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Hydraulic Investigation Of Stepped Spillway With Uniform And Non-Uniform Steps

A Thesis Submitted to the College of Engineering, University of Babylon in Partial Fulfilment of the Requirements for the Master Degree of Science in Engineering / Civil Engineering/ Water Resources

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بِسْمِ اللَّـهِ الرَّحْمَـٰنِ الرَّحِيمِ

(أَلَمْ تَرَ أَنَّ اللَّهَ أَنزَلَ مِنَ السَّمَاءِ مَاءً فَسَلَكَهُ يَنَابِيعَ فِي الْأَرْضِ ثُمَّ يُخْرِجُ بِهِ زَرْعًا مُّخْتَلِفًا)

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I certify that **Hassan Jasim Mohammed** has accomplished the preparation of this thesis entitled "**Hydraulic Investigation Of Stepped Spillway With Uniform And Non-Uniform Steps**" under my supervision at the University of Babylon in fulfillment of partial requirements for the Degree of Master's in engineering/ Civil Engineering/ Water Resources Engineering

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Certificate Of The Examining Committee

We certify as an Examining Committee that we have read this thesis entitled *"Hydraulic Investigation Of Stepped Spillway With Uniform and Non-Uniform Steps"* and examined the student **Hassan Jasim Mohammed** in its content and in what is related to it. We found that it meets the standards of thesis for the Degree of Master's in Engineering/ Civil Engineering/ Water Resources

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Dedication

To my parents

To every member of my family

To my supervisor Prof. Dr .Abdul-Hassan K. Al-Shukur

With respect

Researcher
Hassan Jasim
2023

Acknowledgments

In the name of Allah, the most gracious, the most merciful

All thanks and praise to Allah, who enabled me to achieve this research work. Firstly, I would like to express my sincerest gratitude to my supervisor, Prof. Dr. Abdul-Hassan K. Al-Shukur, for his invaluable insight, wisdom, and guidance

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Finally, a special thanks and gratitude to my family for their care, and patience, who has been by my side throughout this endeavor. Without their love, encouragement, and support I would not have been able to complete this academic achievement.

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Hassan Jasim
2023

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ABSTRACT

A spillway is a water source used to control the water level in a dam by draining water and diverting it from the upstream of the spillway to the downstream of the spillway; is serves as a safety valve for the dam. It is allowed to drain the torrents before they exceed the design limit allowed for that dam in order to avoid engineering problems that arise as a result of the water's height on the dam, which may cause the dam collapsing and demolish. In order to increase the energy dissipation and reduce the problems arising from it, the spillway is lengthened and overflows of various shapes are placed inside it, and its guest is to shorten the length of the hydraulic jump and increase the dissipation of energy arising from the water flow in the channels or inside the hydraulic structures.

The aims of This study based on laboratory experimental investigating the flow regime characteristics, dissipations of energy and length of the hydraulic jump on twelve models were made using water wood material was conducted on uniform and non-uniform stepped spillway. they were tested to compare between uniform and non-uniform stepped spillway. Three angles (30°, 40°and 45°), and different step numbers five and ten steps are used for uniform and non-uniform height.

In addition to twenty four models of baffled blocks are used for uniform and non-uniform models, which consisted of two groups, a first group containing one baffled block on first step and the second contains two baffled block on first step with different distances B/2, B/2.5andB/3 installed on the physical model at an angle (45°); and the number of steps five and ten , and thus the total number of models are thirty six models, passed over each of the above models, seven different discharge ranging between (3.11-16.41 ℓ/s) .

The results show the dissipation of energy increases with the decrease in the slope and the number of steps. Also, the percentage of Energy dissipation of the flow is greater at the low discharges, i.e. The flow Energy dissipation rate increases at the nappe flow and decreases as the flow turns into a skimming flow, as it reaches the largest amount of the flow energy dissipation at the nappe flow (85.45%), at the transitional flow (79.09%), and the skimming flow (75.71%). by observing the shape of the water above the effluents at the gradual flow, it takes a undulating appearance and with increasing discharge, those waves turn simple and spaced and then it is called the transitional flow. The results of the process are that the non-uniform model is more efficient than the uniform model in dissipating Energy and approximating the hydraulic jump (downstream), thus reducing the size of the stilling basins in the downstream.

The results indicate that the best model for energy dissipation is the model at an angle of 30° and the number of steps is five . For angles of the selected models, the 30° model has the highest energy dissipation while 45° has the lowest energy dissipation. The study confirms stepped that contain a baffled blocks are more efficient in dissipating Energy than ordinary stepped, as the models that contain first group one baffled blocks on first step had the highest percentage of energy dissipation and reduce hydraulic jump from second contain group two baffled blocks first step.in first group one baffled blocks when five steps percentage energy dissipation increase when different distance at B/2.5, as ten steps percentage energy dissipation increase when different distance at B/2.while at first group one baffled blocks for uniform and non-uniform five and ten steps percentage energy dissipation increase when decrease different distance.

