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EXPERIMENTAL EVALUATION OF THE DISCHARGE CAPACITY OF FLOW CONSTRICTIONS BY CHECK DAMS IN MOUNTAIN RIVERS

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ABSTRACT

Open check dams are built to retain bed load in case of major floods and may have filtering, sieving as well as dosing effects on sediment transport. The combination of an upstream reservoir with an open check dam is designated as bed load trap. These structures are crucial elements for flood protection in mountainous regions as the sediment transport capacity of mountain streams is ample, highly unpredictable and therefore an imminent danger for river dwellers. The contemporary design criteria for open check dams are based on theoretical approaches, laboratory experiments or engineering experience. A multitude of different opening types and shapes were studied and built in the past, mostly based on design parameters which are related to grading curves of the river bed. In a series of laboratory experiments, the opening geometry and position is currently optimized in view of sediment transition for frequent floods in order to ensure sediment dynamics downstream. Herein, the results of a first series of experiments are presented, which were dedicated to the evaluation of the discharge capacity of check dam openings, under the influence of bed load transport on a rough river – bed under supercritical flow conditions. Existing experimental and theoretical formulae for purely hydraulic discharges are reviewed and it is found, that the actually applied value for the orifice coefficient μ are too small. These results may also apply for bridges, which serve in some cases intentionally or unintentionally as open check dams.

Keywords: Open check dam, Alpine flood protection, Bed load, Rough steep channels

1. INTRODUCTION

Anthropologic interventions in rivers such as sills or flow control measures interrupt the longitudinal continuity of the valleys, in terms of biotic and environmental parameters as well as in terms of sediments carried by the stream. Certain measures may be taken to mitigate this interruption of continuity, e.g. the implementation of dissolved sills with a maximum step height of about 0.2 m to allow for fish migration. This research is concerned with the most upstream reach of valleys where engineering interventions are constructed in steep regions for the protection of river dwellers situated on downstream alluvial cones, which are threatened essentially by excess sediment transport ensuing from the mountain rivers. Check dams are a possibility to overcome this risk, but also represent one of the before mentioned anthropogenic engineering interventions influencing the longitudinal river connectivity. Open check dams are a sub-category of check dams which may have filtering, sieving as well as dosing effects on sediment transport. These are herein considered and they represent flow constrictions by limitation of the flow cross-section. Figure 1 presents a sketch of two types of open check dams: (a) open gap-crested, i.e. only lateral flow constrictions are imposed to the flow, and (b) closed crested check dams which also include a top-flow constriction.

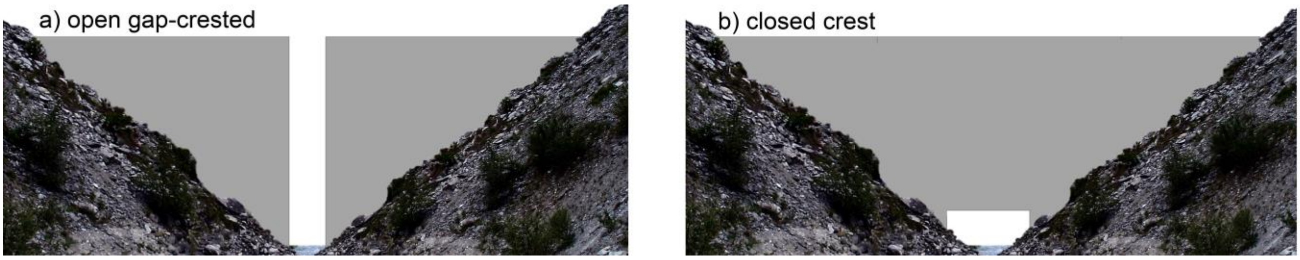

Figure 1: Two types of open check dam (a) open gap - crested, i.e. walls constricting the flow laterally (slit) and (b) closed crested, i.e. an opening (orifice) which constricts the flow at the surface and laterally.

