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JOURNAL OF UNIVERSITY OF BABYLON

For ENGINEERING SCIENCES (JUBES)

Vol.30, No.3.| 2022

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Investigating Energy Dissipation for Different Inclined Spillways and Baffles Blocks

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Received:	19/10/2022	Accepted:	10/11/2022	Published:	13/11/2022

Abstract

The stepped spillway is an important structure for energy dissipation downstream of dams. This study is based on laboratory work, aiming to increase the energy dissipation percentage for uniform and non-uniform stepped spillways. The study is based on twelve models of water-resistant wood, six models uniform and six models non-uniform, with different slopes and numbers of steps where angles were used (30°,40°,45°) and number stepped (10, 5) steps. The total number of trials is 126 trials. The laboratory results showed that the non-uniform model is more efficient in energy dissipation and approximating the hydraulic jump. After that placing baffles blocks in stepped spillways with ten steps and 45° because it records the lowest dissipation energy. The results indicate that the best model for energy dissipation is the seventh model with an angle of inclination (30°) and the number of steps 5.

Keyword: Energy dissipation, Spillways, Baffles blocks, Hydraulic jump.

1. Introduction

A spillway is a structure that enables the managed water to be released from a levee or dam downstream, generally into the bottom of the impoundment river [1]**.** It could be referred to as an overflow channel in the UK. Spillways protect the structure's non-water-conveying components from harm caused by water. Floodgates and fuses plugs are examples of spillways that may be used to control the water level in the reservoir and water flow [2], [3]. By gradually discharging water before the reservoir seems full, operators may avoid an uncomfortably big discharge later. Such characteristics allow a spillway to manage the downstream flow. The word "spillway" is also used to describe outlet channels cut through natural dams like moraines, bypasses of dams utilized throughout high water, and exits of waterways. Only during flooding, once the lake has exceeded its maximum capacity and water comes in quicker than it could be discharged, does water generally go over a spillway. On the other hand, an intake tower regularly regulates water flow for uses like water systems and hydropower production [4]–[6].

Through the implementation of several models and the various flow systems expressed by the skimming, transition, and nappe flow by the calculation of energy dissipation of different models, laboratory experiments have been utilized to identify the ideal height of the step and the ideal slope for energy dissipation [7]. These models' degree of pressure and dispersion distributions were explored using empirical formulas for pressure distributions, including the amount of dispersion across conventional and semicircular crests [8]. Furthermore, findings revealed that the model with roughness enhanced dispersion both for high and low discharge for different types of steps depending on stepped spillways with increased surface roughness to promote energy dissipation [9], [10]. It was also based on the specific geometry of stepped, labyrinth, or quarter circle geometry at step edges for the spillways. These models obtained a percentage of energy gain dissipated [11]. Various layouts on the spillway steps and end sills were also employed, demonstrating a high degree of dissipation in different forms from the standard type and the removal of air pockets [5].

Optimizing the design of stepped spillways is critical for lowering construction costs and maximizing the infrastructure's safe energy dissipation. Because of the enormous flow discharge through spillways, their design and construction are both very challenging, sometimes incorporating issues like cavitation and high flow kinetic energy, and extremely costly, accounting for a significant portion of the dam's construction costs. It accounts for around 20% of major dam building costs and about 80% of small ones [12]. As the usage of stepped spillways has grown, researchers have focused on improving their efficiency, and as a result, numerous solutions have been suggested. Finding the ideal size of the steps based on the passing flow regime might be suggested in this respect [13]. The optimal mix of spillway width, height, and step numbers is obtained to minimize the spillway steps' overall cost and downstream energy dissipaters.

Studies on the hydraulic design of stepped spillways have been done since the 1970s, and various empirical formulae have been produced. Despite their basic shape, the hydraulic behavior of these spillways is complex. Consequently, physical models are evaluated in many situations to validate the design Hunt and Kadavy [14], the results of numerical simulations were compared with the findings of physical models and empirical formulations [15]. A mixed multi-phase flow model and a realizable k-turbulence model provided by are used to simulate flow [16] numerically. In regions where a large gradient of certain parameters occurs, or more accuracy is desired, grid sensitivity is achieved, and the mesh size is lowered. The numerical simulation findings are consistent with the results of the physical model testing. The velocity profile, energy dissipation, and position of the inception point where air entrainment is assured in the flow are explored and compared to the scale model findings.

In order to dissipate more energy, baffle blocks with stepped spillway is always preferred. Energy dissipation at the location where water is discharged through gates or spillway crest is generally accomplished by causing a hydraulic jump formation in the stilling basin.

An approach by Rageh [17] on the effect of baffle blocks on the Performance of Hydraulic Jump' suggests how this baffle block helps in the efficient reduction of hydraulic jump length. Frizell and Connie [18] put their ideas in the paper Performance of Type III Stilling Basins – Stepped spillway studies, which try to show supercavitation high energy dissipation than the standard block.

Some researchers worked on hydraulic characteristics of flow and energy dissipation over a stepped spillway and suggested that a stepped spillway dissipates more energy than the smooth or traditional one. If the number of steps is increased, energy dissipation decreases. Authors with

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different designs of baffle blocks suggested that they found more angry dissipation than standard ones; Eloubaidy et al. [19].

The current research aims to study the energy dissipation experimentally for non-uniform spillways with different types of non-uniform and uniform step lengths, heights, numbers, and ratios between the lengths of the successive steps to improve the energy dissipation of descending water. Also, investigate the changing in the energy dissipation for 45-degree stepped spillways uniform and non-uniform (for ten steps) before and after using baffles block.

2. Theoretical work

Theoretically, many equations are usually utilized to estimate the parameters related to flow over spillways as energy dissipation rate, which can be obtained by calculating the energy upstream and downstream of the spillway:

$$\frac{\Delta E}{E_O}\%=\frac{(Eo-E1)}{Eo}\% \qquad (1)$$

Where:

ΔE: Difference between upstream and downstream energy of the stepped spillways structure.

Eo: the energy upstream of the spillway.

$E1$: the energy downstream of the spillway.

The energy upstream of the spillway is calculated at the critical section by [20]

$$Eo = 1.5y_c + H_d \qquad (2)$$

Where:

E_o =maximum energy of stepped spillways crest

$H_{dam} = H_{spilway} = 30\ cm$

$$E_1 = y_1 + \alpha\frac{V_1^2}{2g} \qquad (3)$$

E_1: downstream energy of the stepped spillway

y_1: water depth of the toe

V_1: Velocity at depth y_1

$V_1=\frac{q}{y_1}$

α=kinetic correction coefficient, for turbulent flow, generally equal to 1 [20]

g=gravitational acceleration;

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3. Experimental Setup

The experimental work is done using a flume located at the fluid laboratory of the engineering college, Babylon university. The flume is rectangular with a width of 30cm, length of 12 m, and height of 45cm. A flowmeter measured discharge. The flume has a pump discharge capacity of 30 l/s. The water surface level at different locations was measured using a level meter. The upstream flow head was measured at a location more than (9 y_c) upstream of the spillway model, where the water depth is over the spillway crest. The length of all crests in all models and the radius of curvature of the upstream face are calculated [9]

3.1. Models Description

Eighteen stepped spillway models were designed from plywood to calculate the length of crest and radius curvature. In this study, the height of all models used was constant equal to 30cm with three model slope angles (θ=30°, 40°, 45°) and the number of steps (5,10. All models have a 30cm width,30cm height, 20cm Lcrest, and radius curvature of 2cm. Each angle of the models was modeled with four different heights of steps, as shown in Table 1.


