Experimental study of increasing energy dissipation on stepped spillway

دراسة عملية لزيادة تشتيت الطاقة في المطافح المدرجة

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ABSTRACT

An experimental study was conducted on flat sloped and stepped spillways in order to specify the efficiency of energy dissipating of flow and then trying to improve that as a new and novel study. Twelve spillways were constructed from plywood and tested to compare between flat sloped and stepped spillways first, and as a conclusion in this study and many previous papers (which is when increasing discharge the energy dissipation decreasing), so it can be choosing the most effective one that dissipate energy at high discharges and try to modify it using two cases of blocks and one case of cascade for increasing energy dissipation secondly , so three downstream slopes of stepped face ($\theta = 27^o$, 32^o , and 40^o) were tested with flat sloped, stepped having two steps, and stepped having four steps. The results showed that when decreasing both number of steps and downstream slops stepped face of the spillway will cause an increase of the ratio of flow energy dissipation, and the stepped spillways are more efficient in flow energy dissipation compared with flat sloped spillways, also when using cascade spillway the energy dissipation will decrease compare with original step spillway that have the same characteristics and increased when using blocks.

Keywords: Stepped spillway, Energy dissipation, improving energy dissipation.

الخلاصة

تم عمل دراسة مختبرية على المطافح المدرجة والغير مدرجة لتحديد كفائتها في تشتيت طاقة الجريان وبعد ذلك المحاولة لتحسين كفائتها. تم عمل اثنا عشر نموذج من المطافح باستخدام مادة الخشب المقاوم للماء وتم اختبارها للمقارنة بين المطافح المدرجة و الغير مدرجة اولا وثم بعد الاستنتاج في هذا البحث وبدلالة عدة بحوث سابقة (انه كلما زاد التصريف يقل مقدار تشتيت الطاقة) لذلك بالامكان اختيار افضل نموذج يشتت الطاقة اكثر بالتصاريف العالية لمحاولة تحسين اداءه لغرض تشتيت طاقة اكبر باستخدام حالتين من العوارض وحالة من سلسلة المطافح ثانيا لذلك تم اختيار ثلاث ميول لاوجه المطافح المدرجة وغير المدرجة ($\theta = 27$ درجة، 32 درجة ، و 40 درجة) وتم استخدام عدد درجات للمطافح المدرجة هو اثنان و اربعة. بينت النتائج انه عند تقليل كلا من عدد درجات وزاوية ميلان الوجه للمطافح المدرجة يؤدي الى زيادة تشتيت الطاقة وكذلك ان المطافح المدرجة تكون اكثر تشتيتا للطاقة من المطافح غير المدرجة بالاضافة الى انه عند استخدام سلسلة المطافح فان تشتيت الطاقة يقل مقارنة بالمطافح المدرجة الاصلية التي لها نفس المواصفات وكذلك فان تشتيت الطاقة يزداد عند استخدام العوارض.

1- INTRODUCTION

Spillway is a major part of a dam, which is built to release and control flood flow. Due to the high flow discharge over the spillways, their design and construction are very complicated and usually faced with difficulties such as cavitation and high flow kinetic energy [1]. It becomes usual to protect the spillway surface from cavitation erosion by introducing air next to the spillway surface using aeration devices located on the spillway bottom and sometimes on the sidewalls [2].

