Effect of Energy Dissipation on Scour Hole Development Downstream of the Chute

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Abstract. An energy dissipation on hydraulic structures is a scientifically highly examined field of study. Gained knowledge can be used to ensure the safety of the hydraulic structures and the channels which is crucial during floods. Above that, those structures are also part of the critical infrastructure therefore their function is necessary. It is assumed that in the Czech Republic the precipitation distribution is changing due to climate change thus episodes of extreme floods may be observed more often. The paper brings brand new knowledge on the kinetic energy dissipation on the chute and in the stilling basin and its impact on the riverbed scour hole development. The presented research was conducted in the Water Management Experimental Centre of Czech Technical University in Prague, Faculty of Civil Engineering. The research aimed to examine the energy dissipation mechanism on different geometric modifications of the construction of spillway chute and stilling basin and its impact on the process of scour hole development. These various types of dams’ flood safety equipment were examined in the hydraulic laboratory: an elementary form of the spillway without any stilling basin; the elementary form of the spillway and the stilling basin (crest and spillway channel had the same width); the chute width was reduced, and the stilling basin had the full width; steps were added on the narrowed chute and the and stilling basin had the full width; only the spillway crest was reduced to a half-width; only the stilling basin width was smoothly reduced; the chute’s width was smoothly reduced along the chute and the stilling basin had full width; the chute’s width was smoothly reduced along the chute and the stilling basin had the width reduced to a half. The flow, water levels, scour hole and deposit dimensions were measured. Then the amount of energy dissipated was computed. The correlation and connection between energy dissipation and scour hole development was investigated. These outcomes can be used as a recommendation of an appropriate construction design to provide better flood safety of the hydraulic structure.

1. Introduction

For thousands of years, one of the basic tasks the engineers are dealing with is part of the design process of various hydraulic structures such as dams, weirs, irrigation canals, etc. In terms of kinetic energy dissipation, it is possible to split these constructions into local and lengthwise energy dissipators. Local energy dissipation is provided by a stilling basin and/or a ski jump, basically placed on the end of the chute. As the lengthwise energy dissipator can be named the chute in which the water stream is continuously shattered, and the energy is dissipated on a longer section. The continuous shattering of the water stream can be reached by adding obstacles of varied shapes and sizes, increasing surface roughness, changing chute direction, etc. Using the “rough chute” which can
dissipate energy along its body can be very advantageous especially on large dams considering its height. Bigger height means the bigger potential energy of water on the spillway crest and so the bigger kinetic energy of water flowing down the spillway chute to the dam’s bottom. As the amount of energy rises, the dimensions of the stilling basin are getting bigger, especially its depth.

If the amount of energy dissipated on the spillway or in the stilling basin, is not big enough, then the water flow velocity is causing that the river bottom particles are washed away and gradually the scour hole is developed. The extra energy is dissipated within the scour hole (frequently by a hydraulic jump). [1] The scour hole can reach large dimensions and there is a possibility to endanger the hydraulic structure’s stability and safety. Since the hydraulic structures, primarily the water supply structures and basins, are part of the critical infrastructure, therefore, their continuous function is necessary.

2. Literature review

Dissipative processes on block ramps and morphology of developed scour hole in symmetrically and asymmetrically expanding stilling basins were investigated by Pagliara and Palermo. The authors state that most of the submitted equations are empirical and thus they are valid in a specific range of values and for a specific geometry. For a better understanding of this problem, the authors recommend further research. Pagliara and Palermo also examined the amount of material, eroded by water down the block ramps. This was done by measurement of sediment material concentration in the water inflow and outflow as a function of time. [2] [3]

Aminpour examined the process of energy dissipation on stepped spillways and scour hole formation down the spillway. He defined the relationship between grain size, chute’s slope, tailwater depth and Froude’s number and derived an exponential equation of development of the scour hole in the time and equations of scour hole dimensions and a volume of transported material. [4] [5]

