DETERMINATION OF DISCHARGE COEFFICIENT AND HEAD-DISCHARGE RELATIONSHIPS OF DIFFERENT HYDRAULIC STRUCTURES

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ABSTRACT

A glass sided tilting flow channel based laboratory study was carried out to determine the discharge coefficient and head-discharge relationships for hydraulic structures i.e.Broad Crested Weir, Crump Weir, Sluice gate, Radial Gate and Dam Spillway. The average value of Coefficient of Discharge for Broad Crested Weir, Crump Weir, Sluice Gate, Radial Gate and Dam Spillway was found to be 0.44, 0.85, 0.76, 0.82 and 1.03 respectively. Furthermore, the C_d with h/a was linearly related and there was power relationship between Discharge and Head with R^2 ranging from 0.80 to 0.99 for all the structures under study.

Keywords: Discharge Coefficient, Head- Discharge Relationship, Hydraulic Structures, Tilting Flow Channel

INTRODUCTION

The measurement of flow in river and open channel is required for irrigation management purposes including water resources planning, pollution prevention, and, flood control. Existing method of river flow measurements consists mainly of the velocity area method and the use of hydraulic structures like weirs and flumes.

Almost any kind of obstacle that partially restricts the flow of water in an irrigation channel can be used as a measuring device, provided that it can be calibrated. A flow measurement structure is generally designed to act as a control in an open channel in order to provide a unique relationship between the upstream head and the discharge. Following structures are commonly used for discharge measurement namely Broad Crested Weir, Crump Weir, Radial Gate, Sluice Gate, Dam Spillway etc.

Gilles Belaud (1943) has studied the contraction coefficient under sluice gates on flat beds for both free flow and submerged conditions based on the principle of momentum conservation, relying on an analytical determination of the pressure force exerted on the upstream face of the gate together with the energy equation. Binne (1952) analysed two-dimensional free motion of a perfect liquid under a sluice-gate in an open horizontal channel. Bose (1989) described hydraulic theory related to hydraulic structure. He has concluded that the major demands on hydraulic structure by providing specialized and technical knowledge on the more common types of structures now being used throughout the world. Keller (1989) has described a hydraulic model study of an existing sloping crest Crump weir is described. Two models of scales 1:10 and 1:3 were tested. At relatively large heads,

the structure behaves as one half of a flat-V Crump weir with the same transverse crest slope. At lower heads, the flow cross section becomes strongly nonsymmetrical with a consequent significant decrease in the value of the discharge coefficient. The critical head at which departure from a constant discharge coefficient commences is sensitive to the extent of upstream sedimentation in the channel. The sloping crest Crump weir should not be used for flow measurement in a straight channel without an associated model study or an extensive field calibration. Hudson (1990) checked the calibrations performed on the Crump weirs show that accurate operation of Crump weirs is feasible in non-standard Conditions provided that their calibrations do not rely solely on British Standard recommendations. The provision of unique independent ratings becomes particularly important for research studies using water balance techniques, where the accuracy of flow estimation is critical. Swami (1990) has concluded that sluice-gate discharge coefficient is an involved function of geometric and hydraulic parameters. For free flow, it is related to upstream depth and gate opening, whereas for submerged flow, in addition to these parameters, it depends on tail-water depth. He developed discharge coefficient equations for free and submerged flows along with the criterion for determination of free and submerged flow. Hager (1992) analyzed the flow features over the broad-crested weir with vertical upstream wall and sharp-crested corner experimentally. Chanson (1995) has concluded that Broad Crested weir can be used for accurate measurement, more importantly he has concluded that Broad crested weir can be used for high tail water submergence. Adulaziz A. Allahamid (1997) concluded that sill shape and sill height plays an important role on the discharge coefficient of sluice gate. Jung-Fu Yen (2001) investigated various characteristics of a vertical sluice gate in a rectangular flatbed channel. Gogus and Define (2006) performed a series of laboratory experiments in order to investigate the effects of width of the lower weir crest and step height of broad-crested weirs of rectangular compound cross section on the values of the discharge coefficient, the approach velocity coefficient, and the modular limit.

To measure discharge rate by means of hydraulic structures, a well-established relationship of head and discharge is needed which can be determined empirically in the laboratory. Coefficient of Discharge is defined as the ratio of actual discharge to the theoretical discharge delivered by the structure. If theoretical discharge delivered by a structure is

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known by some standard formula, actual discharge delivered by the structure can be known multiplying the coefficient of discharge with theoretical discharge. Therefore, a laboratory study was planned to establish head- discharge relationship of commonly used hydraulic structures with the following objectives.

1) To determine the coefficient of discharge of various hydraulic structures.

2) To develop the head discharge relationships for various hydraulic structures.

MATERIALS AND METHODS

Tilting flume channel and hydraulic structures
In the present study, a glass sided tilting flow channel

manufactured by S.D.HARDSON & CO. Kolkata (India) (Fig.1) was used. Study was carried out in the Irrigation and Drainage Engineering Laboratory of Department of Agricultural Engineering, NERIST, Nirjuli, Arunachal Pradesh (India). It has working length ,width and depth of 4 m,75 mm and 250 mm respectively and self contained with adjustable floor support, wheel mounted sump tank, and circulating pump, together with basic sets of accessories. Details of different hydraulic structures used in study are given in Table1.

Flow over a Broad Crested Weir
The channel was first set horizontal, as indicated by the linear and circular scales, by the help of screw jack. The height of the broad crested weir was measured with the help of scale. It was then placed vertically in the tilting flow channel. The discharge

Fig. 1 : Tilting Flume Channel

Table 1 : Details of different hydraulic structures

S.NO.	Name of the Structures	Dimension of the Structures (cm)	Remarks
1.	Broad Crested Weir	Length = 30 Height = 9.85 Breadth = 7.75	Depicted in Fig. 2
2.	Crump Weir	Length = 37 Height = 4.45 Breadth = 7.75	Depicted in Fig. 3
3.	Sluice Gate	Opening of the Gate(a) = 1.55	Depicted in Fig. 4
4.	Radial gate	Opening of the Gate(a) = 1.9	Depicted in Fig. 5
5.	Dam Spillway	Height = 17.51 Breadth = 7.75	Depicted in Figs. 6 and 7

in the tilting flow channel was set by the knob and the water was then allowed to admit in the tilting flow channel from one end such that water flow is passed over the Broad Crested Weir (Fig. 2).

When a constant flow over the weir in the tilting flow channel was obtained the dial vernier depth gauge was set some way on the upstream side of the weir and the water datum reading was recorded. The flow of water inside the tilting flow channel was measured with the help of the pitot tube assembly using the formula given below:

$$V = \sqrt{2gh} \tag{1}$$

Where, V=velocity of flow of water in cm s^{-1}, h=head difference in manometer in cm, g=gravitational acceleration in cm s^{-2}.

In the similar way head over the weir was obtained by adjusting the discharge knob at different levels. The flow is illustrated in Fig. 8. The coefficient of discharge of the Broad Crested Weir was calculated by using the following formula.

$$C_d = \frac{Q}{B \times \sqrt{2 \times g} \times H^{3/2}} \tag{2}$$

Where, C_d= coefficient of discharge, Q = rate of discharge in $cm^3 s^{-1}$, B = width of channel in cm, g = gravitational acceleration in cm s^{-2}, H = head over the weir in cm.