Since the flow is supercritical and has a very high velocity and hence erosive power. Therefore, this energy should be dissipated in order to prevent the possibility of sever scouring of the downstream river bed and undermining of the foundations. Stepped spillways allow continuously dissipating a considerable amount of the flow kinetic energy, such that the downstream stilling basin, where the residual energy is dissipated by hydraulic jump, can be largely reduced in dimensions. Also, the cavitation risk along the spillway decreases significantly due to smaller flow velocities and the large air entertainment rate [3]. Al-Talib [4] found that stepped weirs are more efficient than flat sloped weirs and the maximum energy dissipation ratio in stepped weirs was approximately 10 % higher than in flat sloped weirs. Barani et al. [5] investigated energy dissipation of flow over stepped spillways of different step shapes; a physical wooden model has been built. Experiments have been carried out for different types of step shapes (plain steps, end sill steps with thickness of 1, 2, 3 and 4 cm and steps with bottom adverse slope of 15^o, 26^o, 36^o, and 45°). Overall, the hydraulic parameters of flow over the model were measured and the energy dissipation of flow was calculated. Results show that the energy dissipation of flow on end sill and inclined stepped spillways are more than the plain one, it is increases by increasing the thickness of end sill or the adverse slope size. Comparison of flow energy dissipation over end sill stepped spillway and inclined type show that the inclined type has been dissipated more energy than the equivalent end sill type. Also for stepped spillway of different step shapes investigated in a laboratory study the stepped and flat sloped weirs for steep slope channels which is having high difference in head of water between upstream and downstream in order to find their efficiency for dissipating flow energy. Chamani and Rajaratnam [6] show that, in a stepped spillway, jet flow would occur at relatively smaller discharges and skimming flow occurs at larger discharges. Chen et. al. (2002) [7] analyzed the flow of the stepped spillway , He applied the finite volume technique and used the k-e model for the determination of the flow turbulence. Alghazali and Jasim [8] present an Experimental work on flow regime limits for stepped spillways using twelve stepped spillway models. The models were manufactured with three downstream slope angles: 25, 35 and 45°, and four numbers of steps: 5, 10, 15 and 20. Five configurations of steps were tested, which are conventional Flat, pooled, porous end sills, pooled with gabions and porous end sills with gabions. The results revealed that the end sills highly affect flow regime type; this effect is primarily for the lower limits of skimming flow. Using end sills increases the range of transition flow regime (by increasing the lower limit of skimming flow) as well as increases the instabilities that

occur in this flow regime. Gabions reduce the effects of end sills on the lower limit of skimming flow regime to near the limit of flat steps. New empirical equations were suggested based upon the experimental results. El- Jumaily and Al- Lami [9] take a suggested design of Bastora stepped spillway as a prototype to build a physical wooden model with scale of 1:20 (Lm/Lp). Experiments have been carried out on the model with slope of upward inclined steps of 42^0, 28^0, 14^0 and 0^0. For every slope of the steps, experiments were conducted in three flow regimes, nappe, transition, and skimming. As observed in experiments, the increase in the slope of steps has no significant effect on the flow behavior over stepped spillway. The hydraulic depths of flow over the model were measured and the energy dissipation rate was calculated. Results show that the energy dissipation decreases with increasing the discharge, and the energy dissipation of flow on stepped spillways with upward inclined steps is more than on the horizontal stepped spillways, it increases with increasing the adverse slope of steps

The main objectives of this paper are to study the flow characteristics, energy dissipation, and increasing energy dissipation on stepped spillway.

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a. 1 THEORETICAL ANALYSIS

Based on energy relationships, the general relationship for the flow energy dissipation can be verified. Applying energy equations between U/S and D/S of stepped and flat sloped spillway, one can get [10] :

$$E_o = y_o + \frac{\alpha vo^2}{2g} \qquad \ldots(1)$$

$$E_1 = y_1 + \frac{\alpha v1^2}{2g} \qquad \ldots(2)$$

$$\frac{\Delta E}{Eo}\% = \frac{(Eo - E1)}{Eo}\% \qquad \ldots(3)$$

Where:-

E_o = U/S energy (m),
E_1 = D/S energy (m),
V_o = velocity at U/S (m/sec),
V_1 = velocity at D/S at toe of spillway (m/sec),
α = kinetic correction coefficient, for turbulent flow, generally equal to 1.1, [11] ,
g = acceleration due to gravity (m/s^2),
$\frac{\Delta E}{Eo}$ % = Relative energy dissipation between U/S and D/S of stepped and flat sloped spillway.

3-EXPERIMENTAL WORK

The experiments are realized by means of the complex fluid measurement installation in the hydraulic institute of Al- Qadissiya University / College of engineering using ARMFIELD flume. The dimension of flume is 2.45 m length, 0.25 m height, and 0.075 m width as shown in Figure (1). A sharp crested weir with height 0.048 m was installed at the end of flume to create a hydraulic jump.

Water surface levels were measured at different locations with an accurate point gauge reading to 0.1 mm. Discharges were measured by a calibrated flow meter installed at the channel outlet and the maximum discharge of the flume is 2.64 ℓ/sec. The upstream flow heads were started to measure at a location more than (9 y_c) upstream of the spillway model, where y_c is the depth of water over the spillway crest.

