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RESEARCH ARTICLE

Experimental Study of Drop Length for Vertical and Inclined Narrow Crested Weirs.

Mohamed Gamal Abdalla[1] and Mohamed Tarek Shamaa[2]

1. Associate Professor, Mansoura University, faculty of Engineering, Mansoura, Egypt.
2. Assistant Professor in irrigation and Hydraulics Dept. - Mansoura University.

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Corresponding Author

Mohamed Gamal Abdalla.

Abstract

This study concerns with the determination of average drop length and some characteristics of nappe and brink section for stilling basin of narrow crested weirs. For a horizontal smooth rectangular channel, the experimental investigations were carried out under specific conditions such as a free nappe, which occurred when the atmospheric pressure exists beneath the drop; different discharges; different model dimensions and shapes; subcritical approaching flow; and no tail-water effect. This research work was conducted in a flume with dimensions of 12 m long, 0.4 m deep and 0.4 m wide. Two groups of models were made; the first group for narrow crested weir having height of 15, 19.5 and 25 cm; the second one of narrow crested weir with an inclined downstream face with slope of 1:2, having heights of 15, 19.5, and 25 cm and slopes of 1:2, 1:3, and 1:5 having height of 25 cm each. The momentum equation and Newton's laws of motion were used to derive two theoretical equations to determine the average drop length. From this research, the experimental drop length in all cases of this study was less than that given by the theoretical equations by an average difference ranged from 5% to 7%. This difference is mainly due to the assumptions used for the derivation of the theoretical equation. A coefficient, C_L (drop length correction coefficient) was determined from the comparison between the theoretical and experimental results and its value was found equal to 0.97 for narrow crested weirs. For the two groups of narrow crested weirs with vertical and inclined downstream faces, respectively the experimental drop length was found in a good agreement with the design equation. Comparison between the experimental and designed drop lengths indicated that 70.31% of the designed values were within an error of ±5% of the experimental values, and 85.94% were within an error of ±7%.

Introduction:-

The water velocity downstream the drop is relatively high and the excessive amount of kinetic energy carried in the flow may be of danger to the outlet structure or its surroundings. A drop structure-stilling basin is used to change the exit supercritical flow downstream the drop to a subcritical state by both the jump and circulation in pool beneath the nappe Abdul (Khader et. al., 1970).

The drop structure may be low or high, Little and Murphey (1982) defined the low drop as the drop, in which the relative drop height (P/h_c) (P = drop height, h_c = critical depth) is equal to or less than one, conversely a high drop is the one with a relative drop height greater than one.

The problem of the free overfall has attracted considerable interest for almost 70 years, and a large number of theoretical and experimental studies has been carried out by many investigators. outstanding contributors to the present field are Rouse, Diskin, Smith, Rajaratnam and Muralidhar, Schwartz, Bauer and Graf, Neogy, Kraijenhoff and Dommerholt, Naghdi and Rubin , Little and Murphey, Tung and Mays , Keller and fong, Terzidis and partheniou, Gupta et al., Ferro, and Dey. (Chamani and Beirami, 2002)

Donnelly and Blaisdaell (1965) presented a significant work on vertical drop spillway stilling basin. Hager (1983) used an analytical approach to solve the Bernoulli equation, extended to take account of curvature effects, and applied it to a rectangular free overfall. Bohrer et al. (1998) predicted the velocity decay of free falling jet while the energy loss at free overfall was discussed by Rajaratnam and Chamani (1995).

Numerical solutions include the works of Chow and Han, Khan et al., and Davis et al.

Ali and Sykes (1972) applied free vortex theory to free overfall in rectangular, triangular, and parabolic channels while Marchi (1993) used a relaxation method to integrate the potential flow equations and obtained solutions for the nappe profile and upstream profile in rectangular free overfall.

Recently, Watson et al. (1998), and Rajaratnam (1998) presented the aeration performance of free falling jet.

Khader et. al., (1970). Stated that Birkhoff in 1961 presented a brief survey of the approximate methods available for solving the free surface problems in which boundary layer separation is not likely to play an important role, the employed methods are:

1- Relaxation technique;
   a) In the physical plane.
   b) In the complex potential plane.
2- Complex function theory and conformal mapping technique;
3- Conformal mapping and singularity distribution;
4- Matching technique (inner and outer expansion); and
5- Electrolytic model.