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

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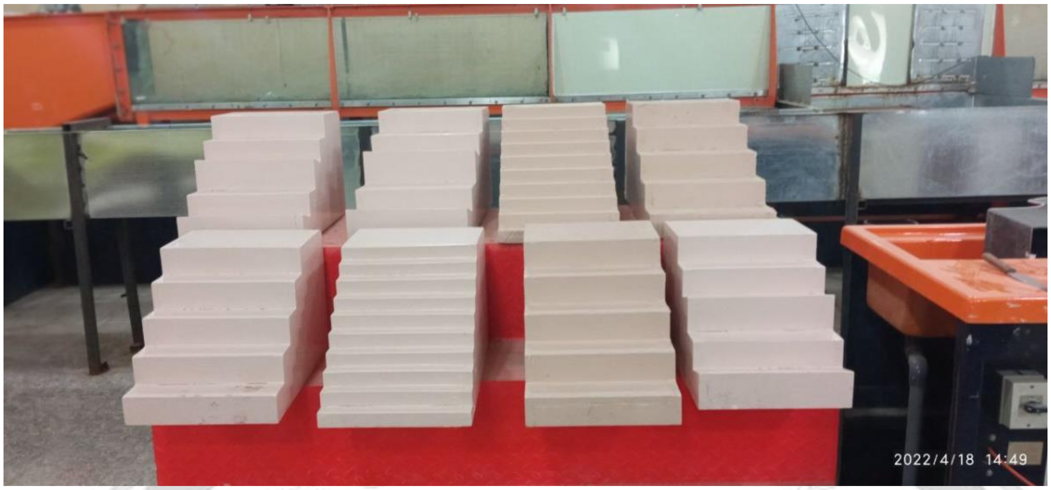
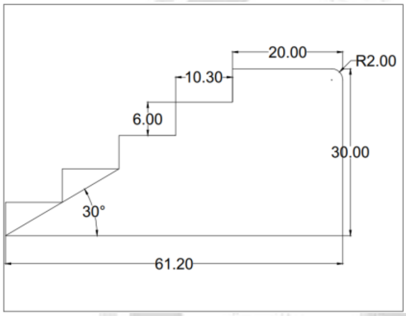
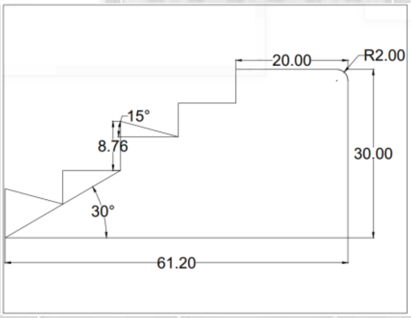


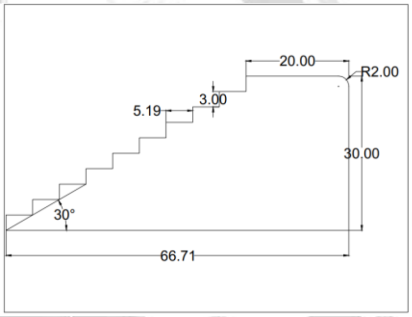
Figure 2. The experimental models.



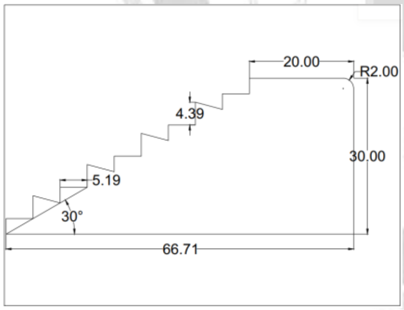
Model (1)



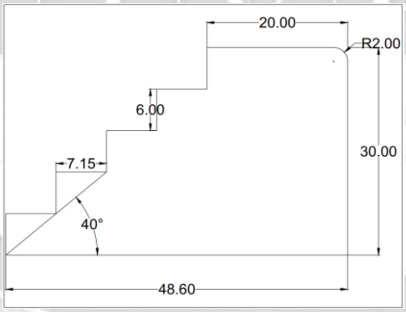
Model (2)



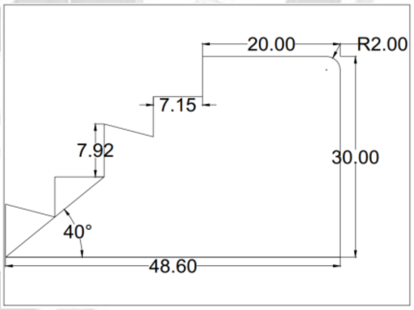
Model (3)



Model (4)



Model (5)



Model (6)

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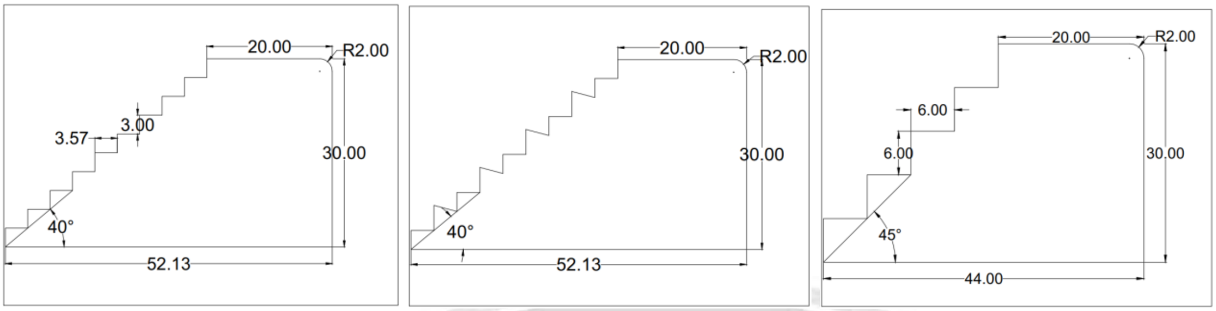
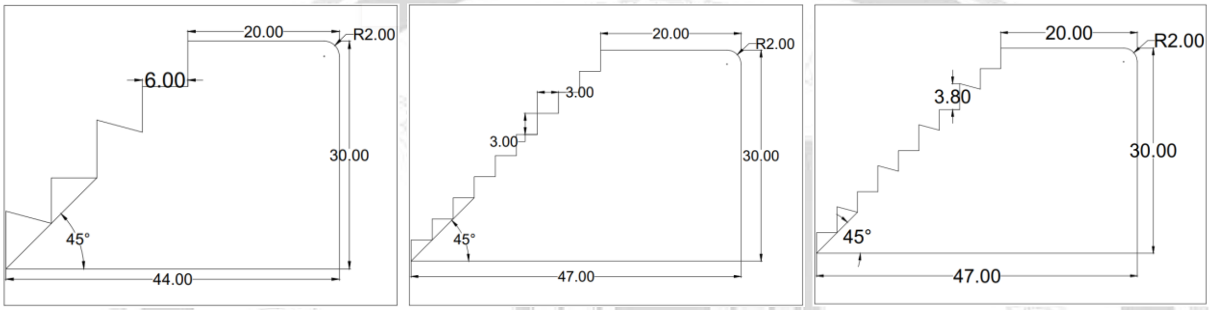


Model (7) Model (8) Model (9)



Model (10) Model (11) Model (12)

Figure 3. Stepped spillway models (all dimensions are measured in cm).

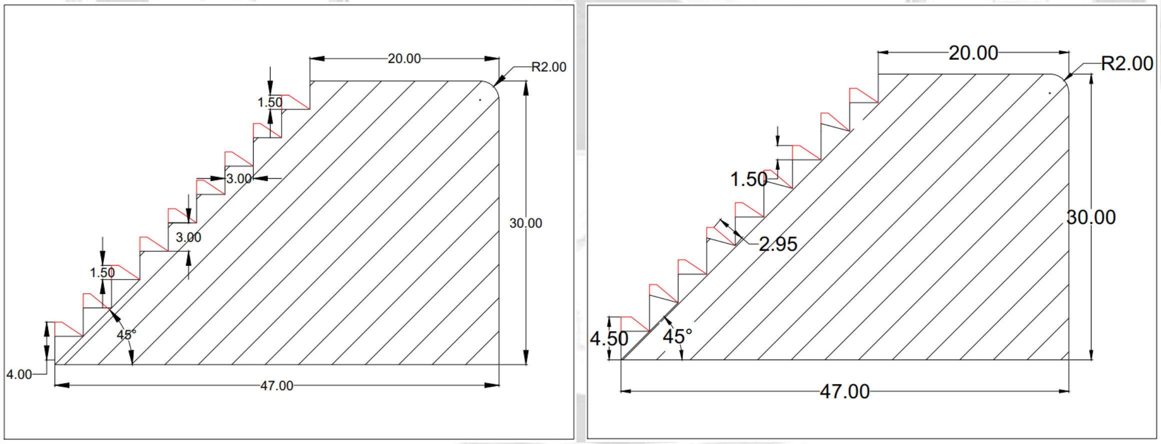


Figure 4. Stepped spillways with baffles blocks (all dimensions are measured in cm).

