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Energy LossesAlong Broad Crested Weir Within a Large Circular Open Channel

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ABSTRACT:*In this experimental investigation some geometrical characteristics and the determination of the energy losses, from the water flow over a broad crested weir within a large circular (D) open channel, are presented, analyzed and discussed. The diameter D=const., while the lengths L of the weir and the upstream hydraulic heads h are varying. The one-dimensional equations are presented and the dimensionless energy losses, $\Delta H/H_1$, from the flow over the weir are calculated – based on laboratory experiments. The dimensionless critical flow depths y_c over the weir's crest are related to dimensionless distances (L_c) from the weir's brink, while the dimensionless downstream (beyond the weir) depth is also investigated and two relative equations are proposed. $\Delta H/H_1$ is related to the ratios h/L and L/D and a dimensionless equation is provided. The authors believe that the present results may help the hydraulic engineer when designing pertinent hydraulic structures.*
KEYWORDS*: Circular open channel,Broad Crested weir, Energy losses.*

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I. INTRODUCTION

When dealing with large conduits (of circular cross section) with a water free surface profile (open channel) and a subcritical flow,there is always a need of discharge measurement. This task is not so easy, especially if the conduits are under the ground (sewers, storm water conduits, large culverts or drainage / irrigation central pipes).

In such cases, for horizontal or slightly sloped conduits, Rekatsinas et al., (2011), [1], Daniilidis et al., (2011), [2], and Dimitriou et al., (2011), [3], have proposed the use of a broad crested weir with a circular transverse base and a plane crest, similar to corresponding broad crested weirs within rectangular open channels. In these three experimental investigations two rounded (r, radius) broad crested weirs, high and low respectively, were proposed, while some basic elements of the flow geometry, the dynamic forces and suitable discharge coefficients equations were concluded. Other interesting works are by Boss (1976), [4], and Hershy (1985), [5].

In the present experimental study a number of more flow characteristics and the mechanical energy losses over the weir, are investigated.Fig. 1 schematically presents the geometry of both the weir and flow over it.The main part of the flow over the weir (of height w=const. and changing lengths, L) starts from the uniform flow cross section 1 (y_1, V_1, E_1, B_1, Fr_1) and ends up at the uniform flow cross section 2 (tailwater depth y_2, and V_2, E_2, B_2), while over the weir's crest a critical flow cross section is appearing (y_c, V_c, E_c, B_c, Fr_c=1). The Froude number at cross sections 1, 2, are

$$Fr_1 = V_1 \cdot g^{-1/2} \cdot (E_1/B_1)^{-1/2} < 1,$$

$$Fr_2 = V_2 \cdot g^{-1/2} \cdot (E_2/B_2)^{-1/2} > 1.$$

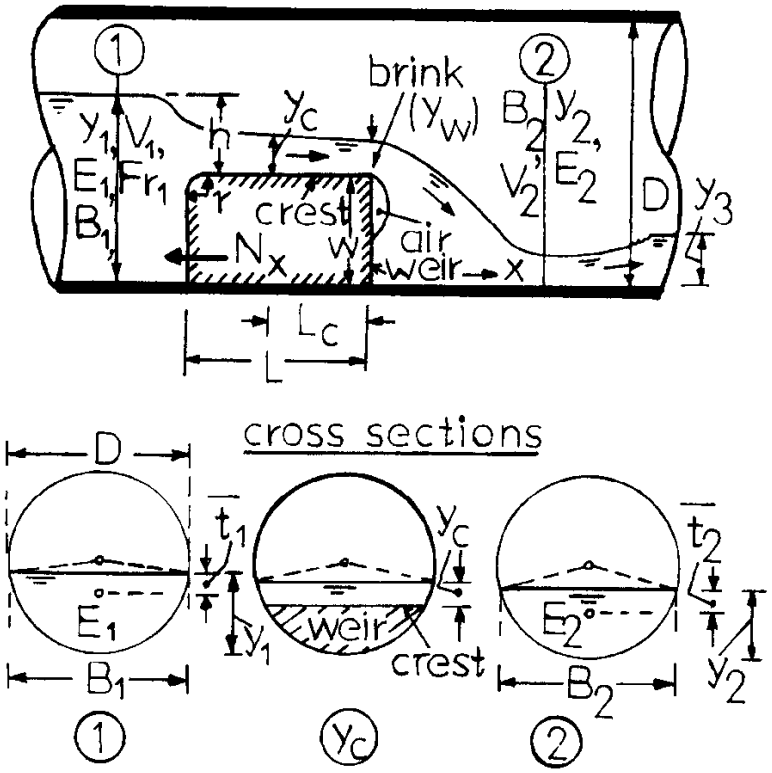

Figure 1: Schematic weir and flow geometry.