Hydraulics of falling jet:-
The brink section divides the flow into the upstream zone, bounded by the channel with straight bottom, and the unbounded downstream jet zone. Two types of jets have been evaluated, a fully air entrained developed jet and non-aerated undeveloped one. The free overfall studies have been restricted to jets with atmospheric pressure conditions on both the upper and lower boundaries (Dey and Kumar, 2002)

Drop Length:-
Donnelly and Blaisdaell (1965) deduced a theoretical equation to compute the vertical drop stilling basin length, Fig. (1). They presented a design chart to determine the drop length. (Ferro, 1992)

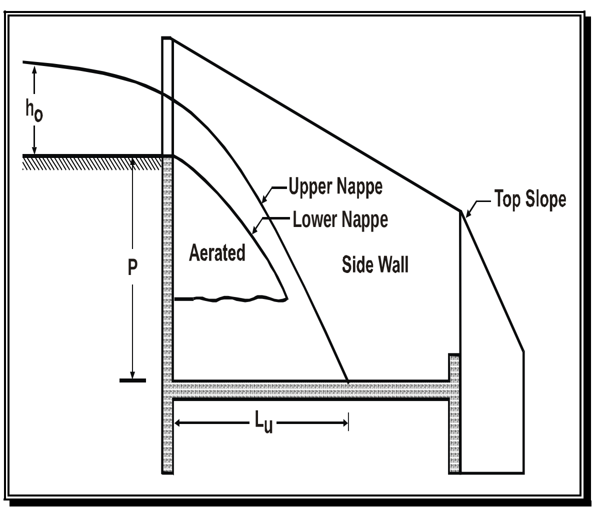

Fig. (1): Vertical drop stilling basin

Theoritical approach:-

The flow narrow crested weirs is analyzed by the one-dimensional momentum equation and Newton's laws of motion in smooth prismatic horizontal channel. The horizontal distance from the crest of weir to the point at which the nappe strikes the stilling basin floor is termed as the drop length, (L_d). For computing the drop length, the momentum equation is applied between the upstream section (I-I) and the brink section (II-II).

The following assumptions are considered in applying the momentum equation:-

1- The case of ventilated jet into the downstream zone is considered.
2- The pressure distribution at the upstream section is hydrostatic.
3- The pressure at the brink section is zero.
4- The horizontal component of the velocity at the beginning of jet is the effective amount, while the vertical component is neglected.
5- The coefficient of non-uniform velocity distribution, the energy coefficient (α = 1.0) and the momentum coefficient (β = 1.0).
6- The crest width, δ= (0.5:2.5) h1.

According to these assumptions, for one-dimensional flow, the theoretical relationships for the average drop length, (L_d) will be deduced.

According to the preceding assumptions, the momentum equation between section I-I and section II-II Fig. (2), could be written as:

$$\gamma\left(\frac{h_o^2}{2}\right)-\gamma\left(\frac{h_o^2}{2}-\frac{h_1^2}{2}\right)=\left(\frac{\gamma\, q}{g}\right)(V_2-V_o)$$

(1)

where:

h_o = upstream water depth at section I-I;
h_1 = water depth over the weir crest; and
V_o, V_2 = mean velocity at sections I-I and II-II, respectively.

Eliminating (γ) from Eqn. (1) and simplifying:

$$\frac{q}{g}(V_2-V_o)=\frac{h_1^2}{2} \qquad (2)$$

Equation (2) may be rearranged to the form:

$$V_2=V_o+\frac{gh_1^2}{2q} \qquad (3)$$

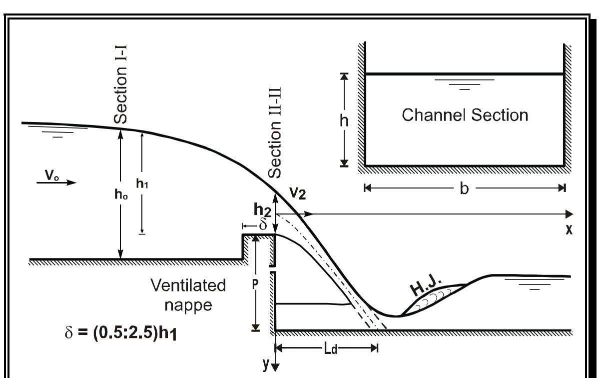

Fig. (2): Definition sketch for narrow crested weir

From the continuity equation in which ($V_2 = q/h_2$), then Eqn. (3) becomes:

$$h_2 = \frac{2q^2}{2qV_o + gh_1^2} \qquad (4)$$

Using Newton's laws of motion for a particle at the origin of axes in figure (2) gives:

$$Y = P + \frac{h_2}{2} = P + \frac{q^2}{2qV_o + gh_1^2} \qquad (5)$$

$$X = 0.452 V_2 \sqrt{Y} \qquad (6)$$

substituting the boundary condition ($X = L_d$) and Eqns. (3) and (5) into Eqn. (6) gives:

$$\boxed{L_d = 0.452\left(V_o + \frac{g\,h_1^2}{2q}\right)\left(P + \frac{q^2}{2qV_o + g\,h_1^2}\right)^{0.5}} \qquad (7)$$

Again multiplying Eqn. (7) by the drop length correction coefficient (C_L) to cover the effects of theoretical assumptions. Then Eqn. (7) becomes:

$$\boxed{L_d = 0.452 C_L\left(V_o + \frac{g\,h_1^2}{2q}\right)\left(P + \frac{q^2}{2qV_o + g\,h_1^2}\right)^{0.5}}$$

(8)

Equation (8) is the final relationship, which represents the average drop length.

