hydraulic research on fortification alternatives improving the scour development conditions was made. 12 different fortifications were examined - with just heavy rock embankment, combination with steel structure, and with surface of concrete blocks. The result of these design was to create a heavy rock embankment with steel structure at the bottom of scour in riverbed (Figure 2). It was assumed that the heavy rocks can protect the riverbed and the steel construction will stabilize them against movements. This measure was constructed, and it partially worked, but its stability was not sufficient and after each flood the embankment has to be refilled.

3. Experimental setup and procedure
A two-dimensional physical model (Figure 3) fitted in a flume was constructed in the hydraulic laboratory. The physical model consists of the weir, the dual radial gates, the stilling basin, and section of the downstream riverbed. Granular material (grain size 2-5 mm) was used as the material of the downstream riverbed, to enable scour creation. The 2D model was designed on the Froude’s modelling criterion, in which mechanical similarity is considered and expresses by the dynamic similarity of hydrodynamic phenomena effected by the exclusive action of gravitational forces. In the observed hydraulic phenomena (overflow, outlet under the gate, dissipation of kinetic energy, etc.) are mostly affected by gravitational force. The basic geometry scale of the model is 1:40. According to the Froude’s modelling criterion, the scales for other relevant physical quantities are as follows: flow rate 1:10 119; specific discharge 1:253, time 1:6.235 and velocity 1:6.235.
The investigated simulations were based on operation manual (Table ) of the Water Structure taking into account the range of operational situation on the weir. Altogether 16 simulation scenarioes were designed, covering the entire operational range of the weir. Based on preliminary analysis [18], in this study only 3 were selected for assessment (Table ). Every simulated scenario started with leveledriverbed and then the water was flowing for 15 minutes. After that, the created scour was measured with a laser gauge for contactless measurement.

**Figure 3.** The 2D physical model in Hydraulic Laboratory.

| Scenario | Flow through 1 gate [m$^3$.s$^{-1}$] | Gates opened | Total flow [m$^3$.s$^{-1}$] | Type of flow control | Upstream water level [m a.s.l.] | Downstream water level [m a.s.l.] |
|----------|-------------------------------------|---------------|----------------------------|-------------------------|---------------------------------|-----------------------------------|
| 9        | 405.75                              | 4             | 1623.00                    | Outflow – lower radial gate | 324.60                          | 320.34                            |
| 14       | 816.70                              | 3             | 2450.00                    | Free overflow – opened radial gates | 323.26                          | 321.52                            |
| 16       | 155.00                              | 3             | 465.00                     | Overflow – upper radial gate | 326.60                          | 317.37                            |

3.1. Stilling basin design variants

Several variants of fortification of the riverbed and secondary stilling basin were designed and investigated on the model (Figure 4). The overview of the designed variants is in the Table 1. Variants of the fortification. The designs of the riverbed fortification had to fulfil the requirements for not interfering with the existing concrete structures of the weir. According to the above procedure, 11 various types of the fortification and the secondary stilling basin were investigated for the selected simulation scenarios.

**Table 1.** Simulated scenarios.

| Scenario | Flow through 1 gate [m$^3$.s$^{-1}$] | Gates opened | Total flow [m$^3$.s$^{-1}$] | Type of flow control | Upstream water level [m a.s.l.] | Downstream water level [m a.s.l.] |
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| L_B [m] | 11 | 18 | 20 | 22 | 24 |
|---------|----|----|----|----|----|
| h_B [m] | 0.9| B  | C  | D  | E  |
| 1.8     | -  | B_1| C_1| D_1|    |

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4. Results

Parameters measured at the model were: the depth of created scour, the length of the deepest point behind the stilling basin and the area size of the created scour (Figure 5). Results of the scour measurements for each investigated variant of the fortification design were compared to the measurements of the basic variant with no fortification of the riverbed. Results for each simulation scenario are compared separately.

Figure 5. Measured scour characteristics at the end of a stilling basin.

From the 3 simulated scenarios, two scenarios (14 and 16) were simulating asymmetric manipulation at the Hričov Weir. The asymmetrical manipulation is used in case one of the weir fields is not operational due to malfunction of the gates or maintenance. The scenario 9 represents a flood discharge which approaches maximum recorded flow at the weir. The discharge flows under the gates and causes severe load on the riverbed resulting in large scour creation due to the high velocity and kinetic energy. The scenario 14 represents maximum flood discharge (100-year flood discharge), that can flow through 3 weir fields. This flow has not yet been recorded at the Hričov weir and is considered as a catastrophic situation at the water structure. The scenario 16 represents maximum discharge overflowing the twin radial gates at an increased upstream water level. The results of the measurements are plotted in Figure 6 and Figure 7.

