Innovative approach to the design of stilling basin: improvement of fish migration and scour utilization for energy dissipation

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ABSTRACT: An original technical solution was designed for the currently prepared project Dry Retention Reservoir Mělčany (Czech Republic). The approach permits migration permeability and thus meets the current environmental requirements for newly built in-stream hydraulic structures. The design envisages the construction of a 19-meter-high earthfill dam with a combined structure, which contains a migration passage, bottom outlets and spillway. Thus, it allows the protection of the downstream area up to 100-years-flood discharge. The approach to the stilling basin design downstream the combined object is unique. The concrete construction of the 6-meter deep stilling basin is filled with a riprap in which a shallow river channel is modelled to ensure migration permeability and continues through the dam. The riprap material has been designed to resist normal flow rates and, in flood situations, to create an equally large scour that will effectively dissipate the flowing water energy. A variety of known formulas and approaches can be used to predict the size and depth of a scour. However, the amplitude of the results is so wide that the results were unclear and unusable for the design of a particular situation. A physical hydraulic model was created to verify and optimize the proposed stone size and the expected range of scours, and finally, the results were generalized. Conclusions of the hydraulic research confirmed the proposed solution as reliable in terms of dissipating the kinetic energy of water concerning the stability of the downstream river channel.

1 INTRODUCTION

The implementation of the Mělčany dam project was motivated by the flood in 1997 and, in particular, by the catastrophic flood in 1998, when extensive flood damage occurred, also claiming human lives in the area downstream of the profile of a dam along the stream of the Dědina. As no significant flood storage spaces have been built in the given catchment area to date to route flood waves, the main purpose of the planned reservoir that was selected was the flood storage effect of the hydraulic structure.

The design of the flood storage reservoir reflects contemporary environmental requirements concerning the migration permeability of a hydraulic structure. The initial concept was reworked in response to requirements from nature conservation authorities. The engineering solution is unique in the Czech Republic since it minimizes impacts on aquatic and water-dependent ecosystems including species subject to special protection as part of the Natura 2000 system as well as adjacent nature reserves. The proposed engineering solution is partly based on similar projects of dry reservoirs in Bavaria, e.g. the Dirlewang polder or Gorisried polder (Ernst et al. 2015, Bernhart et al. 2009), and its author is SWECO Hydroprojekt joint-stock company.

A combined structure was designed based on project assumptions, which enables the passage of normal operational discharges and, simultaneously, the migration of animals. Flood discharges will pass through the crest safety spillway. The stilling basin below the outlet works and spillway will be filled in with riprap. A river bed will be shaped in it and it will pass through the dam below the sluice gate and further continue to the river bed above the dam.

It is generally known that local scour occurs downstream of hydraulic structures with a stilling basin such as dams, weirs etc. owing to a great velocity of the flow of water from the outlet works (Hafez 2016). This phenomenon was utilized in the process of designing the stilling basin to dissipate kinetic energy during heightened discharge situations at the Mělčany hydraulic structure. Therefore, a scour hole is expected to form in the riprap in the concrete stilling basin during flood situations, with the material being washed away, partly or completely, further downstream. The scour hole formed will perform the function of a stilling basin, thereby dissipating the kinetic energy of water. This will protect the river bed from being scoured. A hydraulic jump will occur at the place of the stilling basin during the passage of flood discharges, which causes turbulent flow and scour holes in erosive materials. The turbulent flow due to a hydraulic jump may have a significant impact on the movement of sediment particles and the formation of scour holes (Abbaspour et al. 2016). Hence, the goal of the research was to find such material for the riprap in order that it creates the required scour hole in the stilling basin. The stability of the construction of the concrete stilling basin and, if applicable, of the entire earthfill dam may be put at risk in consequence of inappropriately selected material. The environmentally friendly approach applied for the design of the stilling basin of the Melčany dam could become a model example for new larger hydraulic structures which fulfil the conditions for critical infrastructure. The results presented further thus contribute to improved dam safety field.

