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EXPERIMENTAL ASSIGNMENT OF TOTAL DRAG COEFFICIENTS OF BODIES EMBEDDED IN A FREE SURFACE STREAM

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Summary: *The paper deals with an experimental determination of total drag coefficients of bodies of various shapes embedded in a free stream flow. The shapes of bodies were chosen by such way that they could model simple bridge constructions or culverts. The bodies were mostly overflowed. The drag coefficients can be used to calculate an afflux of the embedded bodies.*

1. Introduction

Nowadays the problems of flood events are still very important. During extreme flood events the hydraulic capacities of many hydraulic structures, bridges or culverts are not sufficient to safely pass the stream through them and sometimes these constructions are overflowed. The water stream also brings a lot of debris that can be caught on the hydraulic structures and they additionally increase an afflux of the upstream section. In this paper we have focused on the problems of hydraulic design of overflowed bodies of different shapes. Usually the hydraulic calculation of overflowed structures combines the pressure flow through structure opening and flow over broad-crested weir [2,5]. In this paper we are presenting somewhat different approach to the problem of hydraulic design of overflowed structures. Similar method was used for calculation of flow through bridge piers [1]. This approach is based on application of the Newton's second law of motion. It means that the change of momentum per unit time in the section of channel flow is equal to the resultant forces acting on the bodies. If the force is known the total drag coefficients can be determined. Since such drag coefficients depend also on position of water surface level the values of drag coefficients are not constant. In the case of sufficient flow depths the influence of free water level will be negligible and the values of drag coefficients should be independent on position of free water surface.

Let we consider a channel flow with an embedded body of arbitrary shape, Fig. 1, where upstream section is marked as profile 1 and section downstream the body is marked as profile 2. For this flow section we can write following equation of momentum (neglecting shear force on the channel bed)

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$$P_1 - P_2 - F = \rho . B . \left(\int_0^{H_2} u_2^{\,2} dh - \int_0^{H_1} u_1^{\,2} dh \right) \tag{1}$$

where $\boldsymbol{P_1}$, $\boldsymbol{P_2}$ are pressure forces in profiles 1 and 2, $\boldsymbol{F}$ is force exerted by the body on the fluid, $\boldsymbol{B}$ is width of the body in the direction perpendicular to the flow, $\boldsymbol{u_1}$, $\boldsymbol{u_2}$ are local velocities. The integrals on the right side of equation (1) are momentum fluxes over the downstream and upstream sections.

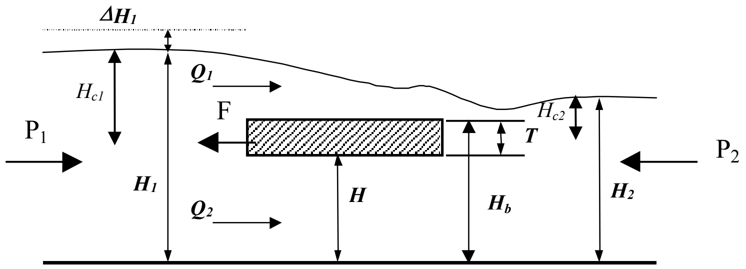

Fig.1 Schematic view of the flow over embedded body

The force $\boldsymbol{F}$ consists of static and dynamic parts ($\boldsymbol{F_S}$, $\boldsymbol{F_D}$). The static part is due to the hydrostatic pressure and can be expressed in the form

$$F_S = \rho\, g\, A \left(H_{C1} - H_{C2} \right) \tag{2}$$

where $\boldsymbol{A}$ is a projection of a front area of the body to the flow direction (for the rectangular body $\boldsymbol{A=B.T}$), $\boldsymbol{H_{C1}}$, $\boldsymbol{H_{C2}}$ are upstream and downstream distances from water surfaces to a centroid of $\boldsymbol{A}$.
The dynamic force is expressed in the common form

