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SHARP-CRESTED WEIR HEAD LOSSES INVESTIGATION

The work is devoted to the rectangular sharp-crested weir calculation methods improvement. This can be realized by using mathematical model developed on energy and momentum conservation principles. In order to get energy conservation equation within sharp-crested weir we have to know weir head losses. This article presents theoretical and experimental investigations of the sharp-crested weir head losses. The height of the weir plate p_w and weir head H are estimated as main operating factors that determine hydraulic weir outbound parameters: threshold depth h and the specific weir flow q. The flow moving over sharp-crested weir suffers sudden vertical contraction and transforms from the uniform flow to a jet. Mentioned above, causes sharp-crested weir head losses. To determine these losses, we propose to use Hind's formula that describes similar contraction losses in the channel. Experimental investigations proved Hind's formula application adequacy to evaluate these losses. Sharp-crested weir energy conservation equation that includes head losses is determined. Graphs set out in the article disclose the influence of the main operating factors and their ratio on the relative head losses.

Keywords: flow energy, total head, head losses, nappe, jet flow

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1. Introduction

Sharp-crested weir or thin-plate weir is hydrotechnical structure over which the fluid must flow. Such weirs are commonly used as means of flow measurements because they are less sensitive to the downstream conditions, the channel roughness and the influence of backwater than the velocity-area method, for example [1].

Famous scientists have made significant contribution to sharp-crested weirs theory development. A.R. Berezinskij, D.I. Kumin, F.I. Pikalov, R.R. Chugaev, V.V. Smyslov, M. Castel, P. Boileau, H. Bazin, James B. Francis, A. Fteley & F. Stearns, T. Rehbock, K. Kindsvoter, R. Carter, A. Ramamurthy, N. Rajaratnam and others are among them. However, we have to admit, that in spite of large amount of carried out theoretical and experimental investigations and large bulk of obtained data, weirs calculation, in most cases, comes down to determination of flow discharge capacity by using empirically obtained weir discharge coefficients. These coefficients are obtained for small-scale weirs models with minor change of operating factors and don't take into consideration peculiarities of the weir in each specific case as well as scale factor. As a result, calculation data by different equations for the same conditions can significantly differ. Studies carried out by different scientists have shown that existing theories do not reflect with sufficient accuracy and completeness phenomena typical for sharp-crested weirs. To produce more specific and accurate solutions, a mathematical model that can link up all operating factors to solve a weir flow problem should be developed. This mathematical model can be based on the fundamental laws of conservation of mechanical energy in the form of energy and momentum equations. To get energy conservation equation for sharp-crested weir head losses should be determined.

2. Theoretical studies of sharp-crested weir head losses

To determine head losses, we consider the simplest form of weir, consisting of a plate set perpendicular to the flow in a rectangular horizontal channel with vertical upper edge running the full width of the channel b. The design circuit of such weir is shown on the figure 1.

Section $1-1$ is located in the channel upstream at a sufficient distance from the weir, where dropping curve doesn't influence the stream line surface and the flow can be suggested as uniform. Flow depth in this section is $p_w + H$, where p_w is the height of the weir plate in *cm*, H is the weir head in *cm*. Section $2-2$ is accepted through weir plate where flow depth above the crest of the weir is h in *cm*.

According to Bernoulli equation [2] total flow energy in section $1-1$ towards datum plane $0-0$ passing through the bottom of the channel, supposing that the flow is uniform, can be find in the following form

$$E_1 = p_w + H + \frac{\alpha_1 q^2}{2g(p_w + H)^2} \tag{1}$$

where α_1 is kinetic energy coefficient in section $1-1$; q is a specific weir flow that can be calculated as $q = Q/b$ in cm^2/s, where Q is total discharge over sharp-crested weir.