Flow over a Crump Weir

Initially tilting flow channel was set horizontally and crump weir (Fig. 3) was placed in it. Water discharge regulated to pass over the crump weir. When a steady state condition over the weir was established, the dial vernier depth gauge was set

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Fig. 2 : Broad Crested Weir

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Fig. 3: Crump Weir

on the upstream side of the weir and the water datum reading was recorded. The velocity of water inside the tilting flow channel was measured as discussed in section 2.2. In the similar way head over the weir was obtained by adjusting the discharge knob at different levels. The flow is illustrated in Figure 9. The coefficient of discharge of the Crump Weir was calculated by using the following formula.

$$C_d = \frac{Q}{B \times \sqrt{g} \times H^1} \tag{3}$$

Where, C_d = coefficient of discharge, Q = rate of discharge in $cm^3\ s^{-1}$, B = width of channel in cm, g = gravitational acceleration in cm s^{-2}, H^1 = total energy head over the weir in cm.

Flow under a Sluice Gate

The channel was first set horizontal, as indicated by the linear and circular scales, by the use of screw jack. Sluice Gate assembly (Fig. 4) was clamped to the sides of the channel after leveling it. The discharge was set by the knob provided and the

Flow under Radial Gate

The channel was first set horizontal, as indicated by the linear and circular scales, by the help of screw jack. Clamp the Radial Gate (Fig. 5) assembly to the sides of the channel after leveling it. The discharge was set by the knob provided and the water was then allowed to admit in the tilting flow channel from one end such that it flows under the opening of the Radial Gate. The opening of the gate under which water flows was measured. The depth gauge was set some way on the upstream side of the Radial Gate and the water datum reading was obtained. The velocity of water inside the tilting flow channel was measured as discussed in section 2.2. The head of upstream of the gate was obtained by adjusting the discharge knob at different levels. The flow is illustrated in Fig. 11.The coefficient of discharge of Radial Gate was calculated by using the following formula.

$$C_d = \frac{Q}{A \times \sqrt{2gh}} \tag{5}$$

Where, C_d = coefficient of discharge, Q = rate of discharge in
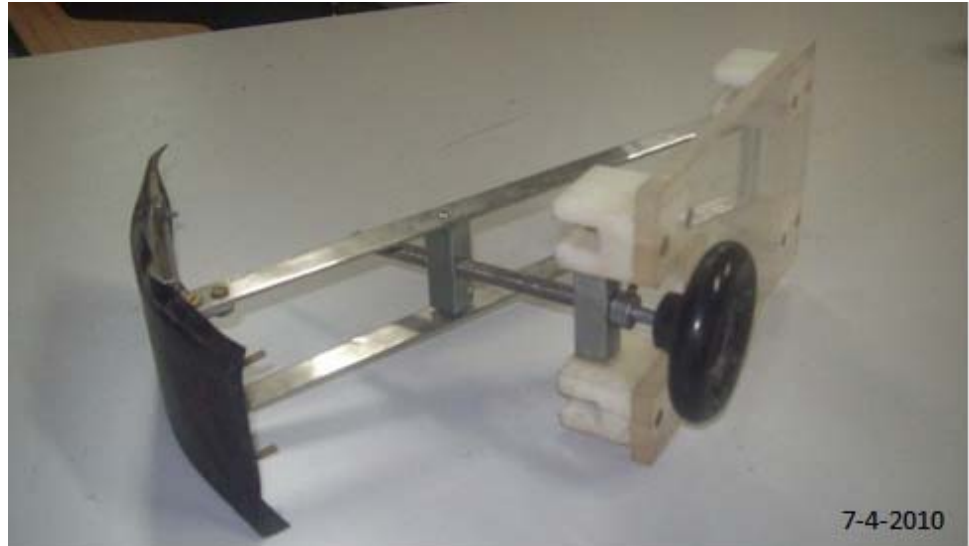

Fig. 4: Sluice Gate

Fig.5: Radial Gate

water was then allowed to admit in the tilting flow channel from one end such that it flows under the sluice gate and the opening of the gate under which water flows was measured. The depth gauge was set on the upstream side of the Sluice Gate and the water datum reading was obtained. The velocity of water inside the tilting flow channel was measured as discussed in section 2.2. The head of upstream of the gate was obtained by adjusting the discharge knob at different levels. The flow is illustrated in Fig. 10. The coefficient of discharge of Sluice Gate was calculated by using the following formula.

$$C_d = \frac{Q}{a \times B \times \sqrt{2y\left(E - \frac{a}{2}\right)}} \tag{4}$$

Where, C_d = coefficient of discharge, Q = rate of discharge in $cm^3\ s^{-1}$, a = opening of the gate in cm, B = width of channel in cm, g = gravitational acceleration in cm s^{-2}, E = specific energy in cm.

$cm^3\ s^{-1}$, A = area of opening of the gate in cm, g = gravitational acceleration in cm s^{-2}, h = head in the upstream section.

Flow over a Dam Spillway

The channel was first set horizontal, as indicated by the linear and circular scales, by the use of screw jack. The height of the Dam spillway (Fig. 6 and 7) was measured using scale. It was then placed vertically in the tilting flow channel. The discharge is set by the knob provided and the water is then allowed to admit in the tilting flow channel from one end such that it discharges over the weir. When a constant flow over the spillway in the tilting flow channel was obtained the dial vernier depth gauge was set some way upstream from the spillway and the water datum reading was obtained. The velocity of water inside the tilting flow channel was obtained as discussed in section 2.2. The head over the spillway was obtained by adjusting the discharge knob at different levels. The flow over various model of Dam Spillway is illustrated in

Fig. 6 : Dam Spillway with sloping apron

Fig.7 : Dam Spillway with apron blended reverse urvature

Fig. 12.The coefficient of discharge of the Dam Spillway was calculated by using the following formula.

$$C_d = \frac{Q}{\frac{2}{3} \times B \times \sqrt{2g} \times H^{3/2}}$$ (6)

Where, C_d= coefficient of discharge, Q = rate of discharge in $cm^3\ s^{-1}$, B = width of channel in cm, g = gravitational acceleration in cm s^{-2}, H = head over the Spillway in cm.

RESULTS AND DISCUSSION

Broad crested weir
Variation of head with discharge
Table 2 presents the discharge, head, velocity and coefficient of discharge for broad crested weir. The results obtained here provide convincing demonstration of the power relation between discharge 'Q' and head 'h' for the Broad Crested Weir (Fig.13).
Variation of discharge coefficient C_d with h/a

Fig. 14 shows the variation of C_d with h/a and the relationship

almost linear. It is found that Coefficient of Discharge 'C_d' is almost constant with increase in h/a and had been found in the range from 0.43 to 0.45 (Table 2). This little variation might be attributed due to fixing of accurate zero value at crest level and recording of h value.

Crump weir
Variation of head with discharge
Table 3 presents the discharge, head, total energy head, velocity and coefficient of discharge for Crump Weir. In this experiment the head over the crump weir was not constant thus we had considered the total energy head to maintain a constant head level. The results obtained here provide convincing demonstration of the power relation between discharge 'Q' and head 'h' (total Energy Head) for the Crump Weir (Fig. 15).
Variation of discharge coefficient C_d with h/a.