$$F_D = \frac{1}{2} c_D\, \rho\, A\, U_1^{\,2} \tag{3}$$

Assuming that the momentum coefficients in the profiles 1 and 2 are equal to one, the equations (1-3) can be rewritten to the following form

$$c_D = \frac{1}{A\, U_1^{\,2}} \left[gB \left(H_1^{\,2} - H_2^{\,2} \right) - 2Q \left(U_2 - U_1 \right) - 2gA \left(H_1 - H_2 \right) \right] \tag{4}$$

where $\boldsymbol{U_1}$, $\boldsymbol{U_2}$ are mean velocities upstream and downstream and $\boldsymbol{Q}$ is total discharge.

2. Experimental facility

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 obstacles were placed in the distance *16 m* from flume inlet and were oriented perpendicularly to flow direction. A downstream weir with horizontal jalousies was used to regulate the flow depth in the channel. The regulations were done by such the way that during the measurements the water levels were parallel with the channel bottom. The slope of the channel was 1:2650. Flow rates were measured using an inductive flow meter, the discharges varied between *20-47l/s*.

Two primary shapes of body cross section were tested. The first one was the rectangular shape of the length *L = 20* cm and thickness *T = 5.0 and 7.8 cm*. The second one was the rectangular shape with rounded upstream face. The radius of the rounding was *R = 5 cm*, the length of upper part of the rounded body was *L = 25 cm*. Three different thickness of rounded body were measured *T = 5.0, 7.8 and 10.6 cm*. The elevation of the bodies over the channel bottom was *H=10 cm*. Also the influence of rectangular side piers was determined for all tested bodies. The length of the piers in flow direction was *Lp=20 cm* and width was *Wp=5 cm*.

To simulate a partial blockage of the overflowed area we measured also the bodies with a simple bar railing on the top of the model of seven bars of diameter *1.1 cm*. Finally the upstream railing area was covered by a plastic gauze of hole size *3.5x3.5 mm* to simulate a very high blockage. Simple sketches of some models tested in this study are shown in Fig. 2. Reynolds numbers based on the upstream hydraulic radius and mean velocity varied from 32000 to 58000, upstream Froude numbers varied from 0,19 to 0,49.

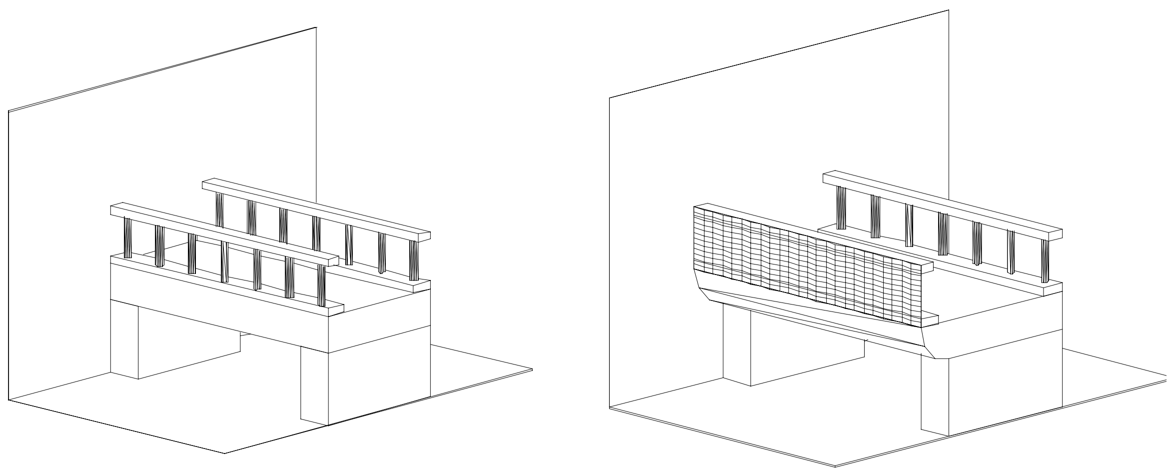

Fig. 2 Examples of the tested models – bar railing on the rectangular body with side piers (left), plastic gauze cover of upstream face on rounded body with side piers (right)

