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Study of Optimum Safe Hydraulic Design of Stepped Spillway by Physical Models

prof. Dr. Abdul-Hassan K. Al-Shukur, Dr. Safaa K. Hashim Al-Khalaf, Ishraq M. Ahmed Al-sharifi

Abstract— This study based on laboratory experiments aims to determine the optimum slope and step height of stepped spillway models, by investigating the flow characteristics and energy dissipation rate on a twelve physical models on conventional step at angles (α= 30, 40, 45 and 55^0). Each angle was modelled with three different heights of steps (h=3, 6 and 10 cm) under different flow regimes (skimming, transition and nappe flow regime). The experiments were done and the hydraulic parameters of flow over the models were measured and energy dissipation was calculated. Results showed that, the optimal height of steps in skimming flow regime was (h=6cm, number of step N=5) at high discharge but with reduction the discharge and tendency toward the nappe flow regime, the optimal height shows decrease (h=3cm, N=10). Also the results of investigations indicated that, the optimum slopes of stepped spillway models at (h=3cm) was ($α=30^0$) at all runs, but with increasing the height of steps to (h=6cm & h=10cm), the optimum slope increasing to ($α=45^0$& 55^0) according to the ratio of critical depth to the height of steps(yc/h).

Index Terms— Critical depth, energy dissipation ,optimal design, physical models, stepped spillways.

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1 INTRODUCTION

Stepped spillways are hydraulic structures that have regained significant interest for researchers and dam engineers in the last two decades, specially due to technological advances in construction of roller compacted concrete (RCC) dams [9]. The stepped channel and spillways have been used for centuries, since more than (3000) years [3] where were selected to contribute to the stability of the dam and for their simplicity in shape [5]. The advantage of stepped spillway include ease of construction, reduction of cavition risk potential, as well as reduction the stilling basin dimensions at the downstream dam toe due to significant energy dissipation along chute [2]. Another common application is the using of stepped overlays on the downstream face of hydraulically unsafe embankment dams as emergency spillways to safely pass a flood such as the PMF over the crest over the dam. [12]. Stepped spillways are also utilized in water treatment plans. The waterfalls were landscaped as leisure parks and combined flow aeration and aesthetics [4]. The step geometry of stepped spillway can be horizontal, inclined (upward or down ward) and pooled step. For a given chute geometry, the flow pattern may be either nappe flow at low flow rates, transition flow for intermediate discharges or skimming flow at larger flow rates [6]

2 Safety Design of Stepped Spillways

Chanson[7], indicated that the safety design of stepped spillway must provide adequate flood discharge facilities, safe channel operation and appropriate control of the water releases. Possible martial deterioration must be also taken into account. Also he refers to that, over twenty documented accident and failure occurred during overflow. A significant number of failures occurred during overflows at transition flow regime e.g. New Corton and Arizone Canal. These flow conditions are characterized by rapid longitudinal flow variations and fluctuating flow properties. This instability could cause fluctuating hydrodynamic loads.

3 Optimum Design of Stepped Spillway

Optimization of designing stepped spillways is essential for reducing the high construction costs and maximize the safe energy dissipation of such infrastructure. Owing to the high flow discharge over spillways, their design and construction are very complicated, usually involving difficulties such as cavitations and high flow kinetic energy, and also highly expensive, comprising a major part of the dam's construction cost. For large dams it is about (20%) of the total dam construction cost, and for small dams it is about (80%) [10]. By the increase of the use of stepped spillways continually, the researchers have been concentrating on the increasing efficiency of this kind of spillways and due to this fact, several methods have been presented. In this regard, finding the optimal dimensions of the steps according to the passing flow regime can be mentioned [11]. The decision variables that are the best combination of spillway width height and number of steps are achieved so as to minimise the total cost of the spillway steps and downstream energy dissipaters. The present study aims to determine the optimum slope and step height at each design discharges were modelled in the experiments laboratory, under different flow regimes (nappe, transition and skimming), by analysed the results and computed the energy dissipation rate for the physicals models according criteria used in this study.

- *prof. Dr. Abdul-Hassan K. Al-Shukur , Civil Engineering Department, University of Babylon / Babil Dr_alshukur @yahoo.com*
- *Dr. Safaa K. Hashim Al-Khalaf , Civil Engineering Department, University of Kufa/Najaf, safaaaalkhalaf@ymail.com*
- *Ishraq M. Ahmed Al-sharifi, Civil Engineering Department, University of Kufa/Najaf, ishraqali93@gmail.com*

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4 Experimental Setup

All experiments were conducted in a prismatic rectangular flume of width 0.5m, depth 0.5m and length 18.6m. The centrifugal pump lies beside the flume at the upstream and it is having a rate capacity of (40 l/s) was used to deliver flow to the flume. For flow discharge measurement a 90 V-notch sharp crested weir located at the upstream to measuring the actual discharge pass through the flume section. At the end of the flume, moveable gate is installed to regulate the tail water depth of hydraulic jump. A water gage with 0.05 accuracy was used to measure the depth of flow after jump was fixed at a distance long enough to be in the non-aerated tail water of the jump (Y2) at (125cm) downstream the toe of the models. Figure (1) show some details of the flume used in this study.

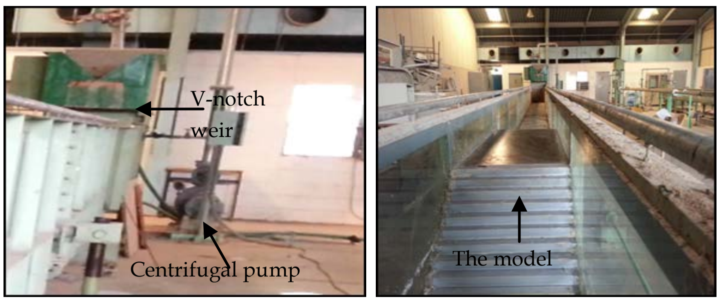

Fig. 1. The details of the flume used in this study

Twelve different models were using in the experimental laboratory as shown in figure (2), the main angles of the chutes are (30^0, 40^0, 45^0 and 55^0) which represented the ratio (H:V) of (1.732:1, 1.1917:1, 1:1 and 0.7:1) respectively. All models have the same total height (Htotal), width (W) of the spillway and length of crest which are: (30cm 50cm and 100cm) respectively. Each angle of the models was modelled with three different heights of steps (3cm, 6cm and 10 cm) as shown in table(1).