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Symbol	Detention	Dimensional
B	flume width	L
E_O	Upstream energy of stepped spillway	L
E_1	Downstream energy dissipation	L
$\dfrac{\Delta E}{E}$	Percentage of energy dissipation of stepped spillway	-
Fr_1	Froude number before jump	-
Fr_2	Froude number after jump	-
F	Friction factor	-
g	Gravitational acceleration	L/T^2
h	Step height	L
l	Step length	L
yc	Critical depth over the crest of stepped spillway	**L**
y_1	Upstream critical spillway model	L
y_2	Measure depth of water of hydraulic jump	L
Hmax	Maximum head over spillway	L
ΔH	Difference in head between upstream and downstream of spillway	L
Lj	Distance from the spillway toe to the location hydraulic jump	L
μ	Dynamic viscosity	M/LT
ρ	Mass flow density	M/L^3
V_1	Velocity of flow depth y1	L/T
V_2	Velocity of flow depthy2	L/T
N	Number of steps	-
Q	Discharge	
q_w	Discharge per unit width	L^2/T
h_w	Head of water above spillway crest	L
θ	Spillway downstream slope angle	-

CHAPTER ONE

INTRODUCTION

1.1. Background:

A spillway seems to be a structure that enables the managed water released from a levee or dam downstream, generally into the river bottom of the impoundment river itself **(Acreman et al., 2000).** They could be referred to as overflow channels 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 reservoir and water flow. By discharging water gradually before the reservoir seems to be 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 times of flooding, once the lake has exceeded its maximum capacity and water is coming in quicker than it could be discharged, does water generally go over a spillway. An intake tower, on the other hand, is a structure that regularly regulates the flow of water for uses like water systems and hydro power production **(Khatsuria, 2004)**.

1.2. Stepped spillway:

Stepped spillway can be built in waterways for a variety of reasons, including transferring water from a high to a low level, escaping excess water entering a reservoir after it reaches its maximum reservoir level and storage capacity, and dumping residual water in the main drains into rivers or lakes, as shown in figure 1.1.

Figure 1.1 Stepped spillways

The water discharging so over the spillway falls from a higher elevation to a lower elevation, giving the flow a high velocity and converting potential energy to kinetic energy at the toe of the spillways .As a result, the back surface of the spillways should be able to dissipate this energy, causing erosion and scouring downstream spillways. The back surface of the spillways can be geometrically altered for this purpose by adding energy-dissipating devices like baffled or stairs, as shown in the figure 1.2. The earliest energy-dissipating devices are steps on the back surface of the spillway. The stepped spillway improves energy dissipation which, allowing the downstream stilling structure to be smaller and less expensive. The spillway efficiency in dissipating energy and aeration the flow is affected by the geometry of the steps, such as their numbers, spillway slope, and step face geometry.

Figure 1.2 Stepped spillways with baffled blocks

Based on the flow rate for a stepped spillway shape, the flow over a stepped spillway may be separated into three different flow regimes: nappe, transition, and skimming flow regimes with rising flow rates (**Comiti et al., 2009).** The nappe flows are recorded for a stepped spillway shape. They may be identified by a series of nappe dropping freely at the edge of each step, followed by a nappe impact on the next step. A variety of intermediate discharges are found to have transition fluxes. The key characteristics of this flow regime are a few severe hydrodynamic fluctuations, splashing, and spraying close to the free surface. Since of prior failures, the transition flow becomes avoided for design flow conditions.

The high discharges are reported to follow the skimming flow regime. As a cohesive turbulent flow, the water skims over the pseudo-bottom created by the

step edges. The voids are filled with vertical structures and severe recirculation under the pseudo-bottom (**Zare & Doering, 2012a**). regarding to energy dissipating, a small dam is said to benefit from nappe flow, while huge dams and lengthy spillway chutes benefit from skimming flow.

1.3. Aim and Objectives :

the main objective of this study can be outlined as follows:

1.Investigation the energy dissipation rate between uniform and non-uniform stepped spillways with various number of steps .

2.Study the effect of downstream slope on the energy dissipation of many step spillways and identify the Flow regime for every selected condition (such as changing the step spillway angle from 30° to 40° and 45°) to investigate the effect of changing spillway angle on the flow.

3.Investigate the change in the flow regime for the canal before and after placing baffled blocks and Investigate the effect of discharge on the hydraulic behavior for the channel before and after placing baffles blocks in different distributions.

