DETERMINATION OF COEFFICIENT OF DISCHARGE FOR AIR-INFLATED DAM USING PHYSICAL MODEL

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Abstract

In general the coefficient of discharge for various types of measuring structures constructed in an open channel can be found from a standard formula. These structures such as a broad-crested weir, sharp-crested weir and circular-crested weir have a constant shape under all overflow conditions; therefore the relationship between the head and discharge over the structures can be found. In the case of inflatable dams this relationship is more complex than traditional measuring structures because the dimensions of inflatable dams may be varied due to internal pressure, overflow head and downstream water head. In this study the coefficient of discharge for inflatable dams was determined from the experimental data under different overflow heads and internal pressures for an air inflated dam.

Keywords: Inflatable dam, discharge coefficient, weir, rubber dam

Introduction

Inflatable dams, also called rubber dams, are flexible cylindrical inflatable and deflatable structures attached to a rigid base at either one or two ends (single or double anchor), made of rubberized material and inflated by air, water, or a combination of the two. Rubber dams have been installed in different parts of the world for various purposes such as irrigation, flood control, tidal defense, water supply and recreation. Inflatable dams can be used in different climatic conditions.

Imbertson (1960) developed the first inflatable dam. This dam was installed in the USA as part of a water supply project for the city of Los Angeles. In Pakistan an inflatable weir with three bags was used in 1965 during the construction of the Mangla Dam to regulate the tail water level at the outlets of the tunnels used for river diversion (Binnie *et al.*, 1973). In Japan, the first inflatable dam for water storage was installed in 1965 (Tam, 1998).

Most of the recently constructed inflatable dams were of an air-inflated type. The advantages of air-inflated dams over the water-inflated dams are discussed in the literature such as Takasaki (1989); Tam (1998); and Zhang *et al.* (2002). These can be summarized as follows:

i) The space needed for air inflated dams

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equipment is less than for water inflated dams.

ii) Water-filled pipes could freeze in cold regions and water-borne debris can clog the pipes.

iii) Water used to inflate the dam could pollute the river when discharged.

iv) Smaller diameter pipes are used with air-inflated dams than water-inflated ones.

v) Air-inflated dams inflate and deflate quicker than with water-inflated dams.

vi) The installation time of air-inflated dams is relatively short.

vii) Air blower systems require less maintenance than water pumping systems.

viii) The shape of the air-inflated dam is more circular than the water-inflated dam; therefore the cross-sectional area of the dam is less, which means that the loads on the foundation are less, thus the required width of the foundation is also less.

However, a water-inflated dam vibrates less and it is more stable than the air-inflated dam under overflow conditions (Anwar, 1967).

The relationship between the overflow head and the discharge over the inflatable dams is more complex than traditional structures because the shape of the dams may be varied due to the change in the internal pressure, overflow head and downstream water depth. In this study the coefficient of discharge was determined from the experimental data under different internal pressures and overflow heads for an air inflated dam.

Anwar (1967) determined the coefficient of discharge of air and water inflated dams by using the following equation:

$$C_d = \frac{q}{\sqrt{2g} \cdot H^{1.5}} \tag{1}$$

where, C_d is the coefficient of discharge, q the discharge over the dam per unit length, H the overflow head as shown in Figure 1, and g is the acceleration due to gravity.

Anwar (1967) also found that the coefficient of discharge of air and water inflated dams ranges from 0.35 to 0.5 and also the coefficient of discharge is dependent on the ratio of H/D_h where D_h is the dam crest height (Figure 1) and high values of C_d occur at a high ratio of H/D_h.

Baker and Clare as cited by Al-Shami (1983), carried out an experimental work to determine the coefficient of discharge C_d for a water-inflated dam by using Equation (1) and it was concluded that the range of C_d varies from 0.386 for low flows to 0.51 for high flows.

Stodulka, as cited by Al-Shami (1983), used equation (1) to calculate the coefficient of discharge and he found that the value of coefficient of discharge C_d varied from 0.25 to 0.40.