The phenomenon of top-flow constrictions, i.e. a limitation imposed at the water surface, can be isolated from other influences like lateral flow constrictions, and is then similar to the effect of sluice gates. A basic requirement for ensuring the longitudinal river connectivity at open check dams is the evaluation of the opening discharges. The discharge formulae which is currently applied by practitioners include an orifice coefficient μ which accounts for the energy losses imposed by the flow constriction. This orifice coefficient μ requires however some review and adaptations for rough and steep mountain rivers under the influence of bed load transport. Some analytical approaches for the derivation of μ exist, like e.g. Werner (1963) or Brooke Benjamin (1955), but neither the influence of a rough bed nor bed load have been considered.

2. OBJECTIVES

One of the most popular formulae for the estimation of discharges of open check dam with a closed crest, i.e. with an orifrice, was introduced by Zollinger (1983):

$$Q = \mu \cdot b \cdot \tfrac{2}{3} \cdot \sqrt{2g} \cdot \left(d^{3/2} - (d-a)^{3/2} \right) \qquad [1]$$

where Q denotes water discharge, μ some orifice coefficient, b and a the width and height of a rectangular check dam opening respectively and g is the gravity constant. Zollinger (1983) assigned a value of about 0.65 to the orifice coefficient μ, which is in the order of the results from Werner (1963), data cited by Lencastre (2008)[a] and Brooke Benjamin (1955) who is cited in textbooks like Henderson (1966). Brooke Benjamin (1955) is dedicated to flow obstacles with an emphasis on sluice gates and includes experiments, which reveal important errors of his analytic approximation of μ for increasing flow depths and smaller opening heights, but proof in retrospect the analysis from Werner (1963). However, according to Figure 3 b), also the analysis from Werner (1963) results in an overestimation of the flow contraction, especially for small sluice gate opening heights. For future research on flow obstacles in mountain rivers, the existing approximations are insufficient, in particular the influences of turbulent flow on a rough river bed and of the presence of bed load are unknown. Therefore, the principle objective herein is the identification of conceivable adaptions of the contraction coefficient ψ, i.e. the ratio between the downstream flow depth h_1 and the opening height a and, thus, the orifice coefficient μ in mountain torrents which applies in steep mountain torrents under the influence of bed load. The μ coefficient will be reinvestigated for turbulent flow on a rough bed with bed load.

3. METHODS

The experiments were run in a 2.5 m long, moderately steep channel with a longitudinal slope of 2 %, and a rough fix bed composed of grains larger than the D_{84} of the bed load supplied at the channel entrance. The channel had a trapezoidal cross-section with a base width of about 0.24 m and a bank slope of 30°. The grain size distribution herein used for the bedload was: D_{30} = 4 mm, D_m = 9 mm, D_{84} = 14 mm and D_{max} = 32 mm. The absolute sediment feeding rate was either inactive for the evaluation of only roughness effects (Q_s = 0 kg/s) or active and invariant (0.07 kg/s); the relative sediment feeding rate varied between 0.1 and 0.3 % of the pump discharges which varied between 5 and 20 l/s.

The top flow constriction was materialized by means of wooden planks of variable suspension height. The flow height was measured by means of ultrasonic probes, which allow for the computation of the flow depth over the fix bed, and the subsequent calculation of the flow energy. The flow conditions here simulated comply with a typical environment in mountain regions and the results regarding the energy losses may be applied for structural elements constricting the free surface flow of mountain torrents, especially in case of floods, like bridges or some types of check dams.

Figure 2 illustrates the imposed top flow constriction which was applied in the model: the base width b was constant with 0.24 m and the opening height a which varied between 0.03 and 0.06 m.

