CHARACTERISTICS OF FLOW OVER UNGATED OGEE SPILLWAY

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ABSTRACT

The study of flow characteristics of ungated ogee spillway gives better understanding of its design criteria. In the present study; the velocity coefficient C_v, the depth of flow at the toe h, and the pressure distribution on the spillway surface are investigated. A semiempirical approach based on the energy equation is used to obtain accurate evaluation of the toe depth. A closed form solution is then developed to estimate the velocity coefficient and the toe depth. A comprehensive experimental study on two different types of spillway shaped crest, having different heights, is carried out to verify the developed relationships. The pressures along the spillway surface are measured, from which the pressure distribution is determined. Accordingly, design charts are plotted to evaluate the pressure forces. A design example is given to demonstrate the solution procedure using the obtained equations and charts.

NOTATIONS

A, B	One-half of the major and the minor ellipse axes respectively;
a	Height of spillway crest;
C	Discharge coefficient, $C=q/H^{3/2}$;
C_o	Discharge coefficient corresponding to the design head H_d, $C_o=q/H_d^{3/2}$;
C_v	Velocity coefficient;
E_o	Total energy, $E_o=a+H_o$;
F	Pressure force acting on the downstream face of spillway;
g	Gravity acceleration;
H	Head acting on the spillway;
H_o	Design head of the standard spillway;
H_o	Total head on the spillway;
h	Flow depth at the toe of spillway;
h_c	Critical depth;
h_L	Energy loss;
P	Pressure;
q	Discharge per unit width;
v_a	Velocity of the approaching flow at the spillway;
v	Velocity of the flow at the spillway toe;
x, y	Cartesian coordinates;
α_1, α_2	Energy correction coefficients;
γ	Specific weight of water;
ρ	Water density;
μ	Dynamic viscosity.

1. INTRODUCTION

The uncontrolled ogee spillways are hydraulic structures, designed to release excess discharges, which might cause unexpected damage. The advantages of the ungated spillway eliminate the need to constant attendance and regulation of the gate and avoid the necessity to regular maintenance and repairs.

The crest of ogee spillway has a shape conforming to the profile of lower nappe of flow passing over a sharp crested weir. To insure a continuous contact between the flow and the spillway surface, the profile is shaped according to the design head H_d, which is defined as the head at which the pressure on the crest is atmospheric. However, the spillway may also be operated at lower or higher heads. Therefore, the characteristics of flow over such spillways should be studied for heads differ than the design head.

The characteristics of the flow over ogee weirs are influenced by the head over the weir, the weir height and geometry, acceleration due to gravity, density of flow, surface tension, viscosity and weir roughness [1].

The most important items which are considered in the design of the ogee spillway are; the crest shape, the free surface profile, the discharge and the velocity coefficients, the pressure distribution on spillway surface and the depth of flow at the toe.

The design of spillway crest is optimal if the profile of flow over spillway closely approximates the fully airated nappe of flow over a sharp crested weir. However, the shape of this nappe is affected by the relative head H/H_d, approaching velocity and the slope of the upstream face of the weir.

Extensive experiments on the crest shape by the U.S. Army Corps of Engineers yielded simple design equations. Studying the measured nappe profils, the U.S. Bureau of Reclamation reported results which are in close agreement with U.S. Army Corps of Engineers. Review of these studies have been given by Chow [2]. Improvement in the design of crest shape has been presented [3,4 and 5].

The free surface profile of flow over ogee spillway has been studied by Cassidy [6] and Ali [7]. The discharge coefficient for such spillways has been extensivly investigated experimentally and theoretically [4, 5, 6, 8, 9, 10, 11 and 12].

The pressure distribution on both the upstream face and the crest was studied [2, 4, 5, 6, 7, 8 and 13]. To the best of the author's knowledge the pressure along the downstream face of spillway has not been thoroughly investigated.

The depth of flow at the toe of spillway is usually obtained using graphs for specific values of velocity coefficient C_v. Some methods solve the energy equation using trial and error procedure for assumed values of C_v which causes difficulties [12].

It is obvious from the previous studies for the characteristics of uncontrolled flow over ogee spillways that both the pressure distribution along the downstream face and the depth of flow at the toe are not sufficiently investigated.

Since the stability of the spillway is affected by the total pressure forces acting on its downstream face, these forces should be determined.

The toe depth of the flow should be accurately estimated, since it influences various downstream conditions such as; flow velocity, Froude number at the toe, the type of the formed hydraulic jump and the design of any required measures for energy dissipation.

Therefore, the present article mainly aims to establishing a criteria to evaluate the pressure forces on the downstream face and to accuratly estimate the flow depth at the toe of an ogee spillway.

2. THEORETICAL STUDY

Flow characteristics on the downstream apron of the spillway depend on many factors. The most important factor is the effect of the energy remained in the flow upon reaching the tail water. This energy is significa affected by the toe depth. The value of the toe depth considerably influenced by the head on the spillway, th height and the shape of the spillway crest.