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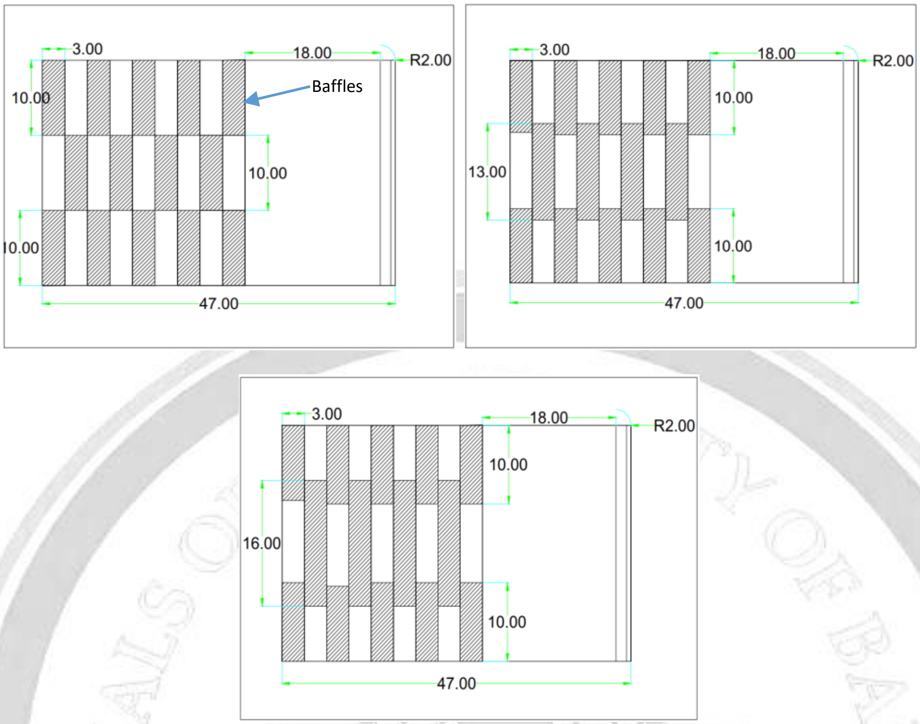

Figure 5. baffles blocks in different distributions a) B/2; b) B/2.5; and c) B/3 (all dimensions are measured in cm);

Table 1. Characteristics of the Models

Model	Main angle (degree)	Height of steps (cm)	Length of steps (cm)	Number of steps	Model Details
M1	30	6	10.3	5	Uniform
M2	30	8.76	-	5	Non-uniform
M3	30	3	5.19	10	Uniform
M4	30	4.39	5.19	10	Non-uniform
M5	40	6	7.15	5	Uniform
M6	40	7.15	7.92	5	Non-uniform
M7	40	3	3.57	10	Uniform
M8	40	-	-	10	Non-uniform
M9	45	6	6	5	Uniform
M10	45	-	6	5	Non-uniform
M11	45	3	3	10	Uniform
M12	45	3.8	-	10	Non-uniform
M13	45	3	3	10	Uniform with B/2 Two-baffle
M14	45	3	3	10	Uniform with B/2.5 Two-baffle
M15	45	3	3	10	Uniform with B/3 Two-baffle

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M16	45	3.8	-	10	Non-uniform with B/2 Two-baffle
M 17	45	3.8	-	10	Non-uniform with B/2.5 Two-baffle
M18	45	3.8	-	10	Non-uniform with B/3 Two-baffle

Table 2. The flow discharge for each flow runs that utilized to simulate the flow in the lab flume.

Run No	Q(l/s)	q(l/s/m)
1	3.11	10.33
2	5.51	18.56
3	7.67	25.56
4	10.28	34.26
5	12.52	41.73
6	14.83	49.43
7	16.41	54.70

4. Results and discussion

The effect of geometry changes in the stepped spillways models on energy dissipation was investigated through two situations:

4.1.Different inclined angles

Once one kind of energy (like potential energy) gets transformed into another (like kinetic energy), it seems to have dissipated since it can no longer be fully transformed into its original form. For instance, friction is a common dissipative process where mechanical energy is transformed into thermal energy and cannot entirely be transformed back into mechanical energy. Therefore, mechanical energy has (in part) been converted into thermal energy. Therefore, energy dissipation is an unstoppable process.

In each case, the slope of stepping is constant (30°,40°and 45°), and for each slope, two constant numbers of steps were used (5 and 10) with two-step angles for each steps number (acute and right angle) to present a uniform and non-uniform steps.

The relationship between $\Delta E/E0$ % and critical depth over the crest of the stepped spillway (yc) for 5 and 10 uniform and non-uniform stepped spillway with 30^{o} inclined is negative, and increasing one lead to a decrease in the other one, as indicated in Figure 6. Sample M4 with ten steps and a non-uniform stepped spillway records the lowest energy dissipation; the obtained results are compatible with Jahad et al. [21] results in which increasing the number of the steps is more effective on energy dissipation rather than increasing the incline for angles less than 30^{o} or increasing the spillway height.

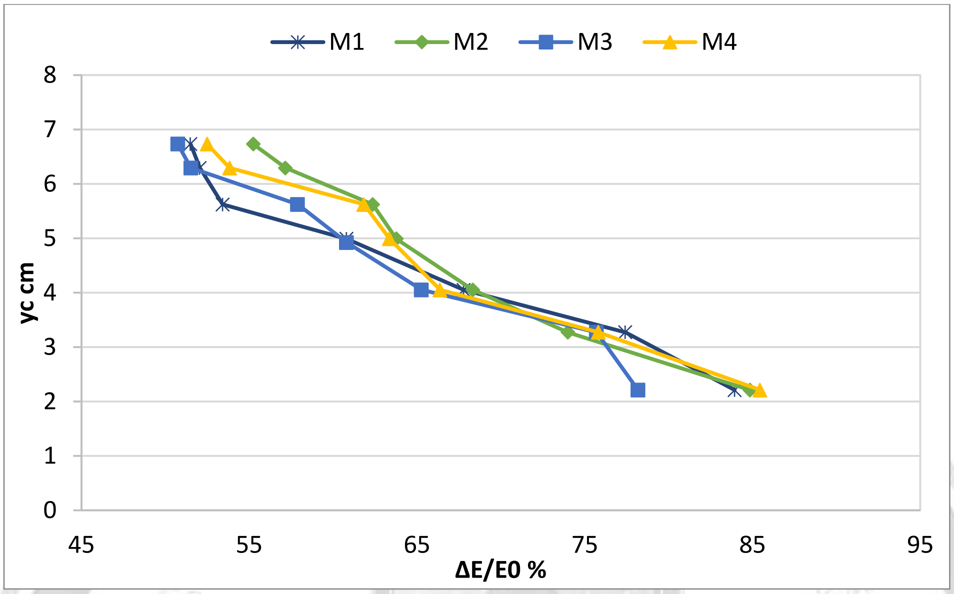

Figure 6. The relationship between ΔE/E0 % and yc for Stepped Spillway inclined with 30.

Figure 7 shows the relationship between ΔE/E0 % and yc for stepped spillway inclined with 40^{o} for samples M5, M6, M7, and M8, the relationship is negative, and the energy dissipation fluctuated for all selected trials. However, sample M5 records a sharp fluctuation comparison with sample M6 with smooth movement. However, samples M8 and M6 record the lowest energy dissipation, about 83 % for both.

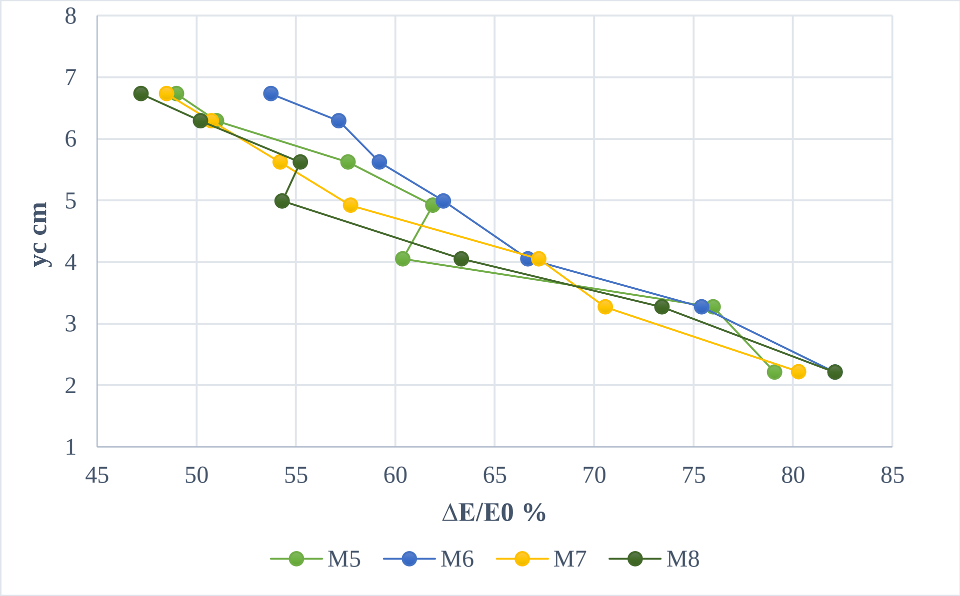

Figure 7. The relationship between ΔE/E0 % and yc for Stepped Spillway inclined with 40^{o}.

