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NAPPE FLOW CHARACTERISTICS OVER STEPPED SPILLWAYS

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خواص السريان الانحنائي فوق المفائض المتدرجة

خلاصة :

يهدف هذا البحث إلى دراسة خواص السريان الانحنائي فوق المفائض المتدرجة والتي تستخدم عادة في تشتيت الطاقة الزائدة في القنوات المكشوفة. وقد تم إجراء الدراسة على نماذج معملية لمفائض متدرجة وكان سطح المفيض الخلفي المتدرج ذو ميول ثلاثة هي ٠,١٢ ، ٠,٢٤ ، ٠,٤٨ ، وأمكن تحديد المعاملات الهيدروليكية التي من خلالها نستطيع معرفة نوع السريان وذلك باستخدام معادلات رياضية تم استنتاجها من هذه الدراسة ومقارنتها بدراسات سابقة. كما تمت دراسة فواقد الطاقة للسريان فوق هذه المنشآت وتم استنتاج معادلات رياضية لحساب هذه الفواقد وذلك باستخدام نتائج الدراسة المعملية بالإضافة إلى نتائج أبحاث أخرى لباحثين آخرين. وقد أمكن باستخدام المعادلات المبتكرة تصحيح الدراسات السابقة في هذا المجال لتصبح أكثر دقة.

ABSTRACT

Stepped spillways are structurally stable, resistance to water loads, and efficient energy dissipators, but there are no clear design rules for such structures to date. In the present study, the flow characteristics over stepped spillways were investigated for three different step configurations and for different flow parameters, using physical models. Nappe flow regime over the stepped spillways was studied. A definite equation representing the onset of the nappe flow regime was developed using the experimental observations and experimental data of other researchers. In addition, the energy dissipation for the nappe flow regime was extensively investigated for different flow hydraulic parameters. The experimental observations were compared to empirical and analytical formulas of other researches. Finally, using the experimental data in addition to that of other researchers, analytical equations have been developed and it can be used for computation purposes of the energy dissipation of nappe flow regime over stepped spillways.

1. INTRODUCTION

Overflow spillways enable flood to release over the dams. One of the most important tools for dissipating the large amount of flow energy is the stepped spillway

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because of their inherent advantage associated with rapid energy dissipation. For a stepped chute, the steps inerease significantly the rate of energy dissipation taking place along the spillway face and reduce greatly the need for a large energy dissipator at the toe of the dam. Experimental investigations of Sorensen [9] and Peyras [7] showed that the flow over stepped spillways can be divided into two types of flow regimes: Nappe flow for low discharges and skimming flow for higher ones.

The Nappe flow regime is characterized by a succession of free falling jets, [4]. Peyras [7] described the limits of occurring of nappe flow with fully or partially developed hydraulic jump. Streeter et al [10] analyzed the hydraulic characteristics of a single-step drop structure. The skimming regime can be defined as the water flows down the stepped face of the spillway as a coherent stream [4]. Chanson, [2], defined the critical values of discharge, at which the flow regime changes from nappe to skimming, introducing the following equation:

$$\frac{(d_c)_{onset}}{h} = 1.057 - 0.465\left(\frac{h}{l}\right) \qquad (1)$$

It was reported that the nappe flow regime occurs for $d_c < (d_c)_{onset}$. Also, it was reported that Eq. (1) was deduced for $0.19 < h/l < 1.2$ only. Rajaratnam [8] reported that the nappe flow regime currently occurs if the value of ($d_c/h = 0.80$) for the range of $0.40 < h/l < 0.90$. Peyras [7], from his experimental studies, defined the separate limit between nappe and skimming regimes to be as $0.62 < (d_c)_{onset}/h < 0.74$ for the range of $0.33 < h/l < 1.0$. Yasuda [11] analyzed the experimental data of Essery and Horner [4], Rajaratnam [8] and Muntes [5] and introduced a chart investigating the limits between the nappe and skimming flow regimes. He reported that for $h/l > 1.40$. the main flow does not always impinge on the step due to the steep slope. Even for small discharge. $d_c/h < 0.18$, an air pocket is formed only in some steps and thus a transition flow is formed for $0.18 \subseteq d_c/h \subseteq 0.80$ and $h/l > 1.40$.