The toe depth may be investigated either by applying th energy equation or using the dimensional analysis. Figu (1) shows a schematic representation of flow over ungate spillway. First the toe depth will be developed accordin to the energy considertation and secondly by using th π-theorem.

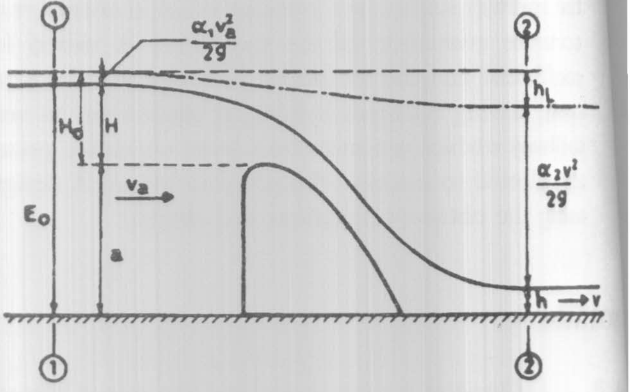

Figure 1. Definition sketch for flow over ungated spillway.

2.1 The Energy Consideration

To apply the energy equation between two sections, the energy losses must be considered. The velocity coefficien Cv is introduced to account for the loss of energy betwee the upstream and downstream sides of spillway.

Equating the total energies at sections 1-1 and 2-2; an take the downstream bed as a datum we get;

$$E_o = h + \frac{\alpha_2 v^2}{2g} + h_L = h + \frac{\alpha_2 q^2}{2g\, c_v^2\, h^2} \qquad ($$

where;

$$E_o = a + H_o \ ,$$

$$H_o = H + \frac{\alpha_1 q^2}{2g(a+H)^2}$$

Assuming, $\alpha_1 = \alpha_2 = 1.0$, and substituting for $\frac{q^2}{g} = h_c^3$ in Eq.(1), where h_c is the critical depth, yields;

$$h^3 - E_o h^2 + \frac{h_c^3}{2c_v^2} = 0. \qquad (2)$$

Eq. (2) is a cubic equation for h. Using Cardan's solution [14], Eq. (2) has the following three roots;

$$h = \frac{E_o}{3}[1 + 2\cos\frac{\theta}{3}], \qquad (3\text{-a})$$

$$h = \frac{E_o}{3}[1 - 2\cos(\frac{\theta}{3} + \frac{\pi}{3})] \qquad (3\text{-b})$$

$$h = \frac{E_o}{3}[1 - 2\cos(\frac{\theta}{3} - \frac{\pi}{3})] \qquad (3\text{-c})$$

where,

$$\cos\theta = 1 - 6.75\,\frac{1}{C_v^2}(\frac{h_c}{E_o})^3 \qquad (4)$$

Eq. (3-c) gives a negative value for h, while Eqs. (3-a) and (3-b) give values of $h > h_c$ and $h < h_c$, respectively. The former value of h represents the toe depth in the submerged downstream condition, while the latter is the depth of the free flow condition. Considering the second case in the present study, the toe depth h can be easily calculated using Eq. (3-b).

2.2 *The Dimensional Analysis Consideration*

An analytic method can be conducted to determine the toe depth of the releasing flow over a spillway of specific shape in a gravity field. As shown in Figure (1) the variables that determine the flow depth at the toe are related as;

$$h = f\,(q, a, H, g, \rho, \mu) \qquad (5)$$

Application of the π-theorem to Eq. (5) produces,

$$f_1(\frac{H}{a}, \frac{h}{a}, \frac{a^3 g}{q^2}, \frac{\mu}{\rho q}) = 0 \qquad (6)$$

If the viscosity effect is neglected, Eq. (6) becomes,

$$\frac{h}{a} = f_2(\frac{h}{a}, \frac{a^3}{h_c^3}) \qquad (7)$$

Eq. (7) can be modified to the form;

$$\frac{h}{H} = f_3\left[\frac{H^{0.25} h_c^{0.75}}{a}\right]^4 \qquad (8)$$

3. EXPERIMENTAL ARRANGEMENTS

The present experiments were carried out in a horizontal rectangular flume having a length of 4.0 m and width of 0.19 m. The flume was fabricated from 8 mm perespex sheet supported by a steel frame. Coated wooden models for the ogee weir were inserted into the flume. Depthes of flow were measured by a point gauge. The discharges passing over the weir were measured by a V-notch weir. As shown in Figures (2) and (3) two different shaped crest models for the spillway with vertical upstream face were used. The first has an elliptical crest shape with axes ratio of 2:1 constructed for a design head $H_d = 9.2$ cm according to the data reported in [12]. The second model was constructed according to the standard shape crest proposed by the U.S. Army Corps of Engineers with design head $H_d = 7.0$ cm. For each shape two heights of spillway were used; 20.8 and 14.9 cm for the first model, and 19.5 and 17.5 cm for the second model.