At 45^{o}, the relationship between ΔE/E0 % and yc for Stepped Spillway for samples M9, M10, M11, and M12 was shown in figure 8. Samples M10 and M12 with ten steps record the lowest energy dissipation comparison with other spillways with 30 and 40 inclined degrees, as shown in Figures 6 and 7. Therefore, the second part of the research focuses on placing baffles blocks on spillways with ten steps [21].

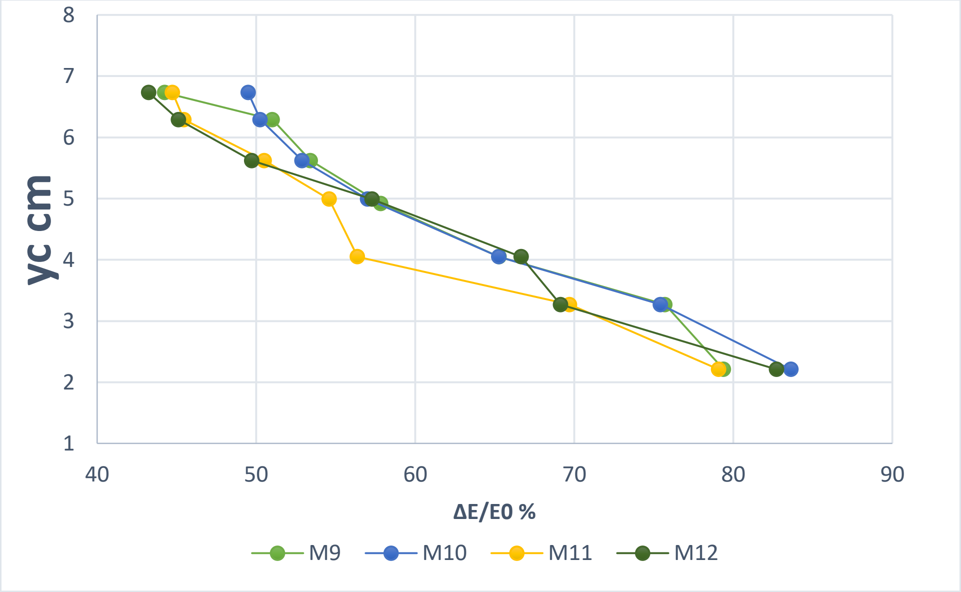

Figure 8. The relationship between ΔE/E0 % and yc for Stepped Spillway inclined with 45^{o}.

At the constant height of steps with different slopes of stepped spillway uniform and non-uniform with 5 and 10 steps, Figure 9-12 show the relationship between flow discharge that has been selected (10.33, 18.56, 25.56, 34.26,41.73, 49.43 and54.7 l/s/m) and critical depth over the crest of stepped spillway yc (0.368, 0.545, 0.675, 0.831, 0.936, 1.04 and 1.12) for uniform five steppes models (M1, M2, M5, M6, M9, M10) that show increasing the discharge leads to increase critical depth over the crest of the stepped spillway. The only changeable value is ΔE/E0% for all selected inclined angles. In low discharge, the differences in energy dissipation are very significant. Increasing the discharge leads to reducing the gap between the models, but at the same time leads to reducing the energy dissipation, especially when the spillway angle is 45.

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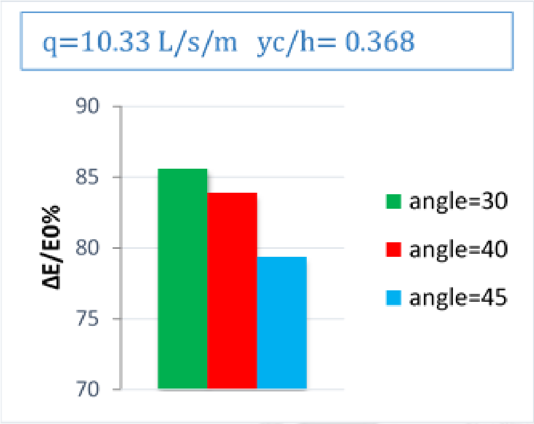
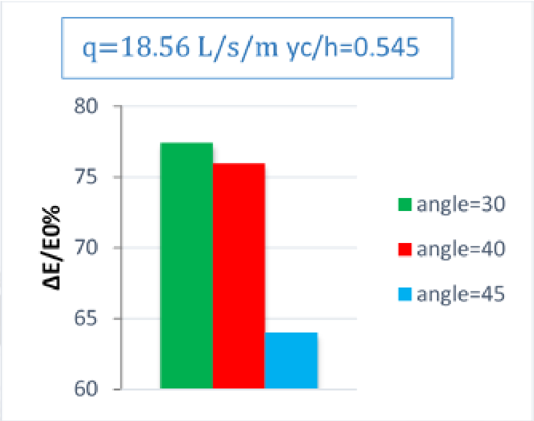
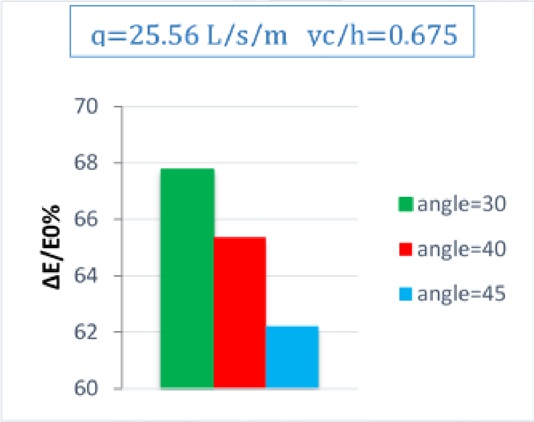
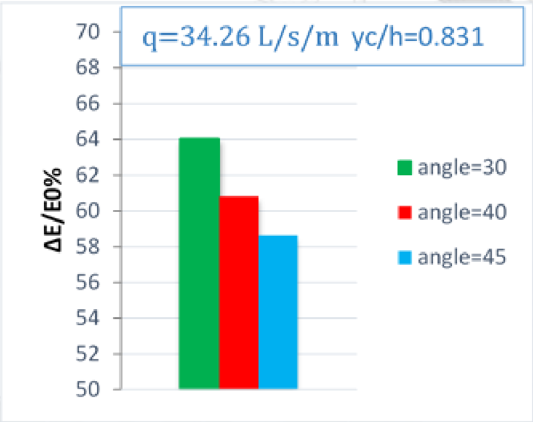
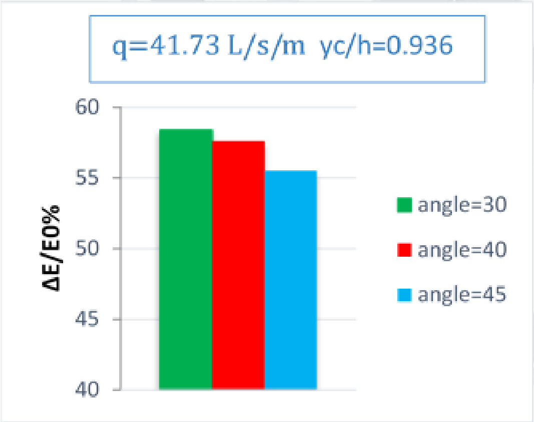
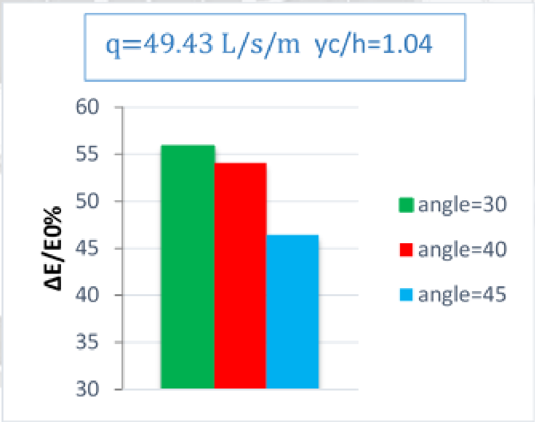