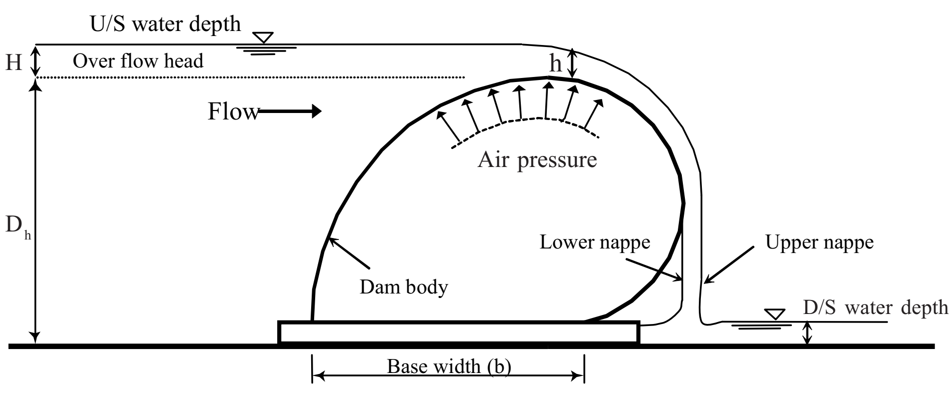


Figure 1. Flow over air–inflated dam

The ministry of overseas development, as cited by Alwan (1979) found that the values of coefficient of discharge of water-inflated dam were dependent on the relation H_o/D_h where H_o is the internal water head above the crest level and the ranges of C_d values varied from 0.3 to 0.4.

Alwan (1979) assumed that the dam operated in a similar manner to a rectangular broad-crested dam and the discharge over the dam could be determined using the following equation:

$$q = \left(\frac{2}{3}\right)^{\frac{3}{2}} C_d \sqrt{g}\, H^{\frac{3}{2}} \qquad (2)$$

Based on data obtained from a physical model and for discharges up to 18 l/s he found that the value of C_d varied from 0.2 to 1.1. Alwan (1979) proposed the following equation to calculate the theoretical values of coefficient of discharge for air and water inflated dams:

$$C_d = \frac{3\sqrt{3}}{(s-1)} \left(1-\frac{h}{H}\right)^{\frac{3}{2}} \left(s-\frac{(1+x)^{\frac{1}{s}}}{(1+x)}\right) \qquad (3)$$

where, h and H are defined in Figure 1, x = s.h/R, R the radius of curvature of the dam crest, and s is a constant that depends on the medium of inflation of the dam and can be computed using the following equations:

$$s = 2.28\,(H/R)^{0.21} \qquad (4)$$

$$s = 2.36\,(H/R)^{0.21} \qquad (5)$$

The application of equations (4) and (5) are for air and water inflated dam respectively. Al-Shami (1983) used equation (1) to calculate the coefficient of discharge of air and water inflated dams and found that they range between 0.35 and 0.4. Also he found calibration equations from the experimental results:

$$C_d = 0.4866\,(H/D_h)^{0.11} \qquad (6)$$

$$C_d = 0.4338\,(H/D_h)^{0.0694} \qquad (7)$$

Equations (6) and (7) are used for air-inflated and water inflated dams respectively.

Abd Alsaber (1997) found an empirical relationship between the discharge Q and the ratio H/D_h for an air inflated dam as given in equation (8).

$$Q = 110.205\,(H/D_h) - 5.9625 \qquad (8)$$

In this study experimental works have been carried out to find the range of the coefficients of discharge for a double anchor air inflated dam.

Materials and Methods

The study was performed using a rectangular glass-sided flume having a length of 20 m, width of 0.9 m and depth of 0.6 m (Figure 2). A rectangular sharp crested weir was placed at the beginning of the flume to measure the discharge in the flume (Figure 3). A baffle was fitted in the flume across the flow located at 1 m downstream of the rectangular weir. This baffle successfully dissipated turbulence in the flow and created more uniform flow conditions. The inflatable dam model was fixed at 8.5 m from the upstream end of the flume. Water surface level and cross-section of dam were recorded using a profile gage (Figure 4).