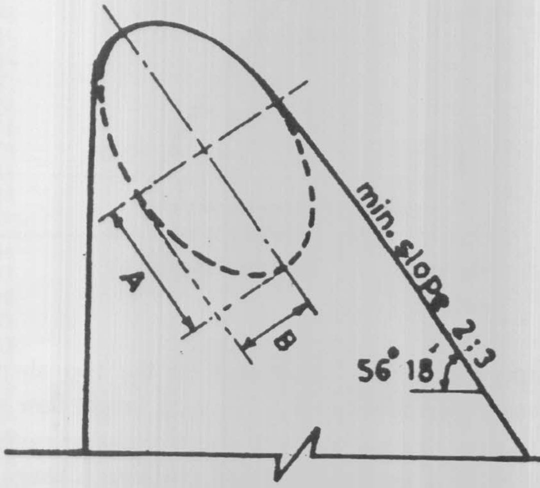

Figure 2. First shape, elliptcal crest, A=2B

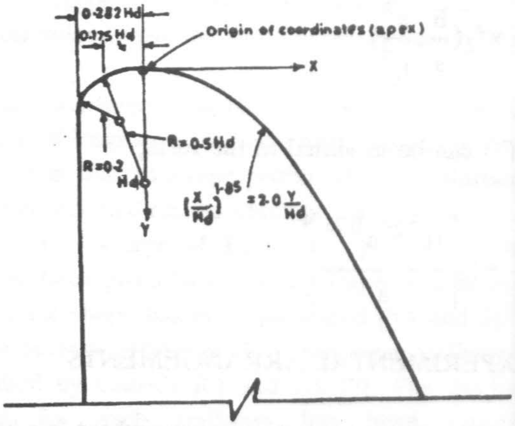

Figure 3. Second shape, standard shape (U.S.A.C. of Engineers).

The pressure distribution was measured by piezometers. Seventeen piezometers were installed along the spillway center line. A copper tubes of 1.2 mm. internal diameter were used for the openings on the spillway face. Polythene tubes were used to connect the copper tubes to open tube manometers, which were mounted on a vertical board. The piezometers were installed at right angles to the face of the spillway and care was taken to insure a smooth surface of contact between the coppper tubes and the spillway surface. Figure (4) shows the arrangement of piezometers along the spillway surface.

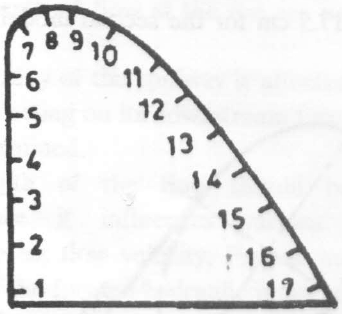

Figure 4. Arrangment of piezometers along spillway surface.

The experiments were conducted on the two shaped models using their four heights. For each height flow was allawed to pass over spillway with a unit discharge ranging from 100 to 1700 $cm^3/sec/cm'$ and covering a range of H/a from 0.10 to 1.0. For each discharge, the head over the weir H and the depth at the toe were measured. The pressures on spillway face were measured for the second model for a relative head H/H_d varying between 0.5 and 2.3.

4. RESULTS AND DISCUSSIONS

4.1 The Depth of Flow at the Toe

To use Eqs. (3-b) and (4) to get the value of the toe depth, the velocity coefficient C_v has to be known a prior. In literatures, an absolute and specific values of C_v are given for the ogee spillway according to the length and the smoothness of the releasing surface, e.g. in Ref. [12], only three values for C_v are reported and equal to 0.9, 0.95 and 1.0 for long, middle and short releasing boundary, respectively. The interpolation between the above values leads to inaccuracy in the calculated toe depth. It is always difficult to evaluate the velocity coefficient theoretically. Hence, obtaining the value of the coefficient C_v experimentally is considered to be the only solution.

The value of C_v depends mainly on the spillway height a and the head on it H. Using the experimental measurements, the value of C_v is obtained from equation, $q=C_v h\sqrt{2,g(E_o-h)}$. These values are plotted against the ratio H/a for various values of a as shown in Figure (5). The figure shows that C_v increases as H/a values increases. For values of $0.1<H/a\leq1$, the following empirical relation is obtained:

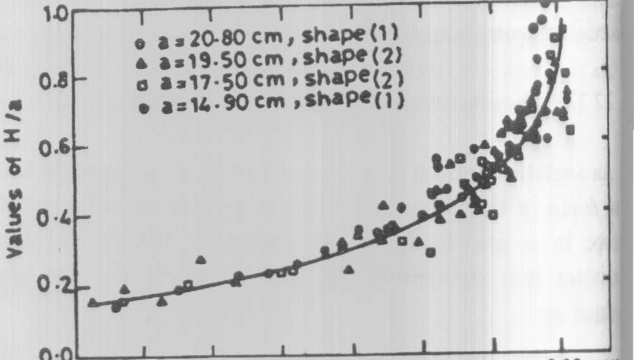

Figure 5. Variation of velocity coefficient C_v with H/a.