The flow depths were measured by means of ultrasonic sensors made by Pepperl+Fuchs type UC500-30GM-IU-V1 with temperature compensation. The sensors measure distances in the selectable ranges 60-500 mm. Due to the short time response (less than 35 ms) they are suitable also for measurements of water level fluctuations. The accuracy of the water level measurement is better than 0.2 mm. The analogue signal form the sensors was transferred via A/D converter and RS232 interface to PC. We applied two sensors, one was located in the upstream section, the second was placed in the downstream section. Several positions upstream and downstream were measured to obtain proper results.

3. Results and discussion

Fig.3 shows literature data [3,4] of the drag coefficients of two-dimensional bodies of rectangular and nose rounded shapes determined in a wind tunnel. Since these results are not affected by the presence of overflowed water stream such values of drag coefficient should express the lowermost limit when the flow depths are sufficiently high and the influence of free stream on flow around the bodies can be negligible.

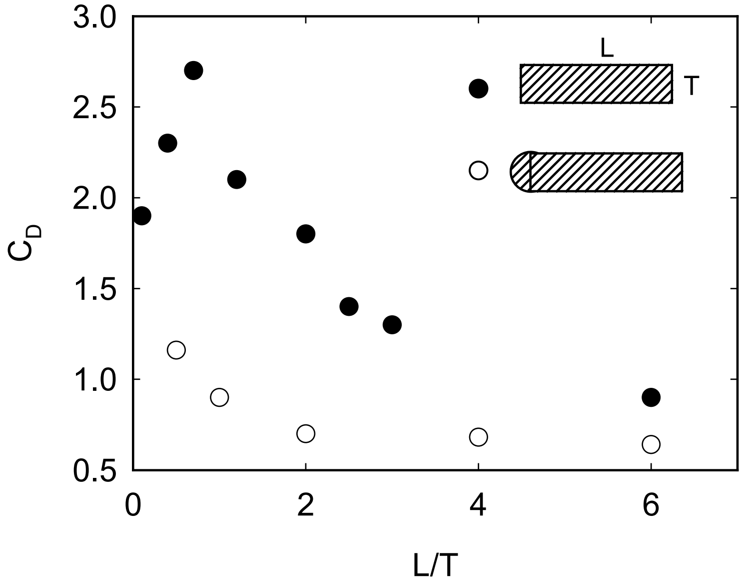

Fig. 3 Drag coefficients of two-dimensional bodies measured in wind tunnel [3,4]

The first run of experiments was performed with simple cross section shapes of the bodies - rectangular and partly rounded - of different Length/Thickness (L/T) ratios. Two values of L/T ratio were tested for rectangular shape - L/T = 4 and 2.56, while for rounded shape three length ratios were examined - L_d/T = 4, 2.56 and 1.89 (L_d means the straight length of lower face of rounded body, L_d = 20 cm). The dependency of total drag coefficients on dimensionless depth, H_2/H_b, (H_b is the elevation of upper edge of the body above the channel bottom) for these simple shapes is shown in Fig. 4. Fig. 4a,c show the drag coefficients of the bodies compounded form horizontal and vertical parts (side piers).

The behaviour of the drag coefficients is very similar for all cases. The coefficients are increasing with increasing depth and their maximum values are achieved for dimensionless depth about 1.1-1.2. With additional increase of the downstream depth the coefficients are decreasing and finally they should approach the values measured in wind tunnels. Based on data in Fig. 3 the drag coefficients measured in wind tunnel for rectangular cross section of L/T ratios equal 4 and 2.56 are 1.07 and 1.4, respectively. Compared these values with experimental data shown in Fig. 4b, it can seen that these values can be used for the dimensionless depths higher than 1.8.