Air pressure inside the dam model was measured with a water manometer tube. An air compressor was used to inflate the air in the dam model. A rubber material was used to build the air inflated dam model. It was made from a rectangular rubber sheet with the perimeter length of 0.55 m, membrane thickness of 0.001 m and base length of 0.15 m and anchored to the model base (double anchor) which was linked tightly to the flume bed as shown in Figure 5 (Alhamati, 2002). Extra length (20 cm from both sides of the model) was added to the model length (90 cm) in order to prevent leakage between the ends of the model and the flume walls. This extra length was folded inside the model before the model was inflated with air.

Results and Discussion

From the experimental work, it is observed that air inflatable dams are not suitable for high overflow (when used as weirs) because high vibration occurred in the body of the dam when the ratio of H/D_h was approximately grater than 0.2. Water-inflated dam is more stable than air-inflated dam and the vibration occurred when the ratio of H/D_h was approximately greater than 0.5 (not included herein). Anwar (1967) found that the dam body of air and water-inflated dams starts to vibrate when the ratios of H/D_h are greater than 0.25 and 0.6 respectively. This vibration may lead to a failure in the dam membrane due to abrasion between the dam body and the concrete foundation and also this vibration causes the flow over the dam crest to fluctuate.

It was observed that for low flows over air inflated dam the lower nappe of the flow over the dam was almost in complete contact with the surface of the dam model from the crest to the downstream anchor. When the flow rate was increased the nappe began to be seperated, forming a series of nappes (Figures 1 and 6).

The separation of the lower nappe from the membrane may produce a negative pressure underneath the nappe due to the removal of air by the over falling jet. Chow (1959) described the effect of the reduction of pressure underneath the nappe, considering it to have undesirable effects, causing;

- Increase in pressure difference on the crest of the dam.
- Change in the shape of the nappe.
- Increase in discharge, sometimes accompanied by fluctuating or pulsation of the nappe which may be very objectionable if the weir is used for measuring purposes.
- Unstable performance of the hydraulic model.

The aeration of the nappe was carried out in this study by fitting two plastic pipes, each 10 mm in diameter on both sides of the downstream side of the dam model to allow atmospheric pressure to be created underneath the nappe (Figure 6).

V-notch behavior was observed in the inflated dam model during the deflation condition or with low internal pressure as shown in Figure 7 (Alhamati, 2002). This behavior was also observed by other investigators such as Alwan (1979) and Al-shami (1983).

Figure 8 shows the variation of cross-section shape of the dam due to overflow head