Zukal et al. verified the final dimensions of the scour hole down the hydraulic structure on a physical hydraulic model of a dam. The examined downstream channel was filled with riprap which was designed to resist normal flow rates. The creation of scour hole is assumed during the flood and its purpose is to dissipate water energy and thus ensure the dam’s safety. In the conclusion, the authors compared the measured data with the results of calculations according to Veronese [6] and Novak [7] and confirmed the validity of these equations. [1]

The authors of the paper have been dealing with the topic of dissipation of energy of flowing water under the chute of dams for a long time. In [8], the modification of the slipway of an existing dam was addressed due to the increase of the design flow rate and thus higher demands on the dissipation of water energy downstream of the dam.

3. Methods

It is neither possible to describe some of the hydraulic phenomena by mathematics, sometimes nor by the words and pictures. To avoid difficulties with the parameterization of these phenomena, physical hydraulic modelling can be used. Building the physical model allows experiments and simulations of flow rates and structure settings to be performed. Hereby the structure can be tested very precisely. [7]

Physical modelling, like the other methods, has some limitations. The whole idea is based on a similarity of physical phenomena on the model and a prototype (actual hydraulic structure). If the flow characteristics on the model fulfil the conditions of similarity law, then it is possible to expect the same flow characteristics on the prototype. All of that is based on dimensional analysis of the investigated phenomenon. If the mathematical description of the hydraulic phenomenon is unknown,
then the variables, e.g. physical quantities which affect it, are determined. A result of dimensional analysis is a homogeneous equation that does not substitute a mathematical description of the problem, however leads to an empirical equation describing the phenomenon. [7] [9] Buckingham gave the “π-theorem”, which states that the equation is dimensionally homogeneous if it can be reduced to the relationship between a set of dimensionless numbers. [9] In fluid mechanics the quantities like force, length, velocity, density, viscosity, gravitational acceleration, etc. often occurs. From those ones, dimensionless numbers such as Reynolds’, Froude’s, Weber’s, etc. are derived. The physical phenomena are similar if their dimensionless numbers equal. [7] Many of the physical quantities affect the prototype, but it is impossible to apply that to the model to reach the complete similarity, thus the influence of dominant quantities is considered (i.e. “approximate similarity”). When gravitational and inertial forces prevail, therefore especially in free surface flow, the Froude’s number is applied. [7]

When the law of conservation of energy is in force then the relationship between headwater and the tailwater (i.e. the profiles 1 and 2) is for a steady flow possible to express in Bernoulli’s equation (1). For a presented model it is shown in figure 1. In conditions of the laboratory, the effect of a difference in atmospheric pressure is considered negligible, therefore the pressure head members of the equation (1) can be removed. The modified equation shows a change of a total head which is the sum of kinetic energy loss as seen in equation (2). The members of the equation are total heads \( E_1 \) and \( E_2 \) and velocity heads that are corresponding to velocities \( v_1 \) and \( v_2 \) divided by double gravitational acceleration \( g \). All the equation members have the quantity of length \( (m) \) and can be seen in figure 1. [4]

\[
E_1 + \frac{p}{\rho g} + \frac{\alpha v_1^2}{2g} = E_2 + \frac{p}{\rho g} + \frac{\alpha v_2^2}{2g} + \Delta E
\]

\[
\Delta E = E_1 + \frac{\alpha v_1^2}{2g} - E_2 - \frac{\alpha v_2^2}{2g}
\]

4. Physical model

The experiments were conducted in the Water Management Experimental Centre of Czech Technical University in Prague, Faculty of Civil Engineering. The physical model was placed in a 0,5 m open channel flume. Water flows into the flume from the upstream reservoir which is filled by a supply pipe with a flowmeter and a control valve on it. Thanks to this valve an upper boundary condition can be set. Water flows over the physical model and outflows down the flume. There is a flap gate on the end of the flume which can set a lower boundary condition.