$$C_v = 1 + 0.07 \ln \frac{H}{a} \qquad (9)$$

The values of C_v calculated by Eq. (9) and the

Table 1. Experimental data and compariso between measuredand calculated values of the toe depth.

a cm	q $cm^3/sec/cm'$	H cm	E_0=a+Ho	$h_c = 3\sqrt{\frac{q^2}{g}}$	C_v using Eq. (9)	$h_{meas.}$cm	h_{cal}. using Eq.3-b	% deviation
14.9	135	3.49	18.39	2.65	0.898	0.81	0.81	0.0
	265	5.26	20.22	4.15	0.927	1.50	1.49	-0.7
	340	6.13	21.13	4.9	0.938	1.87	1.86	-0.5
	450	7.36	22.44	5.94	0.951	2.39	2.41	+0.8
	550	8.25	22.95	6.74	0.959	2.89	2.88	-0.4
	650	9.02	24.27	7.56	0.965	3.28	3.33	+1.5
	790	10.25	25.65	8.60	0.974	3.95	3.93	-0.5
	856	10.66	26.13	9.07	0.977	4.2	4.23	+0.7
	920	11.28	26.81	9.53	0.981	4.52	4.49	-0.7
	990	11.7	27.35	10.0	0.983	4.82	4.79	-1.2
	1060	12.39	28.06	10.49	0.987	5.15	5.08	-1.4
	1200	13.6	29.4	11.34	0.994	5.7	5.57	-2.3
	1260	14.0	29.87	11.73	0.996	5.96	5.82	-2.3
	1350	14.9	30.81	12.28	1.00	6.3	6.12	-2.9
17.5	160	3.57	21.1	2.94	0.889	0.91	0.89	-2.2
	210	4.3	2185	3.57	0.902	1.16	1.18	+1.7
	370	6.33	23.95	5.18	0.929	1.91	1.91	0.0
	475	7.33	25.02	6.12	0.939	2.35	2.40	+2.1
	580	8.33	26.09	7.03	0.948	2.87	2.89	0.7
	685	9.3	27.13	7.82	0.956	3.31	3.31	0.0
	795	10.15	28.07	8.63	0.962	3.77	3.77	0.0
	895	10.94	28.95	9.35	0.967	4.12	4.2	+1.9
	970	11.48	29.56	9.89	0.97	4.54	4.53	-0.2
	1050	12.04	30.19	10.42	0.974	4.86	4.83	-0.6
	1180	12.98	31.25	11.25	0.979	5.39	5.36	-0.6
	1330	13.86	33.27	12.16	0.984	5.95	5.94	-0.2
	1450	14.72	33.25	12.88	0.988	6.45	6.38	-1.1
	1600	15.68	34.37	13.78	0.992	7.07	6.96	-1.6
19.50	114	3.11	22.62	2.37	0.871	0.65	0.63	-3.0
	237	4.96	24.51	3.86	0.904	1.21	1.23	+1.7
	347	6.24	25.83	4.97	0.92	1.72	1.73	+0.6
	455	7.42	27.07	5.96	0.932	2.18	2.21	+1.4
	554	8.26	27.96	6.79	0.94	2.60	2.64	+1.5
	695	9.50	29.29	7.9	0.95	3.21	3.24	+0.9
	770	10.20	30.04	8.46	0.955	3.52	3.54	+0.6
	875	11.10	31.02	9.2	0.961	3.95	3.94	-0.25
	975	11.70	31.7	9.89	0.964	4.32	4.36	+0.9
	1070	12.7	36.76	10.53	0.97	4.73	4.7	-0.6
	1160	13.00	33.15	11.11	0.972	5.03	5.08	+1.0
	1265	13.80	34.04	11.78	0.976	5.50	5.48	+0.8
	1320	14.2	34.48	12.11	0.978	5.65	5.68	+0.5
	1440	15.0	35.39	12.84	0.982	6.15	6.13	-0.3
	1600	16.0	36.55	13.83	0.986	6.8	6.76	-0.6
20.8	113	2.96	23.77	2.35	0.864	0.62	0.61	-1.6
	225	4.76	25.6	3.73	0.897	1.16	1.15	-0.9
	340	6.14	27.07	4.88	0.915	1.66	1.65	-0.6
	420	7.12	28.04	5.67	0.925	2.02	2.02	0.0
	540	8.2	29.18	6.67	0.935	2.51	2.52	+0.4
	650	9.12	30.16	7.57	0.942	2.97	3.00	+1.0
	770	10.21	31.12	8.45	0.950	3.44	3.48	+1.2
	870	11.05	32.23	9.16	0.956	3.83	3.85	+0.5
	930	11.54	32.76	9.57	0.959	4.06	4.07	+0.25
	1000	12.13	33.40	10.08	0.962	4.35	4.36	+0.2
	1090	12.59	33.94	10.68	0.965	4.7	4.73	+0.6
	1155	13.40	34.78	11.08	0.969	4.94	4.92	-0.4
	1230	13.57	35.02	11.56	0.97	5.23	5.25	+0.4
	1320	14.19	35.71	12.10	0.973	5.55	5.57	+0.4