On the cross sections 1, 2 (E_1, E_2), the pressures are hydrostatically distributed,while B_1, B_2, are the corresponding free surface widths. The initial Reynolds numbers, $Re_1 = V_1 \cdot d_1/\nu$, are very large (turbulent flows), while between cross sections 1 and 2a total force N_x is exerted from the weir and the shear stresses along x. The hydraulic head of the entire flow is h=y_1-w, while the internal diameter of the conduit is D (=const.).

Beyond cross section 2 a hydraulic jump is created with a downstream water depth y_3 (cross section 3) and E_3, B_3, V_3, since the downstream sluice gate was properly semi-closed.

II. PREVIOUS RESULTS

Rekatsinas et. al. (2011), [1], have given in the past the following experimental results:
For the water depth (y_w) at the brink,

$$y_w/L \cong 2.38 \cdot [(h/L) - \beta],$$

where β is a parameter depending on D/L ratio.

For y_c,

$$y_c/h \cong 0.735.$$

For the discharge coefficient,

$$c_d = 0.63 + 1.62 \cdot \{(D/L) - 4.97 \cdot (h/L)\} - 0.40 \cdot \{(D/L)^2 - 204.47 \cdot (h/L)^2\} - 7.86 \cdot (h/L) \cdot (D/L)\ ,$$

to be used in the equation,

$$Q = c_d \cdot (2/3)^{3/2} \cdot g^{1/2} \cdot D \cdot h^{3/2}.$$

Dimitriou et al. (2011), [3], have given the equations:

For y_2/wvsy_w/w,

$$y_2/w = 0.314 - 0.0008 \cdot (y_c/w)^{-3}.$$

For the force N_x,

$$K_N = N_x/P_x = -5.131 + 242.26 \cdot (h/L) - 3{,}161 \cdot (h/L)^2 + 17{,}102 \cdot (h/L)^3 - 32{,}860 \cdot (h/L)^4 - 0.421 \cdot (L/D).$$

III. ONEDIMENSIONAL EQUATIONS – ENERGY LOSSES

The one-dimensional equations along x are,

$$Q = V_1 \cdot E_1 = V_c \cdot E_c = V_2 \cdot E_2, \quad (1)$$

while the momentum equation (with ρ=water density and g=gravity intensity) is

$$P_x - N_x = \rho \cdot Q \cdot (V_2 - V_1), \quad (2)$$

where

$$P_x = \rho \cdot g \cdot [(\bar{t}_1 \cdot E_1) - (-\bar{t}_2 \cdot E_2)]$$

is the total pressure force (1, 2), $\bar{t}_1$, $\bar{t}_2$, are the vertical distances of the centroids of E_1, E_2, from the free surface of the flow and N_x is the dynamic force from weir and boundary shear stresses along x.

From the point of view of mechanical energy, the energies at stations 1 and 2 are

$$H_1 = y_1 + (V_1^2/2g),$$

$$H_2 = y_2 + (V_2^2/2g),$$

while the loss of energy is

$$\Delta H = H_1 - H_2.$$

The loss of energy may be expressed in dimensionless terms, e.g. $\Delta H/H_1$. ΔH is a function of h/L and L/D,

$$\Delta H = f(h/L, L/D),$$

i.e. it a function of $h=y_1-w$, L, which had various lengths in the present experiments, D, which was constant, Fr_1, E_1, B_1. All these quantities were measured (or calculated) in the experiments, and a number of $\Delta H/H_1$ were received.$\Delta H/H_1$should be close to zero in order that the weir is properly working.The use of the present experimental results may also be extended in practice, at the same dimensionless parameters' ranges and for any D.