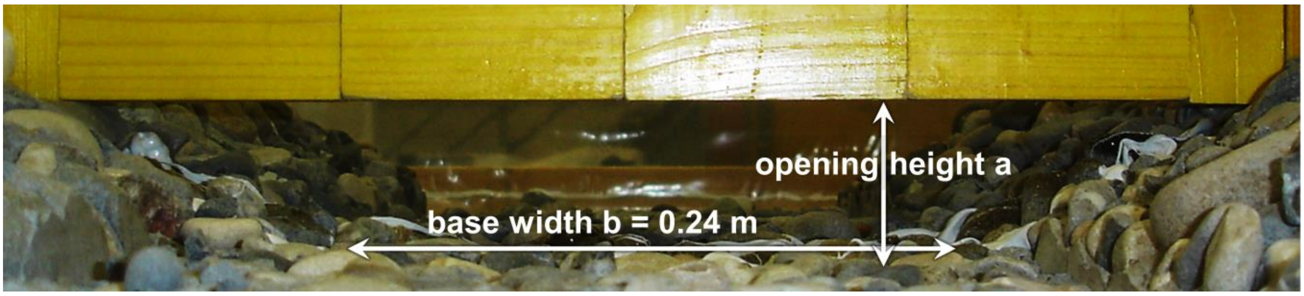

Figure 2: Illustration of the top flow constriction (check dam) in the model in terms of its constant base width *b* and variable opening height *a*.

4. RESULTS

Brooke Benjamin (1955) and Werner (1963) plotted the ratio between the sluice opening height a and the downstream flow depth h_1 against the contraction coefficient ψ which equals the ratio of the upstream flow depth h_0 and the sluice gate opening a. The latter complies with the herein used opening height illustrated in Figure 2. The orifice coefficient μ can then be computed applying equation [2] according to Werner (1963).

$$\mu = \frac{\psi}{\sqrt{1 + \psi \cdot a/h_0}} \cdot \qquad [2]$$

This formula is illustrated in Figure 3 a) for different ratios a/h_0: μ is always only slightly inferior to ψ; with decreasing flow depth (or increasing opening height), the values of both coefficients are approaching. In this study, the simulated flow conditions required quite large opening heights (due to the grain size and bed roughness) but did not allow for submergence heights more than about three times the opening height. Therefore, for the following interpretation of the results, it can be assumed that the value of μ is inferior to ψ by a factor of about 0.9.

Figure 3 b) shows the results obtained within the series of experiments compared with the experiments from Brooke Benjamin (1955), the analytical solution from Werner (1963) for a vertically inclined sluice gate and data cited by

Lencastre (2008)[a]. According to Brooke Benjamin (1955), the upstream flow depth in vicinity of the sluice gate complies with the energetic head, as it can be assumed that the flow velocity directly upstream of the obstacle is very small compared with the downstream flow velocity (Bollrich and Preißler, 1992). The experimental data from the former studies confirm the function developed by Werner (1963) in terms of its shape and its value range for smooth flow conditions. However, for low submergence rates and large opening heights, the former experiments which were conducted in the first half of the 20th century indicate that the contraction coefficient remains in a range between 0.60 and 0.65, and does not follow the exponential-like function from Werner (1963).

