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Investigation of scours on a physical model of the Hričov weir using photogrammetry

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ABSTRACT

Scours creation in riverbed at the Hričov weir is a permanent problem since its construction. It is caused by the shortened stilling basin of the weir. In almost all cases of flow control at the weir the energy is not dissipated sufficiently. A 3D physical model was built in the hydraulic laboratory to investigate the measures for reduction of the scour creation. To simulate uneven loads on the downstream riverbed, a flood discharge controlled by the weir in symmetric and asymmetric operations was used for simulations. The scours were evaluated using short-range photogrammetry for contactless measurements. Based on this method digital models of the riverbed for each simulation were created and the scours were assessed to determine the effect of the investigated measures on scour reduction.

KEYWORDS

stilling basin, scour, energy dissipation, 3D physical model, short-range photogrammetry

1. INTRODUCTION

The dissipation of the kinetic energy reached at the bottom of the weir crest is necessary to bring the flow to the same state as before the inlet for the shortest possible distance. This is required not only to protect the riverbed and banks from erosion, but also to prevent damage to the building itself and parts of the building such as the power-plant, banks etc. Various types of dissipaters are used for dissipation but the dissipation itself occurs by turbulent flow. However, some energy dissipation elements can also have the opposite negative effect [1]. The most proposed dissipating element is called stilling basin in which the flow regime is changed. By various modifications of the basin or by adding baffle blocks or sills, it is possible to achieve smaller dimensions of the stilling basin itself. More than one researcher deals with blocks and their locations. Habibzadeh et al. in their research [2] investigated the influence of the location and dimensions of baffles on energy dissipating in two flow regimes. Research has shown that for both cases of flow, the effect of their height, width, position, and number of rows of blocks is not important for energy dissipation. Baffle blocks only affected the flow regime and the flooding of the water jump. Another research focused on the feature of the scours and the method of flow in stilling basin. The design of the stilling basin was changed in the length and width. Every test was performed for a not submerged water jump. The resulting flow and the scour were significantly affected by the increasing length and width of the stilling basin [3]. In the experimental study of Ali et al. [4] the effect of using different spaced corrugated aprons on the scour making in the riverbed was conducted. The research was realized in a flume that investigated the dissipation effect during the submerged flow. Due to the influence of the aprons, they monitored the optimal wavelength at which smallest scours occur. This fortification improved energy dissipation effect by an average of fifty percent than without the fortification. The generic method of calculation, which has been investigated by researchers was used for stilling basin design [5, 6]. The design of the basin is related with the hydraulic jump. Due to the complex flow conditions in a stilling basin and the adjacent streambed, methods of the hydraulic research are used for a proper design. The most reliable is the physical hydraulic modeling method, although the numerical flow modeling is being used to solve similar problems as well. The research of Chen et al. [7] aims on the geometry of stilling basin on scour features and flow pattern in clear water conditions. Nowadays, mathematical modeling methods, where results are reached faster, are used for the behavior of flow. Čubanová et al. [8] investigated implemented flood protection measures due to the hydrological situation, due to more recently occurring flash floods, which robustness exceeds the capacity of the measures initially proposed. Another researches focused on behavior during the floods [9, 10] investigated the effect of the objects e.g. pillars of bridges, change of slope and flow in the channel.

The long-term problem of the Hričov weir is the constructed shortened stilling basin causing scours in the downstream. During the project approval the originally designed stilling basin and pillars of the water structure were significantly modified. The original design of the stilling basin was of a classic reinforced concrete construction, which length was 41 m with the depth of 1.85 m. The modified design significantly reduced the size of the pillars of the weir and the stilling basin. A physical model of the shortened stilling basin was used for investigation of its efficiency in energy dissipation. The conclusions of the investigations stated that the shortened construction did not show a significant deterioration of function compared to the original design. This design was assuming the rock bed to be stable over the years of operation of the weir and able to withstand the load of the flow. The conclusions of the investigations themselves pointed to a shift of the scour closer to the center of the water structure. The operation of the weir after its construction showed that the rock bed cannot take the load of the flow. Significant scours were occurring close to the weir. A temporary solution of a rockfill fortification supported by a steel structure was used to prevent the scour creation reducing their size. However, the scours in the rockfill fortification need to be refilled after each flood situation [11].

A permanent solution to this problem was investigated by the means of hydraulic modeling by the Department of the Hydraulic Engineering of the Slovak University of Technology in Bratislava. As a part of this research was an investigation of the proposed measures under extreme flood condition on a 3D physical model with a movable riverbed. Short-range photogrammetry was used for contactless measurements of the riverbed deformations to determine the effects of the measures on the scour creation and energy dissipation. The photogrammetry is commonly used to measure and monitor the erosive effects on the banks, based on long-term observation and capture of bank images [12] or in connection with hydraulics was photogrammetry used also in the study various photogrammetry techniques were used for river surveying and correcting errors in the field [13].