In this case, shown in figure (2), the dependent variable drop length, (L_d) is assumed to be a function of the following independent quantities: the drop height (P), the upstream water depth over weir crested (h_1), the upstream water depth (h_o), the upstream mean velocity (V_o), the acceleration of gravity (g), the mass density (ρ), the surface tension (ρ), and the dynamic viscosity (μ).

The general function between the above quantities can be written as:

$$\phi\{L_d, P, h_1, h_o, V_o, g, \rho, \sigma, \mu\} = 0.0 \qquad (9)$$

Which may be arranged in the following non-dimensional form:

$$\phi(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6) = 0.0 \qquad (10)$$

$$\phi_1\left(\frac{\pi_3}{\pi_1}, \frac{\pi_3}{\pi_2}, \sqrt{\pi_4}, \pi_5, \pi_6\right) = 0.0 \qquad (11)$$

$$\phi_1\left(\frac{L_d}{h_1}, \frac{P}{h_1}, \frac{V_o}{\sqrt{gh_o}}, \frac{\rho h_o V_o}{\mu}, \frac{\rho h_o V_o^2}{\sigma}\right) = 0.0 \qquad (12)$$

The effect of viscosity was neglected because of the relatively large size of model and high degree of turbulence generated by viscosity, this being of secondary importance in estimating the drop length. The surface tension effects may become significant in small flow depth, which was not considered in this experimental work, so it can be ignored. Then Eqn. (3.54) may be written as follows:

$$\frac{L_d}{h_1} = \phi_2\left(\frac{P}{h_1}, Fr_o\right) \qquad (13)$$

Eqn. (13) represents the drop length as a function of dimensionless parameters involved in the phenomenon.

Experimental work:-

The present experiments were conducted in a rectangular flume with a mild slope of 0.40 m wide, 0.40 m deep, and 12.0 m long, with 2.0 m long Perspex sides, **Fig. (3),** in irrigation and hydraulics laboratory of the faculty of engineering, El-Mansoura University.

Fig. (3): The Apparatus "Plan View".

The experimental work in this study was performed on two groups of models with different shapes. These models were made of wood at the faculty workshop and painted several times to be watertight.

The first group:-

Consists of three models with different heights for the narrow crested weir.

The second group:-

Consists of five inclined models with different dimensions

Aeration was provided to the downstream face of the model by means of an orifice of diameter 19 mm approximately, connected with a hose and located near the top of the model face. The definition sketches for these groups of models are shown in Figs. (4) to (5).

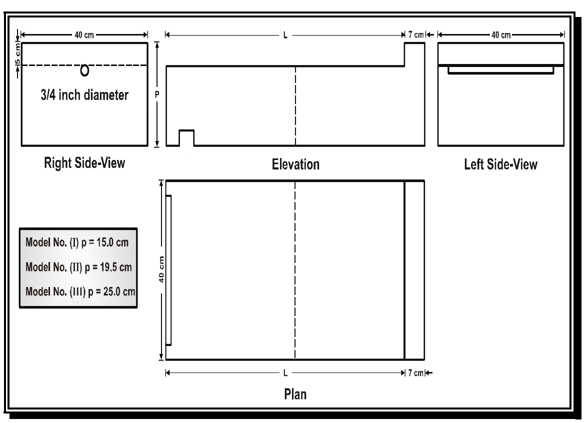

Fig. (4): Definition sketch for the second group of narrow crested weir.

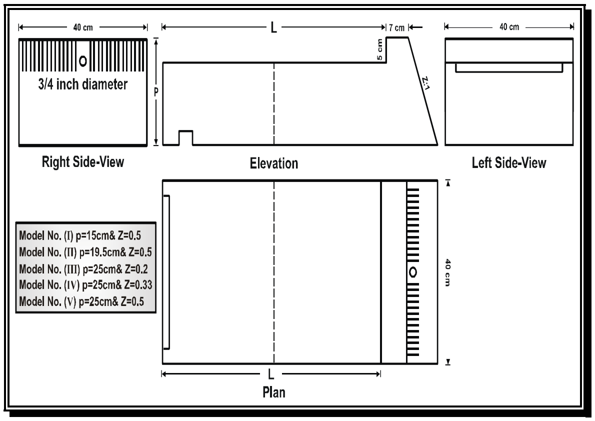

Fig. (5): Definition sketch for the second group of narrow crested weir with an inclined downstream face:-

Data of the first group:-

		Model Height P (cm)	Model Width b (cm)	Model Length L (cm)
First Group	1	15.0	40	93
	2	19.5	40	93
	3	25.0	40	93

Data of the second group:-

Mode l No.		Model Height P (cm)	Model Width b (cm)	Model Length L (cm)	Inclinati on Z : 1
Second Group	1	15.0	40	92.50	0.50 : 1
	2	19.5	40	90.25	0.50 : 1
	3	25.0	40	95.00	0.20 : 1
	4	25.0	40	91.67	0.33 : 1
	5	25.0	40	87.50	0.50: 1

Experimental Preparation:-

The experiments were performed using different models with different values of discharge to determine the following items, Fig. (6):

- The horizontal length of lower nappe profile, L_L.
- The horizontal length of upper nappe profile, L_u.
- The average drop length, L_d.
- The brink depth, h_e.
- The upstream water surface profile.
- The upper nappe angle, φ.
- The average pool depth beneath the nappe, h_p.