2 HYDRAULIC FUNCTION AND MIGRATION PERMEABILITY AT THE MĚLČANY DAM

The design of the Mělčany dry flood storage reservoir allows for a capacity of ca 3.2 mil m^3, making it possible to protect the area downstream of the hydraulic structure up to the value of the 100-year flood discharge (Q_{100}). The approximately 500 m long dam of the dry reservoir will be built around 3 km upstream of the town of Dobruška. The maximum height of the dam above the foundation is 19 m, the dam crest width is 5.0 m. The dam is conceived as a homogenous earthfill dam made from local materials. The gradient of the upstream slope of the dam is 1:3.3, with the downstream slope having a gradient of 1:2. Both the upstream and downstream slopes of the dam will be provided with humus and grassed up to the crest.

The designed combined structure is located in the left part of the dam and it will serve for the passage of normal operational discharges, during which it will enable animals to migrate, and for the passage of flood discharges. The combined structure is designed in a passage through the dam, separated from the earth body by concrete contact wing walls. Outlet windows and the migration pass are designed in a reinforced-concrete wall that is in the direction of the dam axis. There is a frontal safety spillway above the outlet windows and migration pass with a total spillway crest length of 15.1 m. The layout and cross-section of the hydraulic structure are shown in Figure 1.

An opening (migration pass) will serve for the passage of normal operational discharges. It will also allow the migration of animals. The migration pass with a size of 6.6 m in width and 1.5 m in height will be equipped by a sluice gate. The project envisages that the migration pass will be situated perpendicularly to the dam axis and it will go through the dam at the place of the original stream bed and its bed will be designed, near as possible, as a natural stream. The length of a shaded section (passage through the dam) of the migration pass will only be 6.2 m in this proposed solution. Side wings both on the upstream and downstream side of the structure will be opened considerably, which will cause sufficient lightening of the migration corridor (Fig. 2) to ensure good functioning thereof.

For the passage of flood discharges, the combined structure will be equipped with two outlet windows and a safety spillway. The dimensions of the windows are 2.5 × 2.25 m and they are equipped with adjustable radial gates featuring pushed arms. The gates of the bottom outlets and of the migration pass are situated below the spillway structure.

