Model Investigations of Scouring at the Hričov Weir Using Short-Range Photogrammetry

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Abstract. Stilling basins are commonly used to efficiently dissipate energy of flow at weirs. Different types of stilling basins are used at weirs due to different conditions – hydraulic, operational, constructional. At the Hričov water structure a short stilling basin has been built. Its operation over the years showed that it does not dissipate the energy of the flowing water sufficiently, which causes intense scouring in the riverbed downstream. To partially deal with this problem and to protect the riverbed from scours, a rockfill embankment supported with a steel construction was constructed adjacent to the stilling basin’s toe. Despite this riverbed fortification, scours are being created in the riverbed and even in the fortification itself for different cases of operation conditions of the weir. A hydraulic research on a scaled model of the weir was used to investigate the problem and to propose a permanent solution significantly improving the scouring downstream the weir. The proposed fortification of the riverbed downstream the weir was tested at different operational conditions, which simulated extreme situations at the weir. To assess the effects of the investigated fortification, the simulations were performed for the weir without and with the fortification. After each simulation, the deformations in the riverbed (scours) were measured and evaluated. For measuring the riverbed deformations on the model, the method of short-range photogrammetry was used as a very effective and contactless method. This method allowed to examine the investigated area with a very high accuracy and speed. Digital models of the riverbed deformations created after each simulation on the hydraulic model were used to determine the locations and sizes of the deepest scours. Final assessment of the results showed the improvement in the reduction of scouring by the proposed fortification by almost 50% in the size of the scours. The investigations and the results are described in this paper.

1. Introduction
Scouring is a natural phenomenon caused by the flow of water in rivers. They occur naturally as a part of morphologic changes of rivers. However, a scour can uncover the foundations of the water structures, which can lead to significant stability problems of the water structures. To protect the water structures against the scouring can be very expensive. To minimize the risks of failure of water structures, it is necessary to design of the water structure so it can guide and control the process of scouring. The stilling basins of water structures are the objects, where the energy of the flow can be dissipated, and which mainly protects against scouring. All experiences on scouring came from the studies in laboratories and from field experiences. Despite this wide range of knowledge, the principles of analysis of scouring are not well established, and the results of various investigations often show different trends. This is mostly due to
different specific conditions on investigated water structures. [1] At the large structures like dams or weirs, which control the water level in channels and rivers, is a considerable potential for scouring in the downstream. Novak (1955, 1961) [2,3] in his studies stated that the stilling basin which is sufficiently long can reduce the scour to somewhere between 45% to 65%, unlike when the stilling basin is not built. In later studies, most researchers dealt with dissipation energy and minimizing the length of the stilling basin. Stilling basin and its length can be reduced by using e.g., baffle blocks, end sill, different geometry etc. However, it is not always possible to use them in every situation. Ranga Raju [4] in his study reanalysed laboratory data and their relationship for drag force on baffle blocks and end sill. The conjunction these relationships with the momentum equation has shown that it has a reasonable procedure for designing stilling basin and reduce scour in the downstream. Smith [5] was focused to create two-stage stilling basin which is seldom used for high head energy dissipating structures. Compared with the structures where the stilling basins are located more than 10 m under the natural riverbed (e.g., Gardiner Dam, Garrison Dam), in the study was considered to design longer basins than deeper. To prevent scouring, different types of the stilling basin geometry may help. In the Ali’s research [6] were used barrage regulators to control upstream and downstream water levels and was focused on its stilling basin. Different shapes of the basin were investigated on the length of the submerged hydraulic jump, velocity, and local scour. Dissipative effect can be also achieved by increasing the downstream water level. An experimental study made by Habibzabeh [7] investigated submerged hydraulic jump when the baffle blocks were installed in the stilling basin. In the study, a series of tests was completed using different ranges of Froude numbers, submergence factors and baffle blocks positions. The influence of the submerged hydraulic jump without any dissipators were studied by Nasrabadi [8] also with range of Froude numbers and two different grain size in the downstream. Its results showed that the submerged hydraulic jump at the gate and energy dissipation were constant regardless of sediment concentration. To control scour in the downstream block ramps or rock chutes are often used, which have great dissipative effect and have peculiarity to be ecofriendly. In the Pagliara’s study [9] these block ramps and rock chutes were analyzed in both influence of the stilling basin tailwater depth and the ramp toe stabilizing structures. Block ramps were stabilized with the piles at the toe, which was found as a relevant parameter for the scour geometry. Very similar study was made by Fošumpaur [10] whose experiments were aimed at setting parameters for an efficient design of the new types and shapes of energy dissipators on chutes of dam spillway. The designed block ramps come up with good energy dissipation efficiency for the stability of the adjacent stream section. The results shows that the higher energy dissipation was achieved with higher roughness of the chute.

