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Hydraulics of overflowed bridge

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Summary: *The paper deals with an open channel flow around model of a bridge when the water depth is higher than height of the bridge opening. Both the pressured flow through bridge opening and free surface flow over the model were studied. For both cases discharge coefficients were determined and for overflowed model also the velocity profiles were measured to evaluate the ratio of discharges going below and over the bridge model.*

Key words: open channel flow, ultrasound velocity measurement, discharge coefficient

Introduction

During extreme floods the flow passing through a bridge may be in a contact with underneath parts of a bridge construction. When both upstream and downstream parts of the bridge are submerged the free boundary flow typical for open channel flow changes to pressured flow. With additional increase of water level the bridge can be even overflowed.

In this paper we have focused on the problem of overflowed bridge using physical modelling. Two experimental arrangements were tested – the first one concerns a situation when both the upstream and downstream parts of the bridge are submerged and whole discharge is flowing only through bridge opening. This situation could come about when flowing debris block the bridge and prevent river stream from flowing over bridge. The second run of experiments concerns the overflowed case when the discharge is going both below and over the bridge construction. For each experimental run two shapes of bridge cross section were tested – rectangular and rounded upstream face with radius equals the thickness of the bridge model. To simplify the situation only sectional models were used, it means that bridge piers were not taken into account. Schematic views of the experimental arrangements are shown in Fig. 1 and 2.

Experimental set-up

The experiments were performed in a horizontal hydraulic flume of the cross section *0.4x0.4 m* and the length of *24 m*. Side walls of the flume are made of glass tables, the bottom of the flume is made of steel plates. The bridge models were placed in the distance *16 m* from flume inlet and were oriented perpendicularly to flow direction. The

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length of the bridge model in flow direction was 20 cm for rectangular model and 20/25 cm for rounded model. Two heights of bridge opening were used – *H = 10 and 15 cm* for pressured flow and one height *H = 10 cm* for overflowed case. The thickness of both models was *5 cm*. A downstream weir of jalousie type was used to regulate the flow depth in the channel. The slope of the channel was 1:2650. Flow rates were measured using an inductive flow meter, the discharges varied between *20-47l/s*.

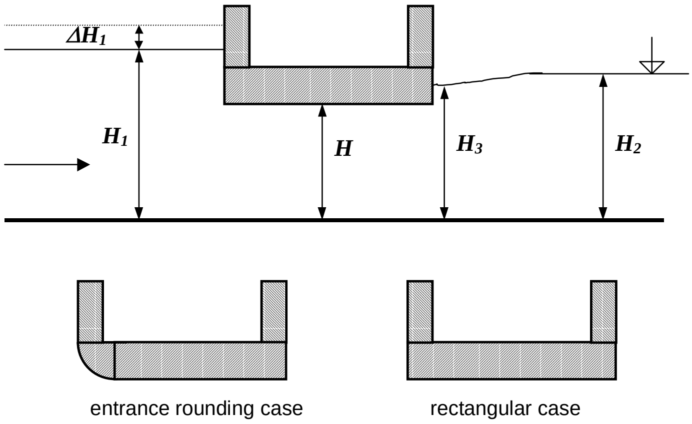

Fig. 1

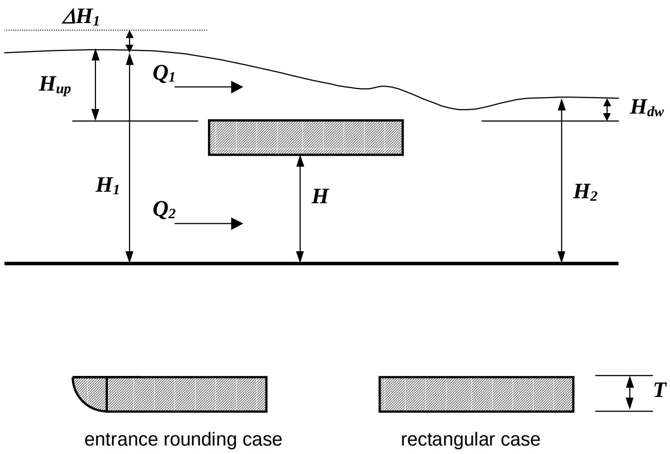

Fig. 2

Needle gauges were used to determine the water levels. Due to the highly fluctuating water surfaces (up to *2 cm* in the upstream part) there exists a good deal of scatter of the experimental data. To improve the detection of water levels we have tested a novel technique, which principle is based on the measuring of the conductivity of water. Two platinum wires of the length *20 cm* are fixed with the distance about 1 cm between them and they are dipped into channel. Water levels are then recorded through a special electrical device connected with PC. In this moment this measuring system is still under development due to high sensitivity to the temperature. The example of recorded water levels is shown in Fig. 3.