The influence of rounding on total drag coefficients was estimated for maximum values of the drag coefficients. In the case without side piers the drag coefficient of rounded shape achieved about 65% value of rectangular shape and for case with rectangular side piers it was higher, about 77%.

The second experimental run was performed with more complicated cross-section. On the basic shape of rectangular and rounded cross-sections (L/T = 4) we built the simple bar railing to simulate partial blockage of overflowed area. The bar railing is manufactured from seven circular bars of diameter D1 =1.1 cm and length L1 = 5.8 cm. The bars were taken hold in two strips of height S1 = 1.1 cm and length over whole width of the channel, see Fig. 2 (right). To simulate higher blockage of the overflowed area, we covered the face part of bar railing by the plastic gauze. The size of holes was 3.5 x 3.5 mm, the width of plastic gauze between the holes was 1 mm. It means that the area of the holes was about 60% of total area.

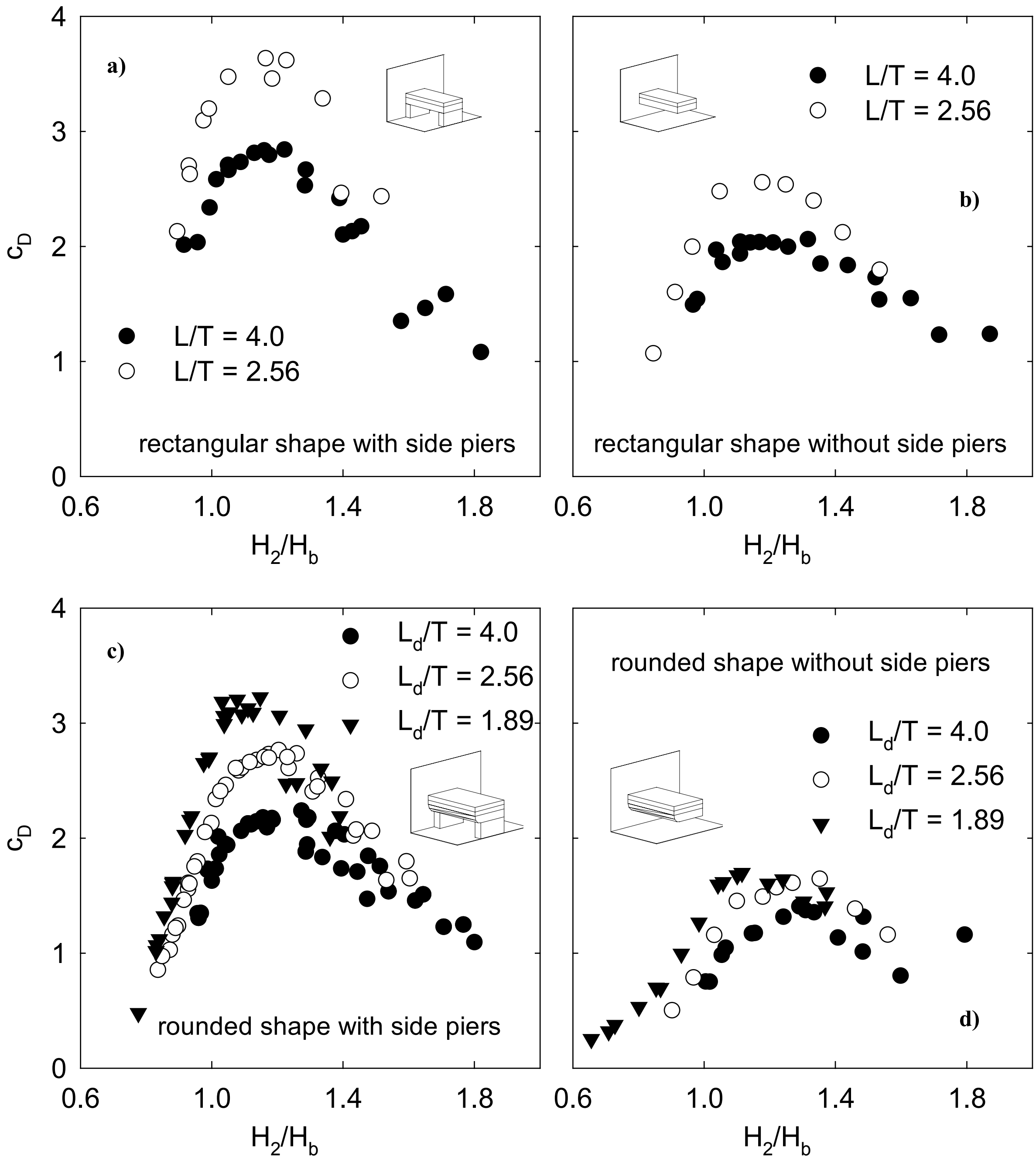

Fig. 4 Drag coefficients of the simple cross-section shapes – rectangular and rounded

The results of the drag coefficients of the partly blocked bodies are shown in Fig. 5 for the cases with (Fig. 5a,c) and without side piers (Fig. 5 b,d). The dimensionless depths were calculated from downstream depths, $\boldsymbol{H_2}$, and elevation of lower bar-keeping strip above the channel bottom ($\boldsymbol{H_b = H+T+S1}$). As can be seen in Fig. 5 there are not such sharp maximums as for simple cross sections (Fig. 4). For the plastic gauze cover the maximum values of the drag coefficients correspond to the downstream flow depth equals the elevation of the uppermost part of the bodies above the bottom. The influence of the rounding on the drag coefficients was calculated for the local maximums. For the case with side piers the drag coefficients of the rounded shape was about 84% of the values of rectangular shape and for the case without the side piers it was about 66%.