The length of all crests in all models and radius of curvature are from the following formulas [10] [11] , respectively.

$$\frac{L\ crest}{HT - he} > (1.5 - 3) \qquad \ldots(4)$$

$$R = 0.2\ (HT - he) \qquad \ldots(5)$$

Where:-

L_{crest} : Length of broad crested weir in the flow direction;
HT : U/S total head above the channel bed (from maximum discharge);
he : weir height above the channel bed.
R: radius of curvature of upstream face.

Twelve models were designed using equations (4) and (5) from plywood to calculate the length of crest and radius of curvature, respectively. The heights of all models were constant in this paper which are equal to 60 % of flume height i.e. 15 cm. All spillways were installed at distance 1 m from flume entrance to eliminate turbulence. Three angles for spillway face are used for all the twelve models which are (θ=27 ^{o}, 32 ^{o} , and 40 ^{o}) which are equal or greater than the critical value defined by Chanson (1994) which is θ = 27°. It concerns an installation allowing fluid circulation in a variable slope glass channel. The installation allows mainly observing the different flow regimes.

Fig.(1): The ARMFIELD flume at Al- Qadissiya University / College of Engineering.

For the designing of the models the maximum U/S head above bed channel can be considered 23 cm, and the height of spillways that was 15 cm, so the length of crest is 12 cm. The U/S edge of all spillways can be considered as 1.6 cm which equal to equation 5 to prevent separation of stream flow from the crest. Considering all that nine models at first was designed and made from plywood as in Table (1) below.

Table (1): Characteristics of the models.

No. of steppe spillway	Model No.		
	Model face slope = 27 ^{o}	Model face slope = 32 ^{o}	Model face slope = 40 ^{o}
0	1	2	3
2	4	5	6
4	7	8	9

All measurements were conducted at the center line of the channel width. In each test (12 tests for each model) , U/S flow depth (y_o), flow depth over spillway (y_c), D/S flow depth (y_1), and discharge (Q) for all models were measured. Figure (2) represents a general view for the laboratory flume work.

Fig.(2): General view for the laboratory flume work.

4-FLOW DESCRIPTION

In this experiment there are three flow regimes. The first regime is that of the Nappe flow and the second is transition flow and the third is that of the skimming flow. The study of experimental results shows that the Nappe flow appears for lesser discharge 0.14 ℓ / s for this case. However, the skimming flows are observed for high discharge ($Q \geq 2$ ℓ / s) in general. Surely, the shape characteristic and the step surface quality affect the flow regime change. Table (2) shows the limitation of Nappe, transition, and skimming flow for the nine models. Figures (3) through (5) show the three types of flow which were established in this study.

Table (2): Flow description

No. of steppe spillway	Flow types and its limit		
	Model face slope = 27 ^{o}	Model face slope = 32 ^{o}	Model face slope = 40 ^{o}
0	1) ordinary, (0-2.64) ℓ/s	2) ordinary , (0-2.64) ℓ/s	3) ordinary, (0-2.64) ℓ/s
2	4) - Nappe < 1.1 ℓ/s - transition (1.12 < Q < 1.9) ℓ/s - skimming (1.91 < Q < 2.64) ℓ/s	5) - Nappe < 1.3 ℓ/s - transition (1.32 < Q < 2.1) ℓ/s - skimming (2.11 < Q < 2.64) ℓ/s	6) - Nappe < 1.0 ℓ/s - transition (1.10 < Q < 1.77) ℓ/s - skimming (1.78 < Q < 2.64) ℓ/s
4	7) - Nappe < 0.61 ℓ/s - transition (0.62 < Q < 1.12) ℓ/s - skimming (1.13 < Q < 2.64) ℓ/s	8) - Nappe < 0.53 ℓ/s - transition (0.55 < Q < 0.83) ℓ/s - skimming (0.85 < Q < 2.64) ℓ/s	9) - Nappe < 0.50 ℓ/s - transition (0.52 < Q < 1.12) ℓ/s - skimming (1.13 < Q < 2.64) ℓ/s

Fig.(3): Nappe flow.

Fig.(4): Transition flow.

Fig.(5): Skimming flow.

5-LIMIT BETWEEN NAPPE AND SKIMMING REGIMES

The flow regime change in a spillway was observed and analyzed. The conditions linked to the flow configuration changes have been quantitatively studied. The parameters which have been considered to quantify this change are the parameter related to flow critical depth (y_c) and to the spillway shape, which are the non-dimensional ratio y_c / h where h is the height of step. Table (3) represents the values of y_c / h for the nine models.