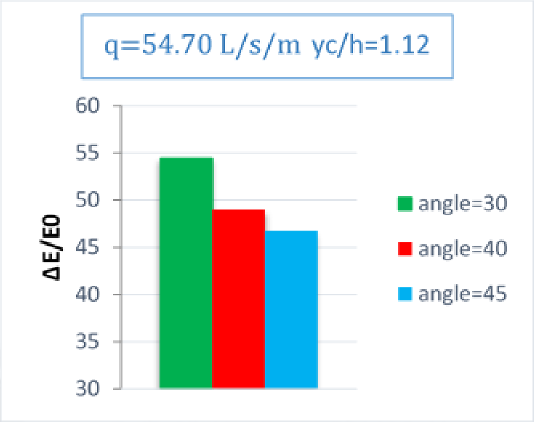
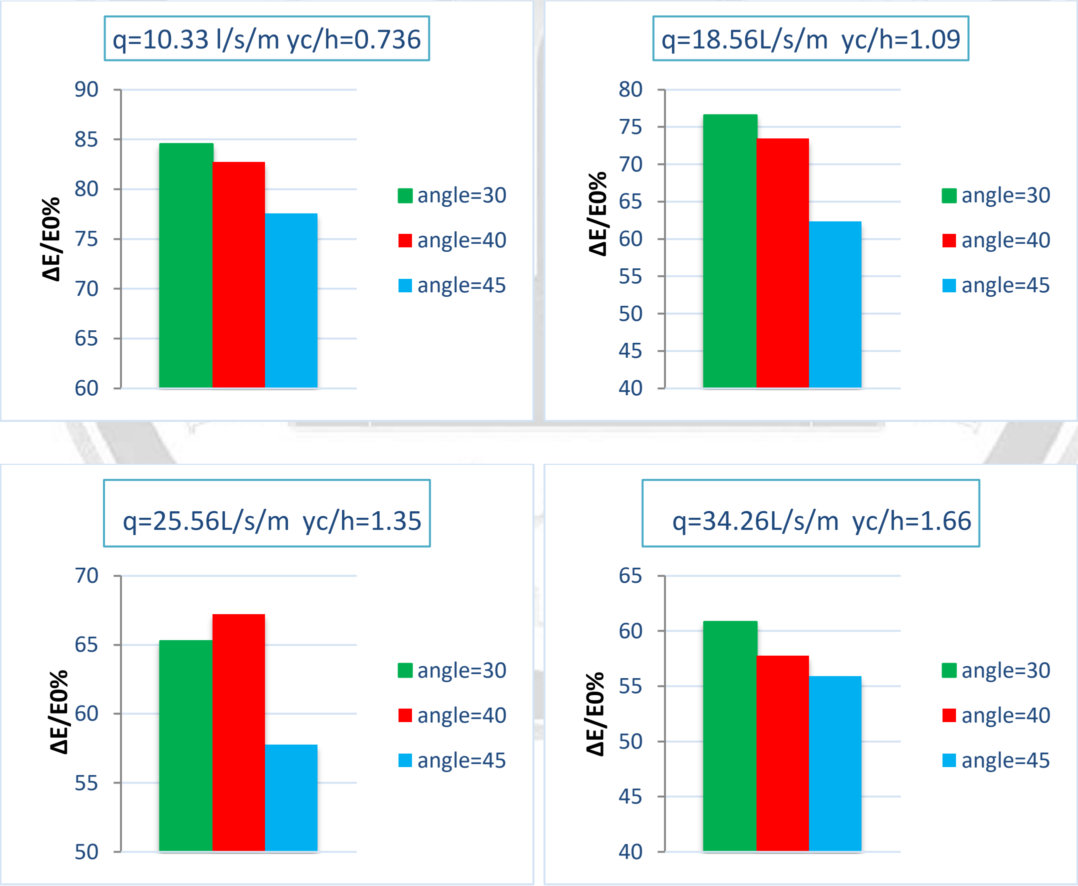


Figure 9. The effect of the modeled angle at constant height on energy dissipation rate with uniform five steppes



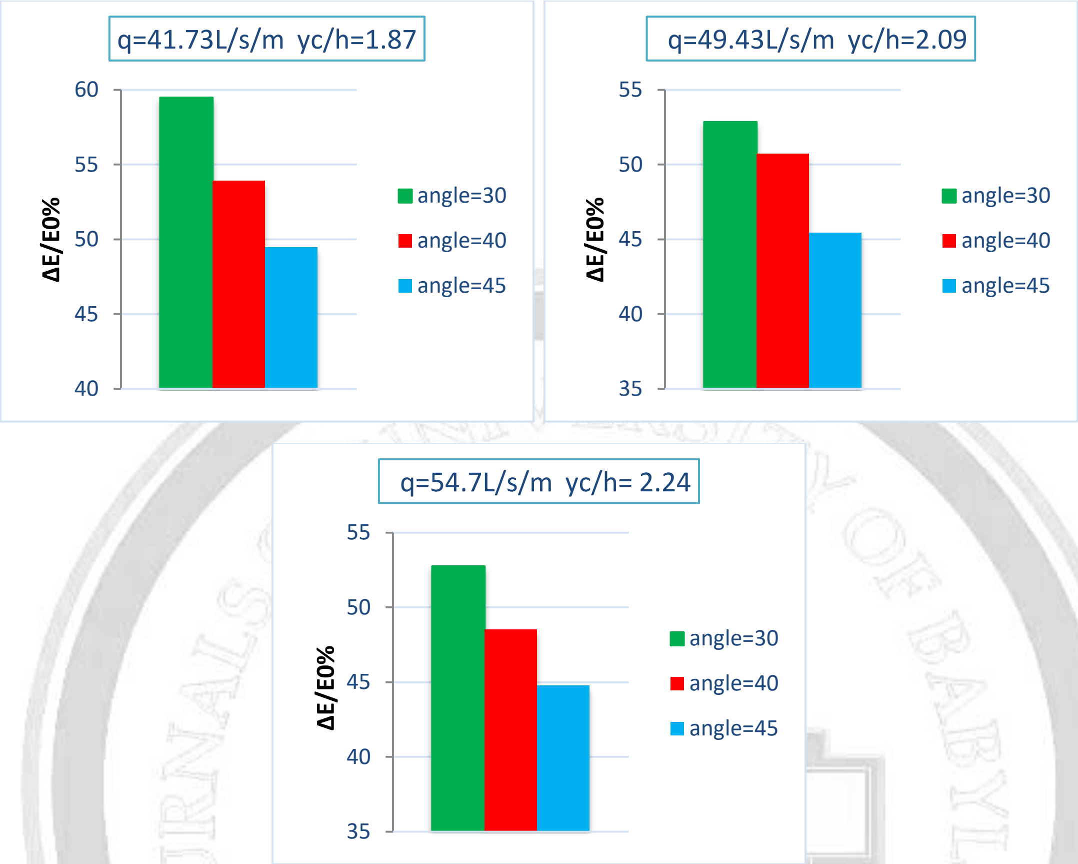
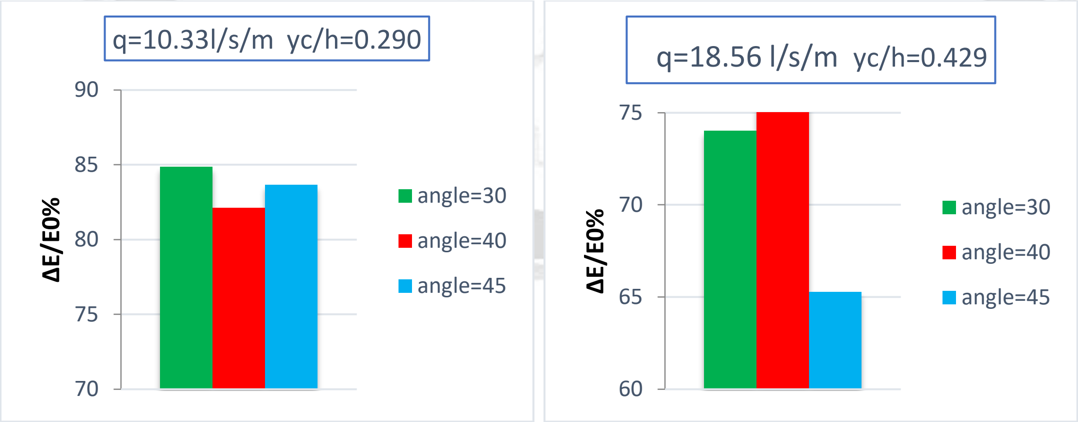


Figure 10. The effect of the modeled angle at constant height on energy dissipation rate with uniform ten steppes