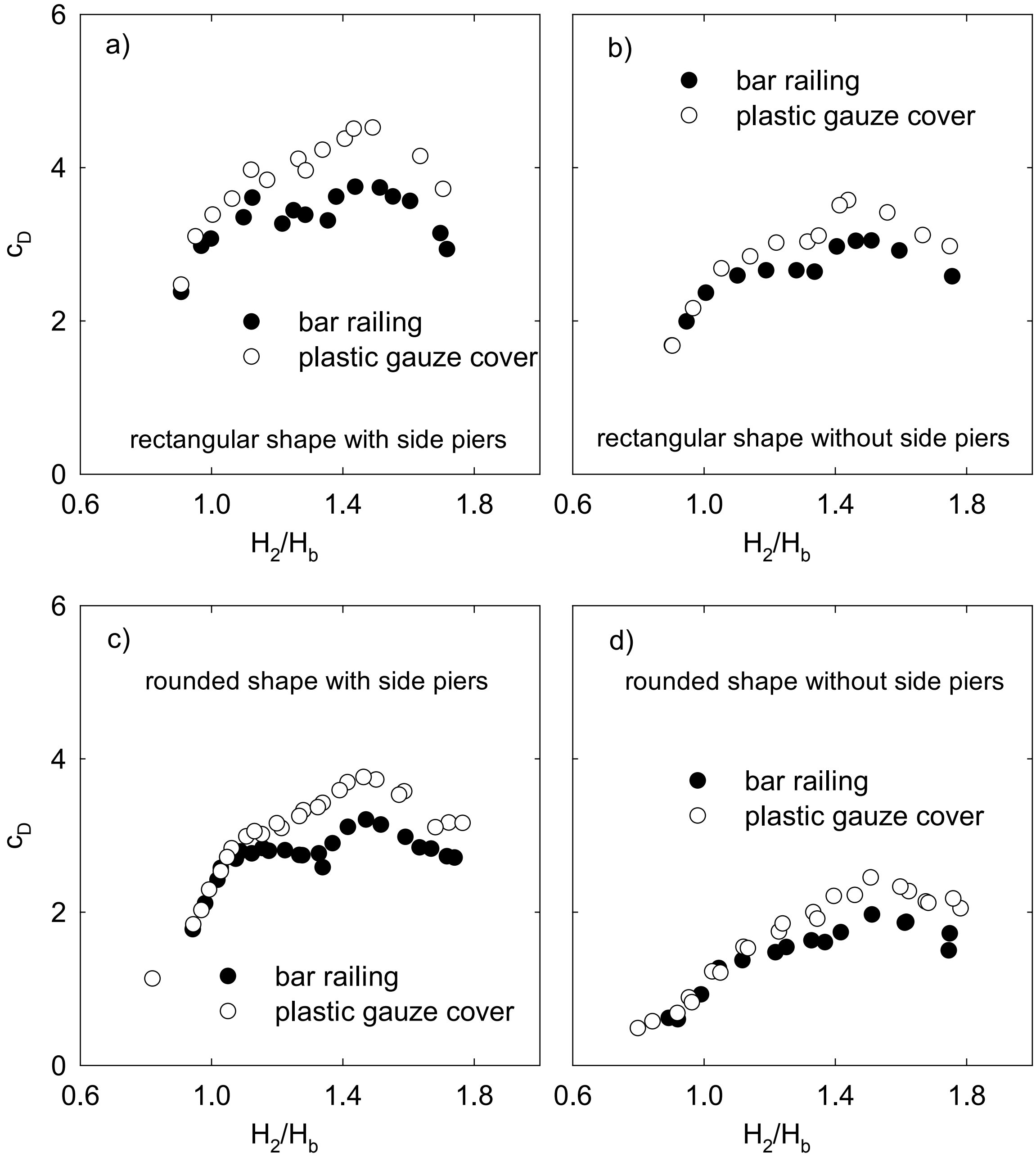

Fig. 5 Drag coefficients of partly blocked models – bar railing and plastic gauze cover

The primary aim of this paper was to determine the afflux of the embedded bodies by help of the drag coefficients. If we assume that the total discharge (***Q***), downstream flow depth ($\boldsymbol{H_2}$) and the total drag coefficient ($\boldsymbol{c_D}$) are known, the upstream flow depth can be calculated from equation (4) rearranged to the following polynomial equation

$$a_1 + a_2 H_1 + a_3 H_1^{\,2} + a_4 H_1^{\,3} + H_1^{\,4} = 0$$

$$\begin{aligned} &\textit{where} \\ &a_1 = -\frac{c_D A Q^2}{g B^3} \\ &a_2 = \frac{2Q^2}{gB^2} \\ &a_3 = -\left(H_2^{\,2} + \frac{2Q^2}{gB^2 H_2} - \frac{2AH_2}{B} \right) \\ &a_4 = -\frac{2A}{B} \end{aligned} \qquad (5)$$

In equations (5) ***A*** is the projection of the front area of the body to the flow direction, ***B*** is width of the channel and ***g*** is gravitational acceleration. The equations (5) can be used to test the influence of the drag coefficient on calculation the afflux (upstream and downstream flow depths differences). If we consider the simple rectangular cross-section of L/T ratio equals 2.56 the measured maximum value of the drag coefficient is 2.55 (Fig.4b). According to the results in wind tunnels shown in Fig.3, for the same L/T ration the drag coefficient is 1.4. Applying the equations (5) for both drag coefficients it can be shown that the afflux calculated for c_D =1.4 is only 60% of the measured value.

4. Conclusion

This paper has presented the method for determining the aflux caused by the overflowed bodies of different shapes and sizes embedded in the open channel flow. The procedure is based on application of momentum equation with appropriate values of drag coefficients of the bodies. The values of drag coefficients were determined experimentally and it was found that they are function of downstream depth.

5. Acknowledgement

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6. References

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