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ORIFICE FLOW IN A GATED SPILLWAY

by

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ABSTRACT

Theoretical value of discharge for orifice flow in a gated Ogee spillway was computed using U.S.B.R. and Sinniger equations. Experimental values were found to be substantially different from the theoretical values. Pressure correction factor found to be a function of both head and gate openings, was calculated by least square curve fitting. Discrepancy between theoretical and experimental values of discharge were reduced substantially with the introduction of the pressure coefficient C_p.

KEY WORDS : Coefficient of discharge, Orifice flow, Ogee spillway, Radial gates.

INTRODUCTION

A gate on an Ogee type spillway is provided for regulation and control of outflows from a reservoir. Radial or tainter type gates are very popular due to ease of operation and smaller amount of power required for lifting of the gates. Depending on the reservoir level and the gate opening, the flow over a gated spillway may be (i) free flow type, (ii) orifice flow type, and (iii) partially overflow and orifice flow type. The coefficient of discharge for free flow Ogee spillway is known accurately from U.S.B.R. (1) studies. When the gate seat is kept at the crest level, coefficient of discharge for orifice flow condition can be obtained from U.S.B.R. (1) experimental curves. However, very few experimental studies exist when the gate seat is provided slightly downstream of the crest (Fig.-1). Due to the curvilinearity of the flow, a suction effect predominates and the flow increases for the same gate opening and reservoir level. It is economical to provide a gate slightly below crest as it reduces the cost of the spillway structures which has to conform to the shape of the jet for the orifice flow. The Ogee profile, determined for free flow condition, may be subjected to cavitation damage for orifice flow, especially for small gate opening. When the gate seat is provided slightly downstrean of the crest, the cavitation problem is also reduced. The theoretical discharge equation for such a case has been given by Sinniger (2).

A physical model of the spillway with radial gate slightly below the crest, was constructed in the Advanced Hydraulics Laboratory of the Delhi College of Engineering. Experiments

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were performed to study the flow characteristics under orifice flow condition to determine the accuracy of the formulae given by U.S.B.R. (1) and Sinniger (2).

MODEL

The model was constructed from the prototype data of Salal Dam Spillway. Due to limitations of space in the laboratory, it was decided to study the flow characteristics on a single prototype bay of 15.24 m using a scale ratio of 1:55 which was chosen from the consideration of availability of discharge in the laboratory and the maximum discharge in the prototype. To reduce friction in the approach channel and the overflow section, acrylic sheets were fixed on spillway faces both upstream and downstream. The salient features of the prototype and the model are given in Table 1 and the plan and cross-section of the spillway are shown in Fig.-2. It was found that with the above scale of 1:55, the Reynolds number of flow in the model corresponding to minimum flow was 4450 which ensured that the flow is turbulent all through.

TABLE-1

SALIENT FEATURES OF THE MODEL AND THE PROTOTYPE

Feature	Prototype	Model
Length ratio	55	1
Discharge ratio	22434	1
Maximum discharge	1960 m^3/s	87.4 *l*/s
Maximum reservoir level	494.08 m	
Crest level	478.678 m	
Maximum head over crest	15.402 m	28 cms
Centre line of trunion axis of gate above crest	3.870 m	7 cms
Position of gate seat below crest	0.32 m	5.8 mm
Radius of gate	14.52 m	26.4 cms

Other dimensions of the model are given in Fig. -1.