Table (3): Values of y_c / h

No. of steppe spillway	Values of y_c / h		
	Model face slope = 27 º	**Model face slope = 32 º**	**Model face slope = 40 º**
0	1) -	2) -	3) -
2	4) 0.66-0.82	5) 0.72- 0.92	6) 0.60-0.98
4	7) 0.77- 0.93	8) 0.67-0.83	9) 0.63-0.97

Several authors have taken this proposition into account in their research work as indicated in Table (4).

Table (4): Values of y_c / *h* for some authors.

Author	Essery et.al. (1978) [12]	Rajaratnam (1990) [13]	Degoutte (1992) [14]	Chanson (1994) [15]	Kells (1995) [16]	Matos et. al. (1995) [17]	Chafi (2010) [18]
y_c / h	0.81	0.8	0.69	0.80	0.50	0.83	0.67

6-ENERGY DISSIPATION STUDY

Figure (6) shows the results of the relative energy dissipation as a function of discharges for the nine models using equations 1 through 3.

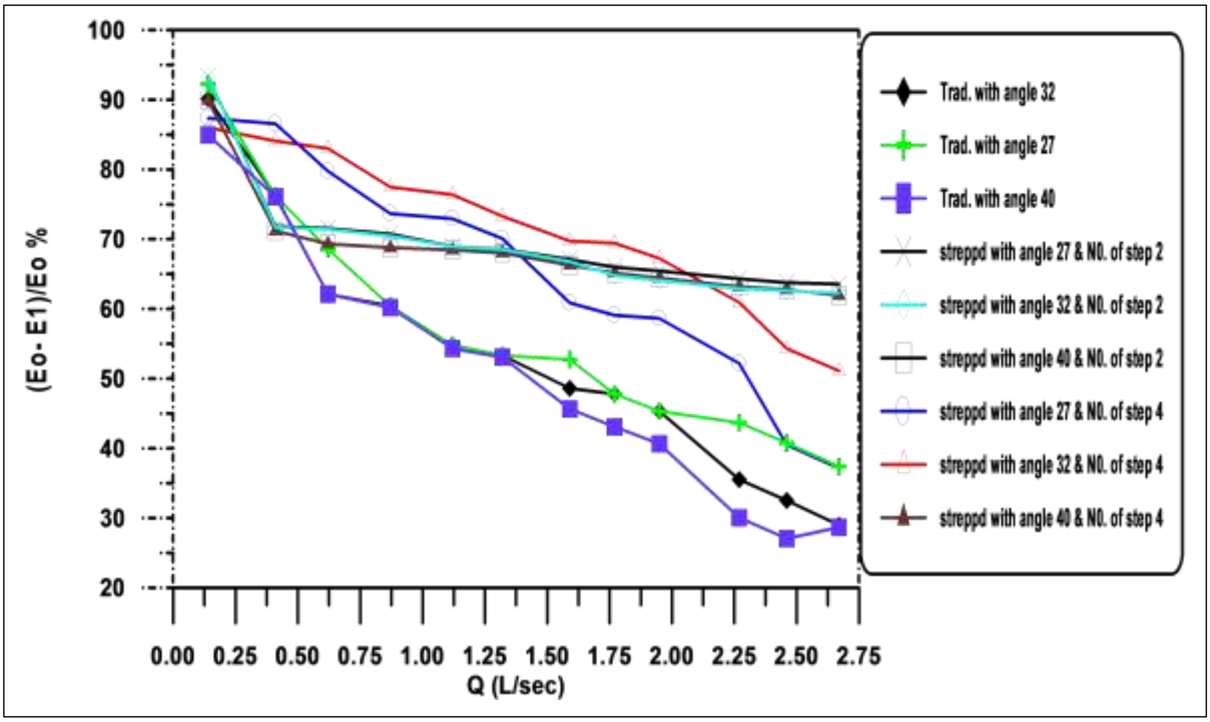

Fig.(6): Relations between discharge and relative energy dissipation.

Also, Figure (6) indicates that the relative energy dissipation decrease with increasing discharge for all the nine models and as indicated in many papers. The results showed that when decreasing both number of steps and downstream slops stepped face of the spillway will cause an increase of the ratio of flow energy dissipation, and the stepped spillways are more efficient in flow energy dissipation compared with flat sloped spillways. Model No. 4 (stepped spillway with angle 27^o and number of step is two) have the larger energy dissipation with large discharges. So, a trial to increase the energy dissipation specially for large discharges. Model No. 4 was selected for trying to increase the energy dissipation since it have the large energy dissipation at higher discharge as shown below.