![Figure 1. Physical model scheme: green line – total head in profile 1; red line – total head; I – height gauge; II – the model of spillway; III – ultrasonic probe (scour hole measurement); IV – scour hole; V – material deposition; VI – ultrasonic probe (water level measurement).](image)

A scheme of the experiment, including labels is presented in figure 1. Various modifications of the construction of the chute and the stilling basin were investigated. The water level on the spillway crest was measured using the height gauge. This equals the overflow height. The water level in the channel
Beyond the scour hole was measured using the ultrasonic probe. The duration of every experiment was determined on the basis of observations of developing the scour hole beyond an ending sill. The experiment was stopped in a quasi-stationary state when the speed of scour hole progression fell below the limit of an observable movement in a 15-minute step. The duration of every experiment was at least 1 hour. According to the length model scale $M_l = 20$, the time model scale is $M_t = 4.47$. Therefore, the experiment on the prototype should have lasted at least 6.7 h. Additional material was not supplied during the whole experiment, so the water was “hungry” with an excessive transportation capacity and higher erosive potential. After the experiment was terminated, a deformed river bottom was surveyed using the ultrasonic probe. As a result, the topographic map of the bottom (including elevation) was produced in the orthogonal coordinate system.

Examined model represents a prototype of a spillway 5.9 m high and 10 m wide, which equals the height of 295 mm and width 500 mm in the length scale $M_l = 20$. Ogee spillway with a corbel added on an upstream face is connected to the straight chute which has a slope of 1:1.3. As a part of the research, the 8 variations of this structure were investigated. The variations as can be seen in figure 2. are described below:

Var. a. The basic variation of the spillway in full width (500 mm) and without the stilling basin nor a riverbank stabilization.

Var. b. Downstream of the spillway, the 700 mm long, 500 mm wide and 100 mm deep stilling basin was added. The river bottom beyond the stilling basin was reinforced with riprap size 8–32 mm.

Var. c. The width of the whole spillway was reduced to half (250 mm). The stilling basin width was preserved. The river bottom beyond the stilling basin was reinforced with riprap size 8–32 mm.

Var. d. The reduced width (250 mm wide) of the chute was interrupted by 5 steps of 25 mm high and 25 mm wide. Unfortunately, the steps played rather the role of a ski jump. The stilling basin

![Figure 2. Illustration of investigated variations of the model.](image_url)
width was preserved. The river bottom beyond the stilling basin was reinforced with riprap size 8–32 mm.

Var. e. The width of the spillway crest was reduced to half (250 mm), the chute’s width was 500 mm. The stilling basin width was preserved. The river bottom beyond the stilling basin was reinforced with riprap size 8–32 mm.

Var. f. The whole spillway was 500 mm wide. The stilling basin width was along its 700 mm length smoothly reduced from 500 mm to 250 mm by 100 mm high training walls (corresponding with the stilling basin depth). The river bottom beyond the stilling basin was reinforced with riprap size 8–32 mm.

Var. g. The width of the spillway crest was 500 mm, the chute’s width was smoothly reduced along the chute to 250 mm on the spillway’s bottom. The stilling basin width was preserved. The river bottom beyond the stilling basin was reinforced with riprap size 8–32 mm.

Var. h. The width of the spillway crest was 500 mm, the chute’s width was smoothly reduced along the chute to 250 mm on the spillway’s bottom. The stilling basin and a downstream channel had the width reduced to a half.

5. Results and discussion
Formation and a final dimension of the scour hole downstream the hydraulic structure depend on a flowing water velocity. The scour hole dimensions can be reduced or avoided by slowing down the water velocity, which in the other words means reducing the kinetic energy of flowing water. [6] Since the kinetic energy dissipation happens on the spillway’s crest and the chute, in the stilling basin and in the tailwater channel, there are many options and alternatives how to modify each of the elements and thus dissipate more kinetic energy.