Fig. 16 shows the variation of C_d with h/a and the relationship

is almost linear. It is found that Coefficient of Discharge 'C_d'

increased with increase in h/a and had been found in the range 0.73 to 0.96 (Table 3). This variation might be attributed due to fact that as head level increased, the flow cross section at the weir became more strongly nonsymmetrical owing to the influence of the weir and this was also reflected in a progressive increment in the value of discharge coefficient.

Sluice Gate
Variation of specific energy with discharge
Table 4 presents the discharge, head, velocity, specific energy and coefficient of discharge for Sluice Gate. The results obtained here provide convincing demonstration of the power relation between discharge 'Q' and specific head 'E' for the Sluice Gate (Fig. 17). Coefficient of Discharge 'C_d' had been found in the range 0.7 to 0.8 (Table 4).

Table 2: Discharge, head, velocity, coefficient of discharge of Broad Crested Weir under study

S No.	Discharge 'Q' (L/min)	Head 'h' (cm)	Velocity 'V' (cm/s)	C_d	h/a
1.	60	3.44	34.31	0.45	0.34
2.	70	3.85	34.31	0.44	0.39
3.	80	4.27	37.06	0.44	0.43
4.	90	4.65	37.06	0.43	0.47
5.	100	4.92	37.06	0.44	0.49
6.	110	5.24	39.62	0.44	0.53
7.	120	5.52	39.62	0.44	0.56

Table 3: Discharge, head, total energy head, velocity, coefficient of discharge of Crump Weir under study

Sl. No.	Discharge 'Q' (L/min)	Head 'h' (cm)	Velocity 'V' (cm/s)	Total Energy Head 'H¹' (cm)	C_d	h/a
1.	20	1.23	14.00	1.32	0.73	0.38
2.	30	1.69	14.69	1.79	0.81	0.44
3.	40	2.09	21.69	2.33	0.83	0.52
4.	50	2.37	30.68	2.85	0.85	0.64
5.	60	2.70	34.31	3.29	0.88	0.73
6.	70	3.00	34.31	3.59	0.94	0.80
7.	80	3.32	37.06	4.02	0.96	0.90

Table 4: Discharge, head, velocity, specific energy and coefficient of discharge of Sluice Gate under study

S. No.	Discharge 'Q' (L/min)	Head 'h' (cm)	Velocity 'V' (cm/s)	Opening of Gate 'a' (cm)	Specific Energy $(E = h + \frac{V^2}{2g})$ (cm)	$\left(E - \frac{a}{2}\right)^{\frac{1}{2}}$	C_d
1.	40	3.00	31.32	1.55	3.50	1.65	0.7
2.	50	4.29	28.01	1.55	4.68	1.97	0.8
3.	60	6.08	34.31	1.55	6.68	2.43	0.7
4.	70	7.48	34.31	1.55	8.07	2.70	0.8
5.	80	9.63	37.06	1.55	10.33	3.09	0.8
6.	90	11.54	37.06	1.55	12.24	3.38	0.8
7.	100	14.50	37.06	1.55	15.20	3.79	0.8

Table 5: Discharge, head, coefficient of discharge of Radial Gate under study

S. No.	Discharge 'Q' (L/min)	Head 'h' (cm)	C_d
1.	60	4.17	0.75
2.	70	5.09	0.79
3.	80	6.95	0.77
4.	90	7.57	0.83
5.	100	8.91	0.86
6.	110	10.50	0.86
7.	120	11.69	0.89

Table 6: Discharge, head, coefficient of discharge of Dam Spillway under study

Sl. No.	Discharge 'Q' (L/min)	Head 'h' (cm)	C_d	h/a
1.	50	2.3	1.04	0.13
2.	60	2.6	1.04	0.14
3.	70	2.9	1.03	0.16
4.	80	3.2	1.01	0.18
5.	90	3.5	1.04	0.19
6.	100	3.6	1.06	0.20

Variation of discharge coefficient with $\left(E - \frac{a}{2}\right)^{\frac{1}{2}}$

Fig. 18 shows the variation of C_d with $\left(E - \frac{a}{2}\right)^{\frac{1}{2}}$ and the relationship is almost linear. As the small aperture i.e., a = 1.55 cm used, the approach velocity head was quite small and the difference between static head and specific energy was

virtually negligible. It was found that Coefficient of Discharge 'C_d' increased with increase in specific energy head.

Radial Gate
Variation of head with discharge
Table 5 presents the discharge, head, velocity and coefficient of discharge for Radial Gate. The results obtained here provide convincing demonstration of the power relation between

discharge 'Q' and head 'h' for the Radial Gate (Fig. 19). Coefficient of Discharge 'C_d' has been found in the range 0.75 to 0.89 (Table 5).

Dam Spillway
Variation of head with discharge
Table 6 presents the discharge, head and coefficient of