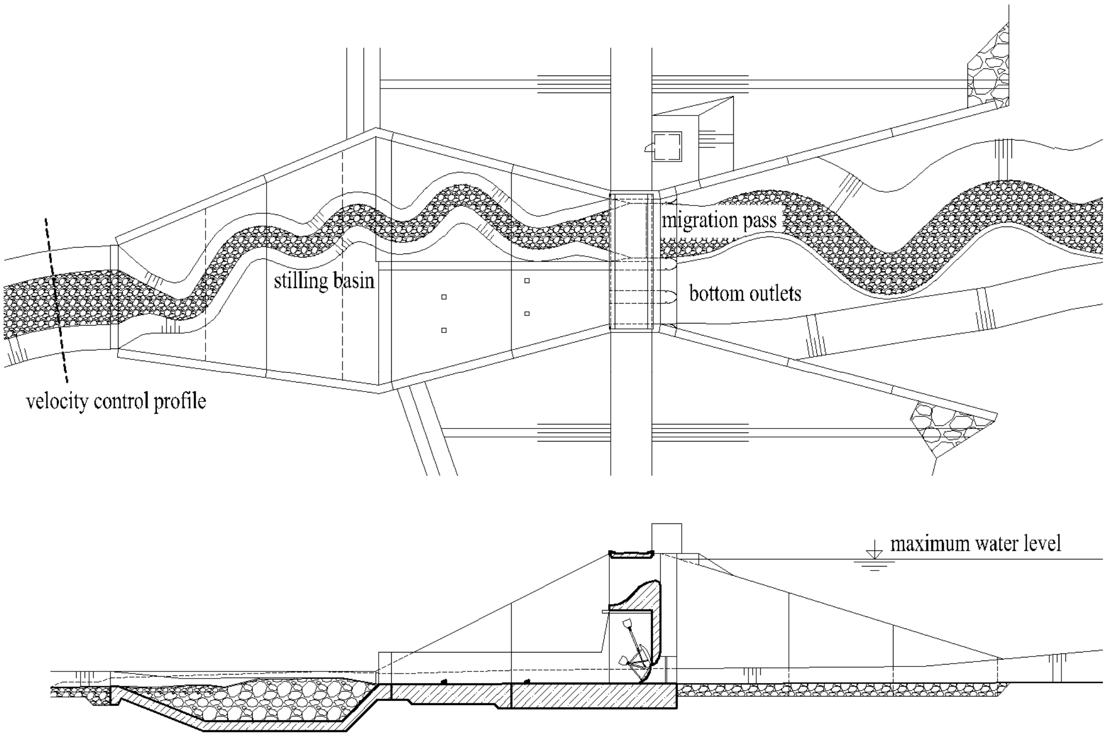

Figure 1. Layout of the combined structure (up) and section of the dam (down).

The concrete structure of the stilling basin will be filled in with aggregates and a natural channel will be formed therein. The channel will pass into the space below the sluice gate of the migration pass and it will further continue to the river bed upstream of the dam in the submerged area. It is necessary to point out the fact that when water falls over the spillway, the material from both the migration corridor and the stilling basin area will be washed away. Thus, it will be necessary to restore the migration corridor following a flood situation. The future administrator of the hydraulic structure takes this fact into account.

Figure 2. Visualization of the filled stilling basin and combined structure.

3 SCOUR IN THE RIPRAP IN THE STILLING BASIN

Dissipation of the kinetic energy of water from the spillway and bottom outlet works during a flood will take place in the stilling basin filled in with riprap, in which a scour hole will form during floods. The stilling basin is situated behind the combined structure near the dam toe. Considering the requirement for animal migration (the water depth is in the order of tens of centimeters, not individual meters), the stilling basin will be filled in with riprap and in the upper part the riprap will be overlaid with gravel. A migration route will be shaped therein in the form of a close-to-nature channel. River gravel is only used for spreading it over the heavy riprap in the top layer in order to provide a gravel substrate in the channel and in the stilling basin, for environmental reasons. Also, an adjustment to the inlet of the channel formed in the stilling basin to the channel further downstream has been proposed with the aim of ensuring a continuous link, thus eliminating the risk of the channel downstream of the hydraulic structure being scoured during floods (see e.g. Slezinger & Zelenakova 2011).

Studies of scour holes downstream of hydraulic structures such as dams and weirs represent an important field of research because of their frequent occurrence in engineering applications. Flows through and over these structures often occur in the form of concentrated streams of water. These streams usually lift up sediment particles and transport them downstream of the affected area where a scour hole has formed. Energy dissipation with the generation of turbulences occurs in the area of impact of a jet (Hoffmans 1998). Great velocities may destroy the protective layer of the bottom and disrupt the exposed bottom downstream of the hydraulic structure. The existence of large scour holes downstream of hydraulic structures causes scour of the material underneath the foundation with the structure subsequently collapsing (Hafez 2016). In the case of the proposed engineering solution by means of a filled concrete spilling basin, however, the formation of such a scour hole in the spilling basin is desirable to achieve an increased energy dissipation.

To calculate scour, it is necessary to distinguish what type of flow it concerns. There exist two types of flow, submerged flow and free flow. Submerged flow is shown in Figure 3. Free flow takes place when the stream of water is surrounded by air with atmospheric pressure upon entry into tail water (Bormann & Julien 1991).