2. MATERIALS 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 fields, each 18 m wide. 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 flow the carried gravel material away back to the end sill of the basin. And the riverbed just below the stilling basin was fortified with heavy rock stones, which were supported by a steel construction at the bottom. The capacity of the weir is up to 3,800 $m^3 s^{-1}$, where single field flow capacity is up to 1,000 $m^3 s^{-1}$ Most of the flows through the weir create scours in the downstream riverbed even in the rock fortification.

2.2. Physical modeling

The physical model of he of the Hričov weir was built in the hydraulic laboratory (Fig. 1) as a 3D model in the length scale of 55. The main modeled part of the water structure was the upstream part of the reservoir, the weir with dual-radial gates and the downstream riverbed with moveable bed. The model itself was designed according to Froude's criterium of dynamic similarity. The basic scales used for the model were: length (M_l) is 1:55; time (M_t) is 1:7.416; velocity (M_v) is 1:7.416; discharge (M_Q) is 1:22 434.

The model used a moveable riverbed created by gravel material with the grain fraction of 2–4 mm. 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.). And as the research was focused on the dissipative effect in the downstream the qualitative similarity of the riverbed deformations was sufficient.

Fig. 1. The physical model in the Hydraulic Laboratory

Table 1. Simulation scenarios

Scenario	Flow through 1 gate [m^3 s^{-1}]	Gates opened [–]	Total flow [m^3 s^{-1}]	Type of flow control
13	612.50	4	2,450.00	Free overflow – opened radial gates
14	816.70	3	2,450.00	Free overflow – opened radial gates

Flow situations on the model (Table 1) 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 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 are more significantly scoured. For the model simulations, clean water without any sediment in the reservoir was used. Movable riverbed with gravel material was constructed in the model only downstream the weir, where the scouring effects were observed.

The flood discharge was simulated for 15 min of the model time (approximately 111 min in real time). Riverbed was always leveled before another simulation. After the simulation, the size of the created scours was measured by photogrammetry method. Two variants of the fortifications of the riverbed (Figs 2 and 3) 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 (L) of 22 m, connected to the end of existing construction of stilling basin (Fig. 4). The next was the same desk improved with added 2.5 m high (h) 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 and asymmetrical operation of the weir was described by indexes. The index 0 was used for the symmetrical operation (indicated as A_0, B_0, C_0) and the indexes 1–4 for asymmetrical operations (indicated as $A_{1\text{-}4}$, $B_{1\text{-}4}$, $C_{1\text{-}4}$), where the number of the index describes the number of the weir field which was closed during the simulation.

Fig. 2. Physical model of the Hričov – fortified riverbed of solid horizontal desk

Fig. 3. Physical model of the Hričov – extended pillars on the fortification

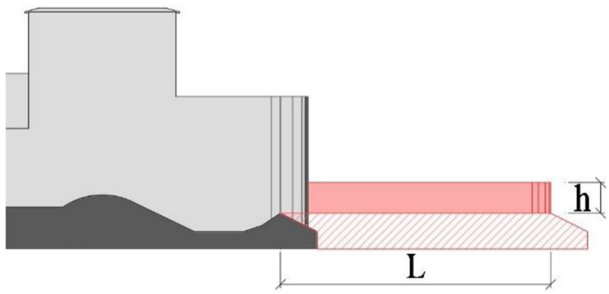

Fig. 4. Scheme of the tested fortifications for energy dissipation

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 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. The main result of the photogrammetry is a point cloud, which can process in different forms. The advantage of this created object is that it can be low textured [14]. Due to the point detection methods, images must be captured with overlapping areas. User manuals suggest overlapping between 60 and 80%. User can manually or automatically manage overlapping [15].

For improved precision, special fitting marks have been placed around the physical model to enable precise fitting of the taken pictures. Based on these fitting marks the considered pictures were subsequently transformed into 3D point clouds including a precise coordinate system. The resolution of the point clouds was 1 mm, resulting in about 6 million points for each point cloud.

Figure 5 shows one of the point clouds created from the pictures that serves for next processing. By processing the point clouds, maps of the riverbed were created, which were subsequently used to analyze the deformations and scours in the downstream riverbed due for each simulation.

3. RESULTS AND DISCUSSION

The investigated measures for dissipation of the kinetic energy were assessed on the basis of the size of the resulting scours in the riverbed behind the stilling basin. For each simulation a digital map of the riverbed was created (Fig. 6). Based on the maps basic geometrical characteristics of the scours for each scenario were determined (scour length, scour area, and volume of created scour).