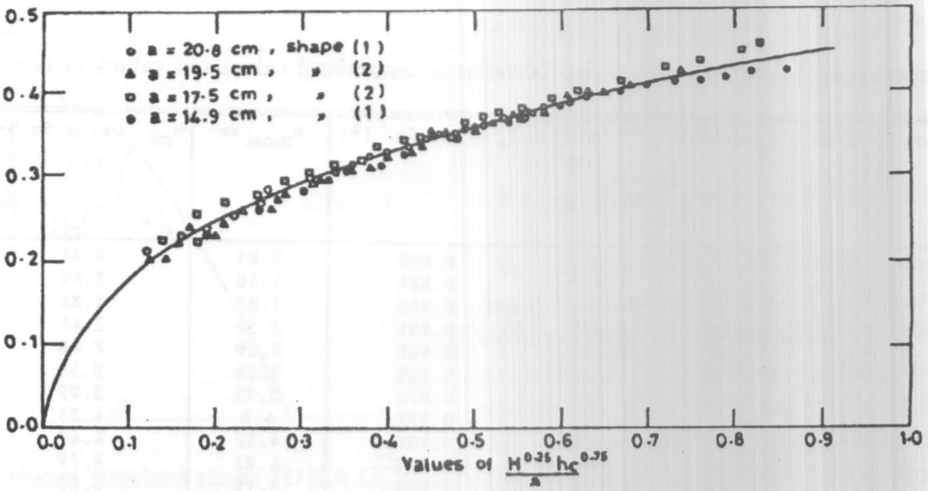

Figure 6. Variation of the toe depth h with both acting head H and critical depth h_c.

Table 2. The discharge coefficient and the minimum pressure on crest for a spillway of height a = 17.5 cm and H_d = 7.0 cm.

q cm^3/sec/cm'	H cm	H/H_d	$C = \frac{q}{H^{1.5}}$	$\frac{C}{C_o}$	$(P/\gamma)_{min}$ cm	$\frac{(P/\gamma)_{min}}{H_d}$
150	3.5	0.5	22.92	0.945	1.75	0.25
450	7.0	1.0	24.25	1.0	0.0	0.0
860	10.5	1.5	25.25	1.04	-5.7	-0.81
1360	14.0	2.0	25.95	1.07	-15.0	-2.15
1680	16.0	2.3	26.20	1.08	-3.07	-3.07

experimental data are arranged in Table (1) to verify the toe depth calculated by Eq. (3-b). Good agreement was found between the calculated and the measured values of the toe depth for different heights of weir.

Equation (8) is plotted in Figure (6), from which empirical relationship is developed to get the value of the toe depth h, as follows;

$$h = 0.475\left(\frac{H^{1.1}\,h_c^{0.3}}{a^{0.4}}\right) \qquad (10)$$

4.2 *Pressure Distribution on Spillway Surface*

The pressure head, P/γ along the weir surface was measured for values of the relative head H/H_d up to 2.0 as shown in Figure (7). For values of H/H_d equal to 0.5, 1.0, 1.5 and 2.0 as listed in Table (2), the values $P/\gamma H_d$ are plotted in Figure (8). The pressures zones on spillway surface may be classified into three zones; pressures on the upstream face, on the crest and on the downstream face.

The pressure distribution on the vertical upstream face does not change much from the normal linear distribution. For low heads there is no significant increase in pressures above their hydrostatic values due to velocity of approach. Near the crest the pressure deviates from the linear distribution as H/H_d increases.

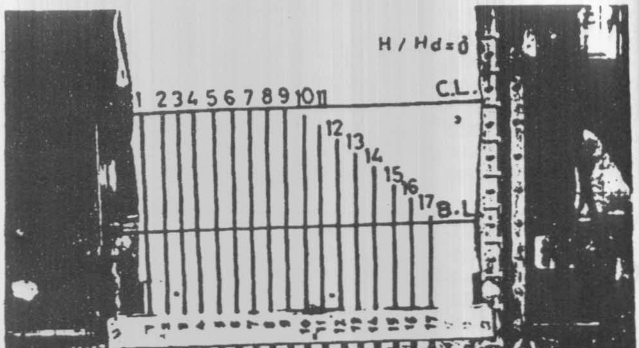

Figure 7. Typical pictures show the pressare along spillway surface. a) H/H_d = 0.0.