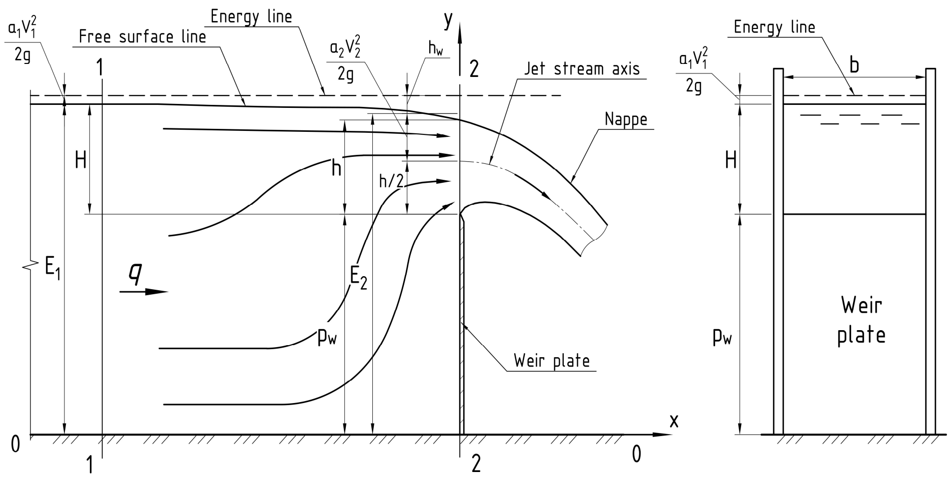

Fig. 1. Rectangular sharp-crested weir geometry

The flow moving over sharp-crested weir suffers sudden vertical contraction and transforms from the uniform flow to the nappe. As the pressure above and under the nappe is atmospheric, we consider it, with some assumptions, as jet stream flow. Hence, flow energy in section $2-2$, according to Bernoulli equation, can be calculated as following [2]

$$E_2 = p_w + \frac{h}{2} + \frac{\alpha_2 q^2}{2gh^2} \tag{2}$$

where $p_w + h/2$ is high-altitude position of the jet stream axis in cm; $(\alpha_2 q^2)/2gh^2$ is the jet stream kinetic energy in cm; α_2 is kinetic energy coefficient in section $2-2$.

To determine head losses h_w we accepted a hypothesis that they can be evaluated with Hind's formula [3], which describes similar head losses caused by sudden flow contraction in the channel

$$h_w = \zeta \frac{q^2}{2g}\left(\frac{\alpha_2}{h^2} - \frac{\alpha_1}{(p_w + H)^2}\right) \tag{3}$$

where ζ is the loss coefficient, that is determined experimentally.

Utilizing equation (3) energy conservation equation for sharp-crested weir can be given in following form

$$H + \frac{\alpha_1 q^2}{2g(p_w + H)^2} = \frac{h}{2} + \frac{\alpha_2 q^2}{2gh^2} + \zeta \frac{q^2}{2g}\left(\frac{\alpha_2}{h^2} - \frac{\alpha_1}{(p_w + H)^2}\right) \tag{4}$$

3. Mathematical processing of experimental data

In order to determine loss coefficient ζ special experimental investigations were conducted in the hydrotechnical laboratory at National University of Water Management and Environmental Engineering [4]. The height of the weir plate p_w and weir head H were estimated as main operating factors that determine weir head losses h_w. Experimental conditions are shown in table 1.

Table 1. Hydraulic experimental conditions

Factors		**Levels of variation**									**Int. of var.**
natural view	**code view**	**-1**	**-0.75**	**-0.5**	**-0.25**	**0**	**0.25**	**0.5**	**0.75**	**1**	
p_w, cm	***X_1***	5				25				45	20
H, cm	***X_2***	5	10	15	20	25	30	35	40	45	5
Experimental order for each X_1		7	21	1	2	26	15	27	5	22	
		12	3	13	18	9	20	25	14	19	
		8	6	10	16	11	23	24	17	4	

In experiments the relation between main operating factors H/p_w ranged from 0.11 to 9.0; Reynold number *Re* from 17 954 to 764 797 that corresponds to wholly turbulent flow and Froude number *Fr* from 0.003 to 0.930 that corresponds to lower flow regime.

In experiments weir plate height p_w was changing according to experimental conditions (table 1). Required weir head H was provided by changing input sharp-crested flow rate. The matrix to study the influence of the main operating factors on the average hydraulic weir outbound parameters, for example for the weir plate height $p_w = 25\,cm$, is shown in Table 2.

Table 2. Influence of the main operating factors on the weir head losses hw

Factors				**Averaged experimental values**		**Calculated values**			
code view		**natural view**							
						weir head losses h_w		**relative weir head losses h_w/E_1**	
X_1	**X_2**	**p_w**	**H**	**specific weir flow q**	**threshold depth h**	**exp. (5)**	**theor. (3)**	**exp.**	**theor.**
		cm	*cm*	*cm²/s*	*cm*	*cm*	*cm*		
0	-1	25	5	205.76	4.29	1.63	1.64	0.054	0.055
	-0.75		10	596.65	8.63	3.25	3.26	0.093	0.093
	-0.50		15	1134.68	13.05	4.89	4.88	0.121	0.121
	-0.25		20	1777.11	17.34	6.47	6.49	0.141	0.142
	0		25	2570.96	21.84	8.12	8.10	0.158	0.158
	0.25		30	3457.50	26.22	9.73	9.72	0.170	0.170
	0.50		35	4449.69	30.59	11.34	11.33	0.180	0.180
	0.75		40	5562.86	35.02	12.98	12.95	0.188	0.188
	1		45	6705.77	39.19	14.52	14.56	0.194	0.194