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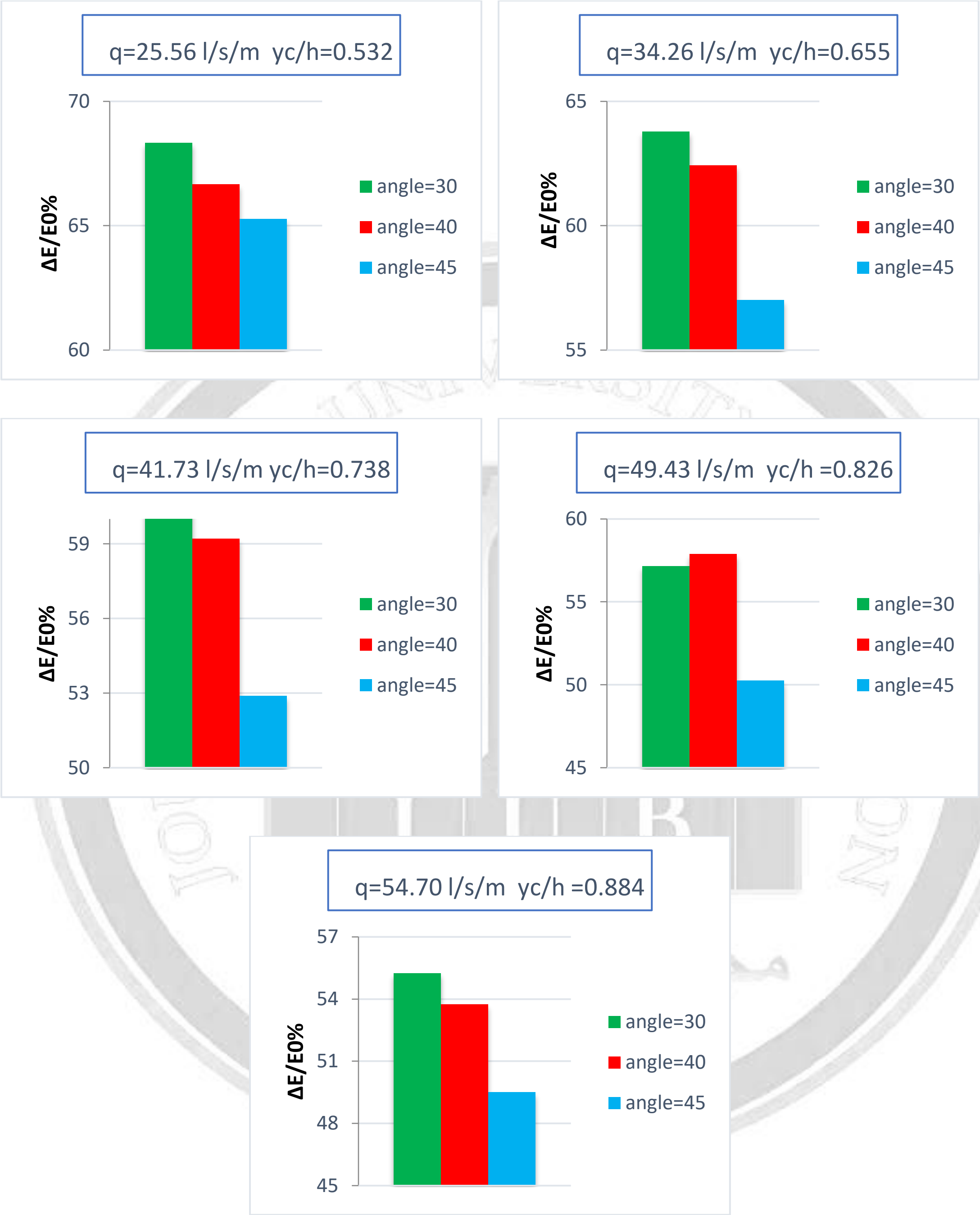

Figure 11. The effect of the modeled angle at constant height on energy dissipation rate with non-uniform five steppes

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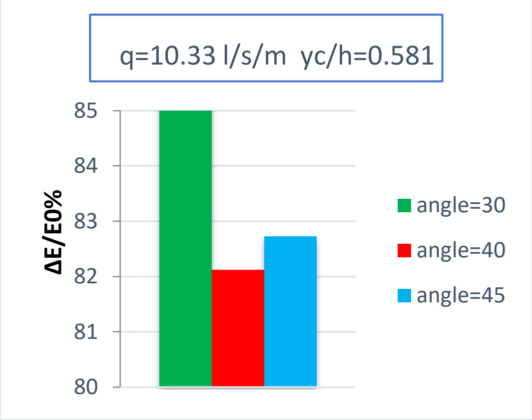

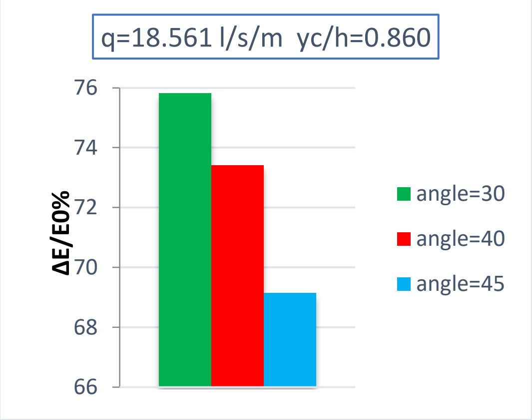

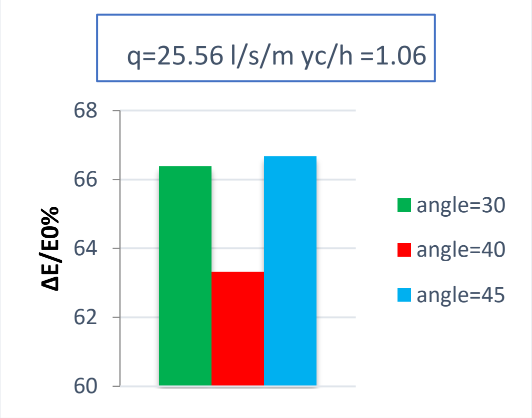

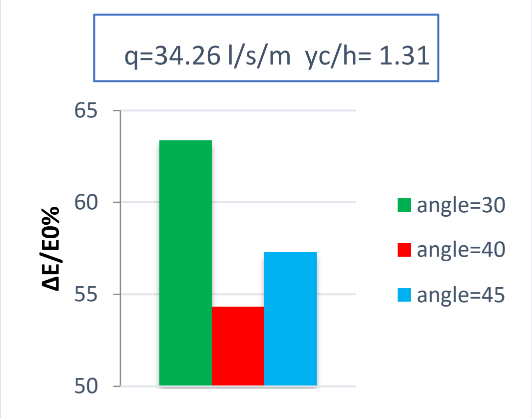

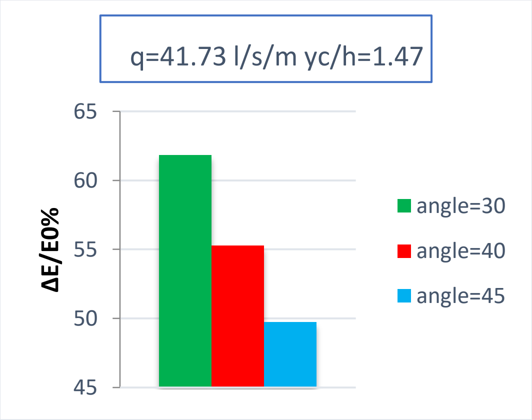

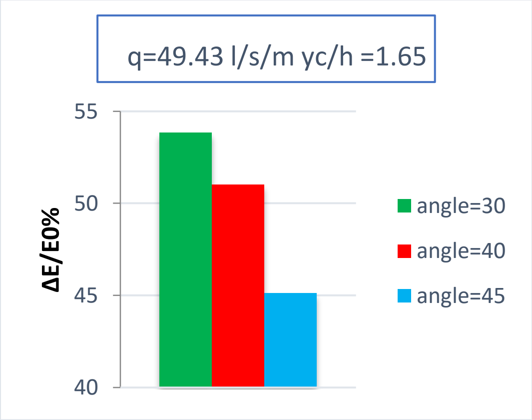

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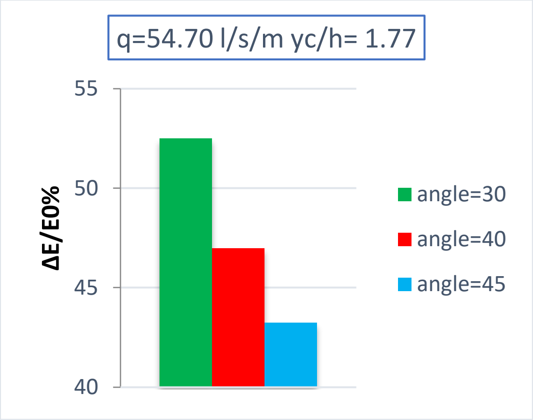

Figure 12. The effect of the modeled angle at constant height on energy dissipation rate with non-uniform ten steppes

4.2.Applying Baffles blocks

When applying baffles blocks on ten uniform and non-uniform steps, spillways increase energy dissipation for spillways with 45^{o} inclined, as shown in figure 13. Figure 13 shows the relationship between critical depth over the crest yc and energy dissipation ΔE/E0% for stepped spillways before and after applying baffles blocks. The results show that sample M14, with uniform steps and Two-baffle in ratio B/2.5, records the highest energy dissipation compared to other cases.