Combining the definition of the spillway energy loss with momentum equation, Chanson [1] introduced an equation estimating the energy loss for nappe flow regime over un-gated stepped spillways in the form:

$$\frac{\Delta E}{E_o} = 1.0 - \frac{0.54(d_c/h)^{0.275} + 1.715(d_c/h)^{-0.55}}{1.5 + H_{dam}/d_c} \quad (2)$$

Rajaratnam et al [9] developed a method estimating the energy losses on stepped spillway of jet flow regime for $d_c/h \subseteq 0.80$. He introduced the idea of average relative energy loss per step and introduced the following equation:

$$\frac{\Delta E}{E_o} = 1.0 - \frac{\left[(1-\alpha)^N \{1.0 + 1.5(d_c/h)\} + \sum_{i=1}^{N-1}(1-\alpha)^i\right]}{N + 1.5(d_c/h)} \quad (3)$$

Peyras et al [7] investigated the energy dissipation over stepped spillways. He gave some design rules for stilling basin downstream the stepped spillways. Using the experimental results of other researchers, they found that firstly, α decreased continuously as d_c/h increased. Secondly, for $d_c/h < 0.25$, α is unaffected for the range $0.421 < h/l < 0.842$, and for $d_c/h > 0.25$, α decreases as h/l increases. Thirdly, α is larger for multiple steps than for single step.

2. EXPERIMENTAL WORK

The experiments have been carried out, in the laboratory of the Dipartmento di Ingegneria delle Acqne of Politecnico di Bari, Italy, using a mobile-bed iron channel. The channel was of length 30m and width 0.75m. The sidewalls were of glass type with height 0.65m aod thickness 10mm. The physical models of the stepped spillway were installed 1.75m from the tank sluice gate. Fourteen equal steps of height 2.40cm were chosen for all the models with three different values of h/l ratio as 0.48, 0.24 and 0.12. The spillway physical model crest width, in the lateral direction, was 75cm while in the flow direction, the crest was horizontal with length 60cm. However, Fig. (1-A) is a difinition sketch for the physical model.

More than fifty different passing discharges with different spillway U.S water levels were carried out for the three step configurations. The range of passing discharge was 0.73 to 19.65 lit/s. For each step configuration, the water profile upstream, over and D.S the spillway was measured. The U.S flow energy was computed as the average of the measured water depths at (60, 45, 30, 15cm) U.S of the crest plus the velocity head. Also, the D.S flow energy was computed as the average of the measured water depths at (65, 75, 85, 95cm) D.S the spillway plus the D.S velocity head.

3. RESULTS AND ANALYSIS

3.1 NAPPE REGIME ONSET

The flow regime was classified to be either nappe, skimming or lying in the transition zone according to the experimental observations. In the nappe flow regime, the flowing water bounce from one step to the next one as a series of small free falls followed by a fully developed or partially developed hydraulic jump, see Fig. (1-B&D), [1,2,4,7]. On some flow cases of the first and second step configurations, especially for relatively large discharges, a nappe flow without hydraulic jump was occurred before the apparition of the skimming flow as shown in Fig. (1-C). In such cases, it was clear that the flow surface over the steps seems to be stepped as the spillway profile

If the water profile over the spillway was of smooth surface due to increasing the discharge and the flow seems to be uniform, the flow was considered of skimming regime. The water flows down the stepped face as a coherent stream, skimming over the steps edge and cushioned by the recirculating vortices trapped between the main stream and the steps, see Fig. (1-E), [1,2,4,7]. Also, the external edges of the steps form a pseudo bottom over which the flow passes. The flow regime was considered in transition zone if it was in between the nappe and the skimming regimes.