7- TRIAL TO INCREASE ENERGY DISSIPATION

Three new cases were designed as a trial to increase energy dissipation at high discharge as a novel study, one as a cascade and two as varies shapes of blocks. The following paragraphs indicate the three cases.

7-1 Case 1

Multi- weirs (cascade) were designed as a study and installed in all steps of the Model No. 4 (which have two steps and angle 27^o) named Model No. 10. Figure (7) represents the dimensions of cascade that was used in this paper.

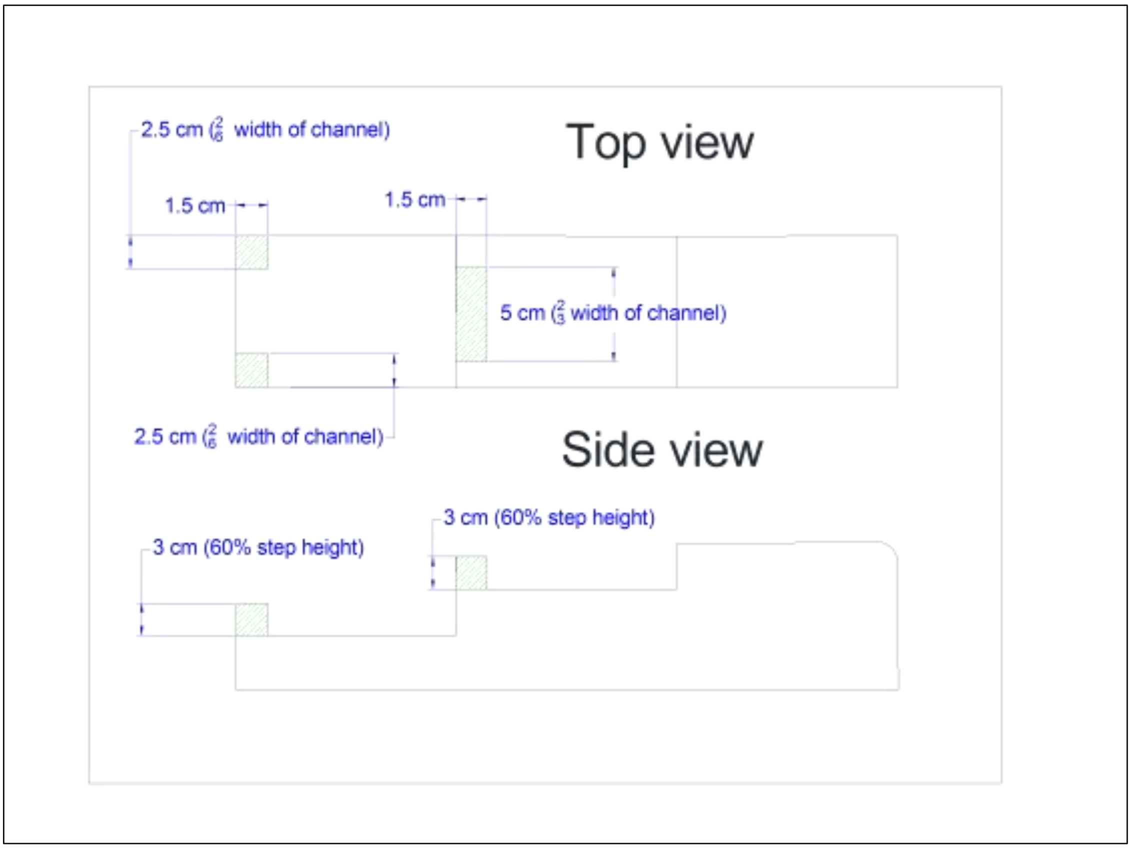

Fig.(7): The dimensions of cascade in Model No. 10 (case1).

Figure (8) shows the application of case 1 at Model No. 10 in the laboratory and series of hydraulic jumps can be notified above the model and that lead to decrease the energy dissipation compared with the original model (Model No.4) but still have energy dissipation greater than the flat sloped model that have the same angle i.e. 27^{o} at high discharges. The range of transition flow in this case was increased.