Eight runs were carried out for every model with a discharge ranged from (3 to 20) Lit./sec. During these runs, the flow was subcritical and the nappe was ventilated.

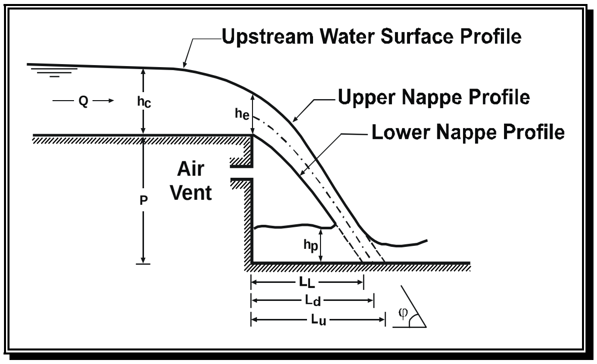

Fig. (6): Definition sketch for models.

Experimental Procedure:-

1- A steady flow of water over the weir is established.
2- Care is taken to ensure that the nappe is ventilated.
3- The discharge is measured using the flow meter and the stopwatch.
4- The upper nappe profile, the lower nappe profile, and the pool profile beneath the nappe are drawn on the millimeter translucent paper.
5- The upstream water surface profile along the centerline of the model is determined by using the movable point gauge at 5.0 cm intervals, starting from the crest of the weir and proceeding upstream.
6- Fluctuation of the water surface is observed during the experimental work. To obtain a proper depth, the reading of the point gauge is adjusted so that the point is submerged and exposed for equal intervals of time at the water surface.
7- After completion of the experiment, another model is placed in the flume and the experiment is repeated.

Results and analysis:-

Determination of drop length:-

The second group of narrow crested weir is given in Fig. (7). In this figure, the linear correlation passes through the origin is used and from this correlation, the coefficient (C_L) is obtained, it is equal to 0.97 for narrow crested weirs. According to this value of (C_L), the drop length could be written as follows:

$$\boxed{L_d = 0.438\left(V_o + \frac{gh_1^2}{2q}\right)\left(P + \frac{q^2}{gh_1^2 + 2qV_o}\right)^{0.5}}$$

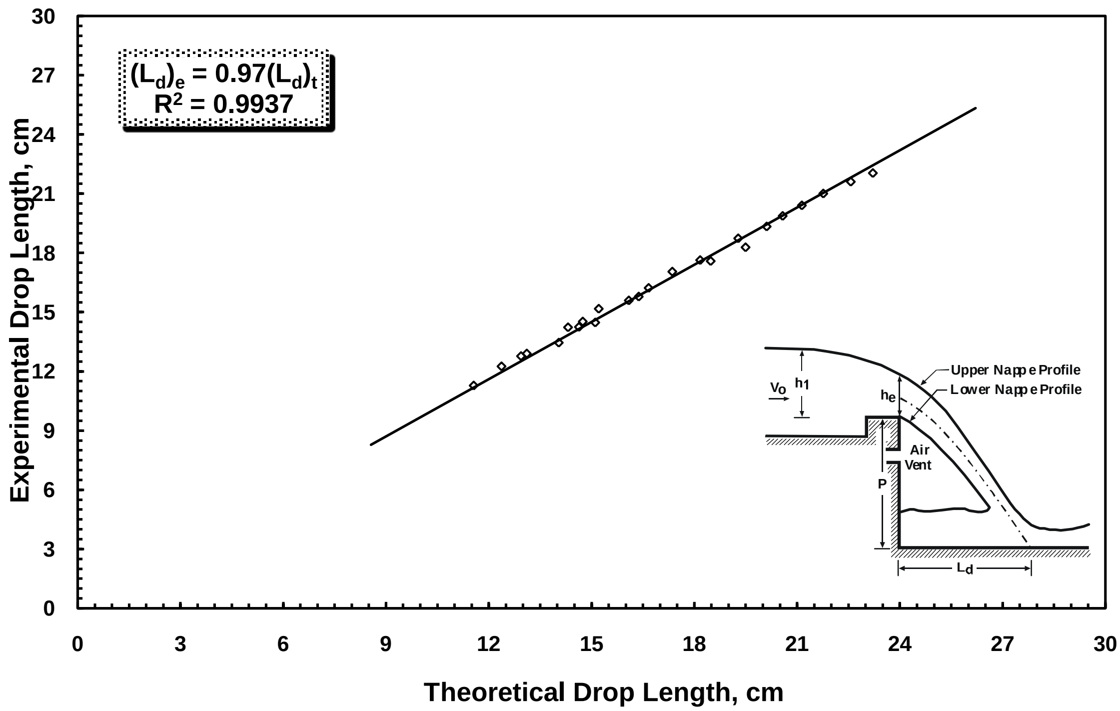

Fig. (7): Experimental drop length $(L_d)_e$ versus theoretical drop length $(L_d)_t$ for narrow crested weir (second group).