Recording the flow characteristics at which the nappe flow regime has occurred, Table (1) shows the onset values of the flow parameter (d_c/h) compared to the Chanson and Yasuda ones for the different examined step configurations. For the purpose of developing an equation representing the nappe flow regime the data of Rajaratnam [8], Essery and Horner [3], Peyras et al [7], Montes [5] and Chanson [2] in addition to the experimental observations are plotted together in Fig (2) for the examined range $0.12 < h/l < 0.48$. The following equation has been developed to be easily used for giving the nappe flow regime onset as follows:

$$\frac{(d_c)_{onset}}{h} = -0.8882\left(\frac{h}{l}\right) + 1.1769 \qquad [0.12 < h/l < 0.48] \qquad (4)$$

The flow of d_c/h less than the onset value resulted by Eq (4) may be considered of nappe flow regime for the range of $0.12 < h/l < 0.48$. The greater values may be considered as transition or skimming regimes.

Moreover, Fig. (3) shows a comparison between the developed equation, Eq. (4), the Yasuda chart and Chanson formula. All the experimental observations of nappe, transition and skimming flow regimes were plotted on Fig. (3). A good agreement has been noticed between the developed equation and the experimental observations. Also, Chanson formula seems to be near to the observations, for nappe flow classification than Yasuda. However, for skimming flow regime classification and defining the features of the transitional zone between the nappe and skimming regimes, it should be defined in future studies.

TABLE (4)

ONSET VALUES OF NAPPE FLOW REGIME

Step Configuration	$(d_c/h)_{Onset}$ Yasuda 1992	$(d_c/h)_{Onset}$ Chanson 1994	$(d_c/h)_{Onset}$ Experimental Observations
0.48	0.783	0.833	0.781
0.24	0.793	0.95	1.04
0.12	0.798	Out of limit	1.095

3.2 NAPPE ENERGY DISSIPATION

The parameters governing the flow energy dissipation over steeped spillway are: 1- spillway slope (h/l), 2- spillway height (H_{dam}), 3- discharge per unit crest width (q), which with h/l govern the flow type, 4- gravity acceleration (g) which predominates over all other forces. These four parameters are necessary and sufficient to describe the dimensionless variables, head loss per unit length of spillway $(E_o-E_d)/H_{dam}$, and d_1/H_{dam} as:

$$\frac{E_o - E_d}{H_{dam}} = f(q,h,l,g) = f_1\left(\frac{h}{l},\frac{q}{gH^3_{dam}}\right) \qquad \text{and} \qquad \frac{d_1}{H_{dam}} = f_2\left(\frac{h}{l},\frac{q^2}{gH^3_{dam}}\right)$$

Figs. (4,5) show $y_1 = (E_o-E_d)/H_{dam}$ and $y_2 = d_1/H_{dam}$ versus $x = q^2/gH^3_{dam}$ based on the experimental results for the different spillway examined slopes, i.e. h/l Since y_1 and y_2

tend to unity and zero, respcctively, as x tends to zero, the curves have the form $1/(1-y_1) = a_1 x^{b1}$; and $y_2 = a_2 x^{b2}$ and then fitted by the least-squares method to the swarm of experimental points, as shown in Figs. (6,7). It can be noticed that, Fig. (6) the relative energy loss y_1 increases as the spillway slope increases for certain value of x. As the y_1 values seem to be very closer to each other for the different step configurations, Fig. (7) was drawn to simulate the energy dissipation over stepped spillways of slope range $0.12 < h/l < 0.48$. The following equations could be developed from Figs. (5,7):

$$y_1 = 1 - \frac{1}{0.3108 x^{-0.4997}} \qquad \text{with} \quad R^2 = 0.9475 \tag{5}$$

$$y_2 = 0.3682 x^{0.2855} \qquad \text{with} \quad R^2 = 0.9750 \tag{6}$$

which can be used for determining the energy loss for nappe flow regimes over stepped spillways for the range of $0.12 < h/l < 0.48$.