discharge for Dam Spillway with blended reverse curvature and sloping apron as the experimental readings for both were similar. The results obtained here provide convincing demonstration of the power law relation between discharge 'Q' and head 'h' for the Dam Spillway (Figure 20).
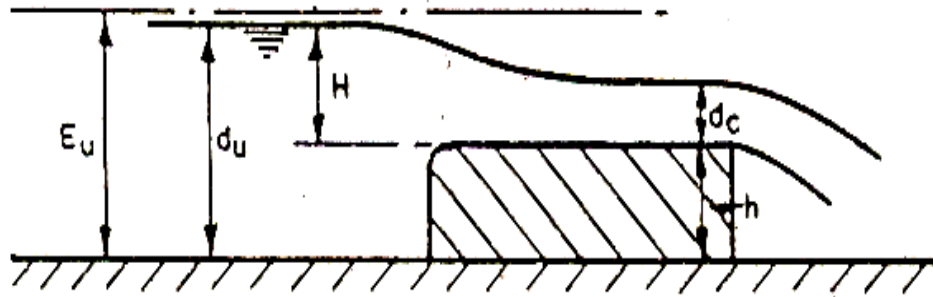
Fig.8 : Broad crested weir
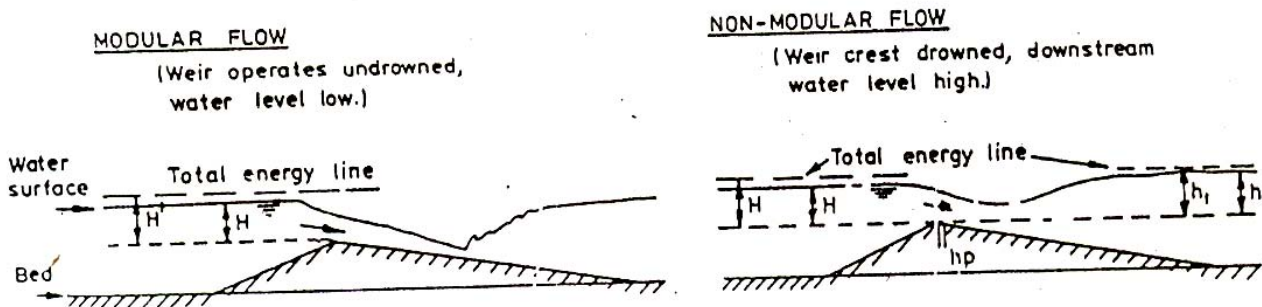
Fig. 9 : Crump Weir
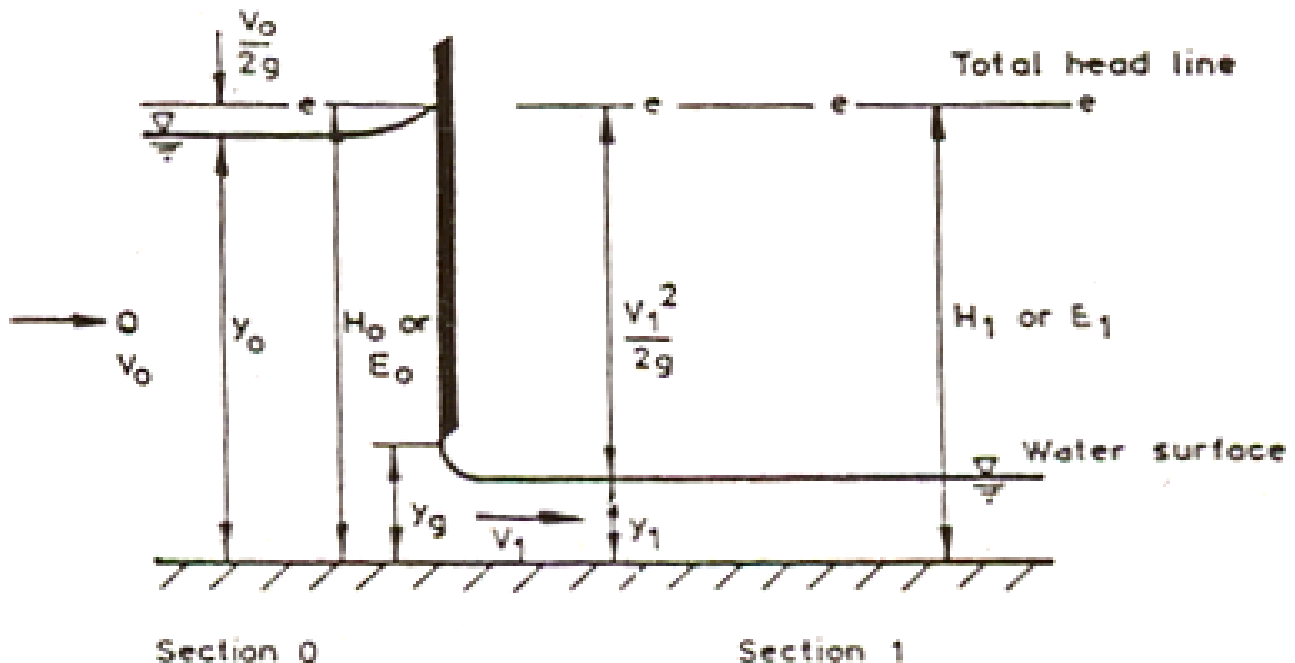
Fig. 10 : Sluice Gate
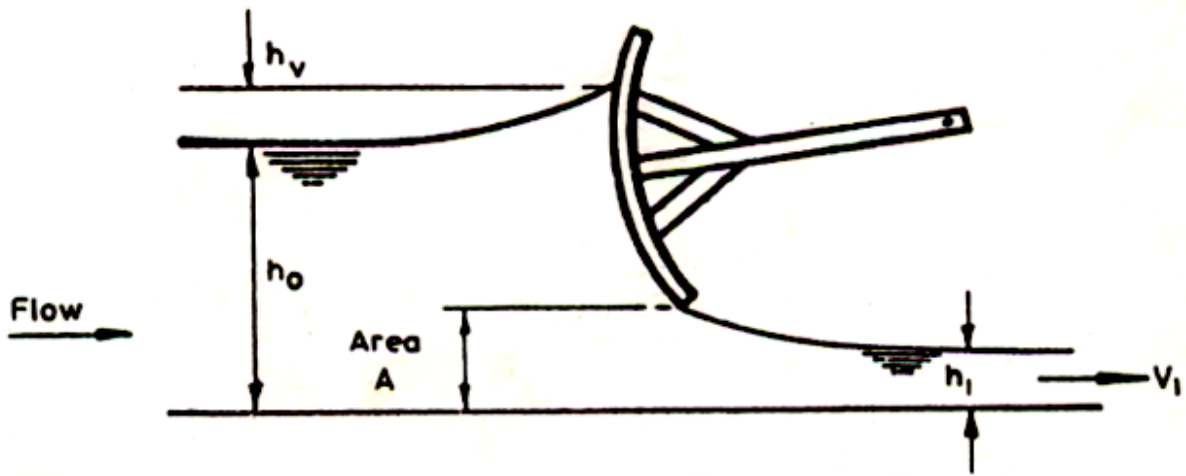
Fig. 11: Radial Gate
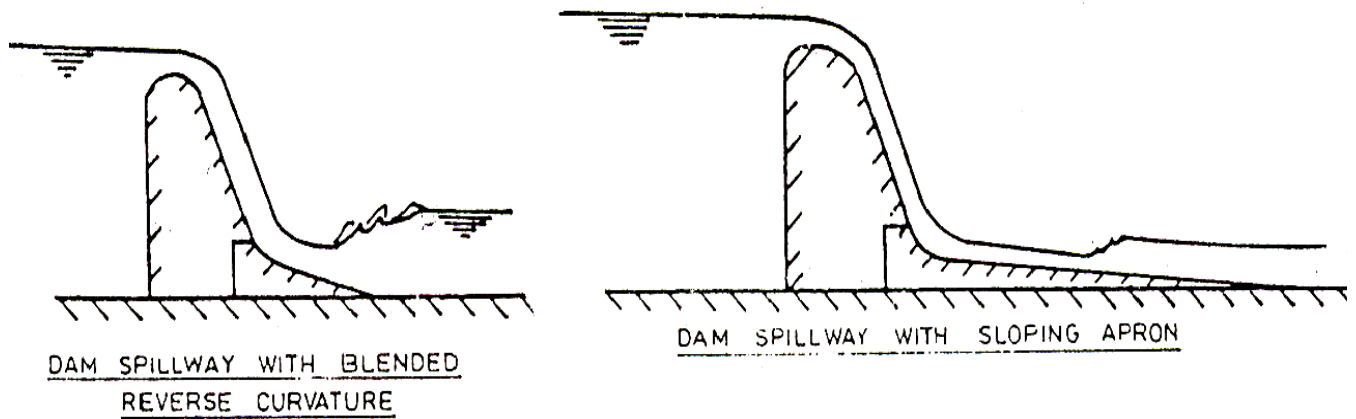
Fig. 12 : Dam Spillway