The graph shows that longer fortification (secondary stilling basin) has positive impact on decreasing the scours size. In the scenario 9 the flat fortification \((h = 0)\) at the length of 22 m reduced the scour depth by 45%. Further elongation of the fortification had slightly better results, but increase is not as significant. The depth of the scour, the area size of the removed bed material has decreased up to over 70%. The scenario 14, when the gates are fully opened, the discharge flows at high kinetic energy causing severe scouring and riverbed changes in the entire riverbed not only in vicinity of the weir. For this scenario, the scours in the riverbed were very large. No significant improvement to the scour size was observed for the tested variants except the shifting of the scour away from the weir structure. The maximum decrease in scour size reached about 20% for the secondary stilling basin with depth of 1.8 m. The fortifications \((h = 0)\) of the riverbed decreased the size of the scour only by 10% in each variant. For the scenario 16 that represents maximum discharge overflowing the gate at an increased upstream water level and the use of only 3 weir fields, the energy of the flowing water can be sufficiently dissipated with no significant scouring of the riverbed. The results of the measurements show for all variants decreased scour depths by 80% based on the fortification (stilling basin) length.
Figure 6. Scour depth for different secondary stilling basin parameters.

Figure 7. Relative scour volume for different secondary stilling basin parameters.
5. Discussion
The Hričov Water Structure is unique for its short stilling basin. Flow through the weir causes severe scouring (Figure 8) in the riverbed downstream the weir. Heavy stone fortification was created to mend this problem, but it works only partially and needs to be fixed after each flood situation. The flow conditions are affected by the relatively wide riverbed, high flows and relatively high-water level difference at the weir are negatively influencing the scour development and the short stilling basin cannot sufficiently dissipate the flow energy.

![Figure 8. Scouring during extreme flood discharge – Scenario 14, Variant D2.](image)

Possible solutions to this problem are constructions of chute or baffle blocks in the existing stilling basin. Similar solution of energy dissipation was investigated by Padulano et al. [19], in their study the authors investigated the effects of the placement of chute blocks at the end of the spillway and at the end of the basin. However, this approach is usually only possible with classic long stilling basins, where the water energy can be sufficiently dissipated, and the blocks help to do this more quickly. Another problem at the Hričov weir is the velocity of water flow, which is very high, and the blocks would probably be abraded soon and would not perform to their full function. In the study of Champagne et al. [14], the authors investigated the reduction of bottom bleaching by injecting air into the lower water level. Research has shown that in this way they managed to reduce the scour by up to 59%, but for the Hričov Water Structure it is not applicable.

Presented research investigated 5 different lengths of the riverbed fortification (11, 18, 20, 22, 24 m) at 3 different depths (0, 0.9, 1.8 m) which were considered as realizable in current conditions and did not required any significant modifications of the existing structures of the weir. Overall, it was proved that the fortification length has significant impact on the scour reduction. The fortification with the length of 22 m performed best, reducing the scour depth to and size by 45% for the main test scenario 9. Increasing the depth of the stilling basin did not have significantly positive effects on scour reduction. For the extreme flood scenario 14, there was no significant improvement to the scour development except of shifting the scour position away from the weir by the length of the fortification (secondary stilling basin). For the scenario 16 all of the tested variants performed similarly well.

6. Conclusion
This paper analyses the impact of the proposed fortifications (secondary stilling basin) behind the stilling basin of the Hričov weir. The experiments were performed on a 2D hydraulic model in the Hydraulic Laboratory. On the model, 5 different lengths in combination with 3 different depths of the proposed fortifications (secondary stilling basins) were investigated. The results showed that the longer the fortification, the better energy dissipation of the water occurs in the riverbed leading to the decrease of the scour sizes. The analysis of the result shows that long horizontal fortification provides
best results in terms of reducing the sour depths and sizes and reducing the turbulence in the riverbed. In contrast to secondary stilling basin where increased depth negatively affected the turbulence in the riverbed and the scour sizes.

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