5.1 Energy dissipation
An evaluation of the measured data was performed, and the amount of dissipated kinetic energy was calculated. From the measured water levels, the depths were calculated. Then from the known depths and flow rates, the velocities (velocity heads) were calculated, so the total heads (red dashed line in figure 1) were found. Total heads in profile 1 and in profile 2 were compared and amounts of the dissipated energy were found. A summary chart, in which the relationship between a unit discharges and the relative energy dissipation can be seen, is presented in figure 3. From this chart, the course of the curve is clearly visible thus the conclusions below can be deduced.

![Figure 3. Relative energy dissipation versus unit discharge.](image-url)
From the perspective of kinetic energy dissipation, definitely the original Var. a was least effective. Naturally occurred hydraulic jump dissipated 26% to 61% of the energy. Variations Var. c, Var. d and the Var. e were similarly effective in the energy dissipation, all of them dissipated 70% to 90% of the kinetic energy of the investigated flow rates. The course of the curve is similar for the Var. c and Var. e due to similar flow characteristics. A similar course is interesting in the case of Var. d where the water jet was thrown into air, broken, and has fallen into the stilling basin, so the characteristic of the flow was slightly different. However, these three modifications influenced the spillway’s rating curve – the capacity of the spillway decreased on average by 34%.

The almost identical similarity in energy dissipation efficiencies which, however, are considerably higher than in the cases of previous variations, was observed on the Var. b, Var. f and Var. g. All three dissipated 59% to 90% of kinetic energy.

The least efficient variation, which brings the benefit as the channel can be narrower is the variation Var. h. The disadvantage of this modification is that the velocities of flowing water are 3 to 6 times higher than in the other cases. The capacity of the spillway slightly decreased. The stages are increased on average by 7% for identical unit discharges.

5.2 Scour hole development
The development of the scour hole downstream the hydraulic structure was evaluated from the measured data for 7 variations of structure. After each experiment was terminated, a deformed river bottom was surveyed using the ultrasonic probe. A location of the deepest spot in the scour hole was subsequently determined. The following chart in figure 4. compares unit discharges and the maximal depths of the scour holes. Findings and results are presented further.

![Figure 4. Chart of maximal scour hole depth versus unit discharges.](image)

The scour hole did not form in any of the variations until the unit discharge on the model reaches 0.02 m²s⁻¹. In general, it can be said that the scour hole depth raised with the unit discharges. The deepest scour holes formed down the variations Var. c, Var. d, Var. f a Var. g, where the water jets were concentrated in one spot in the centre of the channel. The shallowest scour holes formed down the Var. h variation thus it can be considered as the most appropriate from the aspect of scour hole development and the resulting safety and stability of the hydraulic structure as a part of the critical infrastructure. Besides the Var. e, the deepest scour holes occurred by the training walls on the sides of the channel. In the channel downstream of the Var. e, the deepest spot of the scour hole formed in the centre of the channel.
A strong dependence between the amount of dissipated kinetic energy and the depth of the formed scour hole was observed for all the variations of the structure. This dependence is visible from a chart in figure 4. As can be expected, the depth of the scour hole decreases as the number of dissipated energy rises. A correlation coefficient between these two quantities equals -0.84 which means strong dependence. It is important to dissipate enough energy on the hydraulic structure’s body to reduce the risk of scour hole formation and development, and so the flood damages. A comparison of the quantities (maximal scour hole depth, volume and energy dissipation) is listed in Table 1. Compared quantities were measured and the presented outcomes were calculated for identical flow rate 30 l/s as the maximal flow rate achieved on all the model variations.

The volume of the scour hole corresponds with the cost spent on repair works. The smallest volumes of the scour were observed down the Var. e and Var. f. hence the lowest cost can be expected. On the contrary, significantly the largest volume of a washed-away material was observed down the Var. h. Hence this variation seems to be considered inefficient.

| Var. b | Var. c | Var. d | Var. e | Var. f | Var. g | Var. h |
|-------|-------|-------|-------|-------|-------|-------|
| 0.041 | 0.051 | 0.043 | 0.042 | 0.040 | 0.048 | 0.089 |
| 4269  | 5281  | 4253  | 3278  | 2800  | 4103  | 9869  |

**Table 1.** Maximal scour hole depth, volume and energy dissipation comparison for 30 l/s.

**Figure 5.** Relationship between depths of the scour holes and relative energy dissipation for the flow rate 30 l/s, flowing over the 7 variations.