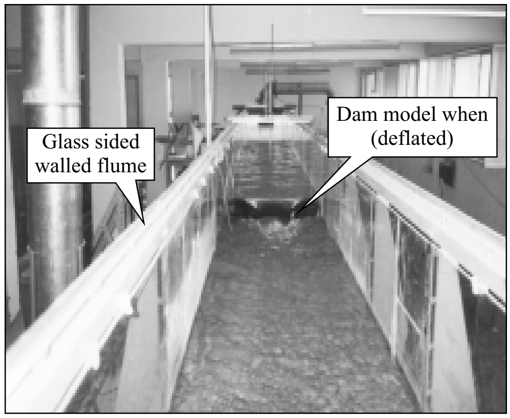


Figure 2. Rectangular glass sided flume

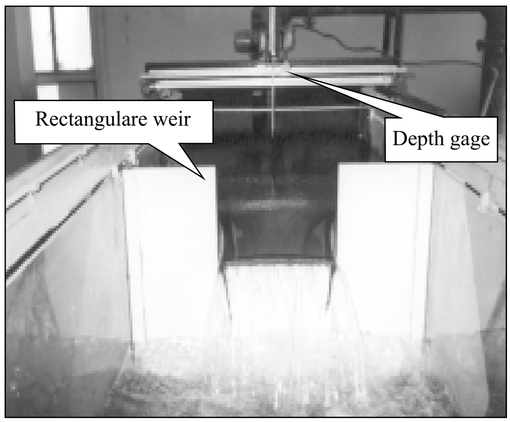


Figure 3. Rectangular sharp-crested weir

Figure 4. Water level and dam profile gage

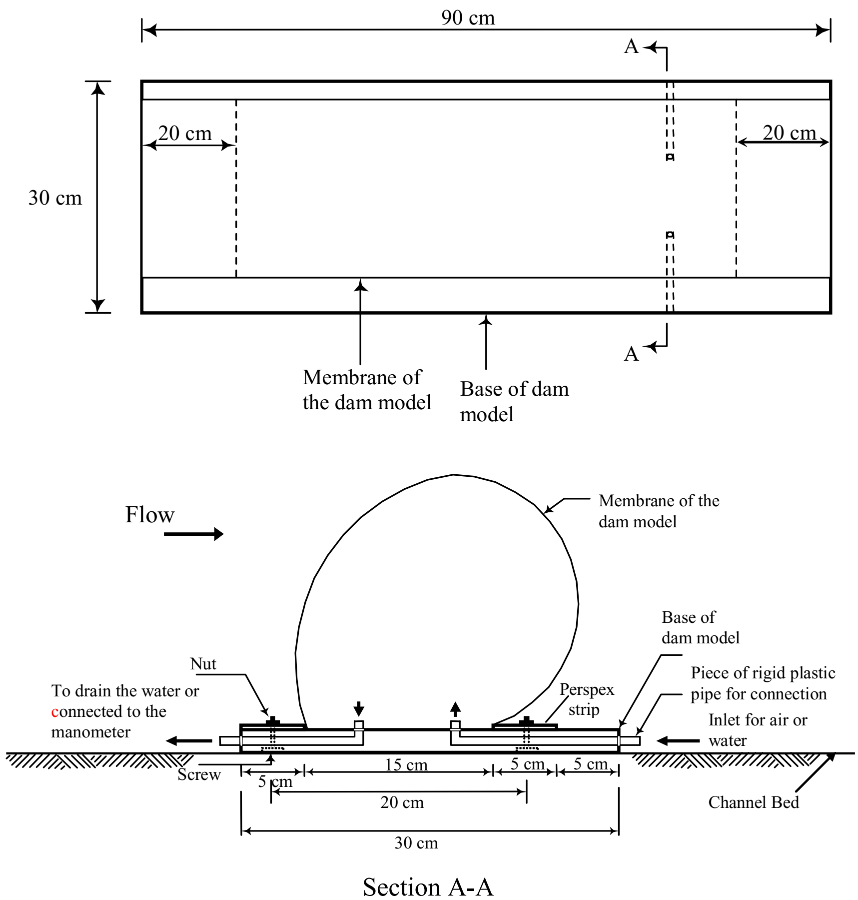


Figure 5. Anchoring the inflatable dam model to the model base

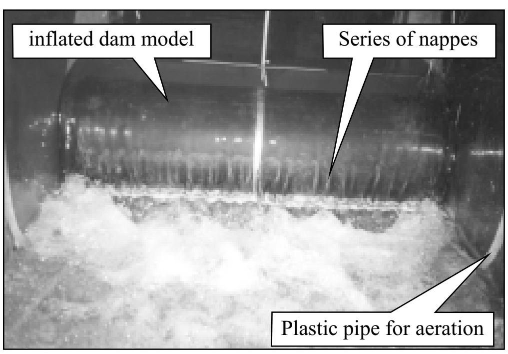


Figure 6. Flow over air-inflated dam model

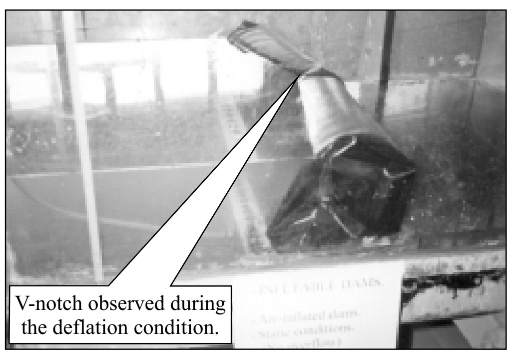


Figure 7. Behavior of air-inflated dam when deflated

H and how it affects C_d values for selected internal air pressure of 3 kN/m^2 (Table 1). The values of C_d increased with increasing overflow head H and the dam cross-section deformed to the downstream direction (Figure 8). The effect of the internal pressure on the deformation of the dam cross-section is more significant than the overflow head but unclear effect on the values of C_d for the conditions as shown in Figure 9.