TABLE 1
Characteristics of the Models

Model	Main angle (degree)	Height of steps (cm)	Lenght of steps (cm)	Number of steps
A1	30	3	5.2	10
A2	30	6	10.3	5
A3	30	10	17.3	3
B1	40	3	3.57	10
B2	40	6	7.15	5
B3	40	10	11.91	3
C1	45	3	3	10
C2	45	6	6	5
C3	45	10	10	3
D1	55	3	2.1	10
D2	55	6	4.2	5
D3	55	10	7	3

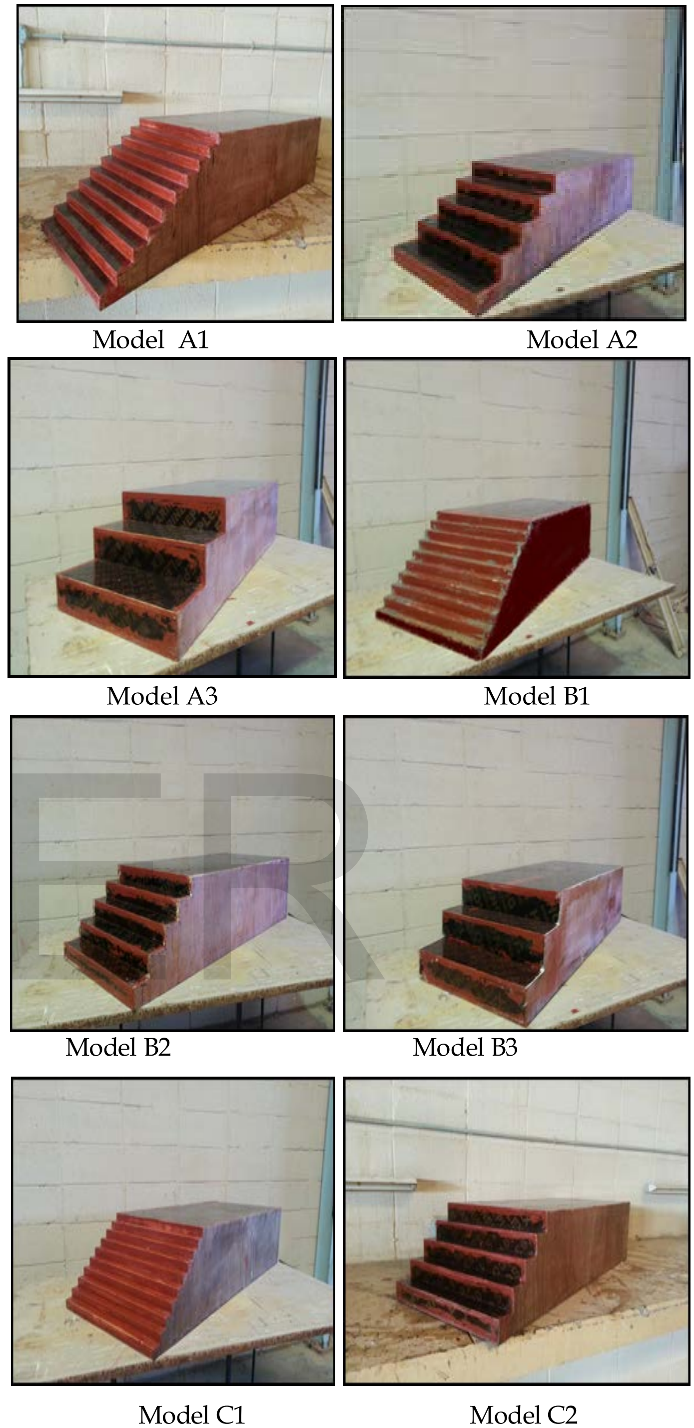

Fig. 2. The experimental models

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Model C3

Model D1

Model D2

Model D3

Fig. 2 cont. The experimental models

All models were built from plaxywood and coated with varnish to avoid swelling and to reduce the roughness coefficient of the models in agreement with concrete roughness coefficient.
The upstream boundary of models was given by horizontal approach channel. The other upstream boundary conditions were given by the discharges; table (2) indicated the range of discharges for each flow regime according to chute slope, regime defined according to [6] by using the critical depth (yc) and height of steps (h) to limit the upper value of nappe flow regime and lower value of skimming flow regime depending on the ratio of the height to the length of steps (h/l), as shown bellow:

The upper limits of nappe flow regime may be approximated as:

$$yc/h=0.89-0.4\ h/l \quad (1)$$

while the lower limits of skimming flow may be estimated as:

$$yc/h=1.2-0.352\ h/l \quad (2)$$

TABLE 2

Modeling Conditions on the Sstepped Chute

Model	Slope	Nappe flow regime	Transition flow regime	Skimming flow regime
A1	1.732H:1V	non	non	1.192 ≤ yc/h ≤ 2.8731
A2	1.732H:1V	yc/h= 0.05962	0.904 ≤ yc/h ≤ 0.744	1.015 ≤ yc/h ≤ 1.436
A3	1.732H:1V	0.34 ≤ yc/h ≤ 0.61	0.862 ≤ yc/h ≤ 0.7114	non
B1	1.1917H:1V	non	non	1.192 ≤ yc/h ≤ 2.8731
B2	1.1917H:1V	non	0.596 ≤ yc/h ≤ 0.903	1.015 ≤ yc/h ≤ 1.436
B3	1.1917H:1V	0.35773≤ yc/h≤ 0.5542	0.608 ≤ yc/h ≤ 0.8619	non
C1	1H:1V	non	non	1.192 ≤ yc/h ≤ 2.8731
C2	1H:1V	non	0.596 ≤ yc/h 0.743667	0.904≤ yc/h ≤ 1.4365
C3	1H:1V	0.3577≤ yc/h≤ 0.4462	0.609 ≤ yc/h 0.81437	yc/h= 0.86192
D1	0.7H:1V	non	non	1.192 ≤ yc/h ≤ 2.8731
D2	0.7H:1V	non	yc/h=0.596	0.744≤ yc/h ≤ 1.44
D3	0.7H:1V	non	0.358≤yc/h ≤0.609	0.7113≤ yc/h ≤0.8619