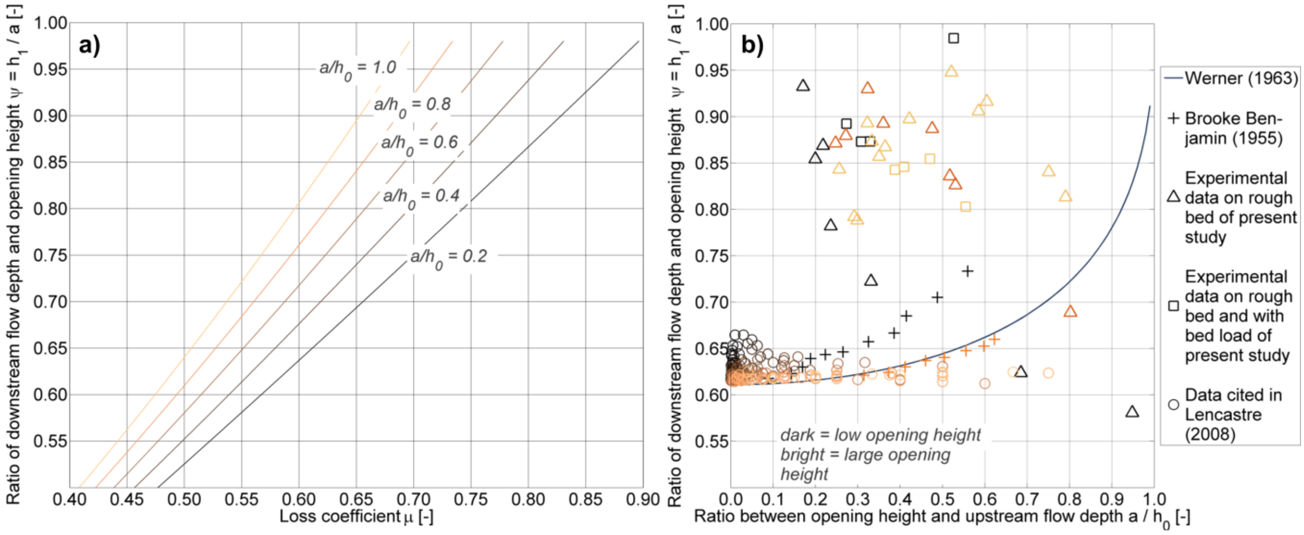

Figure 3: a) Relation between the loss coefficient μ, the ratio between opening height a and the upstream flow depth h_0 and the contraction coefficient ψ according to equation [2] from Werner (1963);
b) Comparison of the results from experiments in the present study with those from Brooke Benjamin (1955), the analytic solution from Werner (1963) for a vertically inclined sluice gate and the data cited by Lencastre (2008)[a].

The results of this study are in line with the idea that turbulent flow conditions, on a rough river bed with a generally steep slope, which cause a more uniform velocity distribution throughout the flow depth, reduce the flow contraction imposed by the sluice gate to minimum values of about 0.8.The resulting average value for the orifice coefficient μ is about 0.75.

The herein observed flow contraction under the influence of bed load vary little from the observations with pure water discharges. The reason for this may be that the flow constriction decelerates the flow upstream and in consequence, a tranquilized water zone occurs where bed load deposits, thus creating a sediment front consisting of the coarser grain size fractions. Throughout the experiments this sediment front never entered or blocked the flow constriction itself. In a steady state of the shape of this bed load front, the finer sediments passed in an undetermined quantity the flow constriction, but the effect on the water surface resembled the situation of pure water discharges.
At all time, the downstream flow conditions were supercritical and therefore, the values apply like also in the former studies, for free outflow conditions (no submergence). However, for future experiments it is important to evaluate the sediment release at the downstream end of the model to distinguish the sediment alimentation rate from the rate of sediments passing the orifice.

5. CONCLUSIONS

The design and dimensioning of flood protection measures in mountain regions require the consideration of the river hydrology, site specific hydraulic data and bed roughness, as well as expected incoming bedload. The existing discharge formulae ensue from (semi-) empirical laboratory data (Zollinger, 1983), where the influence of bed load and rough wall conditions are quite neglected. This research contributes to the adjustment of discharge formulae for flow constricting hydraulic engineering elements with respect to bed load transport and rough river beds by the refinement of the orifice coefficient μ which is currently applied as a constant value of 0.65 in the standard formula (eq. 1). The orifice coefficient μ has already been investigated theoretically by Werner (1963), among others, considering no bed load and no wall friction. The μ coefficient has now been analyzed for top-flow constrictions for rough turbulent flow under the influence of bed load transport.

The results indicate that a higher value for the orifice coefficicent μ has to be considered when a rough bed is present due to the lower flow contraction downstream of the flow obstacle. The herein observed effect of bed load had no significant influence, but this observation may be affected by errors due to the formation of sediment depositions upstream of the flow constriction.

To sum up, for flow obstacles constricting the free surface flow in rough turbulent streams such as mountain rivers, the herein presented results indicate that the orifice coefficient μ has to be considered by values of about 0.75, rather than the formerly applied value of 0.65. However, as in real case applications, not only top-flow constrictions are present, except some types of bridges without bearings and some special types of open check dam, further investigations of the μ

[a] Smith and Walker (1923); Fanning (1906)

coefficient are necessary. Future investigations have to include the effect of side walls, i.e. lateral flow constrictions and the combination of both top-flow constrictions and side – walls.

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