Variables that may affect the dischage per unit width over the weir q are overflow head H, dam height D_h, perimeter length of rubber material l, dam base width b, the acceleration due to gravity g, internal air pressure p, and modulus of elasticity of the rubber material E. Thus

$$q = f(H, D_h, l, b, g, p, E) \quad (9)$$

or

$$f_1(q, H, D_h, l, b, g, p, E) = 0 \quad (10)$$

The pi dimensionless groups are; $\phi(\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5) = 0$. Using q, H, and p as the primary variables, then the pi groups from the dimensional analysis are; $\Pi_1 = g*H^3/q^2$, $\Pi_2 = l/H$, $\Pi_3 = b/H$, $\Pi_4 = E/p$, and $\Pi_5 = D_h/H$. By rearranging the pi groups as desired and each Π can be raised to any power, since they are dimensionless (Franzini *et al*., 1997). Since q is the interested parameter, then

$$\Pi_1^{-1/2} = \phi_2(\Pi_2^{-1}, \Pi_3^{-1}, \Pi_4^{-1}, \Pi_5^{-1}) \quad (11)$$

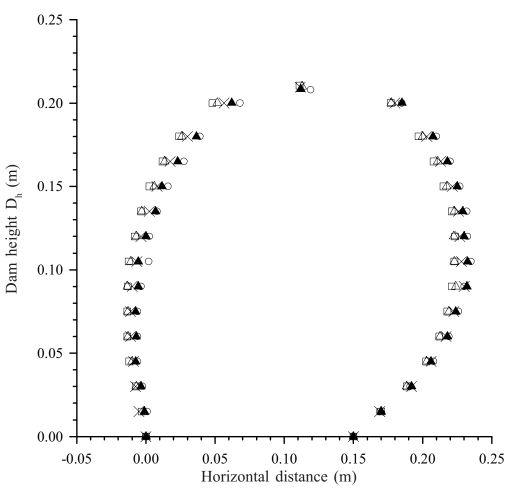
$$q = \phi_2(H/l, H/b, p/E, H/D_h) * g^{1/2}*H^{3/2} \quad (12)$$

$$C_d = \phi_3(H/l, H/b, P/E, H/D_h) \quad (13)$$

In this study, b, E, and l are not changed during the experiments, so, equation (13) reduced to,

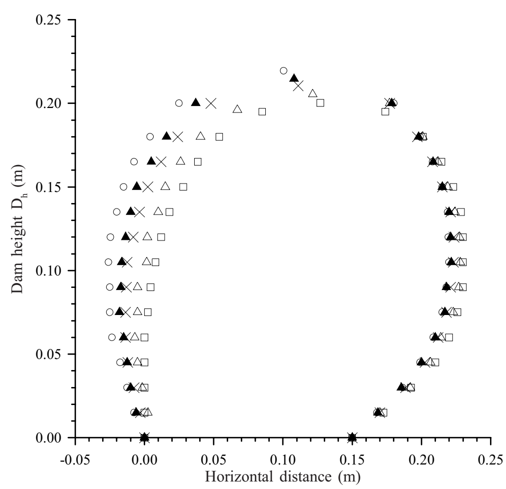
$$C_d = \phi_4(H/D_h) \quad (14)$$

Anwar (1967) also concluded that C_d is a function of (H/D_h). This conclusion is in agreement with equation (14).