5 Analysis of the Results

The effect of geometry changes in the stepped spillways models on energy dissipation were investigated into two situations:
1**) At Constant Slope with Different Heights of Steps:** In one case, the overall slope and slope of each steps was constant, Then the problem was modelled in three cases; first by increase the number of steps into (10) and reduce the height and length of steps, the second and third cases by decrease the number of the steppes into (5 and 3) respectively, and increase the height and length of steps, as showing in table (1) above . In this situation it can determine the following:

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a. Limitations of Flow Regimes for Computed the Energy Dissipation: The relative energy losses can be divided into three zones of flow regime (nappe, transition, and skimming flow regime), based on equations (1) and (2) the limitations of regimes are shown in tables bellow:

TABLE 3:
Limitations of Regimes for Various Heights
(SK: Skimming, NA: Nappe , TR: Transition)

i) At angle=30⁰

Run	q ($m^3/s/m$)	yc/hdam	h=3cm	h=6cm	h=10cm
1	0.0793	0.287	SK	SK	TR
2	0.0728	0.272	SK	SK	TR
3	0.0652	0.252	SK	SK	TR
4	0.0594	0.231	SK	SK	TR
5	0.047	0.203	SK	SK	NA
6	0.0396	0.181	SK	TR	NA
7	0.0295	0.149	SK	TR	NA
8	0.0212	0.119	SK	NA	NA

ii) At angle=40⁰

Run	q ($m^3/s/m$)	yc/hdam	h=3cm	h=6cm	h=10cm
1	0.0793	0.287	SK	SK	TR
2	0.0728	0.272	SK	SK	TR
3	0.0652	0.252	SK	SK	TR
4	0.0594	0.231	SK	SK	TR
5	0.047	0.203	SK	SK	TR
6	0.0396	0.181	SK	TR	NA
7	0.0295	0.149	SK	TR	NA
8	0.0212	0.119	SK	TR	NA

iii) At angle=45⁰

Run	q ($m^3/s/m$)	yc/hdam	h=3cm	h=6cm	h=10cm
1	0.0793	0.287	SK	SK	SK
2	0.0728	0.272	SK	SK	TR
3	0.0652	0.252	SK	SK	TR
4	0.0594	0.231	SK	SK	TR
5	0.047	0.203	SK	SK	TR
6	0.0396	0.181	SK	SK	TR
7	0.0295	0.149	SK	TR	NA
8	0.0212	0.119	SK	TR	NA

iv) At angle=55⁰

Run	q ($m^3/s/m$)	yc/hdam	h=3cm	h=6cm	h=10cm
1	0.0793	0.287	SK	SK	SK
2	0.0728	0.272	SK	SK	SK
3	0.0652	0.252	SK	SK	SK
4	0.0594	0.231	SK	SK	SK
5	0.047	0.203	SK	SK	TR
6	0.0396	0.181	SK	SK	TR
7	0.0295	0.149	SK	SK	TR
8	0.0212	0.119	SK	TR	TR

b) The Effect of Height and Number of Steps at Constant Slope on Energy Dissipation Rate: The available energy in different models was computed for each flow condition at the toe of the spillway close to the upstream end of the hydraulic jump. The aim was to determine the efficiency of step height in releasing the energy losses rate for determination the optimum design of stepped spillway. The energy loses (ΔE) means different between upstream energy of spillway structure (E0) and downstream (toe) of hydraulic jump location (E1) [1], the upstream energy (E0) is depending on critical depth (yc) and height of the spillway (Hdam), while the down stream energy (E1) is depending on the depth at the toe of stepped spillway (y1) and the velocity on this depth (v1) as well as the gravitational acceleration (g= 9.81 m/s2) shown below:

$\Delta E = E0 - E1$ (3)

Where:

$E0 = 1.5yc + Hdam$, $E1 = y_1 + [V1]^2/2g$

And none dimensioned energy loss has been defined as bellow :

$(\Delta E)/E0 = (E0 - E1)/E0$ (4)

Figures (3,4,5 and 6) shows the percentage of energy dissipation, versus the dimensionless parameter (yc/hdam) for various models.

i. **For (α=30⁰) the results of experimental runs are shown in figure(3) below:**

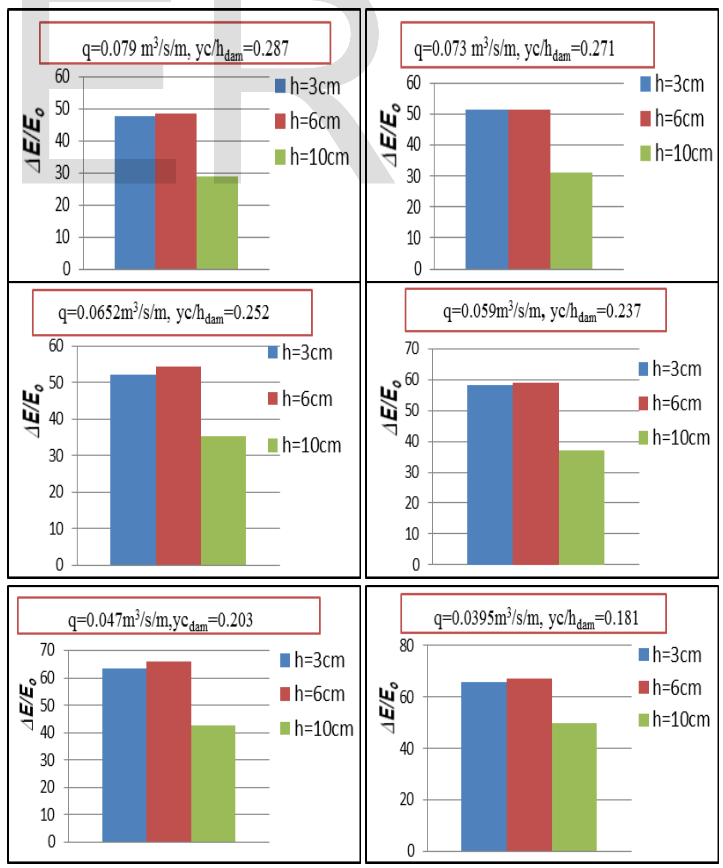

Fig. 3. Percentage of energy dissipation versus the dimensionless parameter (yc/hdam) for model A (α=30⁰)