$$h = 0.2126Q^{0.6823}$$
$$R^2 = 0.9969$$
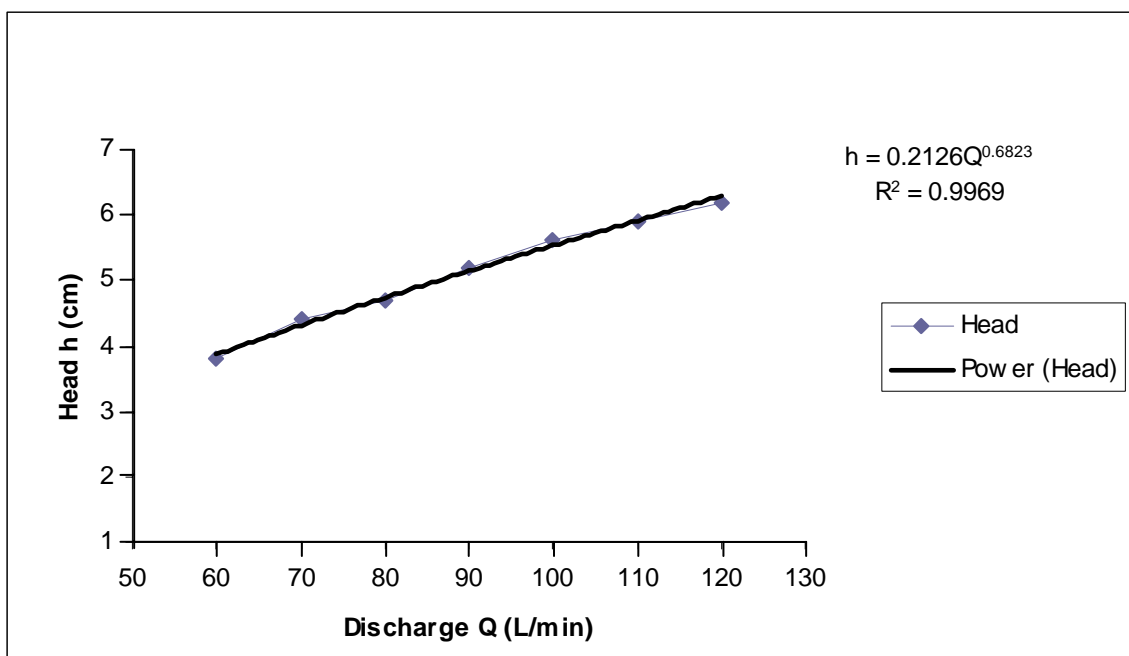
Fig.13: Discharge-head curve for Broad Crested Weir

$C_d = -0.0032h/a + 0.57$
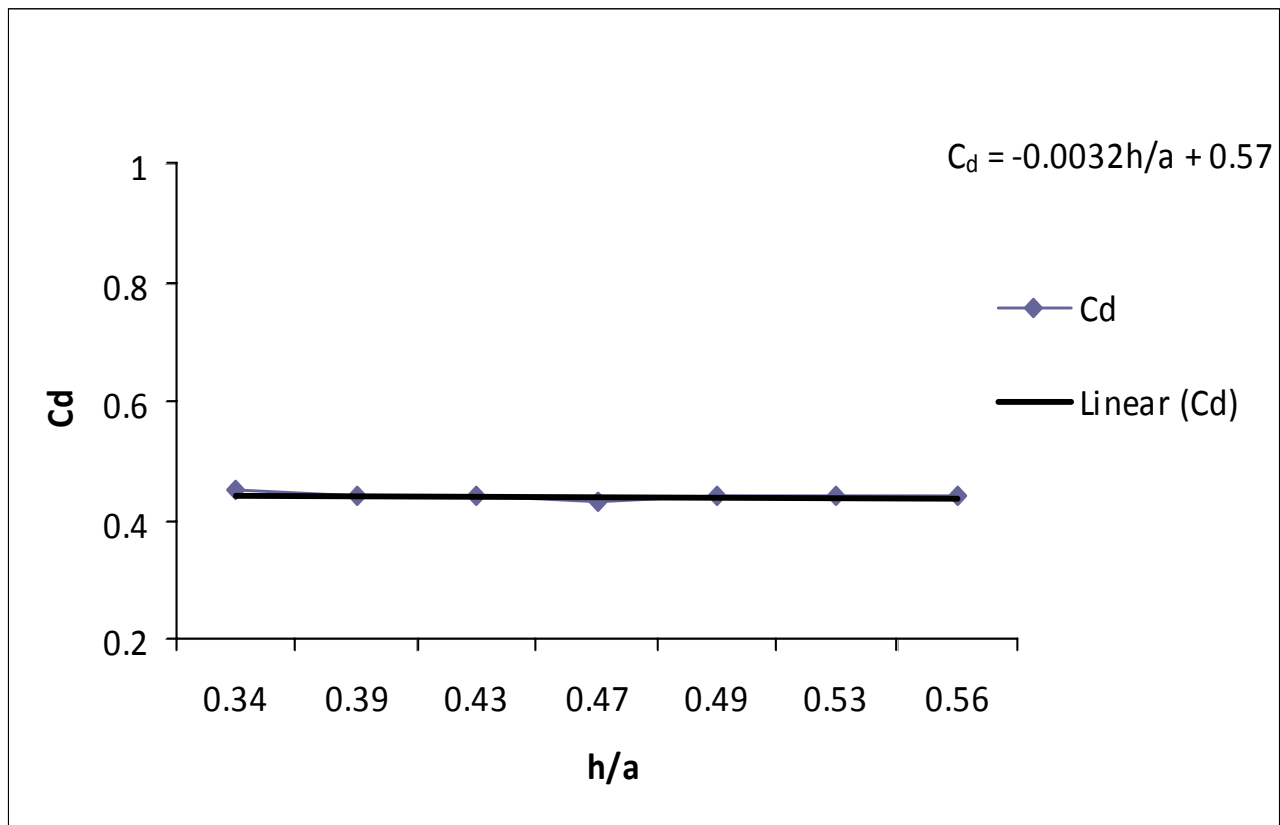
Fig.14 : Variation of C_d with h/a