To determine the velocity profiles we have used the Ultrasound Velocity Profile-meter UVP-Monitor (model UVP-XW-PSi made by Met-Flow, SA) which allows to measure the instantaneous velocity profiles in 128 points projected onto the ultrasound beam direction. The principle of the measurement is based on the Doppler effect. The

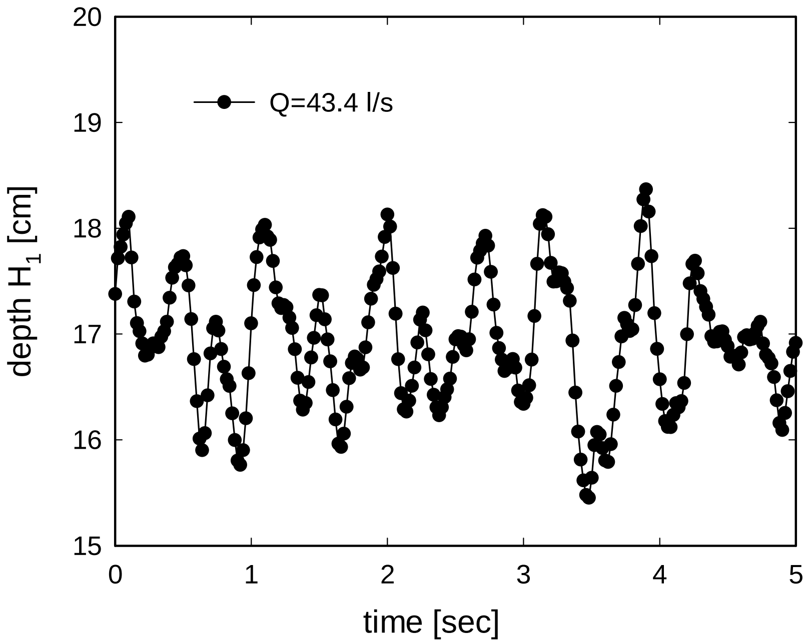

Fig. 3

ultrasonic probe after transmitting a short emission of ultrasound of given frequency starts to receive echoes generated by small particles scattered in the fluid. If the particles are moving along the acoustic axis the echoed frequencies are shifted and from measured frequency differences between transmitted and echoed frequencies and time delays it is possible to determine the local velocity. For the measurements we used the transducers working on the frequency 4 MHz. Seven transducers were fixed vertically with mutual distance about *1.3 cm* on a moveable frame. The multiplexer arrangement of seven probes enabled to cover the velocity field over the flow depth of *8.5 cm* for one position of the frame.

Results and discussion

a) Case A - bridge opening is filled up, no overflow

This situation is shown in Fig. 1. The pressured flow through rectangular opening can be considered as drowned orifice flow. Such flow can be described by the following equation

$$Q = C_D\, A \sqrt{2g\left(H_1 - H_3 + \Delta H_1\right)} \tag{1}$$

where C_D is discharge coefficient, A is cross sectional area of bridge opening, H_3 is flow depth just downstream the bridge and ΔH_1 is velocity head in the upstream section. Using this equation the coefficients of discharge were calculated from experimental data and the results are shown in Fig. 4 together with data collected from [1]. While the discharge coefficients for rectangular case show a decreasing tendency with increasing flow depth the values of C_D for rounded case are, as can be expected, higher and they are more or less constant.