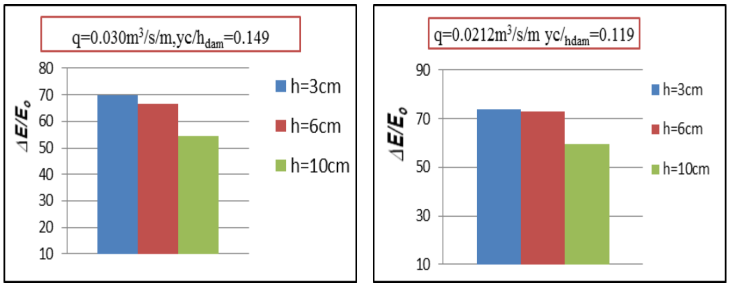

Fig. cont. 3. Percentage of energy dissipation versus the dimensionless parameter (yc/hdam) for model A ($\alpha=30^0$)

ii. For ($\alpha=40^0$), the results of experimental runs are shown in figure(5) below:

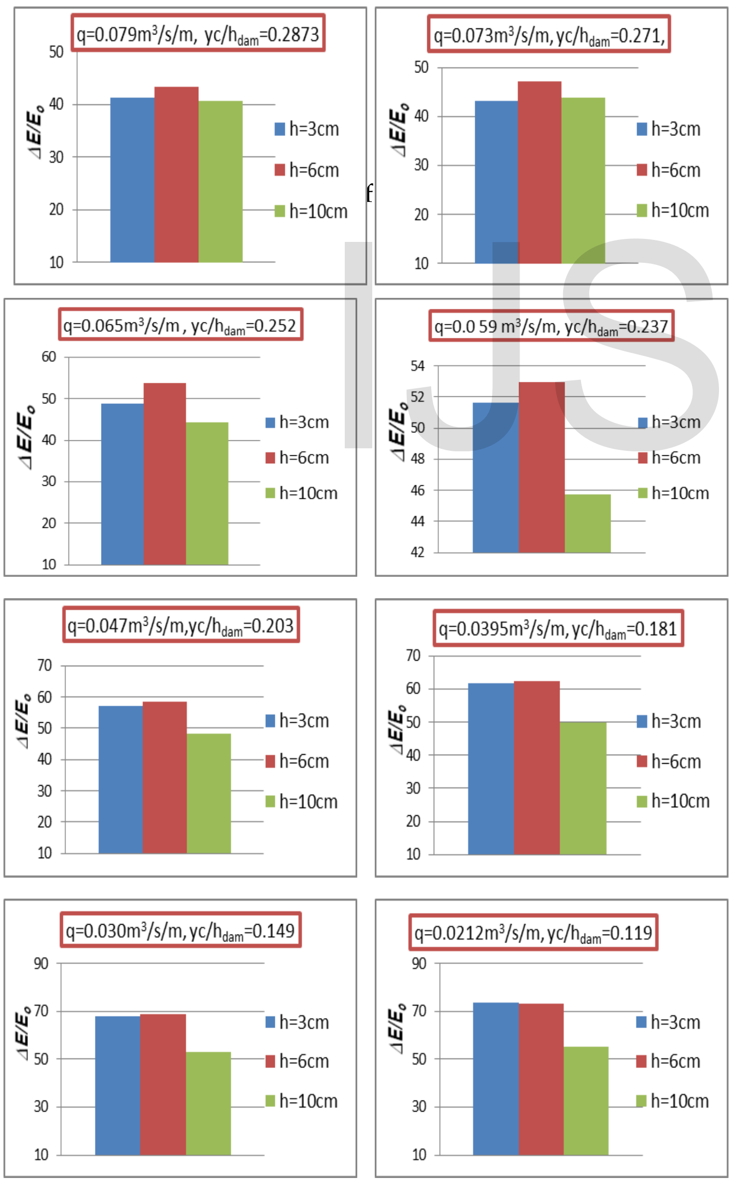

Fig. 4. Percentage of energy dissipation versus the dimensionless parameter (yc/hdam) for model B ($\alpha=40^0$)

iii. For ($\alpha=45^0$), the results of experimental runs are shown in figure(5) below:

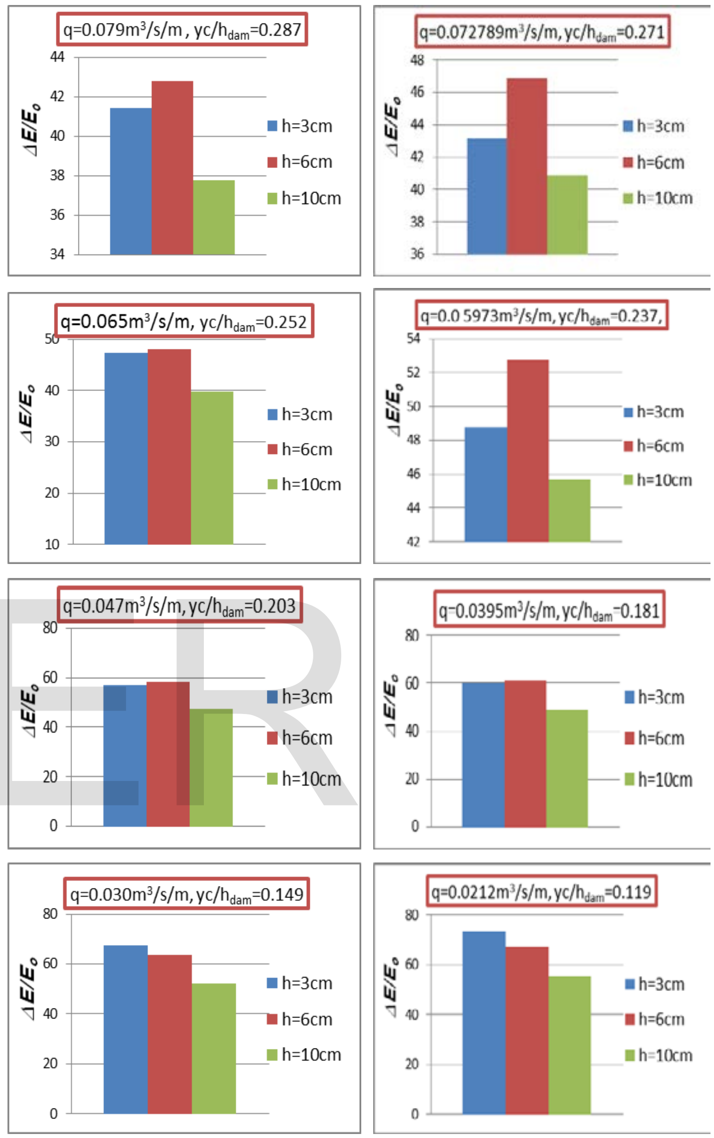

Fig. 5. Percentage of energy dissipation versus the dimensionless parameter (yc/hdam) for model C ($\alpha=45^0$)

iv. For ($\alpha=55^0$), the results of experimental runs are shown in figure(6) below:

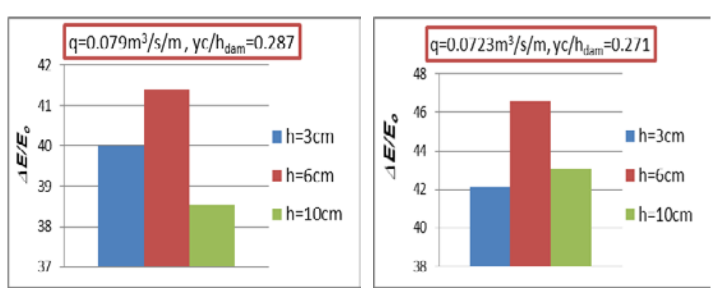

Fig. 6. Percentage of energy dissipation versus the dimensionless parameter yc/hdam for model D (α=55⁰)

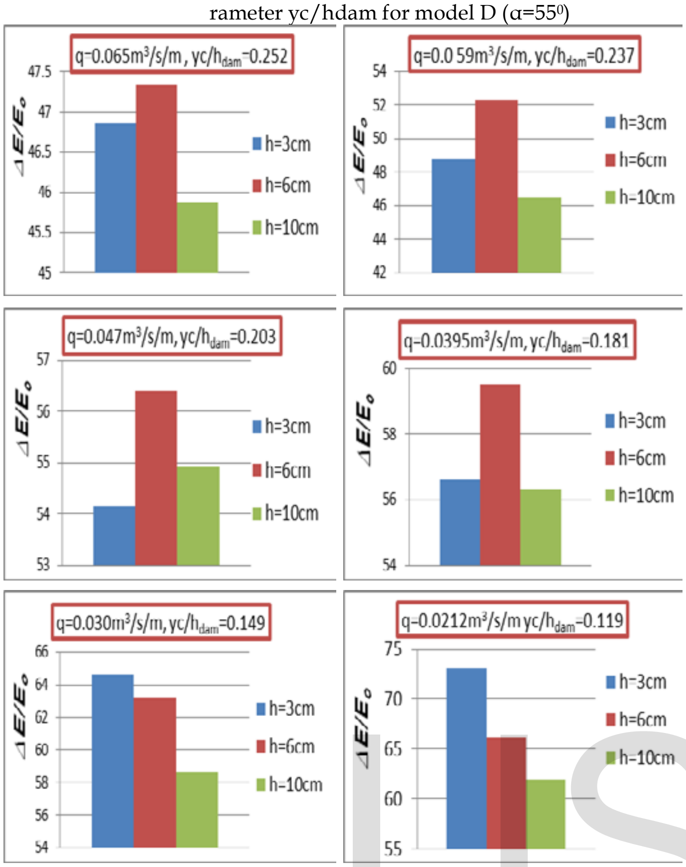

Fig. cont.6. Percentage of energy dissipation versus the dimensionless parameter yc/hdam for model D (α=55⁰)

The results show that, at nappe flow regime which was the chute acts as a succession of drop structure, the characteristic height doesn't much effect on relative energy losses because the most of energy losses is due to the occurrence of hydraulic jump and impact of the jet on the step face, but for skimming flow regime the effect of characteristic height is clearly observed, as characteristic height increases to (h=6cm) the relative energy losses increase by about (1.7% -9 %) at different models. While the height of steps increase to (10 cm) the relative energy loss show decrease for all models at constant slope, this investigations of the results indicated that, with reduction the discharge the optimal height of steps to introduce the maximum energy dissipation also shows decrease, so with skimming flow regime there is an optimal height and number of steps but with reduction the flow and tendency toward the nappe flow regime the optimal height of steps show decrease also, (i.e. increase in number of steps) as shown in tables (4,5,6 and 7).

TABLE 4 The optimum height and number of steps for each design discharges at (α=30⁰)

q(m3/sec/m)	Optimum height of steps(cm)	Optimum number of steps	Remark
0.079	6	5	At higher discharge with skimming flow regime the optimal height of steps increase as unit discharge increase.
0.073	6	5	
0.065	6	5	Observing increase in energy loss in (h=6cm) about (3.7%) than energy losses in (h=3cm), noted the reduction in unit discharge
0.059	6	5	
0.047	3	10	
0.039	3	10	Maximum energy dissipation is lying on (6 cm height, 5 steps), but this height occurring transition flow regime which is not safety (as mention previously) so this height doesn't represented the optimum and consider (h=3cm, N=10) the optimum case.
0.030	3	10	Reducing in unit discharge and tendency toward the nappe flow regime, the optimal height of steps decrease (i.e. increase in number of steps)
0.021	3	10	