Statistical parameters	
Error mean square $\overline{S}_{e}^{2} \cdot 10^4$ for $f_e = 54$, cm^2	285.52
PRESS statistic $\overline{S}_{a}^{2} \cdot 10^4$ for $f_a = 26$, cm^2	292.50
Calculated F-test $\overline{F}_p$	1.025
Table F-test F_m	1.70
Error $\pm\bar{\varepsilon}$, % reporting to $\zeta = 1.35$	$\pm$ 1.70

Experimental weir head losses h_w for each point of experiment plan according to obtained experimental values of specific weir flow q and threshold depth h were determined by equation (4), that is given in the following form

$$h_w = H - \frac{h}{2} + \frac{q^2}{2g}\left(\frac{\alpha_1}{(p_w + H)^2} - \frac{\alpha_2}{h^2}\right) \tag{5}$$

For verification accepted hypothesis, weir head losses computed with Hind's equation (4) were compared with experimental values calculated with equation (6). Unknown loss coefficient ζ in equation (4) was determined according to statistical experimental data processing, with probability of 95%, and assumed equal to $\zeta = 1.35$.

The influences of main operating factors: height of the weir plate p_w, weir head H and their ratio H/p_w on the weir head losses h_w were made by relative head losses h_w/E_1 – ratio of the weir head losses to total flow energy in section $1-1$ calculated with equation (1).

$$h_w/E_1 = h_w \Bigg/ \left(p_w + H + \frac{\alpha_1 q^2}{2g(p_w + H)^2} \right) \tag{6}$$

Relative head losses h_w/E_1 were calculated for experimental weir head losses h_w obtained by equation (5) and for theoretical values by the Hind`s formula (6). Calculation data is shown in table 2.

Figures 2–4 displays experimental points of the relative weir head losses, depending of main operating factors: height of the weir plate p_w, weir head H (fig. 2, 3) and their ratio H/p_w (fig. 4). Experimental points in this diagrams are approximated by solid lines obtained by Hind's formula.