Moreover, following the same concept of Chanson, the experimental relative energy dissipation $\Delta E / E_o$ has been plotted against d_c/h for different step configurations, Fig. (8). It can be noticed that the dissipated energy decreases as the passing discharge increases for different step configurations. Comparing the experimental observations with Chanson formula for energy dissipation of nappe flow Eq. (2), it is clear that there is a noticeable variance especially for smaller values of d_c/h. For correction purposes of the Chanson equation coefficients, it had been adjusted to accurately simulate the experimental data. Using the adjusted coefficients, Eq. (2) may be re-written to be:

$$\frac{\Delta E}{E_o} = 1 - \left[\frac{0.54 (d_c/h)^{0.285878} + 1.715 (d_c/h)^{0.135878}}{1.5 + (H_{dam}/d_c)} \right] \tag{7}$$

The developed equation was compared to Chanson one and to the experimental observations for the examined step configurations, Fig. (8). It is clear that the developed formula represents aecurately the energy dissipation of nappe flow regime for the different step configurations. It results energy dissipation values very close to the observed ones. The value of the correlation factor is 0.9972, which tends to the highly correlation between the developed equation and the observations. However, the developed equation, Eq. (7), is valid only for the examined step configurations, i.e. $0.12 < h/l < 0.48$

In addition, the nappe relative energy dissipation is plotted against the factor H_{dam}/d_c as shown in Fig. (9). All recorded values of H_{dam}/d_c for the nappe flow regime were greater than 15 due to the smallest discharge range, at which the nappe flow occurred The H_{dam}/d_c values less than that limit were recorded for skimming flow regime. However, it is clear that as the factor H_{dam}/d_c increases, i.e. the passing discharge decreases, the resulted energy dissipation increases which satisfies with Horner [3] and Chanson [1,2] observations.

Using Rajaratnam approach, Eq. (4), the average relative energy loss per step, α, has been estimated by trial and error procedure for the three examined step configurations and for nappe experimental energy dissipation. Plotting α against d_c/h, Fig. (10), it can be noticed that firstly α decreases as d_c/h increases. Secondly, for all the examined different step configurations, i.e. $0.12< h/l <0.48$, the relative energy loss α can be correlated to d_c/h by the following logarithmic formula:

$$\alpha = -0.2842 Ln\left(\frac{d_c}{h}\right) + 0.2792 \qquad \text{with} \qquad R^2 = 0.9823 \tag{8}$$

It is clear that the correlation is very good. Thirdly, if the resulted parameter α for stepped spillway is compared to that obtained by Moore [6] for spillway of single step, Fig (10), it can be easily noticed that the parameter α is larger for multiple steps than for single one. This due to the contribution by the full or partial jumps occurred over the steps for nappe flow regimes.

4. CONCLUSIONS

Several experimental investigations showed that the flow over stepped spillways could be divided into two distinguished regimes. Nappe flow for low discharges and skimming flow for higher ones. In this study, the nappe flow regime was experimentally investigated. Using the experimental observations in addition to that of other researchers, an equation defining the stream onset for occurring such flow regimes has been developed, Eq. (4). Also, the energy dissipation of nappe flow regimes has been studied. Analytical formulas representing the dissipated energy for nappe flow has been developed using the experimental observations, Eqs. (5,7,8). The developed equations have been compared to other researchers and it was noticed that the developed equations were of more accuracy.