Still persistent problem is at the Hričov weir, where the scours are created due to the shortened stilling basin. Shortened stilling basin was built due the cost reduction at the water structure, which was designed in the slope that the material of riverbed will be thrown back to toe of the stilling basin. The first recorded flood at the structure caused very deep scours. Despite the partially fortified riverbed with heavy rock embankment supported by steel structure, the scours are formed. To decrease scour development in the riverbed this research investigated modifications of the fortification on a three-dimensional physical model.

2. Material and methods

2.1 The Hričov weir
The Hričov weir was built in 1962 as a part of the Hričov water structure. The weir consists of four 18 m wide fields. The weir fields are fitted with dual radial gates which enable flow control by overflow, as well as outflow or their combination. The shortened stilling basin under the weir is 10 m long and 1.5 m in deep. The shape of the toe of the stilling basin was designed to affect the direction of the flow to carry the flow gravel material back to the end sill of the basin. The riverbed just below the stilling basin was fortified with heavy rock stones which were supported by a steel construction at the bottom of the rock fortification. The capacity of the weir is up to 3800 m$^3$.s$^{-1}$, where a single field flow capacity is up to 1000 m$^3$.s$^{-1}$. Most of the flows through the weir create scours in the downstream riverbed even in the rock fortification.
2.2 Physical model
The physical hydraulic model of the Hričov weir was built in the hydraulic laboratory (figure 1) as a 3D model in the geometric scale of 55. The main modeled part of the weir was the upstream part of the reservoir, the weir structure itself with the dual-radial gates and the downstream riverbed with moveable bed material. The model itself was designed according to Froude’s criterium of mechanical similarity.

Gravel with the grain fraction of 2 – 4 mm was used for the movable bed material in the model. The grain size of the riverbed material in the model did not correspond to the model similarity of the actual material of the riverbed due to insufficient data on the material (grain size curve, level of rock bed layer, etc.). Also, the qualitative similarity of the riverbed deformations was sufficient for the investigation purposes as the research was focused on the dissipative effect downstream the weir.

Flow situations on the model were simulated for the flood discharge equal to the 100-year discharge according to the operation manual of the weir. This flow represents extreme situation on the water structure and can be controlled either by the weir by using all four weir fields in a symmetric operation or in the case of some malfunction of one weir field (regular maintenance, damage, operational malfunction, etc.) by three weir fields in an asymmetric operation, which causes significantly increased load on the downstream riverbed. During this manipulation, the features of the flow changes and the riverbed is more significantly scoured. The flood discharge was simulated for 15 minutes of the model time (approximately 111 minutes in real time). Riverbed was always leveled at the start of each simulation. After the simulation, the size of the created scours was measured by photogrammetry method. Two variants of the fortifications of the riverbed (figure 2) were tested on the model. These were the partial results of the preliminary investigations on a 2D physical model. First was a solid horizontal desk with the length of 22 m, connected to the end of existing construction of stilling basin. The next was the same desk improved with added 2.5 m high pillars connected to the original pillars of the weir. Overall, 15 simulation scenarios were investigated on the model. These were divided into 3 mains groups according to the fortification type, starting with the group A (no fortification, used for comparison of the effects of the fortifications) there were the group B (solid desk) and group C (solid desk with pillars). Symmetrical an asymmetrical operation of the weir was described by indexes. 0 for the symmetrical operation (indicated as A0, B0, C0) and 1 - 4 for asymmetrical operations (indicated as A1-4, B1-4, C1-4), where the number in the index describes the position of the closed weir field.
2.3 Measurement of riverbed deformations

After each simulation, the deformations in the riverbed were measured. Short-range photogrammetry has been used for these measurements. This method enabled fast, contact-less, and precise measurements of the entire riverbed on the model and provided reliable parameters of the measured investigated scours (areas, volumes, and depths of the scours). Photogrammetry as a traditional part of the geodesy belongs to the field of remote sensing. For this it is necessary to get co-ordinates of any point in the taken picture. These geometric data can be calculated for creating maps. To create a three-dimensional object, it is required to have two or more pictures of the same object taken from different positions. Due to the point detection methods, images must be captured with overlapping areas. Overlapping between 60-80% is recommended. The main result of the photogrammetry is a point cloud which can be processed in different forms. [11, 12].