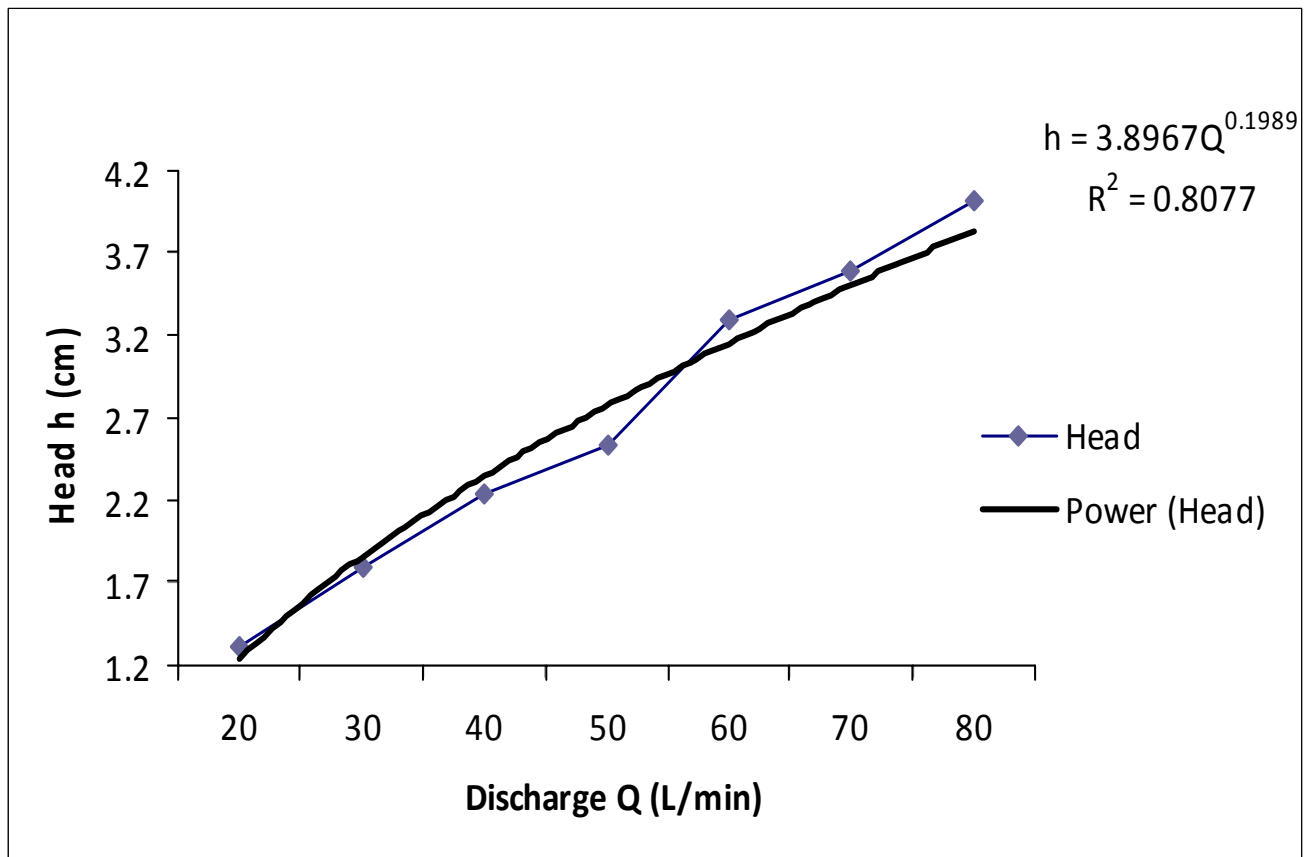$h = 3.8967Q^{0.1989}$

$R^2 = 0.8077$

Fig. 15: Discharge-Head Curve for Crump Weir
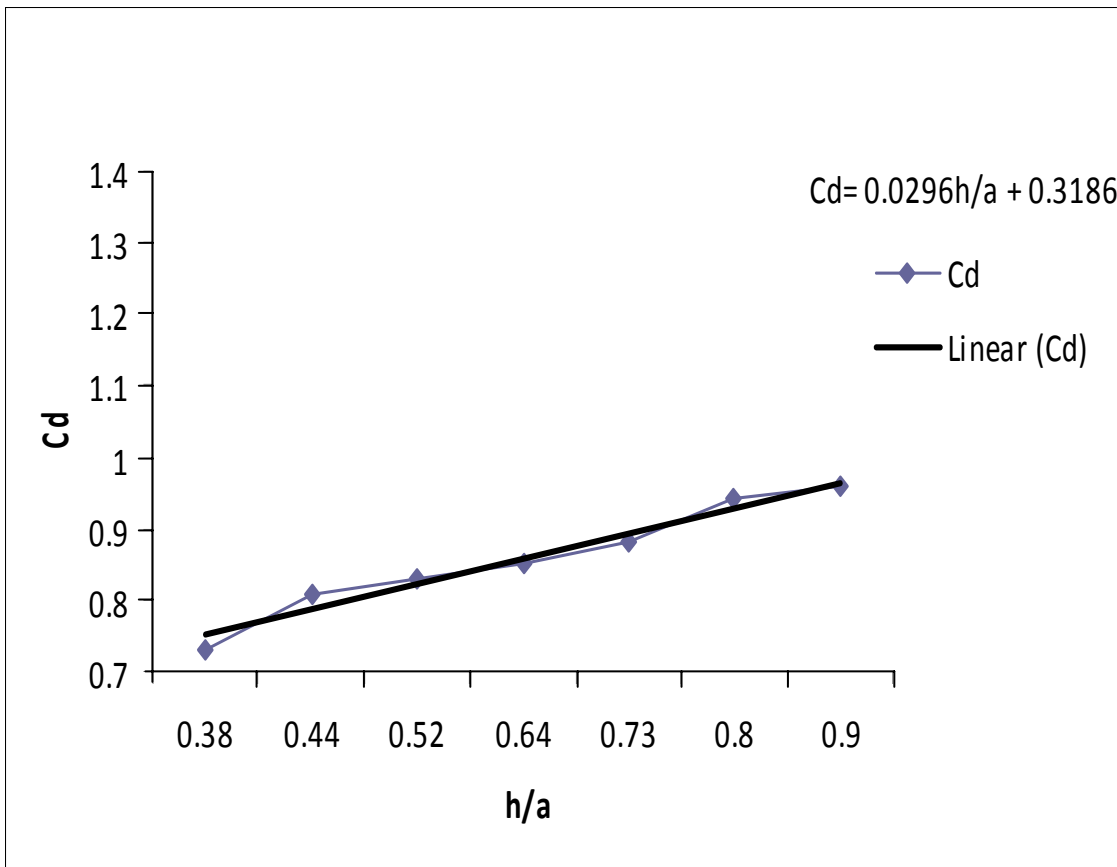
Fig. 16 : Variation of C_d with h/a