Comparative study of drop length:-

Drop lengths for the second group of narrow crested weir for both the experimental results and the design equation (14) are given in Table (1).

Table (1): Experimental and Designed Drop Lengths for the First Group of Narrow Crested Weir:-

Run Number		1	2	3	4	5	6	7	8
Model No. (I)	**q, Lit. / sec. / m**	**8.63**	**11.38**	**13.53**	**16.13**	**18.88**	**20.83**	**23.80**	**26.48**
	Experimental (L_d), cm	**11.28**	**12.25**	**12.78**	**13.45**	**14.23**	**14.52**	**15.18**	**15.59**
	Designed (L_d), cm	**11.21**	**12.00**	**12.55**	**13.62**	**13.88**	**14.30**	**14.75**	**15.61**
Model No. (II)	**q, Lit. / sec. / m**	**9.35**	**15.88**	**20.23**	**24.50**	**29.78**	**35.03**	**41.80**	**47.70**
	Experimental (L_d), cm	**12.90**	**14.47**	**15.79**	**17.06**	**17.59**	**18.29**	**19.34**	**20.40**
	Designed (L_d), cm	**12.72**	**14.66**	**15.89**	**16.84**	**17.93**	**18.92**	**19.51**	**20.51**
Model No. (III)	**q, Lit. / sec. / m**	**10.13**	**15.38**	**19.65**	**24.23**	**29.43**	**34.73**	**39.30**	**44.65**
	Experimental (L_d), cm	**14.25**	**16.22**	**17.63**	**18.74**	**19.87**	**21.00**	**21.60**	**22.05**
	Designed (L_d), cm	**14.13**	**16.17**	**17.62**	**18.70**	**19.96**	**21.12**	**21.89**	**22.51**

Fig. (8) exhibits the relationship between (L_d/h_1) and (P/h_1) for the above mentioned data. It may be concluded that the experimental results are in a good agreement with equation (14).

The dimensional analysis gave a relationship between the upstream Froude's number (Fr_o), which ranges from 0.12 to 0.33, and the dimensionless drop length (L_d/h_1). This result is demonstrated in Fig. (9) for each model of narrow crested weir. (first group).

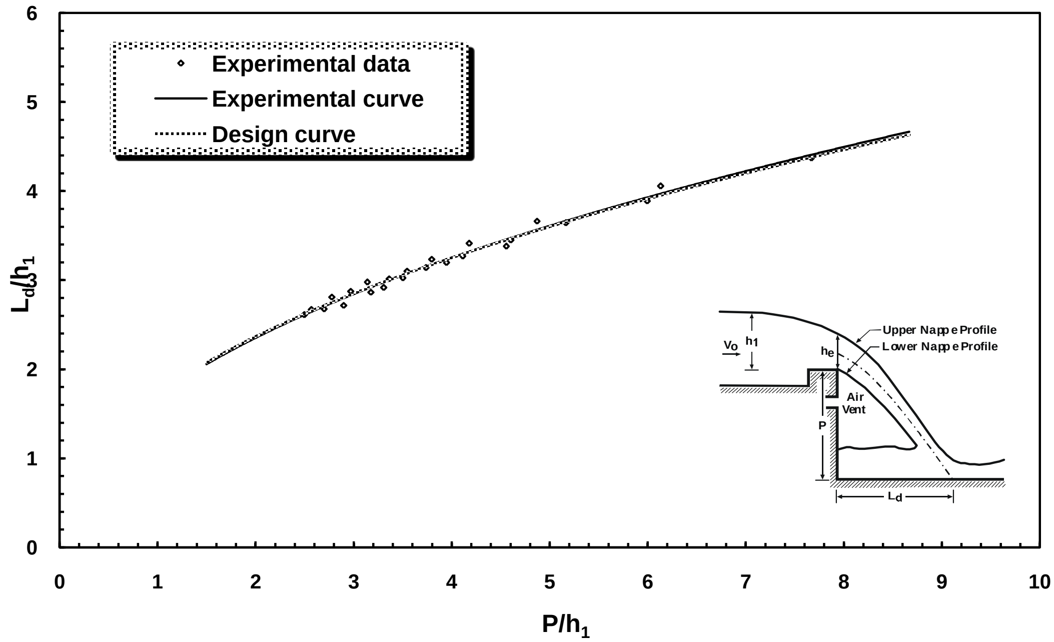

Fig. (8): Relationship between (L_d/h_1) and (P/h_1) (first group of narrow crested weir):-