So, it can be reported that both of Eqs. (4,5,7,8) can be used for defining the nappe flow regime characteristics

NOTATIONS

d_1 = initial water depth of the hyd. Jump created over the spillway steps, d_2 = sequent water depth of the hyd. Jump, d_c = critical water depth, $E_o = H_{dam} + 1.5d_c$ = maximum flow energy over the spillway crest, E_d = flow energy D.S the spillway, f_1 , f_2 , f = functions defined elsewhere, g = acceleration due to gravity, H_{dam} = spillway height, h = spillway step height, l = spillway step length, N = number of spillway steps, q = flow discharge per unit width of the spillway, R = correlation coefficient, x, y_1, y_2 = parameters defined elsewhere, and α = average energy dissipated ratio per spillway step

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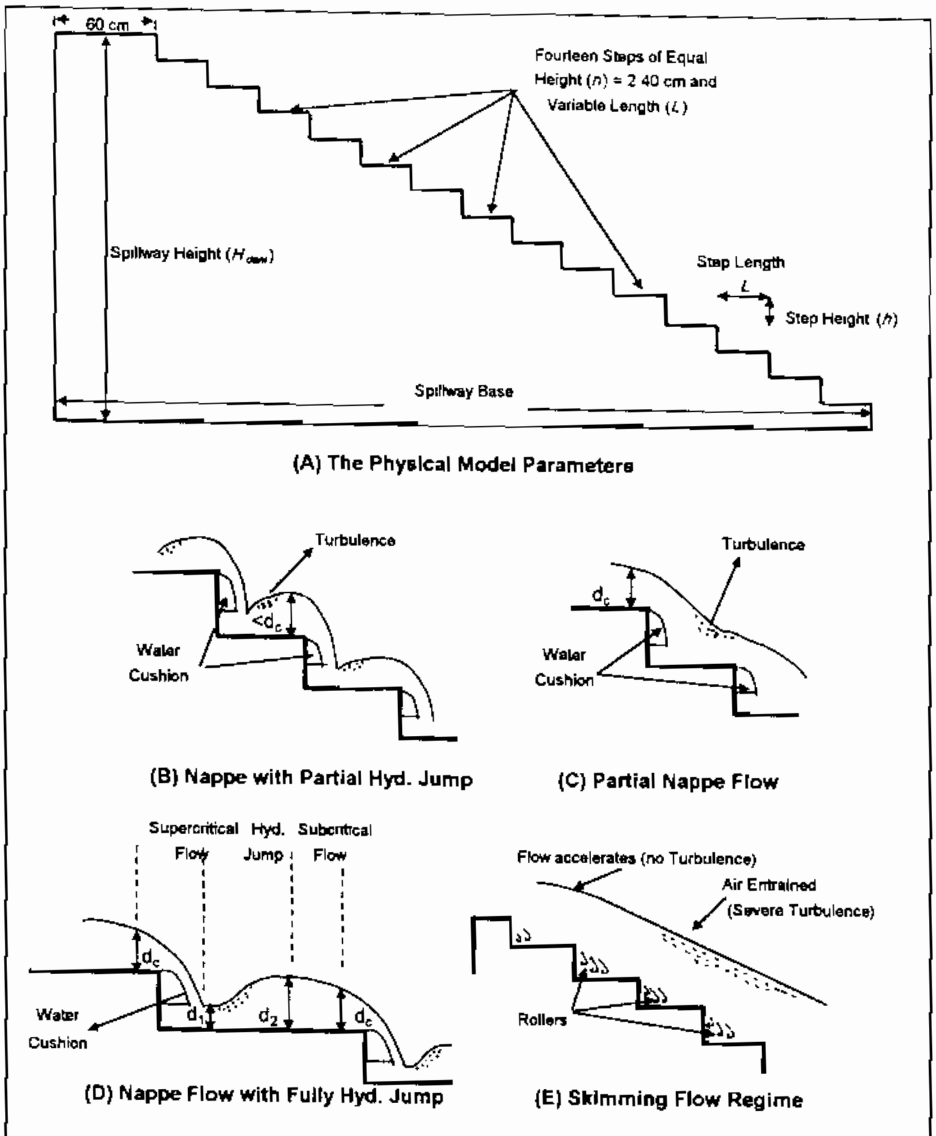