IV. THE EXPERIMENTS

The authors have used a rather large circular PVC conduit of internal diameter D=47.5cm and a length of about 10m. The (smooth) weir, with a circular transverse bottom was placed at a distance 2.3m from the conduit end, while the lengths L=30-40-50-60-70cm, in various combinations with h, were used. w was constant, w=16.7cm (corde=45.36cm), while $0.06 \le h/w \le 0.34$, $0.055 \le h/L \le 0.146$, $0.75 \le c_d \le 1.25$, $13{,}045 \le Re_1 \le 37{,}500$, $(V_1^2/2g)/y_1 \le 5\,^{o}/_{oo}$, and $0.044 \le Fr_1 \le 0.126$. Three constant vertical depth gauges were used far upstream, at 1m distances among them, to confirm the upstream uniform flows (depths' differences less than 0.5mm), while a movable depth gauge was also used on and around the weir. The various discharges, Q_i, were accurately measured through a far upstream Venture tube and a vertical manometer, while a large number ofy_1, y_2, and y (especially y_c) depths were also determined for y_c/L. The mean velocities V_i at any crosssection E_i were calculated as $V_i=Q/E_i$, while the water free surface widths B_i were geometrically determined. h and L were also used in the ratios h/L, D/L, while h/D varied between 0.064 and 0.137. All geometrical quantities were measured along the centerline vertical plane of the conduit.

Based on the above experimental details, the following ratios may also be useful, D/w=2.84, D/L=1.58-1.19-0.90-0.79-0.68, which also may used in practical examples by the hydraulic engineer.Table 1 gives all characteristics of the experimental Runs.

V. RESULTS AND DISCUSSION

Fig. 2 presents the relationship between the ratios L_c/L and y_c/L. A suitable line is traced among the experimental points (least squares' method of best fit) and an equation is deduced,

$$L_c/L = -0.138 + 0.003 \cdot (y_c/L)^{-2} \quad (3)$$

holding for $0.166 \le L_c/L \le 0.812$ and $0.06 \le y_c/L \le 0.106$.

It is to be noticed that along some experimental Runs, more than one places with depth y_c – over the weir's crest – were appearing. In this study only the closest to the weir's brink y_c were taken into consideration.

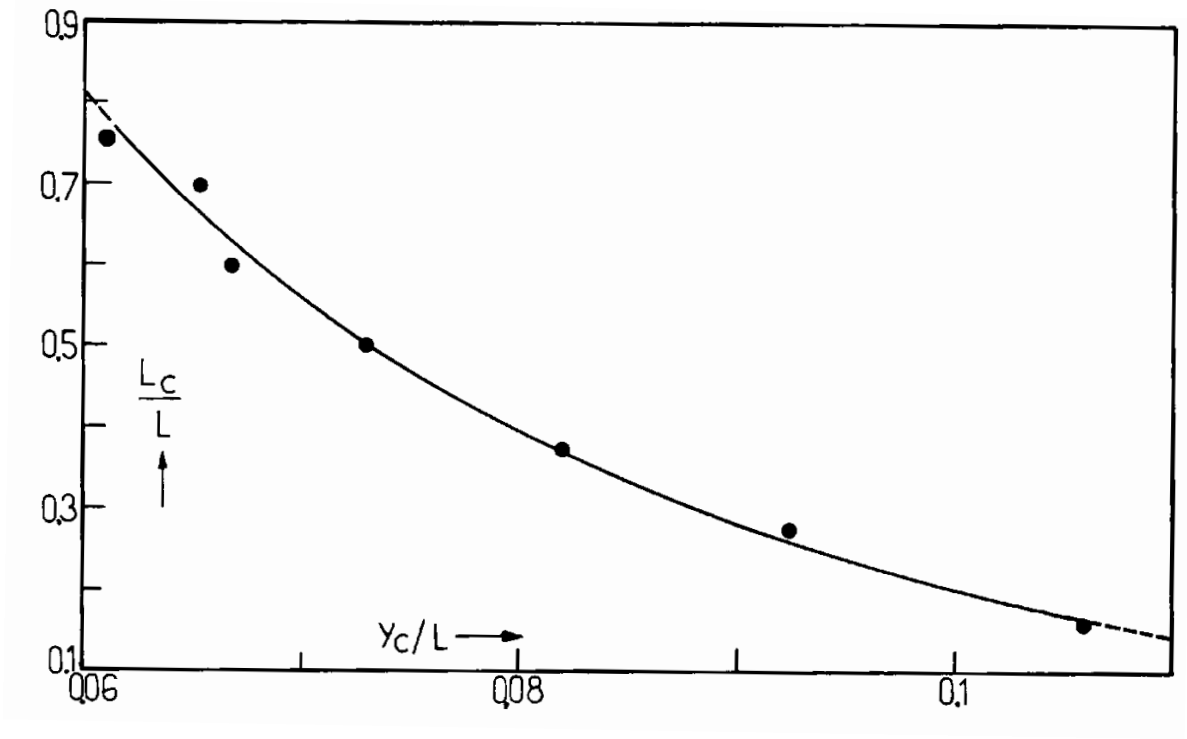

Figure 2: L_c/L vs y_c/L.