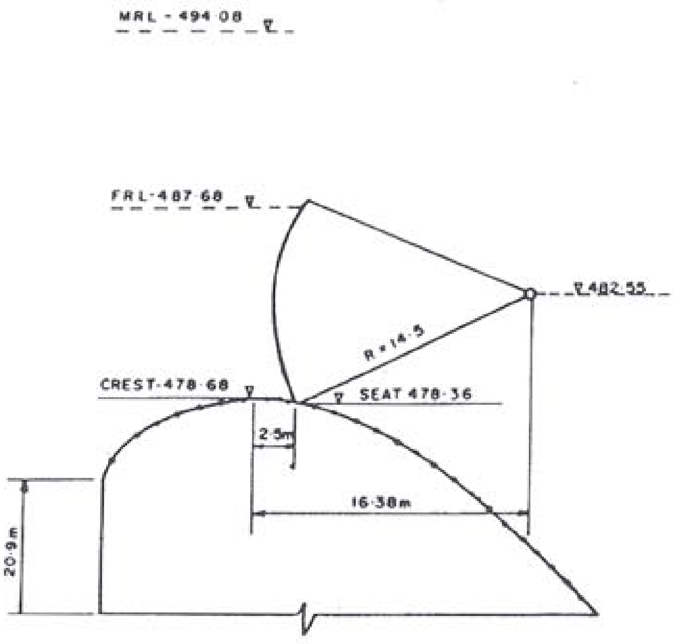

FIG. 1 : SHOWING DIMENSIONS & R.L'. s OF OGEE SPILLWAY & RADIAL GATE

EXPERIMENTAL SETUP

The scale model of the spillway and gate was constructed in the hydraulics laboratory and was installed in a 150 cm wide by 9 m long fixed bed concrete flume. Water was pumped from the underground sump by means of two pumps of 20 and 15 HP capacity respectively. The water was delivered to the flume through two pipe lines 15 cm diameter each. The pipe lines were provided with a venturimeter calibrated using the underground volumetric tank. Water from pipelines was admitted to an inlet tank as shown in Fig.-2. In order to dampen the turbulent fluctuations, stilling arrangement in the inlet tank was introduced through distributors and two rows of wire mesh screens of different sizes. Additionally, plastic balls wrapped in wire meshes were provided in the inlet tank. With these damping arrangements, it was observed that the water surface profile upstream of the spillway was very smooth, ensuring accurate measurements of water levels. A radial gate with the given scale ratio of 55 was fabricated and installed as per the prototype conditions. Two gate guides were provided on the two abutments and M-seal was used for sealing the grooves on sides. Radial movement of the gate was controlled by a bevelled gear so as to control gate opening at any desired level. Extra care was taken to ensure the correct seat level and crest level of the spillway. In order to avoid the effect of viscosity, a very smooth surface was provided on the face of the spillway both upstream and downstream and also on the sides of the abutments by fixing the acrylic sheets. Water surface profiles were measured by means of a pointer gauge with a vernier having a least count of 0.1 mm. All the levels were transformed to the prototype by taking the gate seat level as reference point.