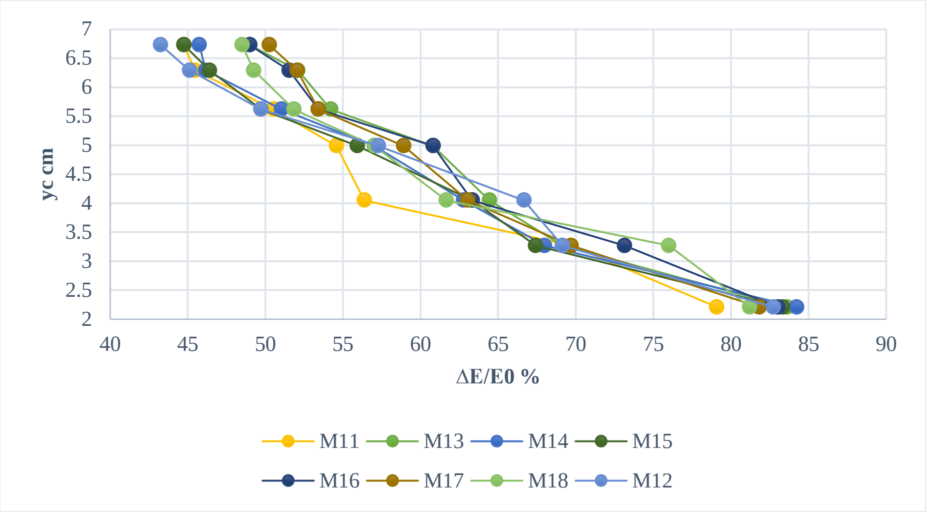

Figure 13. The relationship between ΔE/E0 % and y_c for Stepped Spillway for uniform ten-stepped spillway with different baffles blocks distribution.

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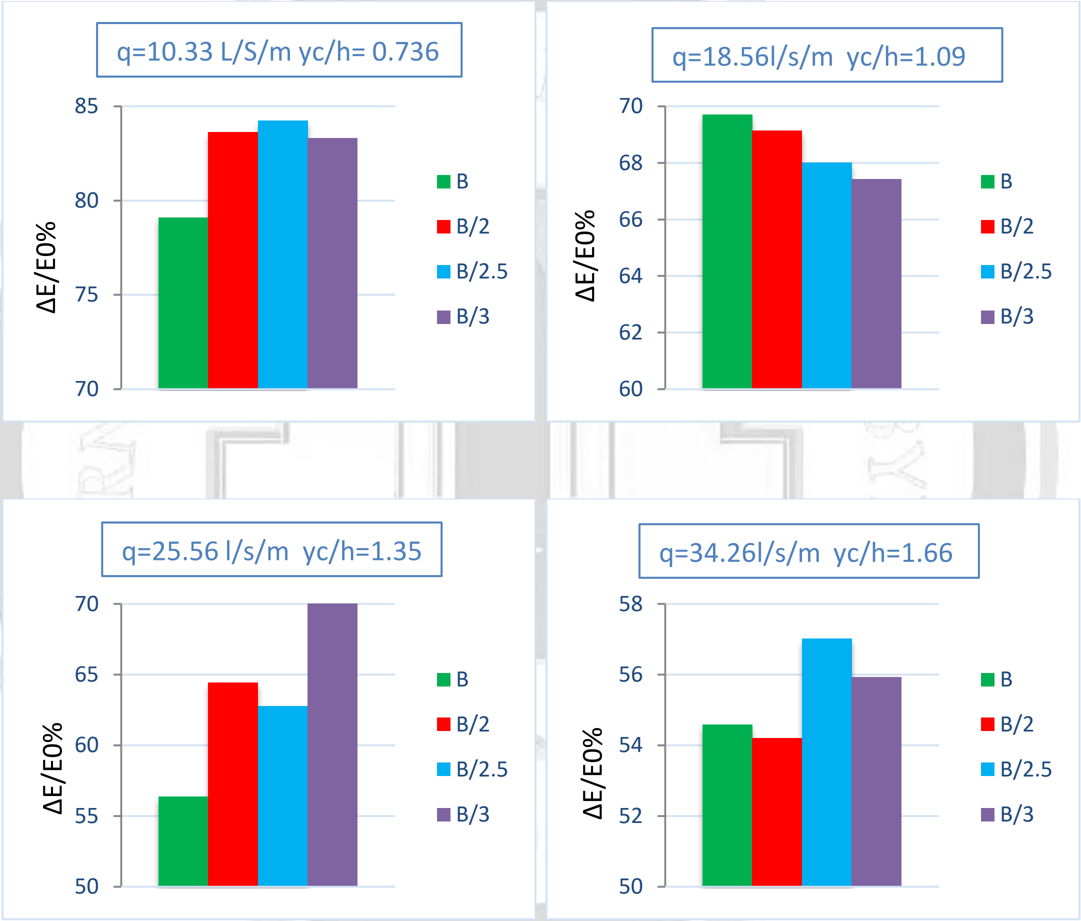
At the constant height of steps with different slopes of stepped spillway uniform and non-uniform with ten steps, Figures 14 and 15 show the relationship between flow discharge and critical depth over the crest of stepped spillway; and the energy dissipation for stepped spillways before and after placing baffles blocks in different distributions B/2, B/2.5 and B/3. Increasing the discharge leads to increase critical depth over the crest of the stepped spillway. At the same time, most of the cases show high discharges. Placing baffles in ratio B/2 record the highest energy dissipations.



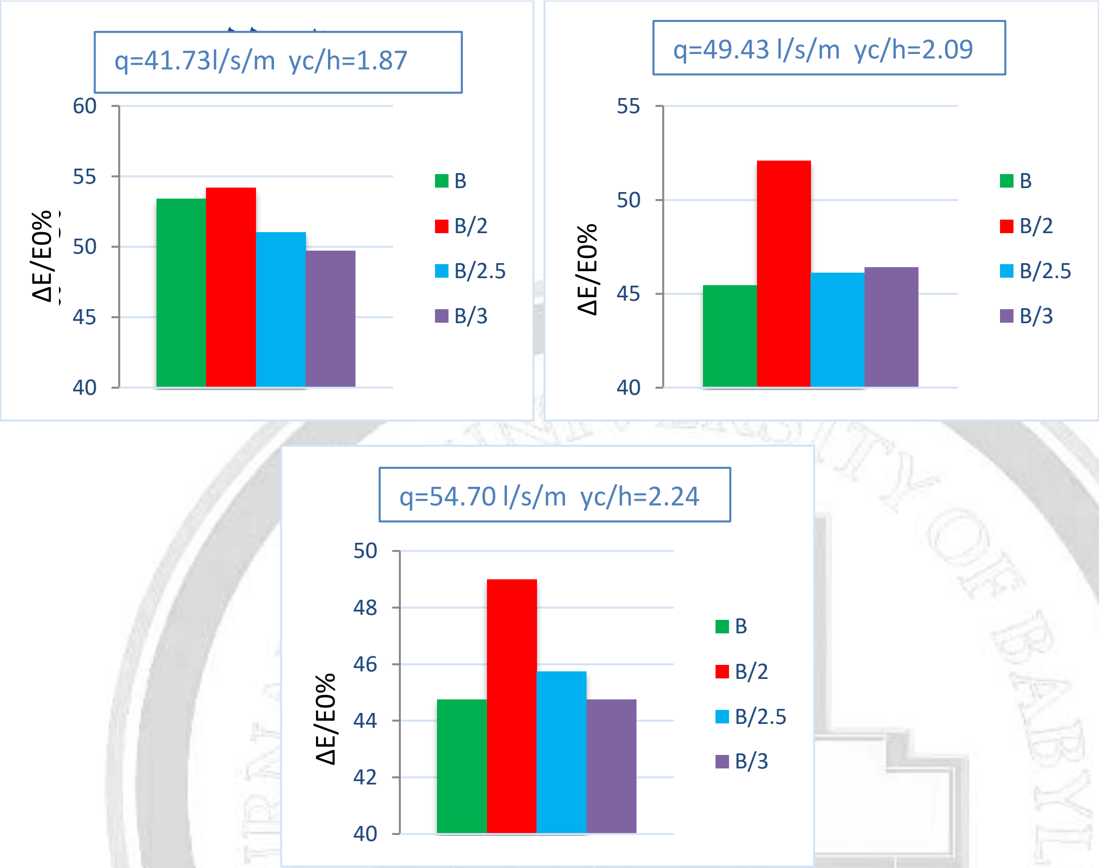
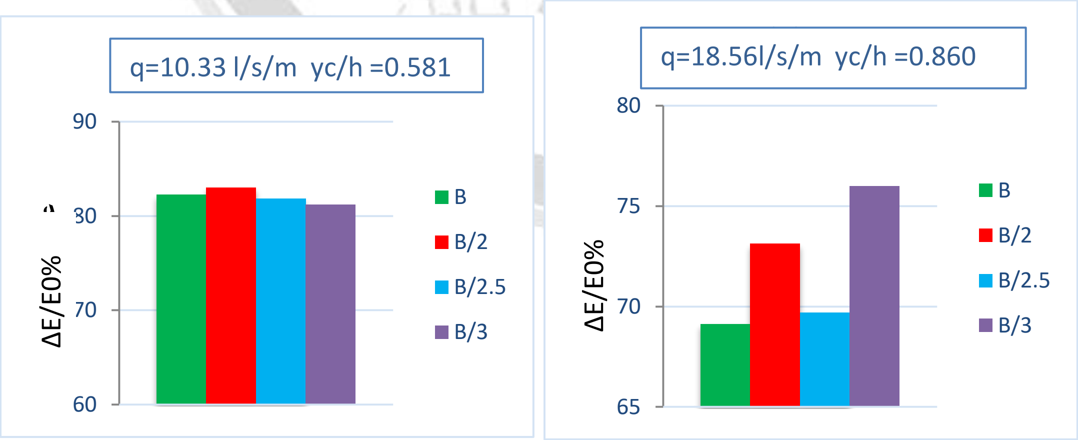