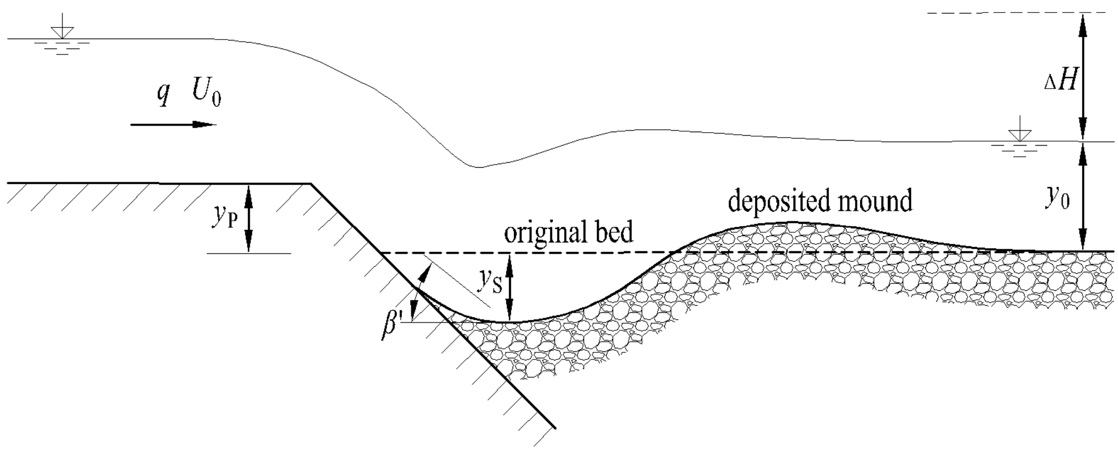

Figure 3. Definition sketch for scour downstream in-stream hydraulic structures

According to Pagliara et al. (2012), it has been proved that the dynamic equilibrium shape of a scour hole that has been scooped out does not depend on the time of water flow. Nevertheless, there are two types of scour hole formation depending on the presence of sediment in the streaming water. Firstly, scour by clear water, in which sediment is transported from a scour hole but new sediment is not supplied into the scour hole. Secondly, a scour hole that is supplied with sediment by means of the flow of water. In this case, a stable depth of a scour hole is reached only after the rate of supply of sediment into the scour hole is equal to the rate of removal of sediment from the scour hole.

Bibliography concerning the prediction of scour hole formation is extensive, and the physical process of scour hole formation has been explored since the initial work by Schoklitsch (1932). A whole range of relations for calculating scour depth has been derived in the past. Despite numerous explorations, however, there does not seem to exist sufficiently robust calculation describing the maximum scour depth in a broad range of limiting conditions (Scurlock et al. 2011).

Empirical equations to predict y_s quasi-equilibrium scour depth were summarized by Bormann & Julien (1991) and are based on the empiric equation (Eq. 1) proposed by Mason & Arumugam (1985):

$$y_s + y_p = K \frac{q^a U_0^b \Delta H^c y_o^d \beta'^e}{g^f d_s^i} \quad (1)$$

where a, b, c, d, e, f, i = exponents of the scour equation; K = constant in scour equation; q = unit water discharge; U_0 = jet velocity entering tailwater; ΔH = head drop across structure; y_0 = tailwater depth; β' = jet angle near bed; g = gravitational acceleration; and d_s = sediment size.

According to Novak (1955), Jaeger's form of the equation is another frequently used empirical equation that serves to calculate scour depth y_s downstream of hydraulic structures (Eq. 2):

$$y_s = 0{,}55\left[6\Delta H^{0.25} q^{0.5} (y_0/d_s)^{1/3} - y_0\right] \quad (2)$$

Based on the values of coefficients a to i determined by the individual authors that were summarized by Bormann & Julien (1991), it is possible to produce a graph (Fig. 4) for the configuration of the Mělčany project and the specified unit discharge (q = 9.9 $m^2.s^{-1}$), which shows a considerable spread of the calculated scour depths, ranging from 0.45 m to 6.28 m.