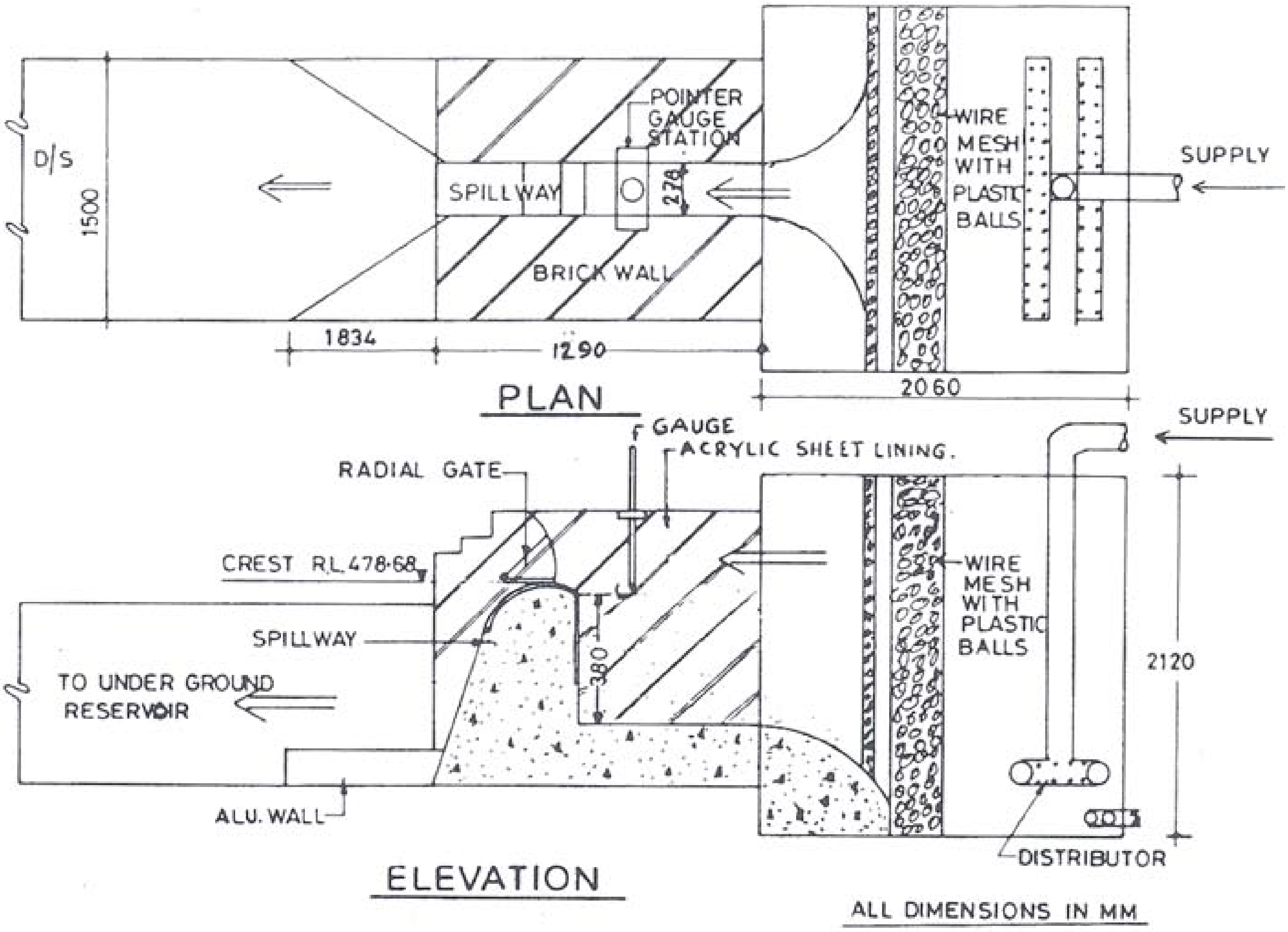

FIG. 2 : EXPERIMENTAL SET UP

DISCHARGE EQUATIONS

U.S.B.R. Equation For Gated Spillway (Gate seat at crest level)

The discharge equation for orifice flow, when the radial gate is placed at crest, is given by Eq. (1) below

$$Q=C\sqrt{2g}.L[H_1^{1.5}-H_2^{1.5}] \quad (1)$$

where, Q = discharge in m^3/s, C = coefficient of discharge from U.S.B.R. curves, L = effective length of the spillway, H_1 = head over crest in m, H_2 = head over bottom of gate in m.

Various dimensions are shown in Fig.-3 and C-values are given in reference-1.

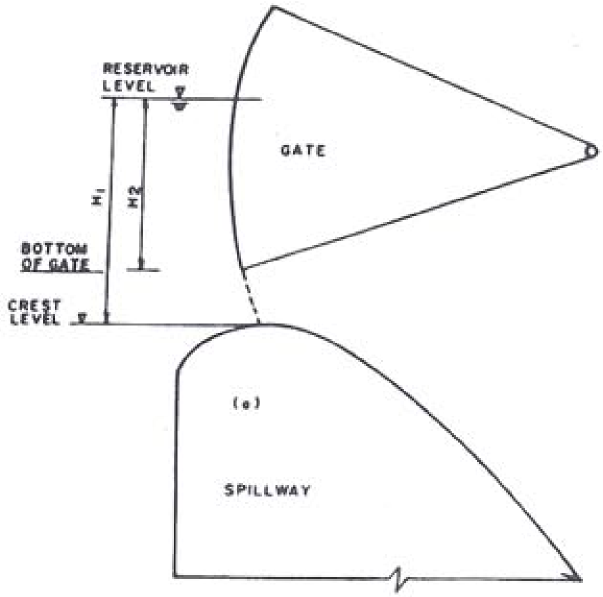

FIG. 3 : OGEE SPILLWAY WITH GATE LOCATED AT CREST (DEFINITION SKETCH FOR U.S.B.R. EQUATION)

Sinniger's Formula for Gated Spillway

To find out the value Q_s for gated spillway, Sinniger and Hager also have given the following formula,

$$Q_s = C_{dg}\, b(G H_d)\sqrt{2gH_e)} \tag{2}$$

where, Q_s = Discharge, C_{dg} = Sinniger's discharge coefficient, b = width of a single bay, H_e = actual energy head, H_d = design head, g = gravitational acceleration (Fig.-4).
For $X_i < 0$, $X_o = 0.0$, $Z_o = 0.0$, $\rho_o = 0.5$

$$G = [(X_I - X_o)^2 + (Z_I - Z_o)^2]^{1/2} - \rho_o, \quad \text{for} -0.176 \subseteq X_w \subseteq 0.0 \tag{3}$$

$$X_w = -\rho_o[\{(Z_I - Z_o)/(X_I - X_o)\}^2 + 1]^{-1/2} + X_o, \ \text{for} -0.176 \subseteq X_w \subseteq 0$$