TABLE 5 The optimum height and number of steps for each design discharges at (α=40⁰)

q(m3/sec/m)	Optimum height of steps(cm)	Optimum number of steps	Remark
0.079	6	5	This optimum height lies within skimming flow regime, it can observed that no significant influence for the number of spillway steps on energy dissipation
0.073	6	5	Increasing in energy losses in (h=6 cm) about (8.69%) than energy losses in (h=3cm)
0.065	6	5	
0.059	6	5	
0.047	6	5	
0.039	3	10	As noted above the transition flow regime is not safety for spillway steps, so h=6cm consider as the height that gave the maximum energy losses and doesn't give the optimum design
0.030	3	10	

0.021	3	10	Reducing in unit discharge and tendency toward nappe flow regime, the optimal height of steps decrease

TABLE 6 The optimum height and number of steps for each design discharges at (α=45⁰)

q(m3 /sec/ m)	Optimum height of steps(cm)	Optimum number of steps	Remark
0.079	6	5	The energy losses is increasing about (3.2 %) than energy losses in h=3cm
0.073	6	5	
0.065	6	5	
0.059	6	5	
0.047	6	5	
0.039	6	5	
0.030	3	10	Optimum design is lying in h=3cm, but maximum energy losses lies in (h=6cm) at transition flow regime
0.021	3	10	Decreasing in optimal height at decreasing in unit discharge

TABLE 7 The optimum height and number of steps for each design discharges at (α=55⁰)

q(m3 /sec/ m)	Optimum height of steps(cm)	Optimum number of steps	Remark
0.079	6	5	It can observed high increasing in energy dissipation in h=6cm than h=3cm in this chute slope, even up to (9%) in some runs, compared with increasing in the energy dissipation with another chute slopes
0.073	6	5	
0.065	6	5	
0.059	6	5	
0.047	6	5	
0.039	6	5	
0.030	3	10	Increasing in the number of stepped and reducing in the optimum height
0.021	3	10	

2) At Constant Height with Different Slopes of Stepped Spillway Models: Experimental results show that the effect of slope is depending on flow regimes and steps heights. Table (8) show the flow characteristics at modeled angels with different heights depending on equations (1 and 2) above.

TABLE 8 Limitations of regimes for various slopes

(SK: Skimming, NA: Nappe , TR: Transition)

i. **The flow characteristics at modelled angels for h=3cm**

run	q(m3/ sec/m)	yc	yc/hdam	Yc/h	α= 30⁰	α= 40⁰	α= 45⁰	α= 55⁰
1	0.0793	0.086	0.287	2.873	SK	SK	SK	SK
2	0.0728	0.081	0.272	2.715	SK	SK	SK	SK
3	0.0652	0.076	0.252	2.522	SK	SK	SK	SK
4	0.0594	0.071	0.231	2.371	SK	SK	SK	SK
5	0.047	0.061	0.203	2.029	SK	SK	SK	SK
6	0.0396	0.054	0.181	1.808	SK	SK	SK	SK
7	0.0295	0.045	0.149	1.487	SK	SK	SK	SK
8	0.0212	0.036	0.119	1.192	SK	SK	SK	Sk

ii.**The flow characteristics at modelled angels for h=6cm**

run	q	yc	yc/hdam	Yc/h	α=30⁰	α=40⁰	α=45⁰	α=55⁰
1	0.0793	0.086	0.287	1.437	SK	SK	SK	SK
2	0.0728	0.081	0.272	1.357	SK	SK	SK	SK
3	0.0652	0.076	0.252	1.261	SK	SK	SK	SK
4	0.0594	0.071	0.231	1.186	SK	SK	SK	SK
5	0.047	0.061	0.203	1.0147	SK	SK	SK	SK
6	0.0396	0.054	0.181	0.904	TR	TR	SK	SK
7	0.0295	0.045	0.149	0.744	TR	TR	TR	SK
8	0.0212	0.036	0.119	0.596	NA	TR	TR	TR

iii.**The flow characteristics at modelled angels for h=10cm**

run	q	yc	yc/hdam	Yc/h	α=30⁰	α=40⁰	α=45⁰	α=55⁰
1	0.0793	0.086	0.287	0.862	TR	TR	SK	SK
2	0.0728	0.081	0.272	0.814	TR	TR	TR	SK
3	0.0652	0.076	0.252	0.756	TR	TR	TR	SK
4	0.0594	0.071	0.231	0.712	TR	TR	TR	SK
5	0.047	0.061	0.203	0.609	NA	TR	TR	TR
6	0.0396	0.054	0.181	0.542	NA	NA	TR	TR
7	0.0295	0.045	0.149	0.446	NA	NA	NA	TR
8	0.0212	0.036	0.119	0.358	NA	NA	NA	TR

according these tables, it can observed the effect of step height and chute slope on development the flow behaviour which is effect directly on relative energy dissipation ratio as shown in figures(7,8 and 9) bellow:

i) For (h=3cm), the results of experimental runs are shown in figure(7) below:

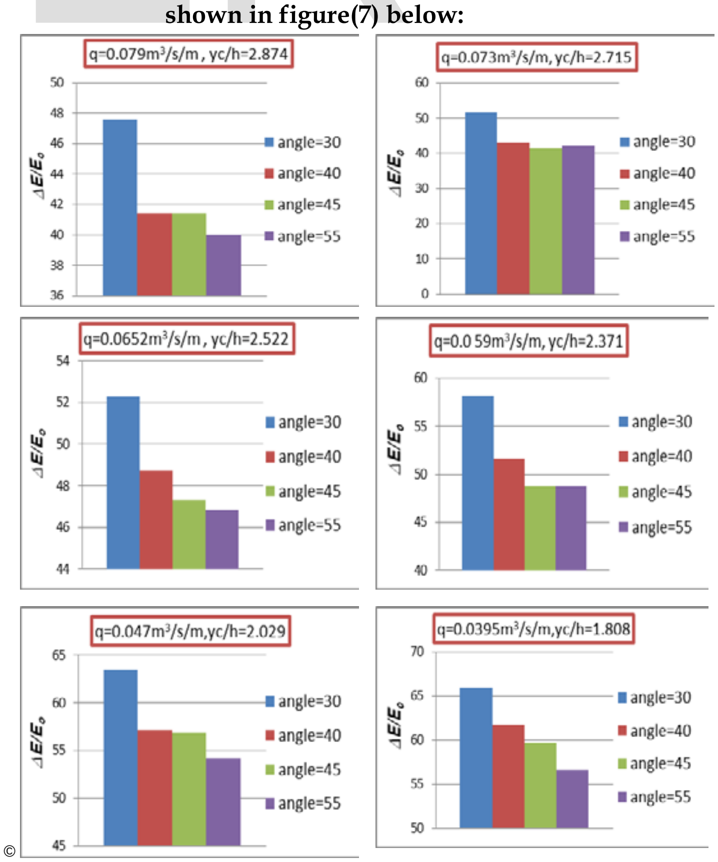

Fig. 7. The percentage of energy dissipation versus the dimensionless parameter (yc/h) for h=3cm