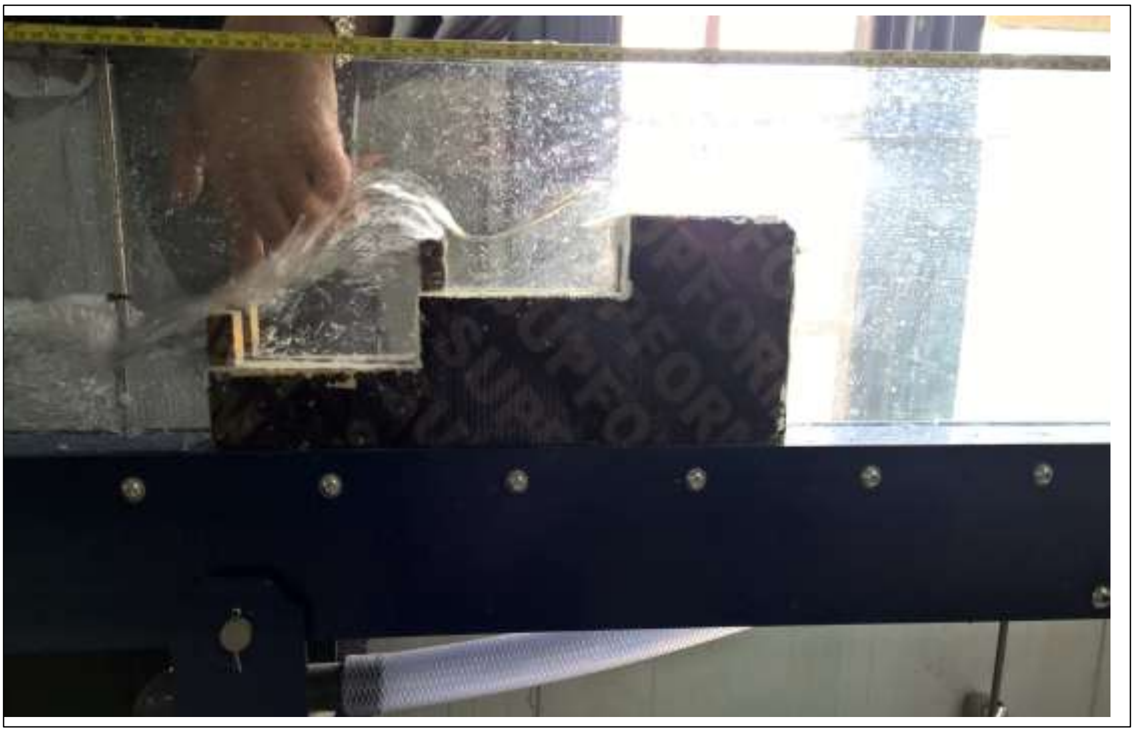

Fig.(8): Application of cascade in Model No. 10.

7-2 Case 2

Many blocks were designed as a study and installed in all steps of the Model No. 4 which named as Model No. 11. Figure (9) represents the dimensions and distribution of blocks that were used in these papers.