For $X_I > 0$

$$G = (1 - (2/9)X_I^{3/2})(Z_I + (1/2)X_I^{1.85}) \tag{4}$$

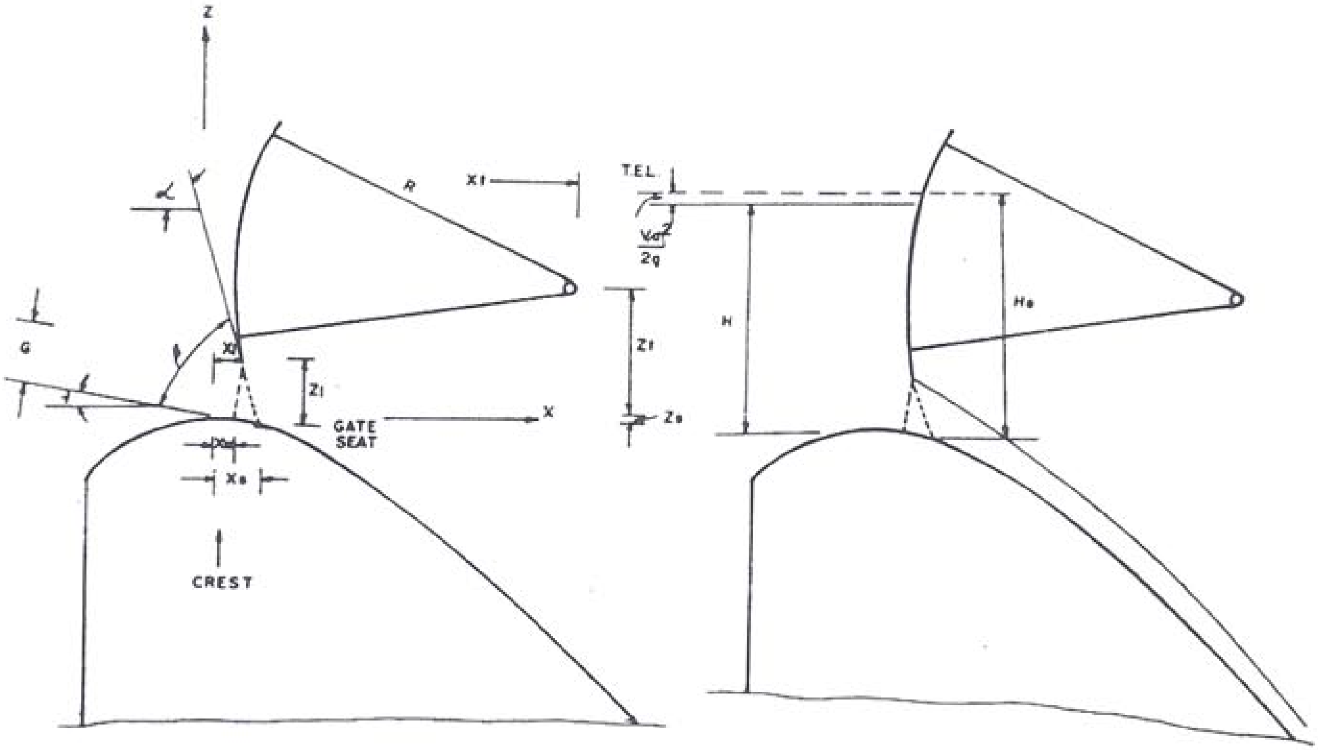

FIG. 4 : OGEE SPILLWAY WITH RADIAL GATE LOCATED BELOW CREST (DEFINITION SKETCH FOR SINNIGER'S EQUATION)