Pressure (kN/m^2)	U/S water depth (mm)	Weir height (D_u) (mm)	Overflow head (H) (mm)	Discharge (Q) (l/s)	C_d	Symbol
3	236.20	210.50	25.70	5.12	0.312	□
	241.50	210.00	31.50	7.17	0.322	Δ
	246.10	209.50	36.60	9.50	0.340	×
	256.30	208.40	47.90	14.56	0.348	▲
	265.40	208.00	57.40	19.96	0.364	O

Figure 8. Effect of increasing overflow head on the behavior of air-inflated dams for constant internal pressure



Pressure (kN/m^2)	U/S water depth (mm)	Weir height (D_u) (mm)	Overflow head (H) (mm)	Discharge (Q) (l/s)	C_d	Symbol
1.5	227.10	200.30	26.80	5.25	0.300	□
2	232.30	205.40	26.90	5.25	0.298	Δ
3	236.20	210.50	25.70	5.12	0.312	×
4	240.60	214.60	26.00	5.25	0.314	▲
5	245.70	219.50	26.20	5.25	0.311	O

Figure 9. Effect of increasing internal pressure on the behavior of air-inflated dams for constant overflow head

Table 1. Experimental tests of air-inflated dam model

Test no.	Air pressure (kN/m^2)	Upstream water depth* (H_u) (mm)	Weir height (D_h) (mm)	Overflow head (H) (mm)	Discharge (Q) l/s
1		210.80	203.20	7.60	0.64
2		216.30	201.00	15.30	1.93
3		221.00	200.70	20.30	3.37
4		227.10	200.30	26.80	5.25
5	1.5	233.30	200.10	33.20	7.28
6		237.20	199.80	37.40	9.52
7		247.10	199.00	48.10	14.56
8		254.20	197.40	56.80	20.11
9		216.10	207.70	8.40	0.73
10		221.40	205.70	15.70	1.93
11		226.00	205.60	20.40	3.34
12	2	232.30	205.40	26.90	5.25
13		237.30	204.40	32.90	7.28
14		241.60	204.30	37.30	9.47
15		250.80	204.00	46.80	14.29
16		261.50	203.70	57.80	20.26
17		220.30	211.50	8.80	0.73
18		226.70	211.10	15.60	1.93
19		231.20	210.90	20.30	3.45
20	3	236.20	210.50	25.70	5.12
21		241.50	210.00	31.50	7.17
22		246.10	209.50	36.60	9.50
23		256.30	208.40	47.90	14.56
24		265.40	208.00	57.40	19.96
25		224.00	215.50	8.50	0.73
26		229.00	215.00	14.00	1.75
27		235.20	214.80	20.40	3.45
28	4	240.60	214.60	26.00	5.25
29		245.60	214.20	31.40	7.28
30		251.00	213.90	37.10	9.71
31		260.30	213.40	46.90	14.34
32		269.50	213.00	56.50	20.26
33		229.20	220.50	8.70	0.73
34		235.30	220.20	15.10	1.93
35		240.90	219.90	21.00	3.50
36	5	245.70	219.50	26.20	5.25
37		250.60	219.20	31.40	7.28
38		255.00	218.80	36.20	9.29
39		265.20	218.10	47.10	14.56
40		275.00	217.60	57.40	20.26

* Downstream water depth below the base of the model

The coefficients of discharge were calculated from equation (1) and the discharge over the inflatable dam was measured by using a calibrated rectangular sharp crested weir (Figure 3). Table 1 shows various recorded discharges for different heads over the inflatable dam with different internal air pressures.

Analysis of the experimental data was carried out to find the relation between the C_d with the ratio H/D_h for an air-inflated dam model as shown in Figure 10. Data was best fitted by the following equation and the correlation coefficient was found to be 0.94:

$$C_d = 0.5066\ (H/D_h)^{0.2447} \qquad (15)$$

When the ratio of H/D_h changed from 0.04 to 0.3 the C_d values of the inflated dam model varied from 0.22 to 0.38 and increased as the internal pressure increased (Figure 10). Similar behavior was also reported by Anwar (1967) and can be explained by the fact that the dams with a lower internal pressure have a more broad crest than the dams with a high internal pressure under the same conditions of overflow head and downstream water head.