The comparison of the lengths of created scours for each simulation is shown in Fig. 7. For symmetrical 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 asymmetrical 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 8 shows the results of the areas of created scours. As for the scour lengths, for the symmetrical operation the results have improved for more than 30% (31.5% for solid desk and by 38.4% solid desk with pillars). For the

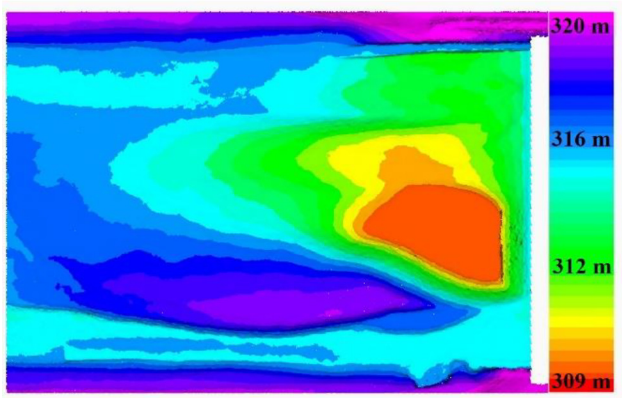

Fig. 6. Map of deformations (Scenario C_4)

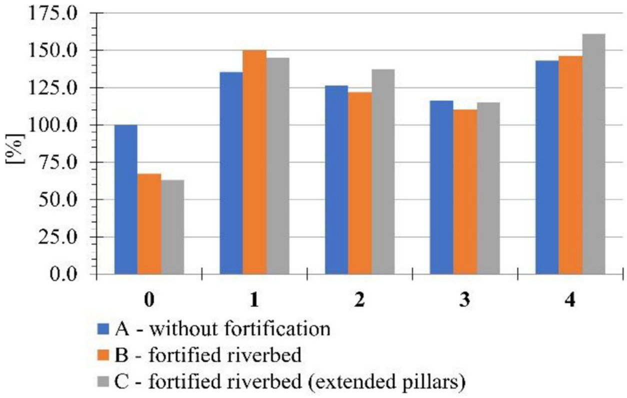

Fig. 7. The relative length of the created scours

Fig. 5. Point cloud model of the measured area

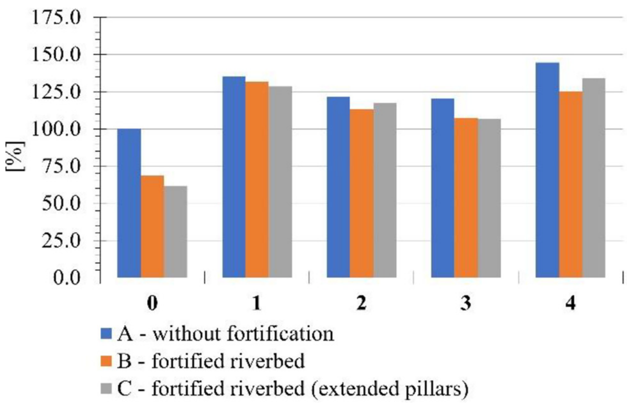

Fig. 8. The relative areas of the created scours

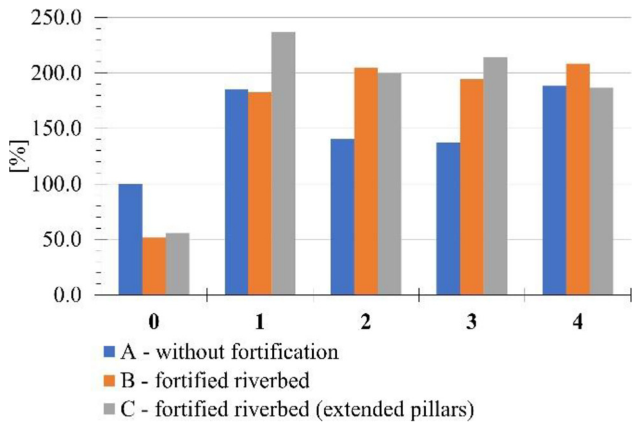

Fig. 9. The relative volumes of the created scours

asymmetric operation, the investigated measures show slight improvement to the areas of scours created.

Main characteristic of the dissipation energy is the volume of the material carried away from the downstream riverbed (Fig. 9). 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.

Overall, it can be concluded that the tested 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. The proposed fortification by a flat desk show 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 by 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 state, it can be said that the size of the scours has decreased by 50%. Asymmetrical manipulation did not significantly improve 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 affect the stability of the Hričov water structure.

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