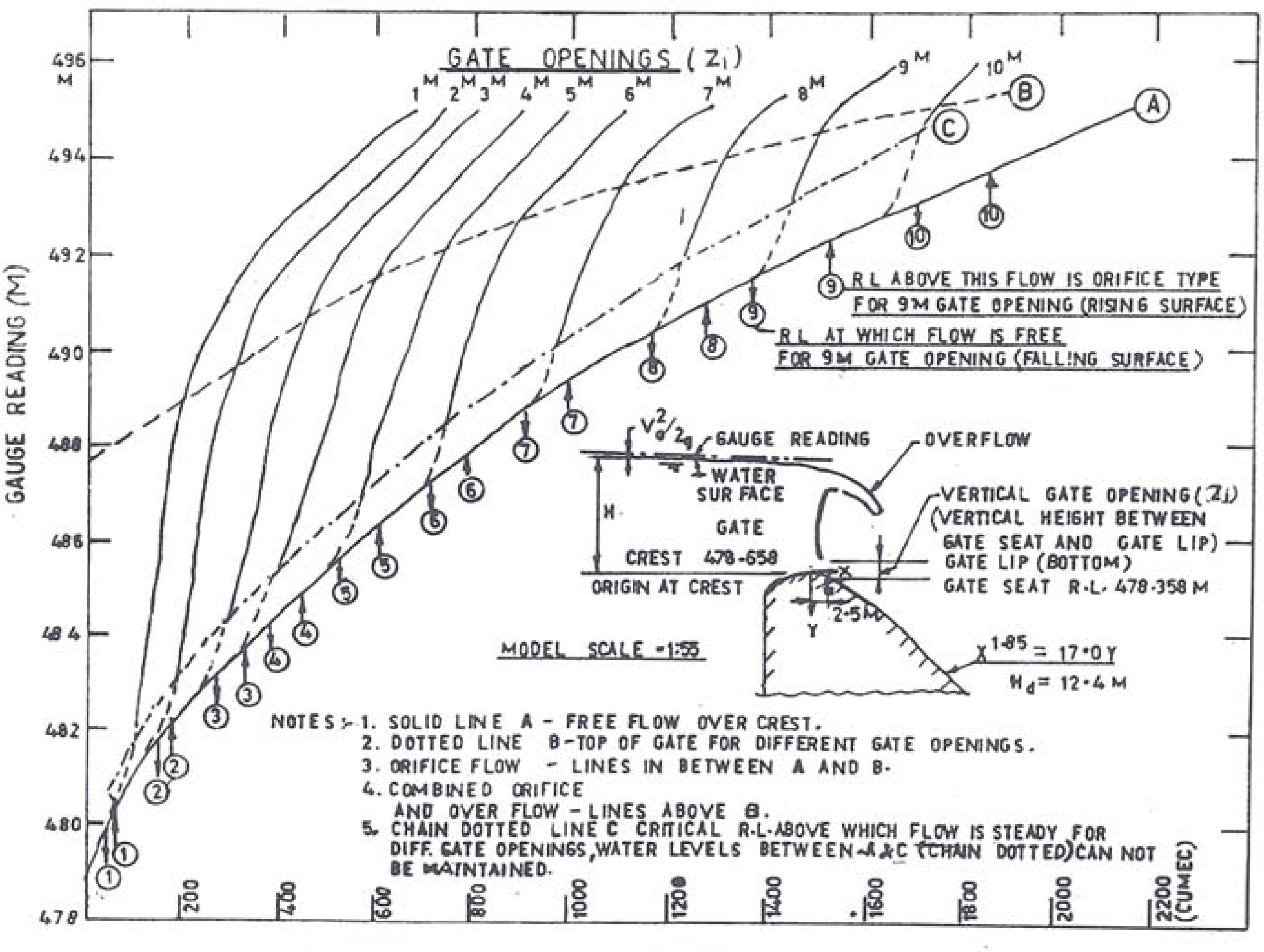

FIG. 5 : DISCHARGE PER SPAN OF 15.24 M

The angles given in Fig.-4, α, β, γ are given by

$$\tan\alpha = [\{R/(X_I - X_t)\}^2 - 1]^{-1/2} \quad (5)$$

$$\tan\gamma = [2X_I/(2Z_I + 1)], \ \text{for} -0.176 < X_w < 0 \quad (6)$$

$$\tan\gamma = -(1.85/2)[X_I\{1 + (1.85/2)X_I\, 1.85(Z_I + (1/2)X_I)\} - 1]^{0.85} \quad (7)$$

The angle β can be found out by the relation

$$\alpha = \beta + \gamma \quad (8)$$

and the C_{dg} value is given by :

$$C_{dg} = 0.908[1 - \beta/277^{\circ})](H/H_d)^{0.12} \quad (9)$$

The terms used in the equation are duly shown in Fig.-4. To find the discharge by Sinniger's formula, computer program in FORTRAN-77 was developed.