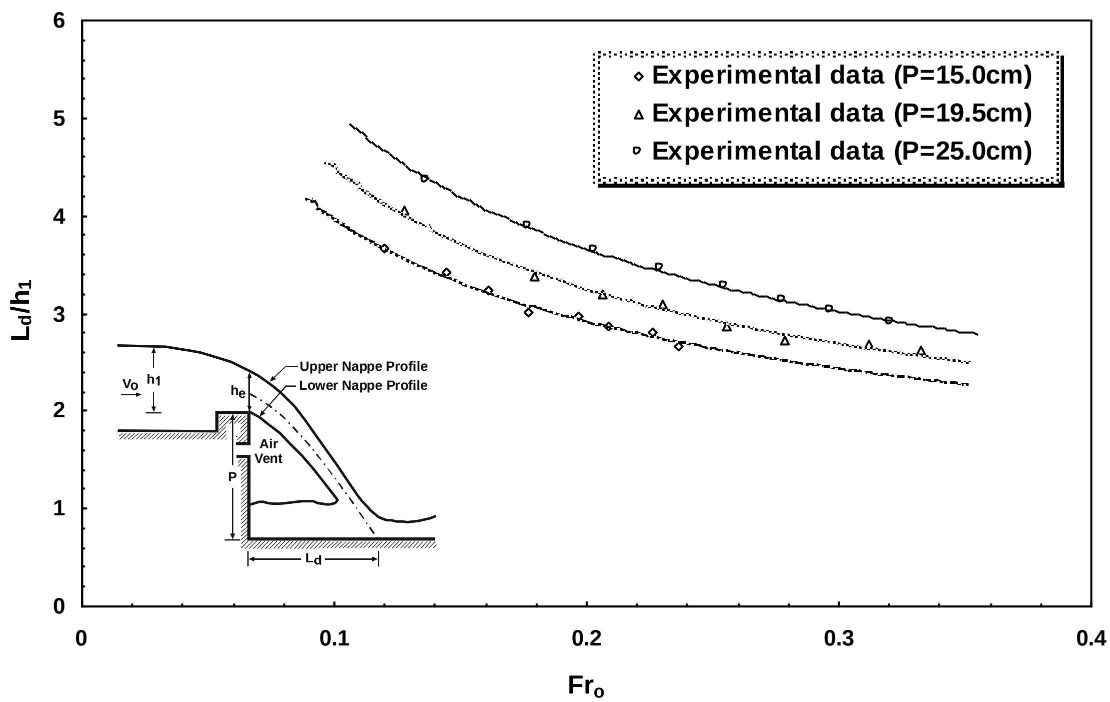

Fig. (9): Relationship between (L_d/h_1) and upstream Froude's number (Fr_o) for Models of narrow crested Weir (first group):-

Narrow Crested Weir with an Inclined Downstream Face (second group):-

For the second group of narrow crested weir with an inclined downstream face, the designed points are obtained from equation (14) and are presented with the experimental data in Table (2). The narrow crested weir with an inclined downstream face may be considered as a special case of the narrow crested weir.

Table (2): Comparison between experimental and designed drop lengths for narrow crested weir with an inclined downstream face (second group):-

Run Number		1	2	3	4	5	6	7	8
Model No. (I) P = 15.0 cm	**q, Lit. / sec. / m**	**8.78**	**11.33**	**13.35**	**16.30**	**18.33**	**21.40**	**24.05**	**26.88**
	Experimental (L_d),cm	**11.05**	**12.05**	**12.29**	**13.46**	**13.81**	**14.61**	**15.09**	**15.43**
	Designed (L_d),cm	**11.32**	**11.93**	**12.45**	**13.72**	**13.79**	**14.46**	**14.75**	**15.75**
Model No. (II)	**q, Lit. / sec. / m**	**10.18**	**15.08**	**19.85**	**25.00**	**29.90**	**35.13**	**40.98**	**47.80**
	Experimental (L_d),cm	**12.25**	**13.83**	**15.60**	**16.10**	**16.58**	**17.31**	**18.53**	**19.20**
	Designed (L_d),cm	**12.73**	**14.26**	**15.81**	**16.78**	**17.94**	**18.92**	**19.48**	**20.54**
Model No. (III)	**q, Lit. / sec. / m**	**11.03**	**15.30**	**20.00**	**24.60**	**29.53**	**36.23**	**40.98**	**47.45**
	Experimental (L_d),cm	**14.15**	**15.62**	**16.34**	**17.61**	**18.82**	**20.32**	**21.18**	**22.00**
	Designed (L_d),cm	**15.09**	**16.00**	**17.96**	**19.11**	**20.06**	**21.58**	**21.82**	**22.64**
Model No. (IV)	**q, Lit. / sec. / m**	**10.43**	**12.75**	**15.53**	**17.35**	**20.00**	**22.73**	**26.63**	**30.13**
	Experimental (L_d),cm	**13.88**	**14.31**	**15.65**	**16.29**	**16.80**	**17.01**	**18.26**	**18.70**
	Designed (L_d),cm	**14.34**	**15.21**	**16.31**	**17.19**	**17.87**	**18.39**	**19.86**	**20.22**
Model No. (V) P = 25.0 cm	**q, Lit. / sec. / m**	**10.18**	**15.15**	**20.33**	**25.10**	**30.20**	**35.23**	**40.08**	**43.85**
	Experimental (L_d),cm	**13.64**	**16.26**	**17.79**	**18.12**	**19.03**	**19.80**	**20.88**	**21.21**
	Designed (L_d),cm	**14.48**	**16.18**	**17.97**	**18.92**	**20.29**	**21.38**	**21.84**	**22.46**