Fig. 17: Discharge Q as a function of E

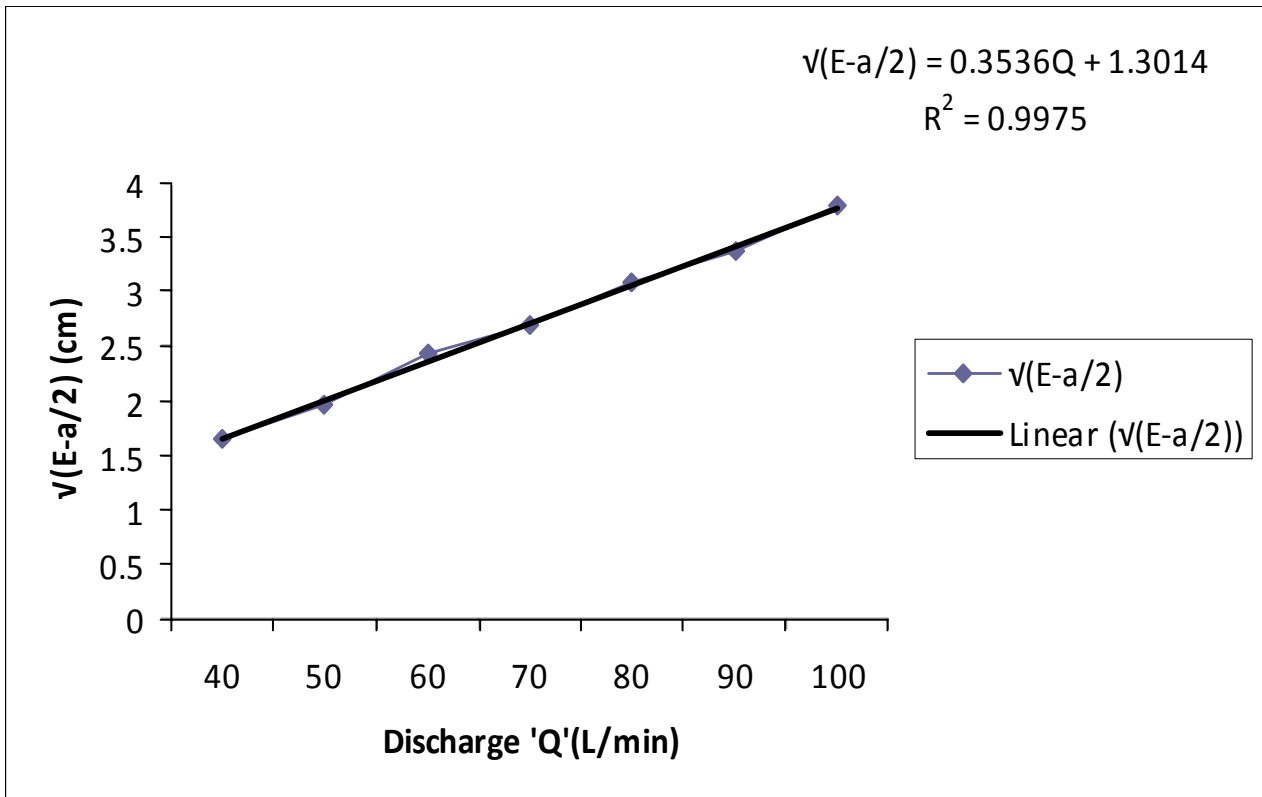$$\sqrt{(E-a/2)} = 0.3536Q + 1.3014$$
$$R^2 = 0.9975$$
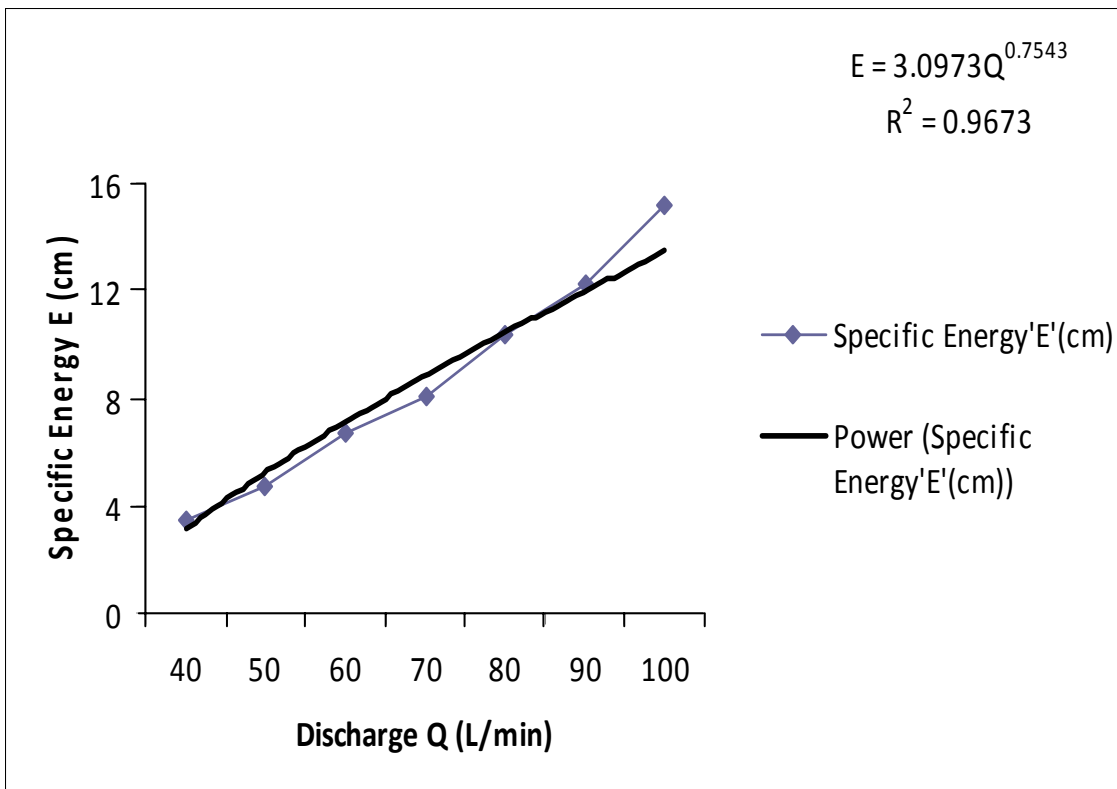
Fig. 18 : Discharge Q as a function of $\left(E - \dfrac{a}{2}\right)^{\frac{1}{2}}$

$$h = 3.845Q^{0.537}$$
$$R^2 = 0.968$$
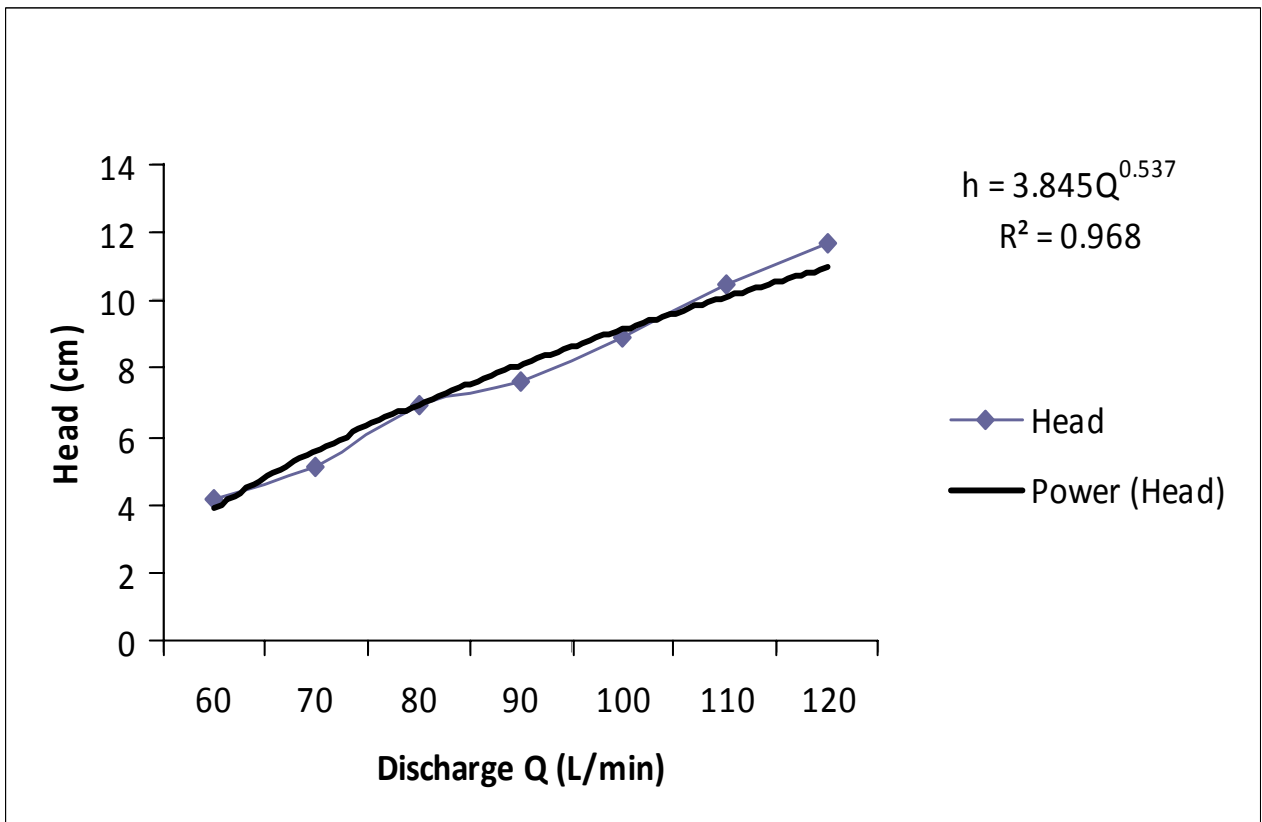
Fig. 19 : Discharge-Head curve for radial gate