Coefficients C and C_{dg} in Eqs. (1) and (2) for gated ogee spillway may be expressed as function of the nondimensional parameters P/H_d, R/H_D, X_S/H_D, H/H_D and G/H_D in which P is the height of spillway, R is gate radius, G is gate opening and X_S is the distance of the gate/seat from the crest. In the present study, value of the first three parameters were kept the same, namely, $P/H_D = 1.67$, $R/H_D = 1.17$ and $X_S/H_D = 0.20$. The only variables were H/H_D and G/H_D.

Calibration Curve For The Spillway For Orifice Flow Showing Transient Flow Condition

Based on the measured discharges, a stage-discharge relation for free and orifice flow were plotted as shown in Fig.-5. As shown in the figure, an important point observed in the present study was the existence of a transient reach when the flow suddenly changed from the free to orifice flow condition. This transient zone occurred at every gate opening. In this zone the flow condition was unsteady and there was a sudden rise in the water level before it became steady orifice flow. Further, it was observed that the stage discharge curve in the transient reach under rising and falling stages did not coincide on the same point and two limiting points for the free flow are indicated in Fig.-5.

Comparison Of Measured And Computed Discharge

Comparison was made of the measured and computed discharges under orifice flow condition for different gate openings and heads above crest. Discharges were computed using both USBR and Sinniger's equations as discussed earlier. Percentage errors in the flows computed by Sinniger and USBR equations indicated that the errors in both the methods were more or less similar. The average error was found to be 4.04% and 5.37% in Sinniger's and USBR equations respectively. However, it was seen that the errors in general are dependent on both head as well as gate opening in both the equations. On an average the error increases with decrease in gate opening and head above crest.

Modified Equations Of Sinniger & U.S.B.R.

As discussed above there was a systematic change in error with change in gate opening as well as head above crest. This may be due to change in pressure distribution in the vicinity of the crest. When the gate is provided just below the crest section, a suction effect predominates and so a pressure correction factor (C_p) has to be introduced in both the formulae. It is seen that the pressure correction factor varies with both head and the gate opening. So C_p is defined as

$$C_p = f(H / H_D, G / H_D)$$

$$\text{or, } C_p = (H / H_D)^a (G / H_D)^b$$

where $C_p = {}^{Q}\text{measured} / {}^{Q}\text{computed}$, and a, b are constants. The values of C_p for different heads and different gate openings were found from experimental results and theoretical Q values obtained by USBR and Sinniger's equation. Using least square method, the values of a, b, determined by a computer program, were found to be -0.0157, and -0.121249 respectively in Sinniger equation. The corresponding values in the USBR equations were -0.01087 and -0.158909 respectively. Applying these C_p values and correcting the computed discharge, the average error came out to be 1.54% and 0.95% for Sinniger's and USBR equations respectively.

CONCLUSIONS

Based on the experiments performed and the analysis of data, the following conclusions may be drawn.

1. USBR equation for computing orifice flow for a gated ogee spillway is not applicable when the gate seat is downstream of crest.

2. Sinniger's equation gives theoretical value of coefficient of discharge when the gate seat is downstream of crest.

3. Both USBR and Sinniger's equations may be adopted to compute discharge theoretically introducing a pressure correction factor C_p found to be a function of both head and opening.

4. When the flow changes suddenly from free to orifice flow condition, there is a transient zone for all gate openings, when there is a sudden rise in head without any change of discharge.

REFERENCES

1. USBR (1979). Design of Small Dams, Second Edition, pp-386, 387.

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LIST OF SYMBOLS :-

b = Width of a single bay
C = Coefficient of discharge (USBR)
C_{dg} = Discharge Coff (Sinniger)
g = Acceleration. Due to gravity
H_1 = Head over crest
H_2 = Head from bottom of gate
H_d = Designed head
H_e = Actual head (over gate seat)
Q_s = Discharge (Sinniger)
Q = Discharge (USBR)
L = Effective length of Spillway
ρ_o = Constant

G, X_I, X_w, Z_I, Z_w, Z_o, X_o, Z_t, X_t and angles α, β, γ are shown inFig.-4.