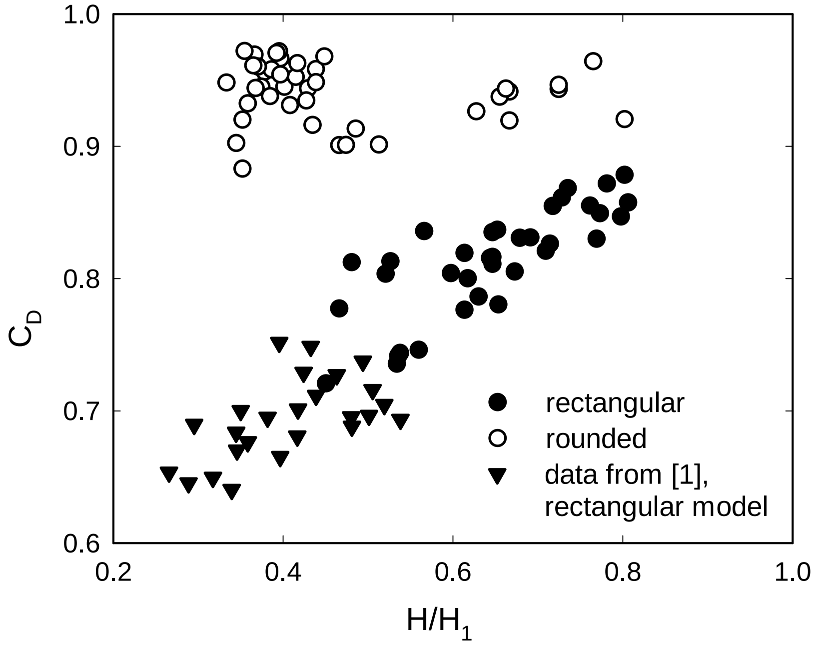

Fig. 4

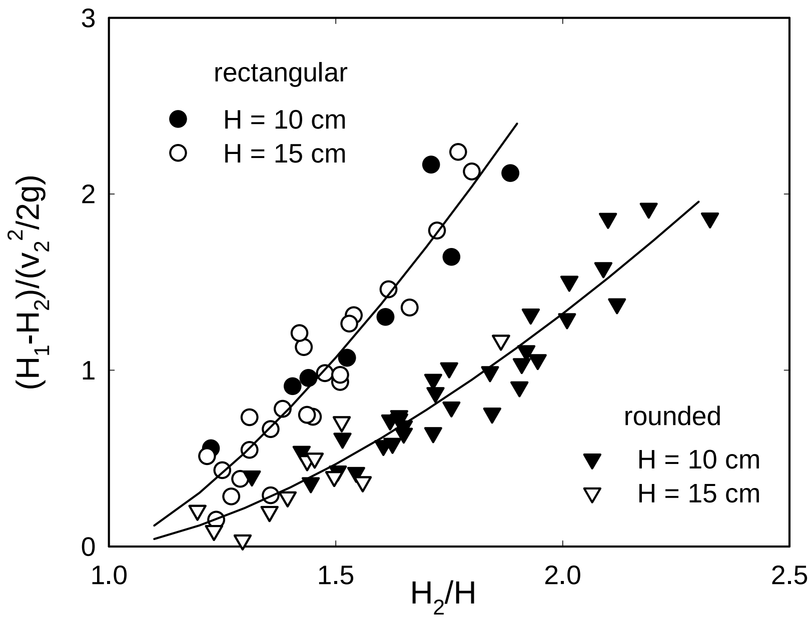

Fig. 5

The influence of the shapes of the cross section on the afflux (e.g. differences of upstream and downstream water levels) is shown as function of downstream flow parameters in Fig. 5. The reduction of about 50% was recorded for the rounded cross section shape. For a single span model with rectangular side piers a reduction of about 30% could be expected [2].