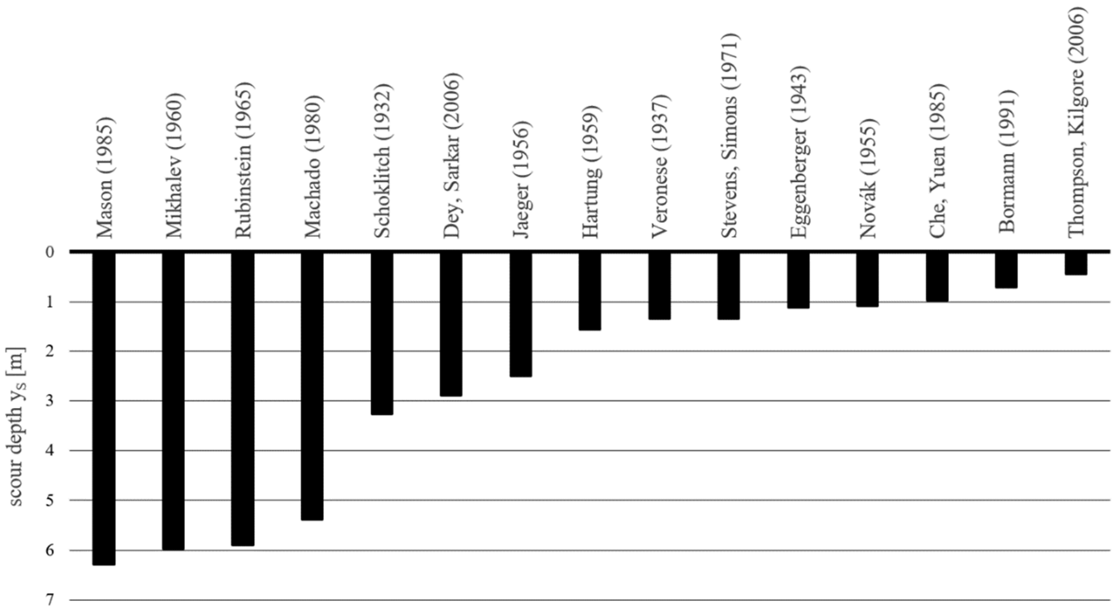

Figure 4. Spread of the depths of scour based on calculations for the Mělčany Structure and q= 9.9 $m^2.s^{-1}$.

Current approaches to predicting scour depth and geometry are generally extrapolated from the case of two-dimensional flow (Scurlock et al. 2011). Therefore, it is not possible to include the asymmetrical arrangement of the inlet and stilling basin into the calculation. As the spread of results based on Equation 1 and Equation 2 is too great and the calculation cannot take account of the asymmetrical arrangement, it was necessary to verify the functionality of the proposed solution on a physical hydraulic model.

4 HYDRAULIC MODEL RESEARCH

The hydraulic model of the combined structure of the Mělčany dam was installed in the Water management laboratory of the Faculty of Civil Engineering of the Czech Technical University in Prague. It was an object model that primarily was to determine the functionality of the proposed design of the stilling basin filled in with riprap. A geometric scale of 1:20 was chosen for the construction of the hydraulic model. The overall extent of the hydraulic model at the selected scale was 3 m in width and 7.5 m in length. The model's scale was determined based on the construction possibilities and conditions of representative research according to the conditions of model similitude which are stated by Novak et al. (2018). The said conditions were derived subject to the validity of Froude's law of mechanical similitude, in which conditions of the dynamic similarity of hydrodynamic phenomena are expressed with the sole action of gravitational forces (Novak et al. 2018).

Overall, the behavior of flow and the stability of the riprap in the stilling basin were verified and documented during the passage of ten flood discharges starting from discharge Q_{100} up to $Q_{10\,000}$. The individual discharge situations were kept on the model for approximately 1.5 hours at a time (which corresponded to 6 hours in reality) in order to ensure that scour stabilized over time.

Riprap with a fraction of 200-500 kg located in the stilling basin space was examined on the model. The riprap was simulated on a geometric similarity scale of 1:20 by quarry stone with a fraction of 16-32 mm. A scour hole always formed in the stilling basin and it corresponded to the extent and type of hydraulic jump and served for the efficient dissipation of the kinetic energy.

The efficiency of dissipation of the kinetic energy in the stilling basin was documented through the measurement of the velocity of water flow in the follow-up channel downstream of the gate sill of the stilling basin. Velocities were always measured at the beginning when a given discharge situation was set (Fig. 5 left) and after approx. 1.5 hours (Fig. 5 right).