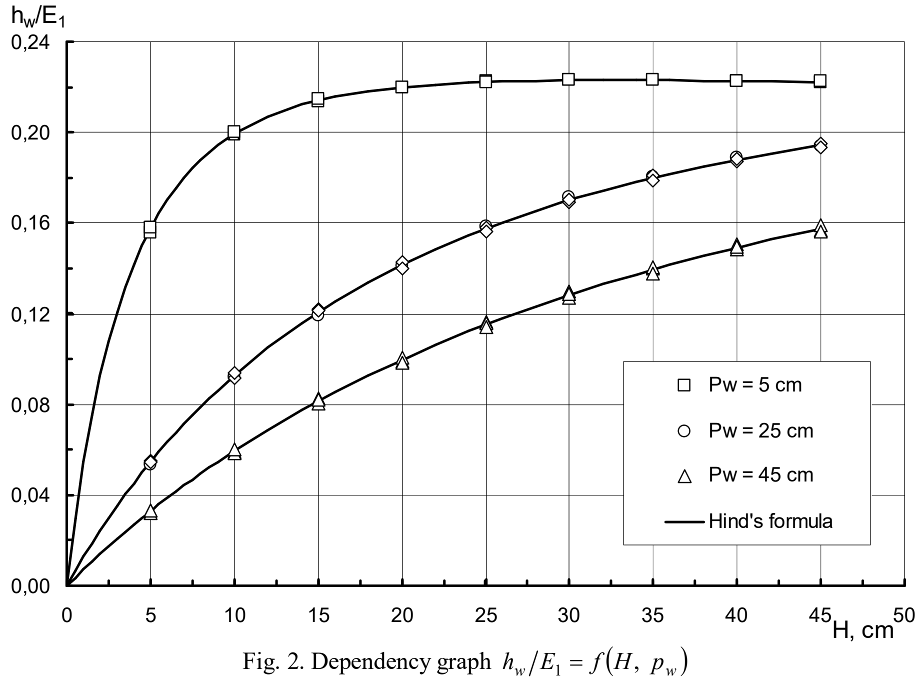

Fig. 2. Dependency graph $h_w/E_1 = f(H,\ p_w)$

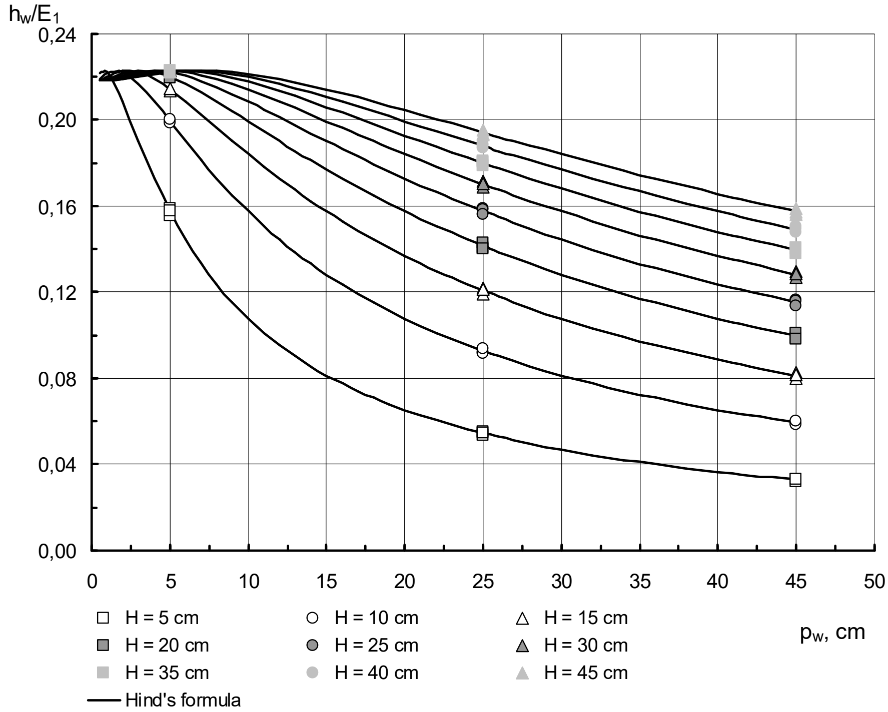

Fig. 3. Dependency graph $h_w/E_1 = f(p_w,\ H)$

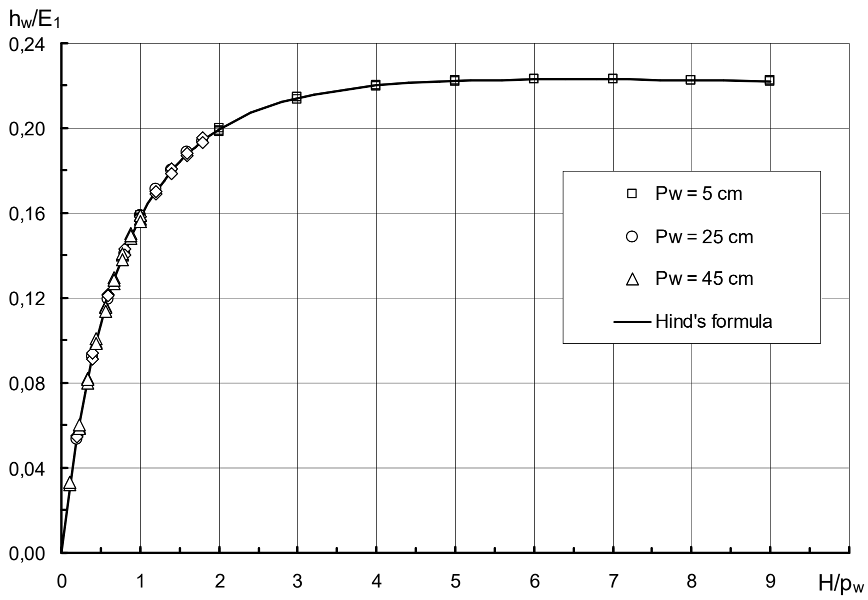

Fig. 4. Dependency graph $h_w/E_1 = f(H/p_w)$

Obtained graphs analysis in figure 2 has shown, that with weir head H rising relative weir head losses h_W /E_1 increase monotonically. Behavior of the relative weir head losses change is strongly pronounced at low weir plate height ($p_w = 5\,cm$), at this time, they rise sharply in low heads and with further increase they asymptotically tend to their maximum.

Obtained graphs analysis in figure 3 has shown, that for small values of the weir plate height p_W relative weir head losses h_W /E_1 go up and under certain weir plate height they reach their maximum value, then these losses are reduced. Behavior of the relative weir head losses change is strongly pronounced in low heads.

Obtained graphs analysis in figure 4 has shown, that experimental relative weir head losses h_W /E_1 are approximated in dimensionless coordinates with universal graph $h_w/E_1 = f(H/p_w)$ that is calculated by Hind`s formula and it does not depend on the weir plate height. Within the range $0 < H/p_w \le 2$ relative head losses rise sharply, with further ratio increase they asymptotically tend to maximum $h_w/E_1 \approx 22\%$.

4. Conclusions

Based on theoretical and experimental investigations an energy equation for sharp-crested weir that considers head losses is determined. Adequacy of Hind`s formula usage to determine weir head losses is proved and the influence of main operating factors: height of the weir plate p_W, weir head H and their ration H/p_W on the relative head losses is disclosed. Obtained energy equation is the part of mathematical model for sharp-crested water flow that will improve weir calculation methods.

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