In this study, the experimental data for an air-inflated dam was combined with other data collected by Anwar (1967), and Sumitomo Electric Industries, Ltd. as cited by Tam (1998) and a relationship was plotted between H/D_h and C_d as shown in Figure 11. In Figure 11, the experimental data for this study covered the low values of the ratio H/D_h (from 0.04 to 0.3) while the experimental data collected by Anwar (1967) and Tam (1998) covered the high values of the ratio of H/D_h (from 0.2 to 0.7).

The best for all these data with a coefficient of correlation equal to 0.91 is shown in Figure 9 and the formula obtained from this is:

$$C_d = 0.5516\ (H/D_h)^{0.2697} \qquad (16)$$

The dimensions of the model used for the inflatable dam were not based on the dimensions of a specific existing prototype but a reasonable scale is used to assume the dimension of model considering the available space in the laboratory to conduct the experiments. The concept of similarity between the model and the prototype should be applied to make use of the results obtained but the material of membrane of the model and that of the prototype must have imilar properties. Also, the relationship of

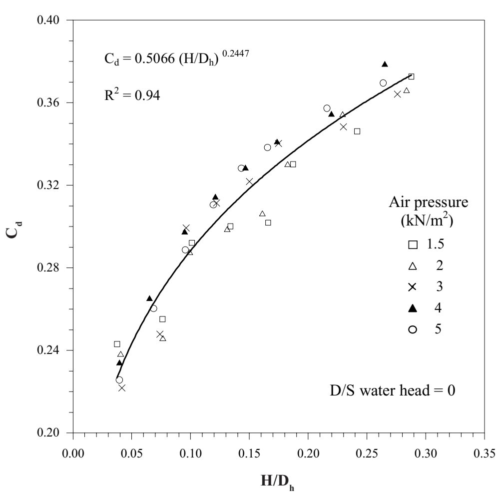


Figure 10. Variation of coefficient of discharge with the ratio H/D_h of air-inflated dam (Present study)

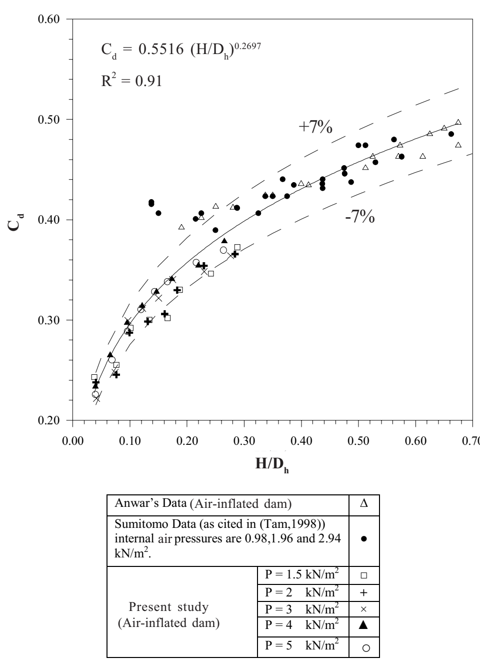


Figure 11. Coefficient of discharge for air-inflated dam (Anwar, 1967; Tam, 1998; and the present study)

the internal pressure between the model and prototype should be considered.

Conclusion

The coefficient of discharge increased with increasing ratio of H/D_h. This study shows that the coefficients of discharge of the air-inflated dam range between 0.22 and 0.38, when the ratio of H/D_h varies from 0.04 to 0.3, and from the combination of all the experimental data the values of the coefficients of discharge vary from 0.22 to 0.5, as H/D_h varies from 0.04 to 0.7.

The results obtained from the experiments showed that the internal pressure has little effect on the values of C_d and increasing internal pressure of the inflatable dam may not increase the value of C_d. Also, it was noticed that a slight increase in the values of C_d for the inflatable dam when the internal pressure was increased.

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