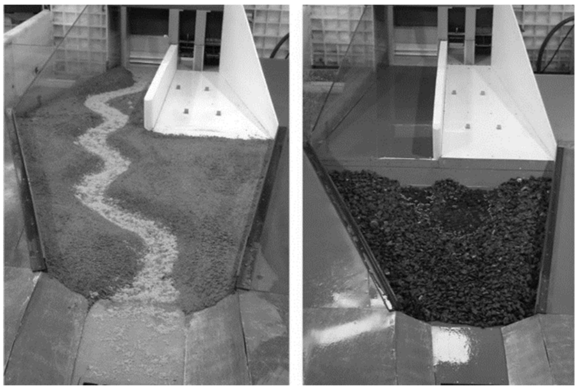

Figure 5. Situation before the experiments (left) and after the experiments with $Q_{10\,000}$ (right).

These velocities vary owing to the formation of a scour hole in the riprap in the stilling basin. There is better dissipation of the kinetic energy usually owing to the scour getting larger and, as a result, velocities in the follow-up channel downstream of the stilling basin were smaller after the end of the test period. The results are documented in Table 1.

Table 1. Measured velocities in the control profile (Figure 1) below the stilling basin in the stream bed.

q	y_s	Start of the experiment			End of the experiment		
		Left bank	Center	Right bank	Left bank	Center	Right bank
$m^2.s^{-1}$	m	$m.s^{-1}$	$m.s^{-1}$	$m.s^{-1}$	$m.s^{-1}$	$m.s^{-1}$	$m.s^{-1}$
4.79	0.75	2.2	2.1	2.2	2.1	1.9	2.0
9.93	1.27	3.4	3.4	4.9	3.0	3.2	4.5
18.44	2.20	4.2	2.9	3.8	3.8	2.6	2.9

The bottom of the concrete stilling basin was not exposed even during the passage of $Q_{10\,000}$. The depth of the scour in the riprap in the stilling basin ranged from 0.75 m to 2.2 m depending on the discharge. The results were compared with the calculations to assess correspondence with the individual computational procedures according to individual authors stated by Bormann & Julien (1991).

The comparison of the measured and calculated depths of the scour holes implies that the relations by authors Veronese (1937) and Novak (1955) achieved the most fitting results. The other relations overvalued the scour depth in a significant up to very significant manner. It should be noted that a similarity of the results with Veronese (1937) and Novak (1955) only occurs in this particular case study, which is limited to the use of one fraction of aggregates and affected by the asymmetrical arrangement of the proposed solution.

5 CONCLUSION

The research on the combined structure of the Mělčany dam was aimed at verifying the functioning of an innovative design of a stilling basin that is filled with riprap in normal discharge situations. The migration of water-dependent animals at the place of the dam is secured by means of a migration pass and an artificially built channel through the dam and via the stilling basin filled in with the riprap. Scour was verified for the passage of Q_{100} up to $Q_{10\,000}$ floods. A scour hole always formed in the stilling basin and it corresponded to the extent and type of hydraulic jump and served to efficiently dissipate the kinetic energy. The bottom of the stilling basin was not exposed even when $Q_{10\,000}$ passed over it. The efficiency of dissipation of the kinetic energy in the stilling basin was documented by means of velocities in the follow-up channel downstream of the gate sill of the stilling basin. It was possible to observe a decrease in velocities there after a scour hole formed by up to approximately 20% compared to the velocities measured at the beginning of the experiment.

Based on calculations of scour depth according to various authors, it was possible to compare the calculations with the data measured for the particular case study. The measurements were used to assess correspondence with computational methods according to the individual authors. The best correspondence was reached based on the calculation according to Veronese (1937) and Novak (1955). However, it is necessary to point out a limited validity of the measurements as only the discharge value was a variable, and scour was also accompanied by the influence of an asymmetrical arrangement of the inlet into the stilling basin and affected by the actual layout of the stilling basin.

The results of the hydraulic research certified a reliable functionality of the proposed structural design of the stilling basin in terms of safe passage of a reference flood wave through the hydraulic structure. The stilling basin filled in with riprap performs the function of reducing the kinetic energy of water reliably. The stability of the stream downstream of the dam is not at risk. The prepared design of the combined structure also ensures the migration permeability of the hydraulic structure and provides suitable conditions from an environmental point of view, as well.

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