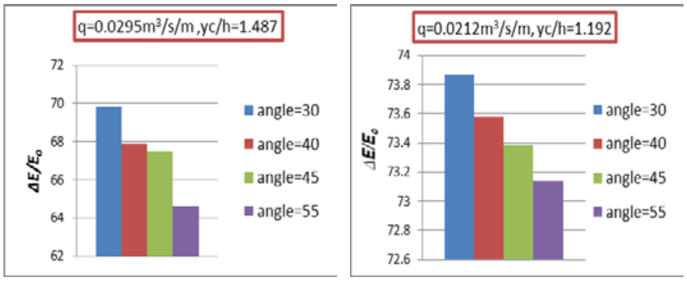

Fig. 7. cont. The percentage of energy dissipation versus the dimensionless parameter (yc/h) for h=3cm

ii) For (h=6cm), the results of experimental runs are shown in figure(8) below:

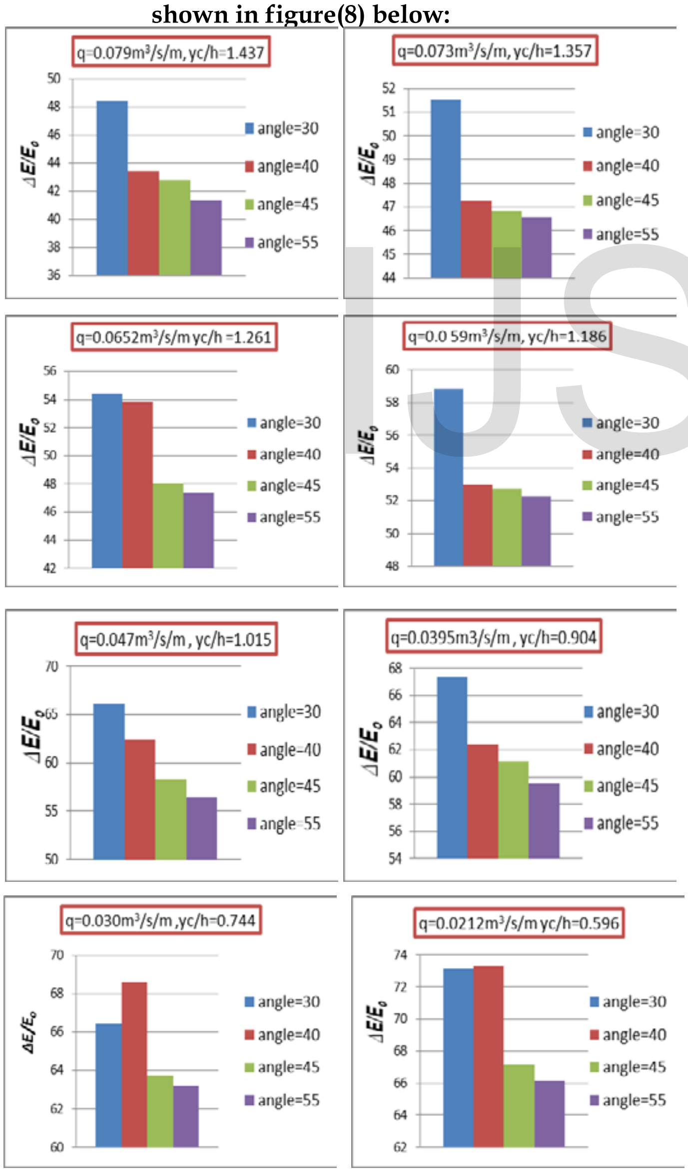

Fig. 8. The percentage of energy dissipation versus the dimensionless parameter (yc/h) for h=6cm

iii) For (h=10 cm), the results of experimental runs are shown in figure(9)below:

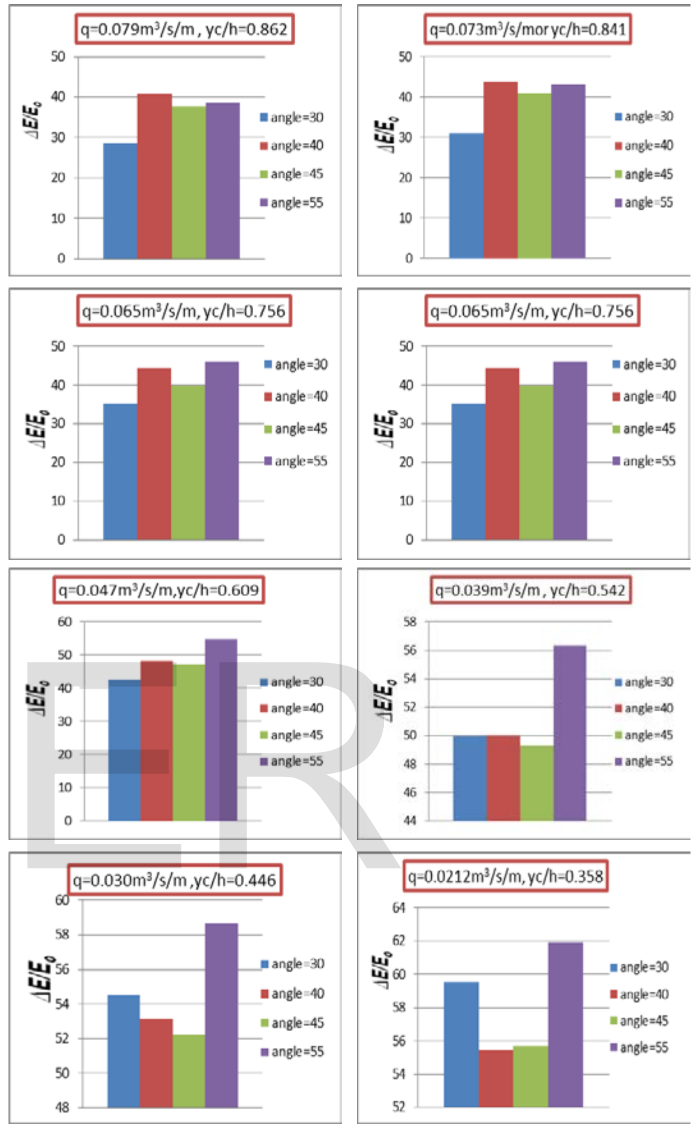

Fig. 9. The percentage of energy dissipation versus the dimensionless parameter (yc/h) for h=10cm

The effect of slope on energy dissipation rate is depending on the flow regimes and the height of steps. It can determine the optimum slope due to the maximum energy dissipation and the safety regimes for the structure. Experimental results show that, for skimming flow regime at step height (h=3cm & h=6cm) the relative energy dissipation increase with decrease the discharge and the slope of spillway. For (h=10cm) the energy dissipation show increase at steeper slope for skimming flow regime and show decrease for nappe flow regime as shown in figure(9).The optimum slope of stepped spillway at different heights of steps can summered in tables (9,10 and 11)

TABLE 9 The optimum slope of stepped spillway for each design discharge at (h=3cm)

q (m3/sec/m)	Yc/h	slope of stepped spillway (H:V)	The angle of optimum slope of stepped spillway (degree)	Remark
0.0793	2.873	1.732:1	30	Depending of flow regime which represented the skimming flow regime in this height , the energy dissipation increase with decrease the chute slope
0.0728	2.715	1.732:1	30	
0.0652	2.522	1.732:1	30	
0.0594	2.371	1.732:1	30	
0.047	2.029	1.732:1	30	
0.0396	1.808	1.732:1	30	
0.0295	1.487	1.732:1	30	
0.0212	1.192	1.732:1	30	

TABLE. 10.The optimum slope of stepped spillway for each design discharge at (h=6cm)

q (m3/sec/m)	Yc/h	Optimum slope of stepped spillway (H:V)	The angle of optimum slope of stepped spillway (degree)	Remark
0.0793	1.437	1.732:1	30	The energy dissipation increase with decreasing the slope at constant height (h=6cm)
0.0728	1.357	1.732:1	30	
0.0652	1.261	1.732:1	30	
0.0594	1.186	1.732:1	30	
0.047	1.0147	1.732:1	30	
0.0396	0.904	1:1	45	In this two discharges it must increase the optimum chute slope to (45^0 and 55^0) as doing here, to avoid the transition flow regime, so the optimum slope is the slope which providing the maximum energy losses with safety regime.
0.0295	0.744	0.7:1	55	
0.0212	0.596	1.732:1	30	This slope is giving the maximum energy dissipation rate and the optimum design

TABLE 11 The optimum slope of stepped spillway for each design discharge at (h=10cm)

q(m3/sec/m)	Yc/h	Optimum slope of stepped spillway (H:V)	Remark
0.0793	0.862	0.7:1	Increasing in the step height cause tendency the flow towered the nappe flow regime and the skimming flow regime is observed at steeper angles and its provided here the maximum energy dissipation
0.0728	0.814	0.7:1	In those unit discharges, just angle (55^0) make a safety regime
0.0652	0.756	0.7:1	
0.0594	0.712	0.7:1	
0.047	0.609	1.732:1	When decease the unit discharge, the nappe flow regime was observed, although it isn't having the maximum energy but it's have the optimum slope in this design discharge
0.0396	0.542	1.732:1	With decreasing in the unit discharge, the nappe flow can observed in model's angle ($\alpha=40^0$) as well as angle ($\alpha=30^0$), but the optimum slope is lying on ($\alpha=30^0$)
0.0295	0.446	1.732:1	In nappe flow regime, the relative energy losses increase with decrease the angle (α)
0.0212	0.358	1.732:1	

6 Conclusions

1) As characteristic height of step increase at constant slope to (h=6cm) for skimming flow regime, the relative energy losses increases by about (1.74% - 4%) at ($\alpha=30^0$), (2.4%-9%) at ($\alpha=40^0$), (3%-7%) at ($\alpha=45^0$), (1.12%- 6.8%) at ($\alpha=55^0$), but at nappe flow regime the chute act as a succession of drop structure, the characteristic height doesn't much effect on relative energy losses because the most energy losses are due to the occurrence of hydraulic jump and impact of the jet on the step face.
2) At increase the height of step to (h=10cm) at constant slope, the energy losses rate show decrease at all

models.

3) The optimal height of steps in skimming flow regime was (h=6cm) at high discharge but with reduction the discharge and tendency toward the nappe flow regime, The optimal height shows decrease (h=3cm, N=10) i.e. increase in number of steps.
4) The effect of slope on energy dissipation is depending on the flow regimes and height of steps. In skimming flow regime at (h=3cm and h=6cm), the relative energy dissipation show increase with decrease the slope of spillway but at (h=10cm) the energy dissipation show increase at steeper slope for skimming flow regime, and show decrease for nappe flow regime.
5) The energy dissipation at transition flow regime, has not been subject of profound assessment, because it follows both characteristic of nappe and skimming flow, this results from the head losses are a mixture of shear stress due to the not well-developed vortices and due to impact of jet so, there wasn't have a specific pattern.
6) The optimum slopes of stepped spillway models at (h=3cm) was ($\alpha=30^0$) at all runs, but with increasing the height of steps to (h=6cm & h=10cm), the optimum slope was increasing to avoiding the transition flow regime to ($\alpha=45^0$& 55^0) according to the ratio of (yc/h).

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