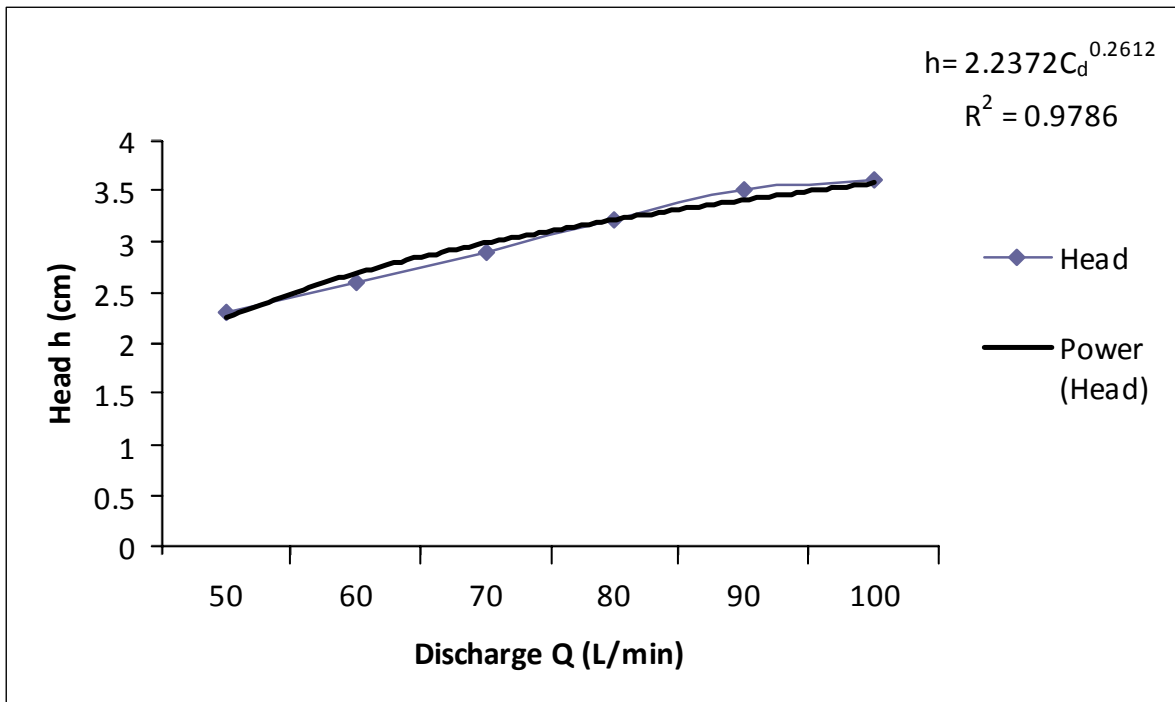$$h = 2.2372 C_d^{0.2612}$$

$$R^2 = 0.9786$$

Fig. 20: Discharge-Head curve for Dam Spillway

Variation of discharge coefficient C_d with h/a

Fig. 21 shows the variation of Coefficient of Discharge 'C_d' with h/a and the relationship is almost linear. Coefficient of Discharge 'C_d' was almost constant with increase in h/a and had been found in the range 1.01 to 1.06 (Table 6). This variation was due to the rounding of the crest as the contraction is not so important in the case of spillway. Therefore, a higher value closer to 1 is obtained during the course of experiment. The value of C_d fluctuated slowly with head and this might be attributed due to the fixing of accurate zero value at crest level and recording of h value.
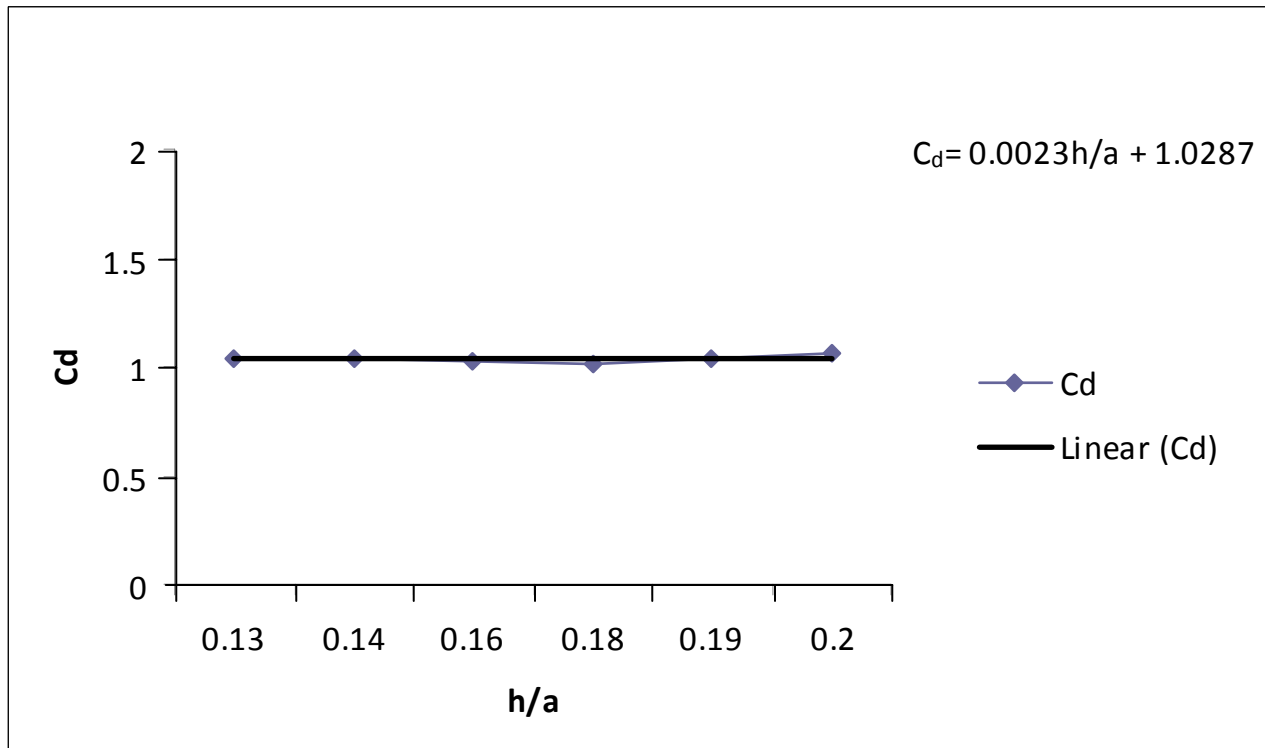
$$C_d = 0.0023 h/a + 1.0287$$

Fig. 21 : Variation of Variation of C_d with h/a

CONCLUSION

1) The average value of Coefficient of Discharge for Broad Crested Weir, Crump Weir, Sluice Gate, Radial Gate and Dam Spillway was found to be 0.44, 0.85, 0.76, 0.82 and 1.03 respectively.

2) Variation of C_d with h/a had been found linear relationship in all cases.

3) For Broad Crested Weir and Radial Gate, 'C_d' was almost constant with increase in h/a.

4) Coefficient of discharge (C_d) increased with h/a in case of crump weir, Sluice Gate, Radial Gate and Dam Spillway.

5) All the selected hydraulic structures showed power relationship between head and discharge.

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