Fig. (10) gives the comparison between drop lengths of both experimental and designed results for models of narrow crested weir with an inclined downstream face (second group). From dimensional analysis it was found that, (L_d/h_1) is a function of the upstream Froude's number (Fr_o). This relationship is plotted in Fig. (11) (with different heights). The percentage error between the experimental data and the design equation for second and fourth groups of narrow crested weir with vertical and inclined downstream faces is illustrated in Fig. (12).

From Fig. (10), it is concluded that the design curve, Eqn. (14) is in a good agreement with the experimental data. The difference is small between the experimental curve and the design one, which illustrates the small effect for the model face slope.

Fig. (12) represents the percentage error for data of first and second groups of narrow crested weir with vertical and inclined downstream faces, respectively.

The comparison between experimental and designed drop lengths indicates that 70.31% of the estimated values are within an error of ±5.0% of the experimental value, and 85.94% are within an error of ±7%.

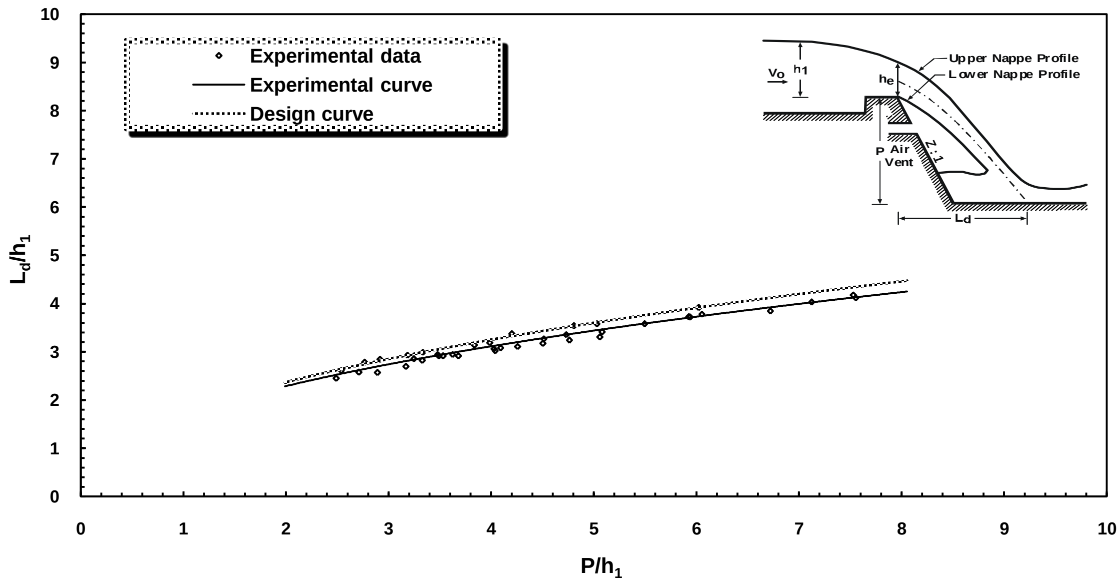

Fig. (10): Relationship between (L_d/h_1) and (P/h_1)

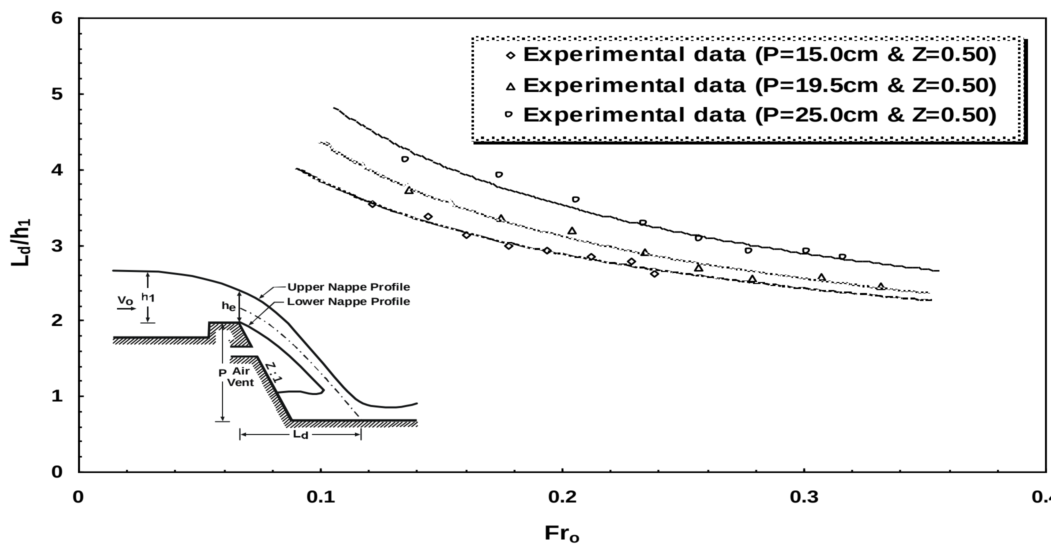

Fig. (11): Relationship between (L_d/h_1) and the upstream Froude's number (Fr_o) for models of second group