Table I. Experimental Measurements

Run	L (cm)	Q (L/s)	y_1 (cm)	V_1 (cm/s)	Re_1	Fr_1
1	30	4.68	19.77	6.70	13,126	0.055
2	30	7.096	20.74	9.54	19,600	0.076
3	30	9.978	21.62	12.71	27,209	0.099
4	40	6.76	20.54	9.21	18,729	0.074
5	40	9.645	21.58	12.31	26,315	0.096
6	40	12.90	22.48	15.62	34,771	0.119
7	50	6.20	20.44	8.50	17,204	0.068
8	50	9.11	21.42	11.74	24,912	0.092
9	50	12.795	22.51	15.46	34,475	0.118
10	60	6.90	20.73	9.28	19,061	0.074
11	60	9.88	21.74	12.495	26,896	0.097
12	60	13.05	22.66	16.252	35,400	0.126
13	70	9.94	22.04	12.34	26,949	0.095
14	70	11.71	22.60	14.08	31,515	0.107
15	70	14.04	23.21	16.32	37,499	0.122
16	30	3.84	20.14	5.37	10,706	0.044
17	30	4.71	20.56	6.41	13,045	0.052
18	30	6.25	21.10	8.22	17,170	0.065
19	40	3.52	19.00	5.32	10,003	0.045
20	40	5.74	19.98	8.11	16,044	0.066
21	40	7.92	20.93	10.53	21,813	0.084
22	50	6.67	19.45	9.76	18,809	0.082
23	50	8.08	21.05	10.66	22,214	0.085
24	50	10.15	22.28	12.43	27,430	0.096
25	60	8.52	21.40	10.99	23,305	0.086
26	60	10.24	21.95	12.79	27,796	0.099
27	60	12.62	22.64	15.14	33,947	0.115
28	70	8.68	21.67	11.02	23,653	0.086
29	70	11.55	22.47	13.99	31,136	0.107

Fig. 3 presents the relationship of y_3/w, at the end of downstream depths of the hydraulic jumps, with the wellknownRand's parameter $T=(y_c/w)^3$. The line through the experimental points has an equation

$$y_3/w = 0.388 - 0.011 \cdot (y_c/w)^{-1.5} \quad (4)$$

and holds for $0.02 \leq y_c/w \leq 0.023$ and $0.17 \leq y_3/w \leq 0.32$.

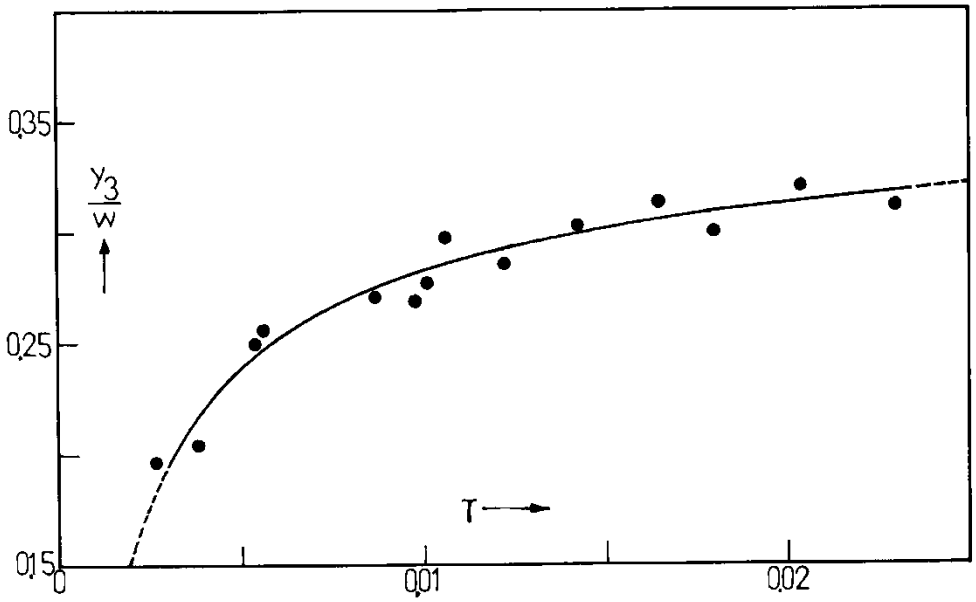

Figure 3: y_3/w vs T.