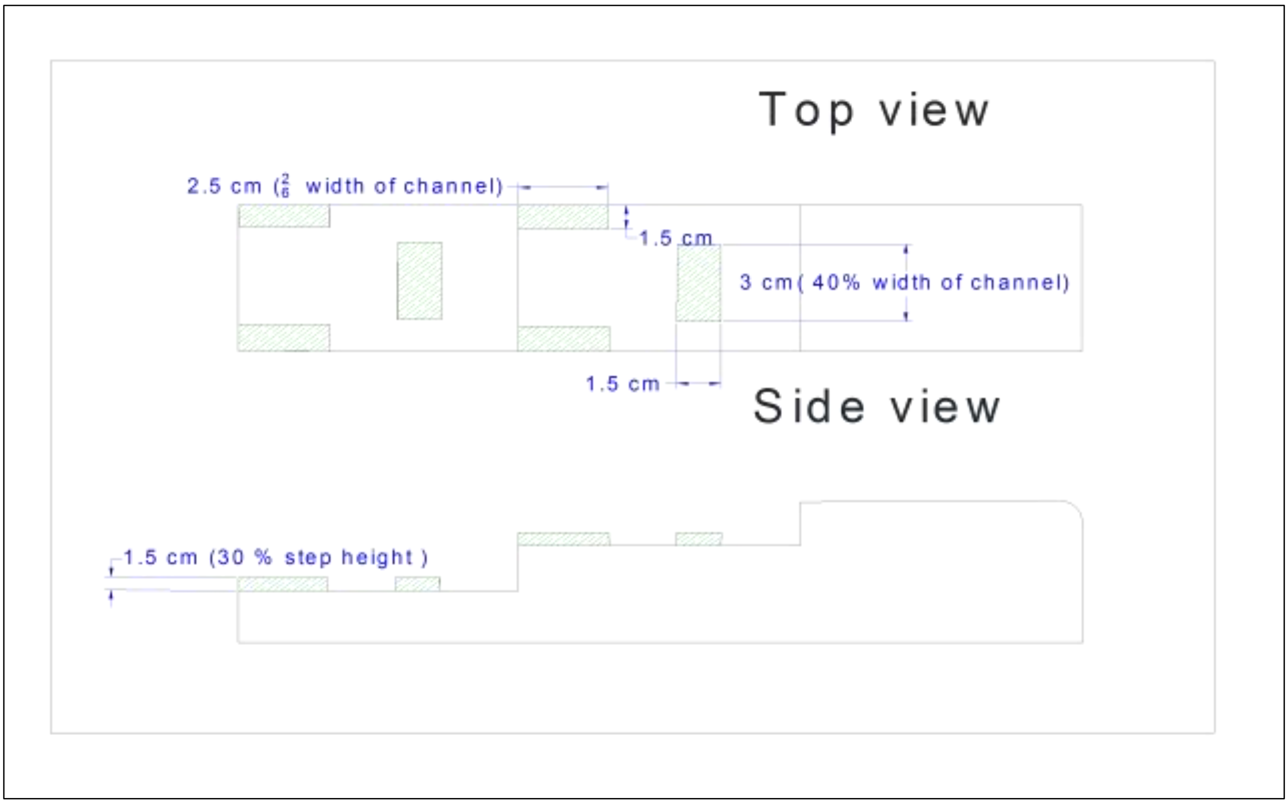

Fig.(9): The dimensions and distribution of blocks in Model No. 11 (case 2).

Also, the range of transition flow in this case was increased. The energy dissipation in this case was increased at high discharges compared with original model (Model No. 4) and also compared with flat sloped spillway that has the same characteristics. Figure (10) shows the flow over stepped spillway (case 2).

7-3 Case 3

Figures (11) and (12) represent the dimensions and distribution of blocks and the application of case 3 which named Model No. 12, respectively that were used in these papers as a trial to increase the energy dissipation.

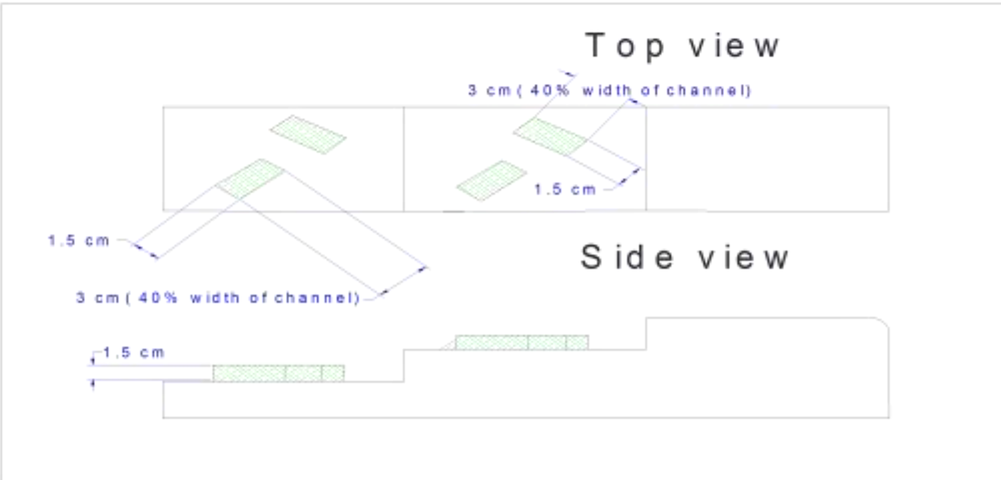

Fig.(12): Application of blocks in Model No. 12 (case 3).

In this case the energy dissipation was decreased compared with original model (Model No. 4) at high discharges and still larger than the flat sloped spillway that has the same characteristics. Also, the range of transition flow was increased.