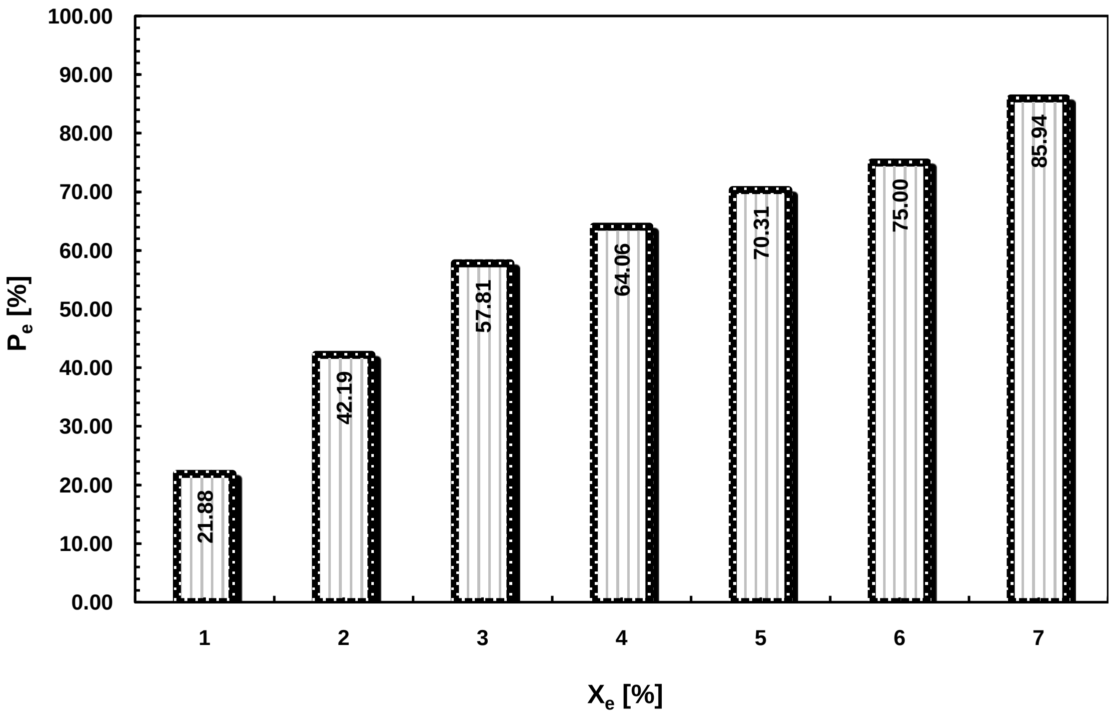

Fig. (12): Percentage (P_e) of estimated values with error less or equal to (X_e) for the first and second groups of narrow crested weir with vertical and inclined downstream Faces.

Conclusions:-

This study concerns with the determination of average drop length for narrow crested weirs. For a horizontal smooth rectangular channel, the experimental investigations were carried out under specific conditions such as a free nappe, which occurred when the atmospheric pressure exists beneath the drop; different discharges; different model dimensions and shapes; subcritical approaching flow; and no tail-water effect.

This research work was carried out in the Laboratory of Irrigation and Hydraulics. This flume has dimensions of 12 m long, 0.4 m deep, and 0.4 m wide. Two groups of models were made; the first group for narrow crested weir having height of 15, 19.5 and 25 cm; the second group for of narrow crested weir with an inclined downstream face with slope of 1:2, having heights of 15, 19.5, and 25 cm and slopes of 1:2, 1:3, and 1:5 having height of 25 cm each.

The momentum equation and Newton's laws of motion were used to derive two theoretical equations to determine the average drop length in two cases.

The following points can be drawn from this study:

Based on theoretical approach, under specific assumptions, an equation, which compute the average drop length, for the narrow crested weir, were developed.

The experimental drop length in all cases of this study was less than that given by the theoretical equations by an average difference ranged from 5% to 7%. This difference is mainly due to the assumptions used for the derivation of the theoretical equation. A coefficient, C_L (Drop Length Correction Coefficient) was determined from the comparison between the theoretical and experimental results and its value was found equal to 0.97 for narrow crested weirs.

For the first and second groups of narrow crested weir with vertical and inclined downstream faces, respectively the experimental drop length was found in a good agreement with the design equation.

Comparison between the experimental and designed drop lengths indicated that 70.31% of the designed values were within an error of ±5% of the experimental values, and 85.94% were within an error of ±7%.

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