Figure (1) Classification of Flow Over Stepped Spillways

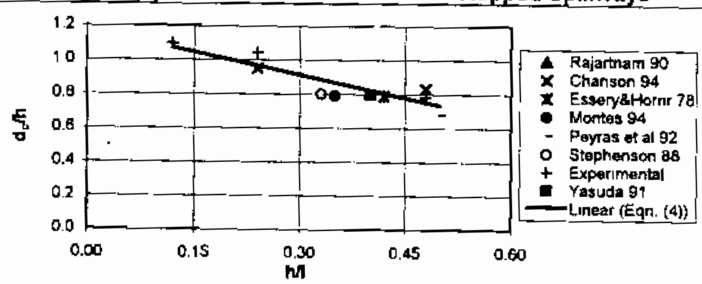

Figure (2) The Onset of Nappe Flow Regime Over Stepped Spillway for 0.12<h/l<0.48

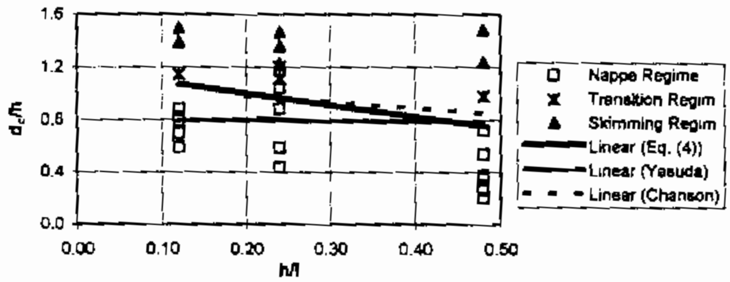

Figure (3) Comparison of Eq.(4), Chanson and Yasuda with the Exp. Observations

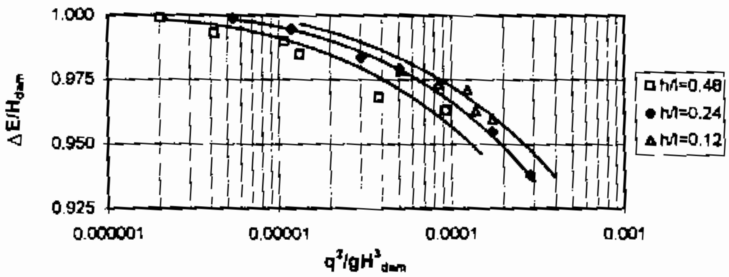

Figure (4) Relationship Between $\Delta E/H_{dam}$ and q^2/gH^{3dam} for 0.12<h/l<0.48

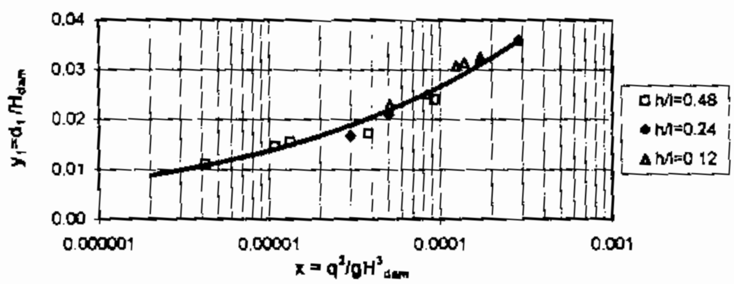

Figure (5) Relationship Between d_d/H_{dam} and q^2/gH^3_{dam} for 0.12<h/l<0.48

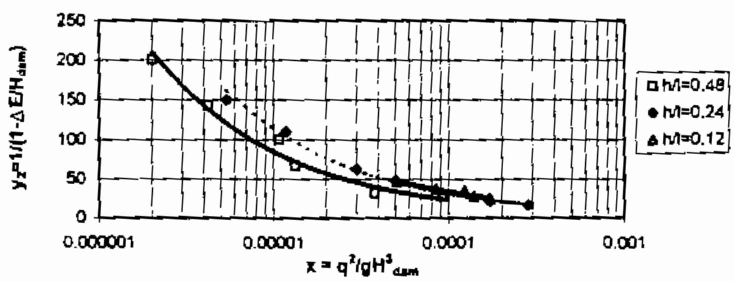

Figure (6) Relationship Between $1/(1-\Delta E/H_{dam})$ and q^2/gH^3_{dam} for Fifferent Step Configurations