Figure 14. **The percentage of energy dissipation versus the dimensionless parameter (yc/h)**

For (N=10) uniform two baffled block



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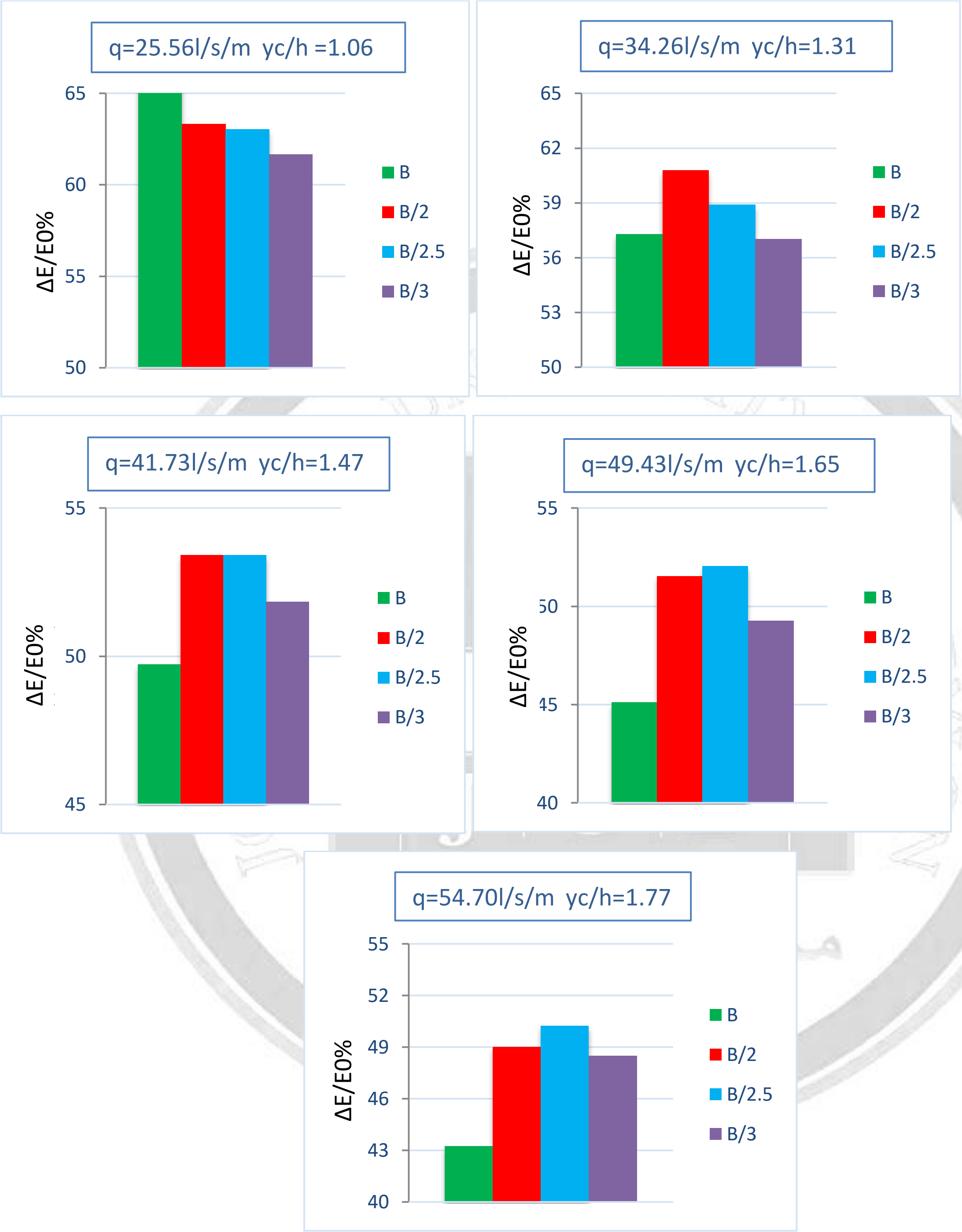

Figure 15. **The percentage of energy dissipation versus the dimensionless parameter (yc/h) for*(N=10) non-uniform two baffled block***

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5. Conclusions

Because of flow characteristics, the energy dissipation at the transition flow regime has yet to be the subject of in-depth analysis. This is because the head losses are a combination of shear stress caused by poorly developed vortices and by the impact of the jet, so there was not a specific pattern.

1. The model with 30^o has the highest energy dissipations, while 45^o records the lowest energy dissipations. As well as increasing the step number lead to an increase in the energy dissipations for the same spillway angle.
2. Increasing the discharge leads to an increase in the critical depth over the crest for all selected conditions, and the use of baffles block in all identified condition lead to a decrease the energy dissipation. However, these decreasements are more clear in high-flow discharges.

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JOURNAL OF UNIVERSITY OF BABYLON

For ENGINEERING SCIENCES (JUBES)

Vol.30, No.3.| 2022

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دراسة تبديد الطاقة للمسيل المائي المتدرج بزويا ميلان مختلفة المحتوية وغير المحتوية على حواجز

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الخلاصة

يعتبر المسيل المائي المتدرج هيكلًا مهمًا لتبديد الطاقة في اتجاه مجرى السدود. استندت هذه الدراسة إلى العمل المختبري الذي يهدف إلى زيادة نسبة تبديد الطاقة لممرات الجريان المتدرجة المنتظمة وغير المنتظمة. اعتمدت الدراسة على ثمانية عشر نموذجا من الخشب المقاوم للماء ستة نماذج موحدة وستة نماذج غير موحدة والنماذج الستة الاخرى مع الحواجز مع تغير الانحدار وعدد الدرجات حيث تم استخدام الزوايا (30°,40°,45°) وعدد الدرجات (10، 5). حيث تصبح العدد الإجمالي للتجارب هو 126 تجربة أظهرت النتائج المختبرية أن النموذج غير الموحد أكثر كفاءة في تبديد الطاقة وتقريب القفزة الهيدروليكية. بعد ذلك يتم وضع الكتل الحاجزة في مجاري تصريف متدرجة بـ 10 درجات و 45° لأنها تسجل أقل طاقة تبديد. أشارت النتائج إلى أن أفضل نموذج لتبديد الطاقة هو النموذج السابع بزاوية ميل (30°). وعدد درجات 5.

الكلمات الدالة:- تبديد الطاقة، مجاري المياه، الحواجز، القفزة الهيدروليكي.