b) Case B - bridge is overflowed

In this case the total discharge is divided onto two parts, underneath pressured flow and free surface flow like flow over broad-crested weir, see Fig. 2. Depending on the water levels the free surface flows may be considered as - free plunging flow (when the downstream level is below the upper edge of bridge construction), normal free flow and submerged flow. Only the last two types were observed in our experiments. Supposing that the critical flow condition occurs somewhere on the crest (Froude number equals one) following set of equations can be derived for calculation of the discharge coefficient

$$Fr_{cr} = \frac{V_{cr}}{\sqrt{g\ y_{cr}}} = 1 \tag{2}$$

$$Q_1 = L\sqrt{g.y_{cr}^{\ 3}} \tag{3}$$

$$H_{up} + \frac{V_1^{\ 2}}{2.g} = y_{cr} + \frac{V_{cr}^{\ 2}}{2.g} \tag{4}$$

Combination of continuity and energy equations we receive final relationship

$$Q_1 = 1.706\,L\left(H_{up} + \Delta H_1\right)^{3/2} = C_W\,L\left(H_{up} + \Delta H_1\right)^{3/2} \tag{5}$$

where V_{cr} and y_{cr} are critical velocity and critical depth, respectively, L is length of the weir over which the flow is passing, in our case this value was width of the channel (0.4 m) and C_W is discharge coefficient for broad-crested weirs. For the trapezoidal shape of the broad-crested weir the discharge coefficient has value of between 1.57 and 1.71, [3].

In order to determine the discharge coefficient for the overflowed case we have measured the velocity field under and over the bridge model by means of UVP profile meter. The measuring system consisting of seven horizontally oriented transducers was placed just downstream the bridge opening against the approaching stream. The results are shown in Fig. 6, where the underneath discharge normalised by total discharge, Q_2/Q, is plotted versus the depth of the approaching stream normalised by height

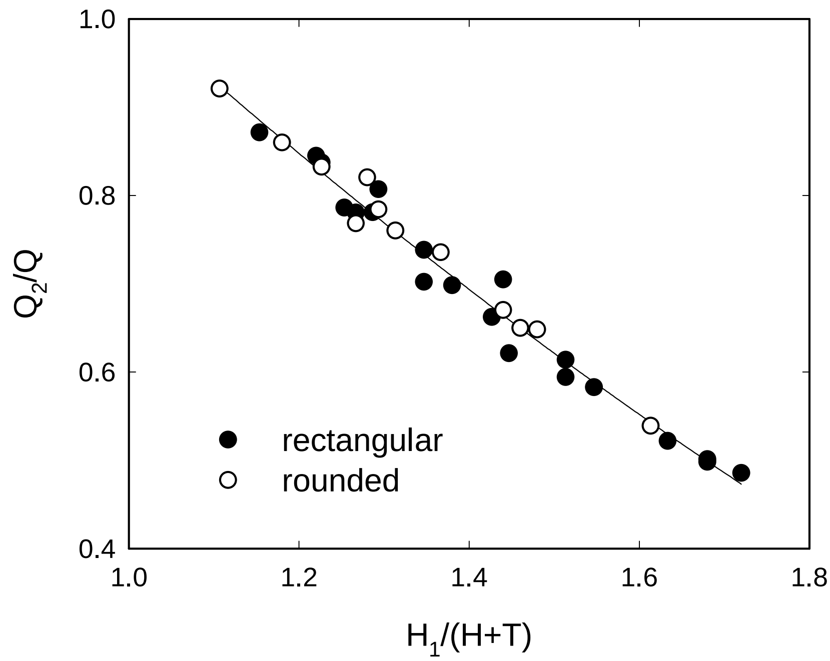

Fig. 6

of bridge opening and thickness of the bridge, $H_1/(H+T)$. It seems that the discharge radio is independent on the shape of cross section.

Using equation (5), the discharge coefficients, C_W, were calculated from the measured velocity field. The results are shown in Fig. 7. For the normal free surface flow the discharge coefficient, C_W, is about 1.65. When the submergence takes place (the ration of H_{dw}/H_{up} is higher than 0.8), the values of C_W are quickly decreasing. No significant differences between rectangular and rounded cases were observed.