In order to have a better perception about the hydraulic jump between cross sections 2, 3, Fig. 4 gives the relationship between y_3/y_2 and Fr_2.

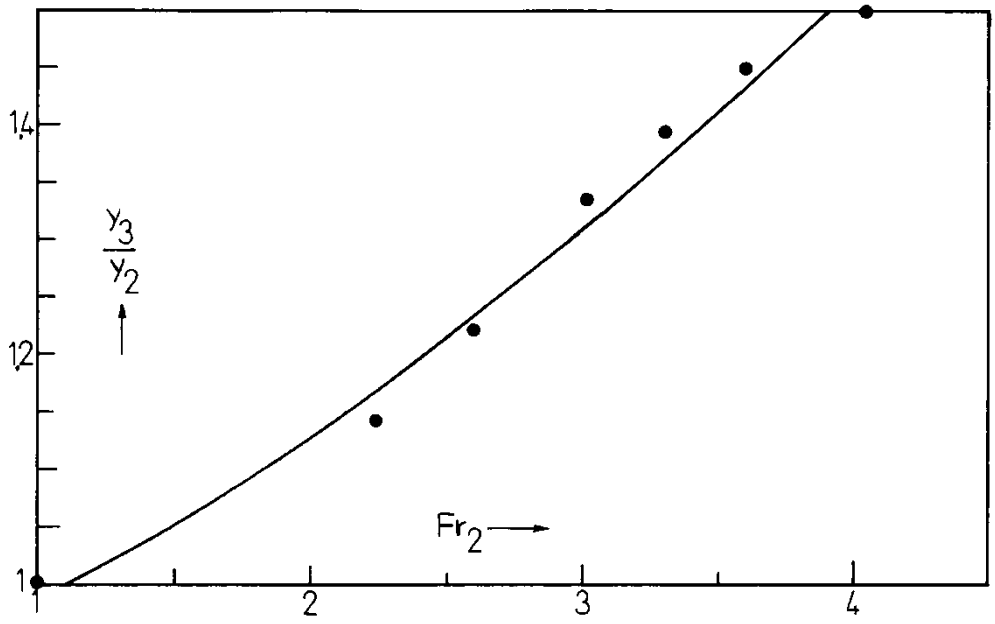

Figure 4: y_3/y_2 vs Fr_2.

A proper curve though the experimental points, gives the equation

$$y_3/y_2 = 0.911 + 0.076 \cdot {Fr_2}^{1.5} \quad (5)$$

which shows that for $Fr_2=1$ y_3/y_2 is very close to unity. Eq. (5) holds in the field $1 \leq Fr_2 \leq 4$and $0.99 \leq y_3/y_2 \leq 1.53$.

Table 2 presents the various parameters concerning the calculated values (based on the present measurements) of $\Delta H/H_1$, vs h/L and L/D, which in general are very small, and show that the weir is functioning well.

Table II:$\Delta H/H_1$ vs h/L and L/D.

h/L	L/D	$\Delta H/H_1$
0.067	1.26	0.24
0.071	1.47	0.42
0.076	1.47	0.31
0.078	1.26	0.43
0.082	1.47	0.39
0.084	1.26	0.32
0.084	1.47	0.30
0.087	1.05	0.31
0.088	1.26	0.29
0.093	1.47	0.30
0.094	1.05	0.39
0.099	1.26	0.30
0.099	1.26	0.19
0.106	0.84	0.23
0.116	1.05	0.21
0.117	1.05	0.56
0.122	0.84	0.32
0.129	0.63	0.38
0.134	0.63	0.20
0.145	0.84	0.20
0.147	0.63	0.52
0.164	0.63	0.29

A computer processing of the data of Table 2, gave an approximate and relatively simple dimensionless equation,

$$\Delta H/H_1 = 16{,}84 + 0{,}006 \cdot (h/L)^{-1} - 68{,}46 \cdot (L/D) + 102.51 \cdot (L/D)^2 - 66.17 \cdot (L/D)^3 + 15.88 \cdot (L/D)^4, \quad (6)$$

holding for $0.067 \leq h/L \leq 0.164$, $0.63 \leq L/D \leq 1.47$, and $0.24 \leq \Delta H/H_1 \leq 0.38$, and in all the intermediate ratios as well.