6. Conclusions
Various modifications of the chute and stilling basin shape were examined. The water levels, flow and the dimensions of the developed scour hole were measured. Then the correlation and connection between energy dissipation and scour hole development was investigated.

It is possible to say, that there is a strong correlation between the scour hole depth and the amount of the dissipated energy. A correlation coefficient $R = -0.84$. This fact is not surprising as the residual kinetic energy causes the process of scour hole development. The recommended variations of the
spillway and stilling basins are Var. b, Var. f and Var. g. Those variations can dissipate enough energy without any negative effects on the spillway flow capacity.

Depths of the examined scour holes are minimal in the case of the Var. e variation. Thus, the impact of flowing water on the riverbed can be considered minimal. Also, the costs of this adjustment are quite small. So, this variation seems to be suitable for the real structure. However, the negative effect on the spillway capacity must be taken into account.

![Figure 6](image)

**Figure 6.** Scour holes formed from the flow rate 30 l/s, flowing over the 7 variations.

These outcomes can be used as a recommendation of an appropriate construction design to provide better flood safety of the hydraulic structure as those structures are also part of the critical infrastructure therefore their function is necessary.

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References

[1] M. Zukal, P. Fošumpaur, T. Kašpar, and M. Králík, “Innovative approach to the design of stilling basin: improvement of fish migration and scour utilization for energy dissipation,” *River Flow 2020: Proceedings of the 10th Conference on Fluvial Hydraulics* (Delft, Netherlands, 7-10 July 2020), 2020.

[2] S. Pagliara and M. Palermo, “Energy dissipation at block ramps,” *Energy Dissipation in Hydraulic Structures*, Taylor & Francis, London, 2015.

[3] S. Pagliara and M. Palermo, “Live-bed scour downstream of block ramps for low densimetric Froude numbers,” *International Journal of Sediment Research*, 2012.

[4] P. Novak, “Study of stilling basins with special regard to their end sill,” *VI IAHR Congress The Hague (C.15)*, pp. 1-14, 1955.

[5] Y. Aminpour et al. “Characteristics and time scale of local scour downstream stepped spillways,” *Scientia Iranica*, Vol. 25, 2016.

[6] N. E. Bormann and P. Y. Julien, “Scour Downstream of Grade-Control Structures,” *J. Hydraul. Eng.*, vol. 117, No. 5, pp. 579–594, 1991.
[7] J. Čábelka and P. Gabriel, “Matematické a fyzikální modelování v hydrotechnice” (in Czech), Academia, Prague, 1987.

[8] M. Králík, L. Satrapa, and M. Zukal “Hydraulic model of the emergency spillways in the Koryčany dam,” MS’10 Prague: Proceedings of the International Conference on Modelling and Simulation 2010 (Prague, Czech Republic, 22–25 June 2010), 2010.

[9] E. Buckingham, “On physically similar systems; illustrations of the use of dimensional equations”, Physical Review, vol. 4, 1914.

[10] P. Novak, A.I.B. Moffat and C. Nalluri, “Hydraulic Structures (4th ed.)” Taylor & Francis, London, 2007.

[11] A. Veronese, “Erosion of a bed downstream from an outlet,” Fort Collins: Colorado A & M College, 1937.

[12] Y. Aminpour and J. Farhoudi, „Similarity of Local Scour Profiles Downstream of Stepped Spillways,“ International Journal of Civil Engineering. 2017

[13] M. Hanel, A. Pavlásková and J. Kyselý, “Trends in characteristics of sub-daily heavy precipitation and rainfall erosivity in the Czech Republic,” International Journal of Climatology, Vol. 36, 2016