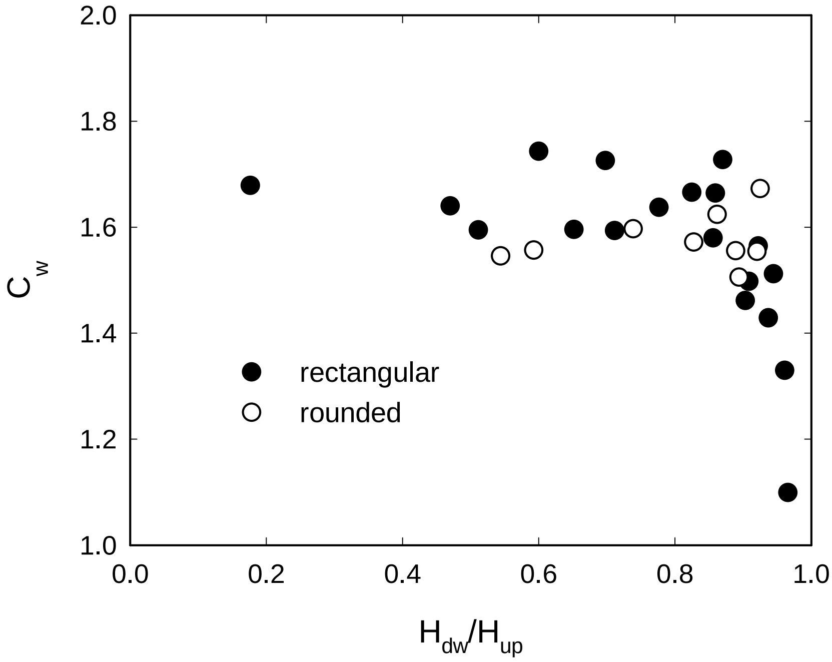

Fig. 7

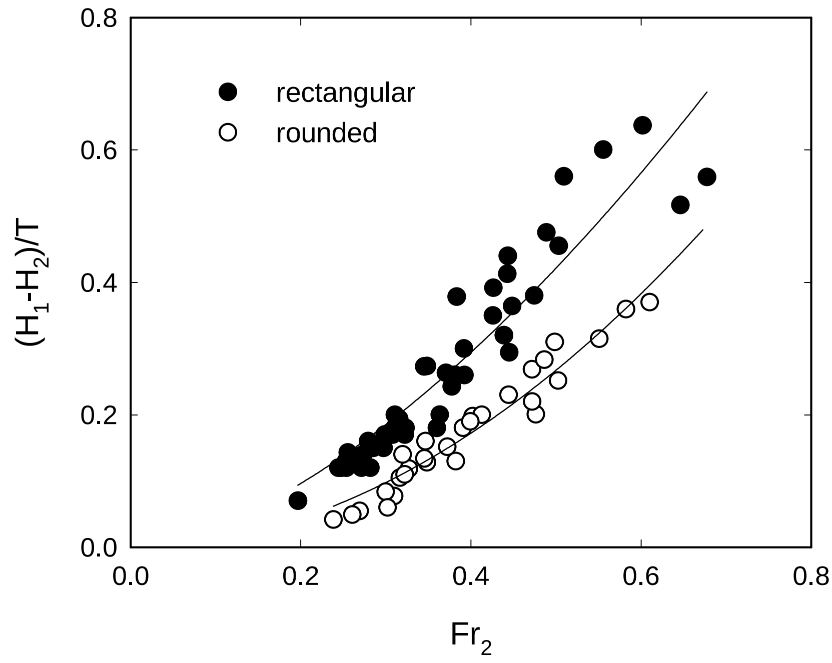

Fig. 8

The dependency of the aflux (for the overflowed bridge model) on downstream Froude number ($Fr_2 = V_2 / \sqrt{g.H_2}$) is shown in Fig. 8. Similarly as for non-overflowed case, the flow over the bridge of rounded shape is less energy consumption and therefore the reduction of afflux is about 40% compare with the rectangular shape.

Conclusion

Two cases of flow over the bridge sectional models were studied. The first one concerns the situation when both the upstream and downstream faces of the models are submerged and flow is passing only through bridge opening. The second case concerns the situation when the discharge is partially going underneath and partially over the bridge model. Two shapes of cross section were used – rectangular and rounded.

It was shown that for non-overflowed case the reduction of afflux up to 50% could be expected using the entrance rounding, for the overflowed case the afflux reduction might be about 40%. For the overflowed case the amount of discharge going underneath was evaluated in dependency of approaching depth. No increase of underneath discharge for rounded shape was observed. For the free flow over the bridge it was shown that the equation of broad-crested weir could be used.

Acknowledgement

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