It appears that there are some smaller $\Delta H/H_1$ ratios - of about $\Delta H/H_1 \cong 0.30$ - in the fields $0.10 < h/L < 0.14$ with $0.75 < L/D < 1.0$, and $0.08 < h/L < 0.105$ with $1.15 < L/D < 1.38$, while between those two fields a maximum $\Delta H/H_1 \cong 0.35$is appearing.

Fig. 5 presents a graph of eq. (6) in terms of iso-($\Delta H/H_1$) lines (in distorted scales). This graph is rather indicative and eq. (6) should be used instead.

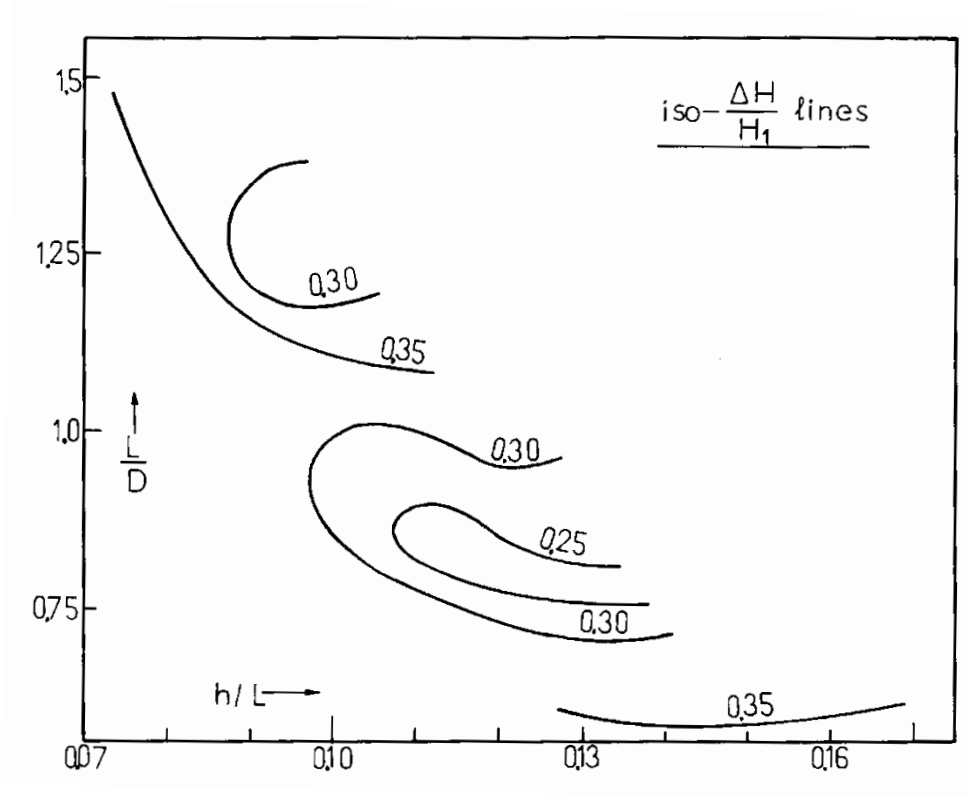

Figure 5: Iso – ($\Delta H/H_1$) lines.

VI. CONCLUSIONS

In this experimental study some geometrical characteristics and the prediction of the mechanical energy losses, from the water flow over a broad crested weir w (with a plane crest and a circular base) within a large circular (D) open channel, are presented, analyzed and discussed. D and ware constant, while the weirs' lengths (L) and the hydraulic heads(h) are varying. The main conclusions are: 1) The dimensionless critical depths (y_c) over the weir's crest, are properly related to the dimensionless distance of them from the brink (L_c) through eq. (3). 2) The downstream dimensionless depths y_3/w are related to y_c/w through eq. (4). 3) Eq. (5) explains the relationship between y_3/y_2 and Fr_2 in the downstream hydraulic jump. 4) The energy losses are related to h/L and L/D through eq. (6). 5) Fig. 5 gives a graph presenting eq. (6). The authors believe that this investigation may help the hydraulic engineer when designing pertinent hydraulic structures.

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