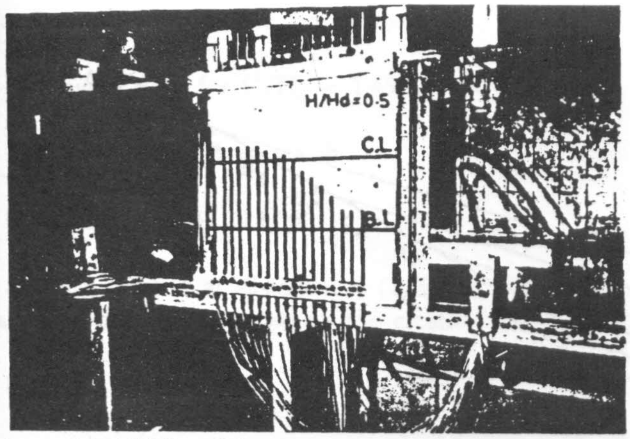

Figure 7-b. $H/H_d=0.5$

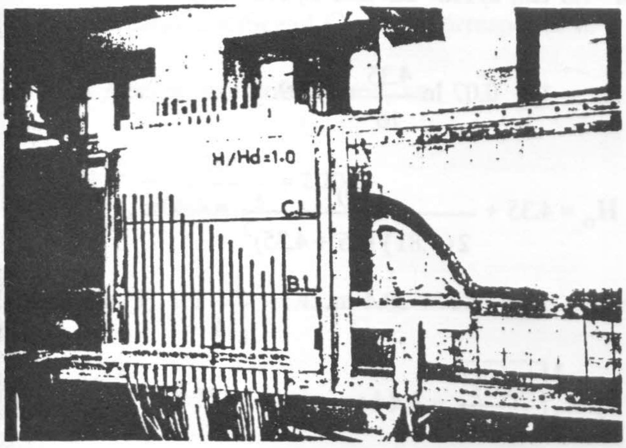

Figure 7-c. $H/H_d=1.0$

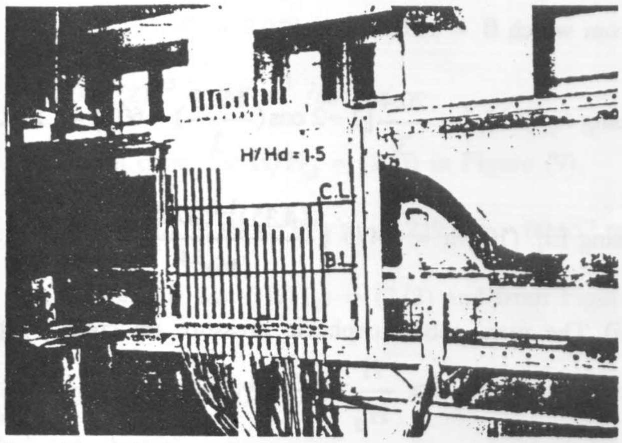

Figure 7-c. $H/H_d=1.5$.

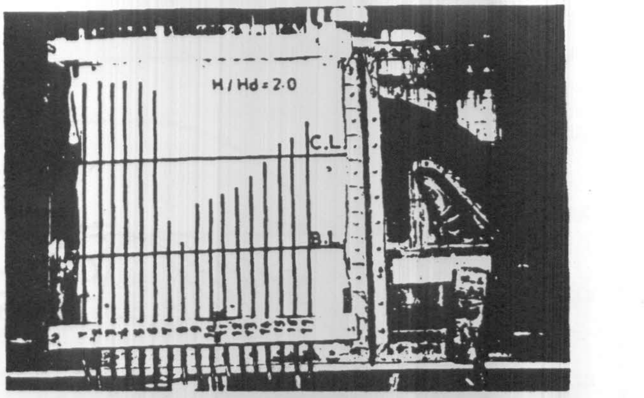

Figure 7-e. $H/H_d=2.0$.

The value of the pressure on the crest depends upon H/H_d. For $H/H_d < 1.0$, the pressure values are allways positive or above atmospheric pressure. When $H/H_d=1.0$, the pressure head P/γ is equal to zero, or atmospheric pressure. In the case $H/H_d>1.0$ a negative or subatmospheric pressure occurs.

Figure (9) shows the variation of the minimum relative pressure $(P/\gamma)_{min}/H_d$ for different values of H/H_d. It is obvious from Figure (9) that the increase of the minimum relative pressure above atmospheric reduces the discharge coefficient, while the decrease of its value below atmospheric pressure increases such a coefficient. It is clear from the Figure that, the actual head H may safely exceed the design head H_d by 50% with 5% increase in the discharge coefficient C. In Figure (9) C_o is the calculated discharge coefficient for the design head H_d. It is evident that seperation of the lower nap from spillway surface did not occur. In the experiments performed by Cassidy [4], seperation occured when $H/H_d \geq 3.0$.