Figure (13) shows the relations between relative energy dissipation and discharged for the three cases and original model (Model No. 4).

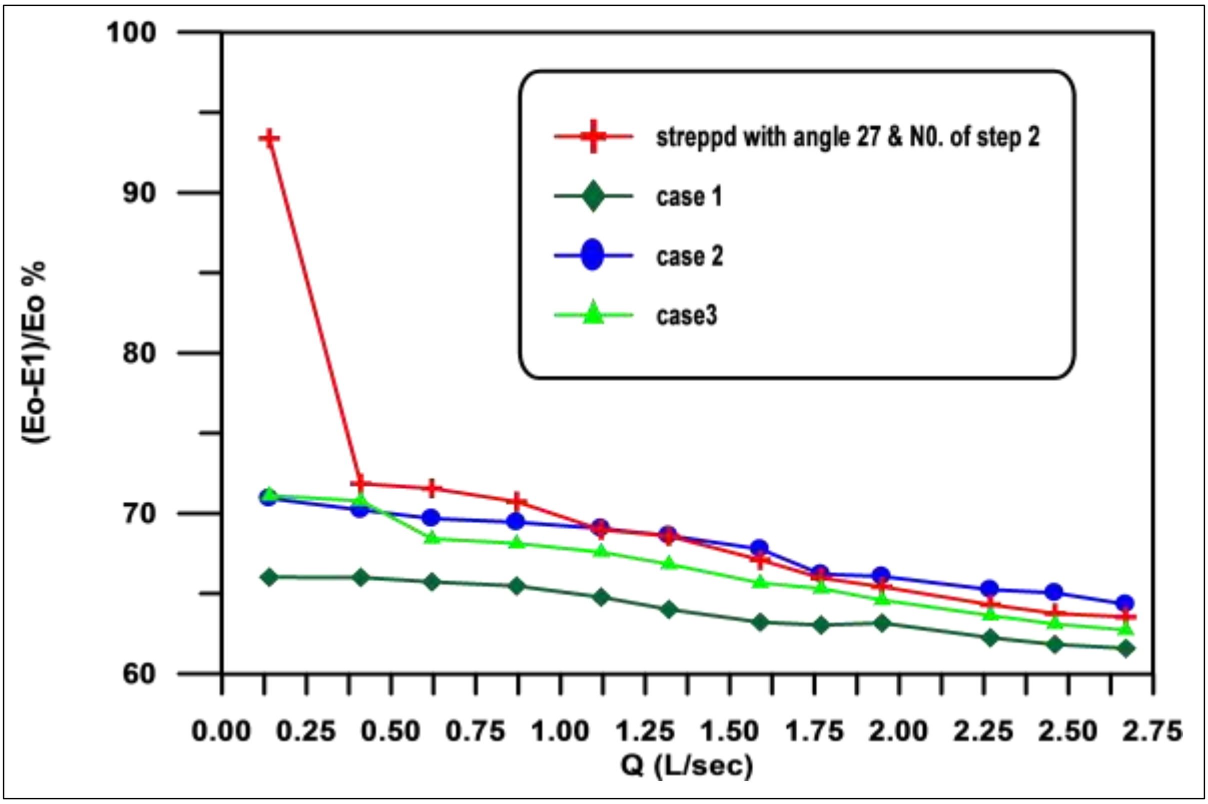

Fig.(13): Relations between relative energy dissipation and discharges for the three cases and model No. 4.

8- CONCLUSION

In this experimental work an attempt were made to increase energy dissipation at high discharges since many papers as well as this paper indicate that when increasing discharges the energy dissipation will decrease. Case 2 gave the largest energy dissipation at high discharges ($Q \geq 1.1$ ℓ/s) although gave less energy dissipation at lower discharges ($Q < 1.0$ ℓ/s) (which considered low discharges) compared with model No. 4 but also gave larger dissipation compared with flat sloped spillway. The range of transition flow was increased in all the three cases. The results showed that when decreasing both number of steps and downstream slops stepped face of the spillway will cause an increase of the ratio of flow energy dissipation, and the stepped spillways are more efficient in flow energy dissipation compared with flat sloped spillways.

9- RECOMMENDATIONS

Due to this experimental work a recommendations can be illustrated as:-

1- Using cases other than cases that used in this work to increase energy dissipation at high discharges.
2- Using special materials for stepped spillway surface which lead to increase energy dissipation.

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