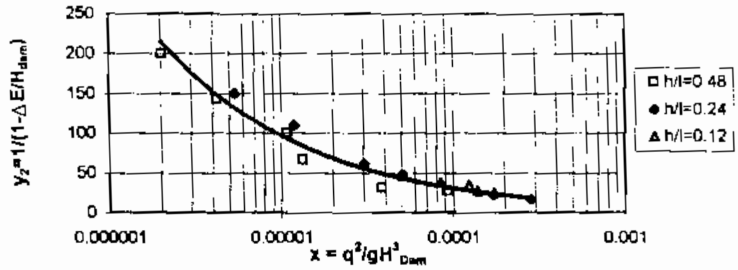

Figure (7) Relationship Between $1/(1-\Delta E/H_{dam})$ and q^2/gH^3_{dam} for 0.12<h/l<0.48

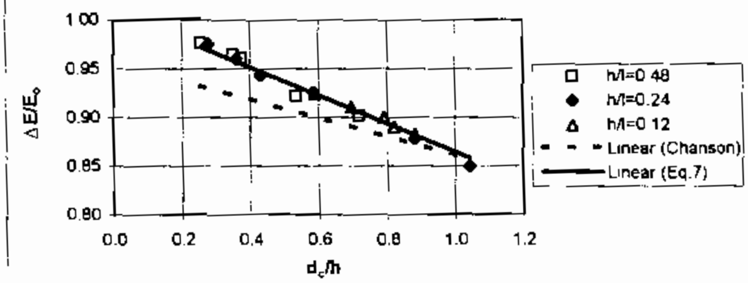

Figure (8) Nappe Energy Dissipation for 0.12<h/l<0.48

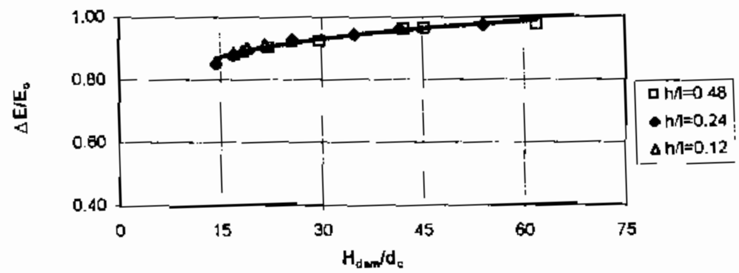

Figure (9) Nappe Flow Regime [$\Delta E/E_o$ - H_{dam}/d_c] Relationship, H_{dam}/d_c > 15

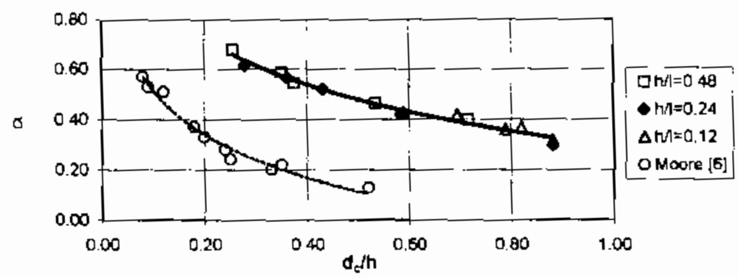

Figure (10) Nappe Flow Regime [α - d_c/h] Relationship, 0.12 < h/l < 0.48