Due to the curvature of flow with high velocity at the toe zone, as shown in Figures (1) and (7), centrifugal force is generated causing an increase in pressure along the downstream face. As shown in Figure (8), the pressure distribution along the downstream face has the maximum value at the toe. The value of pressures is positive for a distance ℓ measured from the toe towards the weir crest. Analysis of the experimental results shows that, the relative distance ℓ/H_d approximatly equals to the relative head H/H_d. Also it was found that the relative value of the maximum pressure at the toe $P/\gamma H_d$ varies as a function of H/H_d.

To compute the pressure force resulting from the centrifugal force, the pressure diagram for any value of H/H_d is approximated to a triangular shape with base equals to ℓ and height equals to P/γ at the toe. The area of this triangle gives the pressure force exerted on the downstream face.

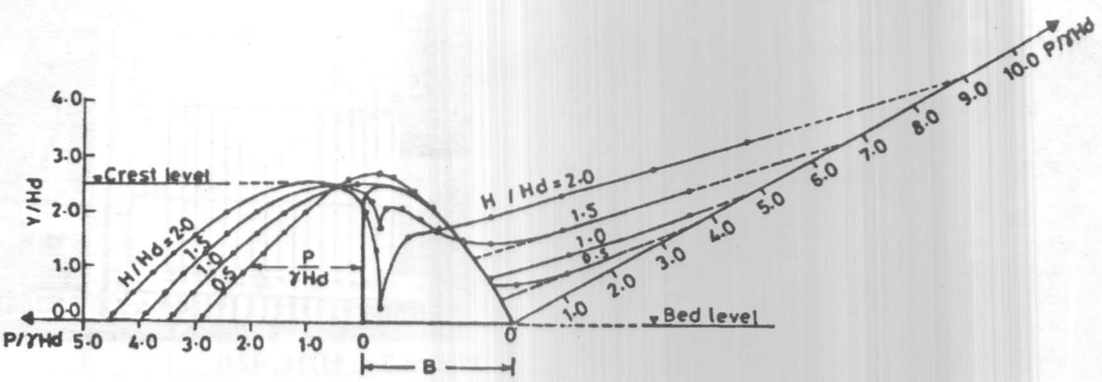

Figure 8. Pressure distribution on spillway surface (Hd=7.0 cm, a/Hd=2.5 and B/Hd=2.7).

The pressure forces F are plotted against H/H_d as shown in Figure (10). Empirical equation is then obtained and used to calculate the pressure force for any value of the relative head H/H_d the form:

$$F = 2.62(H/H_d)^{1.7}\ H^2_d \cdot \gamma \quad t/m' \qquad (11)$$

The location of the pressure force F lies at a distance from the toe equals H/3.

5. DESIGN EXAMPLE

In the present study, all developed equations and charts are obtained in a dimensionless form to be directly applied for prototype ogee spillway. The following example will clarify the solution technique.

An ogee spillway is shaped according to the U.S.A.C.E. for a design head H_d=3.0 m. An excess discharge of 20 m^3/sec/m' having an acting head H=4.35 m, will escape. The spillway is 16.0 m high. It is required to calculate the following;

(i) Depth of flow at spillway toe,
(ii) Maximum subatmospheric pressure on the crest,
(iii) Pressure force on the downstream face and its location from the toe,
(iv) The corresponding discharge to a head equal to 2.0 m, the pressure value on crest and the pressure force on the downstream face.

Solution Procedure

(i) The toe depth h, using Eq. (9),

$$C_v = 1 + 0.07 \ln \frac{4.35}{16} = 0.909.$$

$$H_o = 4.35 + \frac{(20)^2}{2(9.81)\,(16 + 4.35)^2} = 4.40\,\text{m},$$

$$E_o = 16 + 4.4 = 20.4 \text{ m}.$$

$$h_c = \sqrt[3]{\frac{(20)^2}{9.81}} = 3.44\,\text{m}.$$

From Eq. (4), $\cos\theta = 1 - \frac{6.75}{(0.909)^2}(\frac{3.44}{20.4})^3 = 0.9608$

from which $\theta = 16.09^o$

using eq. (3-b), $h = \frac{20.4}{3}[1 - 2\cos(\frac{16.09}{3}) + 60)] = 1.1$

using Eq. (10), $h = 0.475\ [\frac{(4.35)^{1.1}(3.44)^{0.3}}{(16)^{0.4}} = 1.14$

(ii) The max. subatmospheric pressure on crest (

using Figure(9), for $\frac{H}{H_d} = \frac{4.35}{3} = 1.45$,

$\frac{(P/\gamma)_{min}}{H_d} = -0.6875$, from which,

$(P/\gamma)_{min} = -0.6875\ (3) = -2.0625$ m.