For improved precision special fitting marks have been placed on the model in a model coordinate system to enable precise fitting of the taken pictures and their transformations into a 3D point cloud with precise coordinate system. The resolution of the point clouds was 1 mm. Resulting in about 6 million points for each point cloud. Figure 3 shows one of the point clouds (scenario B2) created from the pictures that was used for next processing. By processing the point clouds, maps of the riverbed were created, which were subsequently used to analyse the deformations and scours in the downstream riverbed due for each simulation.

![Figure 2. Scheme of the tested fortifications for energy dissipation](image)

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![Figure 3. Point cloud model of the measured area (scenario B2)](image)

**Figure 3.** Point cloud model of the measured area (scenario B2)
3. Results and discussion
The investigated measures for dissipation of the kinetic energy at the weir Hričov were assessed based on the size of the resulting scours in the riverbed behind the stilling basin. For each simulation, a digital map of the riverbed was created (figure 4). Based on the maps, basic geometrical characteristics of the scours for each scenario were determined (scour length, scour area, and volume of created scour).

Figure 4. Map of deformations (Scenario B2)

The comparison of the lengths of created scours for each simulation is shown in figure 5. For symmetric operation of the weir the measures show significant improvement to the scour reduction - by 32.8% for solid desk and by 37% solid desk with pillars. For the asymmetric operation, the improvement it not so significant and in most cases, it even shows worse results. This is caused mostly by the extreme uneven distribution of the flow at the weir.

Figure 5. The length of the created scours

The figure 6 shows the results of the areas of created scours. As for the scour lengths, for the symmetric operation the results have improved for more than 30%. (31.5% for solid desk and by
38.4% solid desk with pillars). For the asymmetric operation, the investigated measures show slight improvement to the areas of scours created.

![Figure 6. The areas of the created scours](image)

Main characteristic of the dissipation energy is the volume of the material carried away from the downstream riverbed (figure 7). For the symmetric operation, the investigated fortifications show significant improvement to the reduction of the scours in the riverbed - by 48.5% for solid desk (Group B) and by 44.2% solid desk with pillars (Group C). Scours created during asymmetric operation covered larger areas and the larger volume of the material carried away. The result show negative effect of the investigated fortifications on the volume of the material carried away.

![Figure 7. The volumes of the created scours](image)
Overall, it can be concluded that the investigated fortifications show improvement in the scouring of the riverbed. The main improvement is the shifting of the position of the scours away from the existing structure of the weir further along the riverbed to a safer location (not endangering the foundations). The proposed fortification shows significant improvement to the size of the scours for symmetric operation of the weir. The extension pillars do not show a notable improvement. Asymmetric operation of the weir causes severe scouring of the riverbed even for the fortifications. The operation of the weir needs to avoid the asymmetric control of the flow as much as possible to minimize the damage to the riverbed.

4. Conclusion

The aim of the research was to evaluate energy dissipation of the proposed fortifications on the formation of scours in the downstream riverbed of the Hričov weir. A three-dimensional physical model was built in the Hydraulic Laboratory based on Froude’s criterion of mechanical similarity. The fortification of the riverbed, a 22 m long solid horizontal desk was investigated on the model as well as the desk with added extension pillars with the height of 2.5 m. Symmetric and asymmetric operations of the weir were simulated for flood flow scenarios. For the recording scours in the downstream riverbed, a short-range photogrammetric method was used, which enabled to record the entire monitored area of the riverbed. This method showed as a fast, reliable, and precise method for investigations of riverbed deformations on physical models. Simulations and subsequent measurements have shown that the proposed fortification significantly reduced the scouring in the riverbed for the symmetric operation even during flood flow. Compared to the existing conditions, the size of the scours has decreased by 50%. Asymmetrical manipulation did not significantly improve the energy dissipation. However, the formed scours in the downstream riverbed were shifted away from the weir by the length of the proposed fortification. At this distance, scours no longer endanger the stability of the Hričov water structure.

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