(iii) Pressure force on the downstream face,

from Figure (10) for $H/H_d = 1.45$,

$F/H_d^2 = 4.81$, from which

$F = 4.81\,(3)^2 = 43.29$ t/m'

and it is located at distance = (1/3)(4.35) = 1.45 m measured from the toe towards the crest.

Using Eq. (11),

$$F = 2.62\left(\frac{4.35}{3}\right)^{1.7}(3.0)^2 = 44.35\ \text{t/m}'.$$

(iv) The discharge coefficient C which corresponds to $q = 20$ m^3/sec/m' can be obtained, as

$$C = q/H^{3/2} = \frac{20}{(4.35)^{1.5}} = 2.204,$$

from Figure (9), for $\frac{H}{H_d} = 1.45$, $\frac{C}{C_o} = 1.0375$, from which,

$$C_0 = \frac{2.204}{1.0375} = 2.124$$

for $\frac{H}{H_d} = \frac{2}{3}$, the ratio $\frac{C}{C_o} = 0.964$, from which,

$C = 2.124\,(0.964) = 2.048$, then ;

$q = 2.048\,(2)^{1.5} = 5.7$ m^3 /sec/m'

- pressure on crest, for $H/H_d = (2/3)$ in Figure (9),

$(P/\gamma)/H_d = 0.219$, then $(P/\gamma) = 0.219\,(3) = 00.657$ m.

- pressure force F, for $(H/H_d) = (2/3)$ and from Figure (10);

$F = 1.225\,(3)^2 = 11.025$ t/m'

using Eq. (11),

$F = 2.62\,(2/3)^{1.7}\,(3)^2 = 11.8836$ t/m',

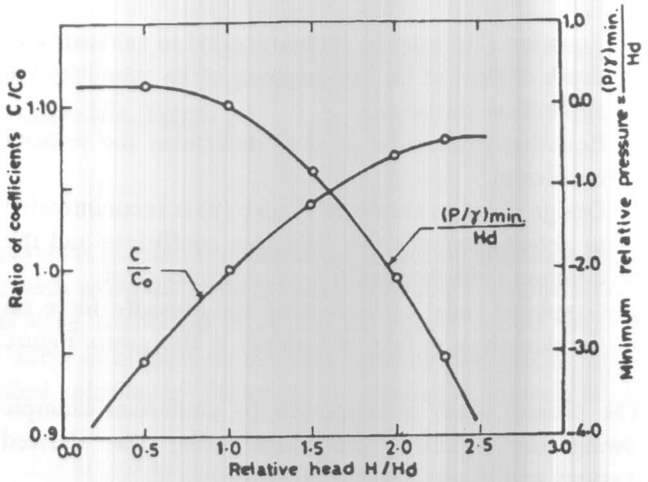

Figure 9. Coefficient of discharge and minimum relative pressure for differnt values of H/Hd (a/Hd=2.5, Hd=7.0 cm).

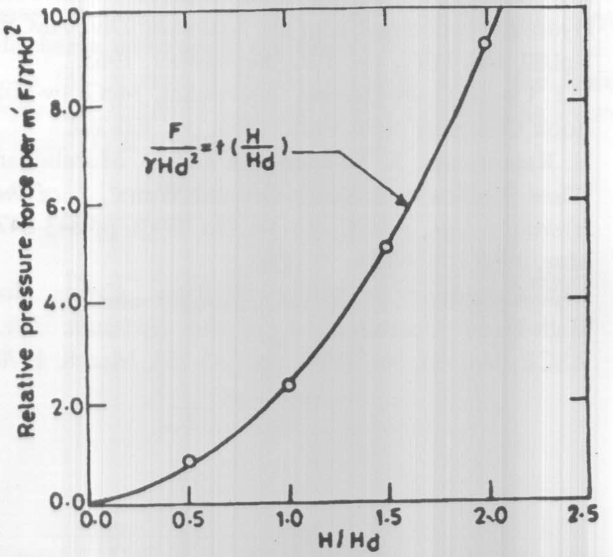

Figure 10. Relative pressure force per m' on the spillway D.S. face for differnt values of H/Hd (a/Hd=2.5, Hd=7.0 cm).

6. CONCLUSION

In the present work a comprehensive experimental study was carried out to investigate the characteristics of the flow over ogee spillway, which sufficently had not been studied in the previous works.

The velocity coefficient, the depth of flow at the toe and the pressure distribution along the spillway surface were investigated analytically and experimentally. as a result of this study analytical and graphical solutions were obtained to determine the above factors as follows;

1. Equation (10) may be recommended to calculate the depth of flow at the toe because of its simplicity for application purposes.
2. Equation (9) can be used to determine the velocity coefficient.
3. Design chart as shown in Figure (9) is recommended to determine both the discharge coefficient and the minimum subatmospheric pressure on crest.
4. Graphical chart to determine the pressure force on the downstream face of spillway is also given, Figure (10).

The present study is supported by numerical example showing the solution procedure using the derived equations and charts.

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