1.4. Study plan:

The present study plan has been arranged as shown in figure 1.3.

```
                              ┌──────────────────────┐
                              │   Stepped spillway   │
                              └──────────────────────┘
              ┌───────────────────────┐        ┌───────────────────────┐
              │       uniform         │        │     Non-uniform       │
              │   Stepped spillway    │        │   Stepped spillway    │
              └───────────────────────┘        └───────────────────────┘
```
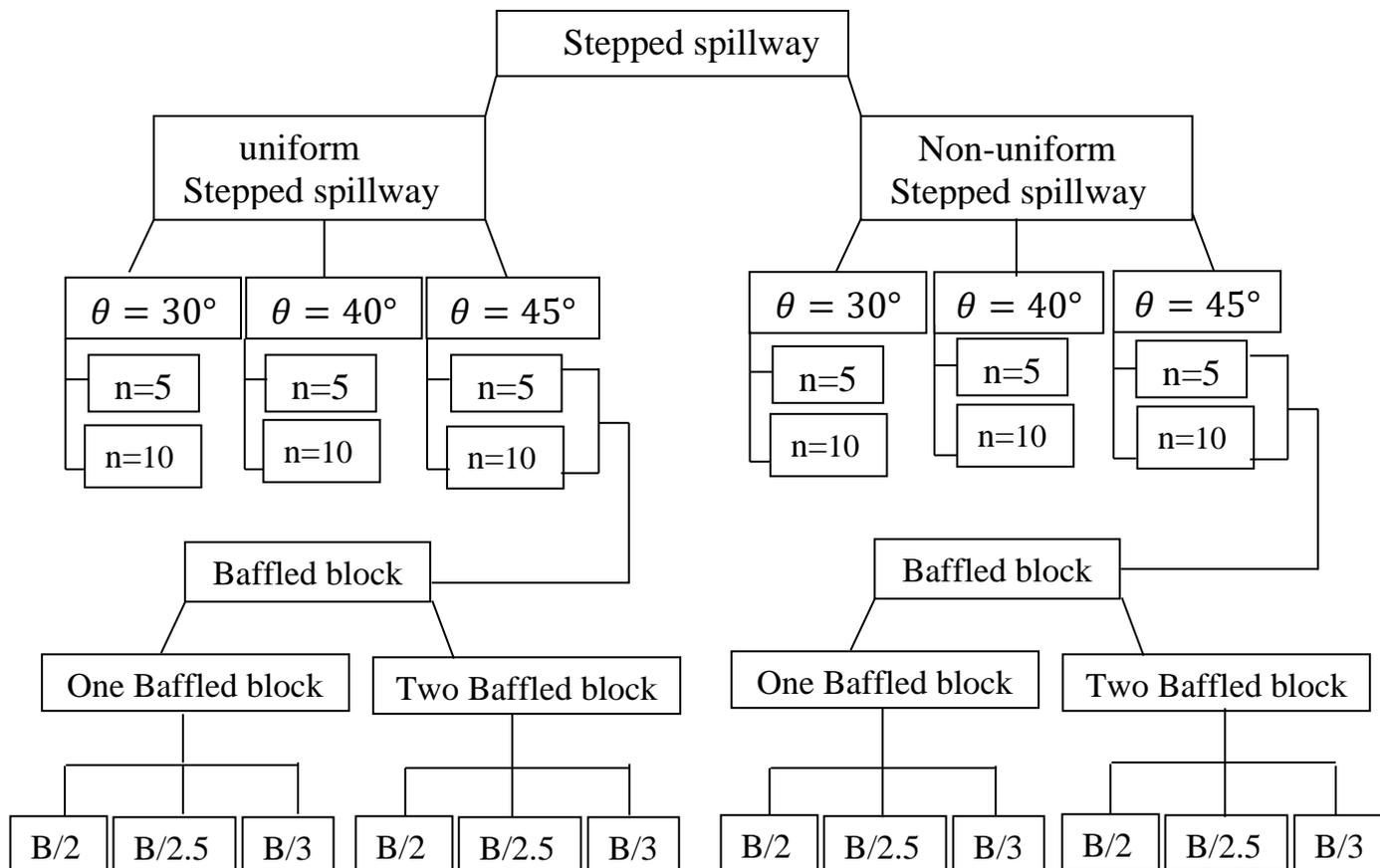
Figure 1.3. Present study plan

The diagram shows branches:

- uniform Stepped spillway:
  - $\theta = 30°$ → n=5, n=10
  - $\theta = 40°$ → n=5, n=10
  - $\theta = 45°$ → n=5, n=10
- Non-uniform Stepped spillway:
  - $\theta = 30°$ → n=5, n=10
  - $\theta = 40°$ → n=5, n=10
  - $\theta = 45°$ → n=5, n=10

Baffled block (uniform):
- One Baffled block → B/2, B/2.5, B/3
- Two Baffled block → B/2, B/2.5, B/3

Baffled block (Non-uniform):
- One Baffled block → B/2, B/2.5, B/3
- Two Baffled block → B/2, B/2.5, B/3

1.5. Limitation of your steady:

Table 1.1 Limitation Of Experiment Works

Parameter	Symbol	Value	Rang		Units
Spillway height	H	30	_	_	cm
Spillway length	L	various	44	66.71	cm
Number of steps	N	various	5	10	-
Height steps	h	various	3	8.76	cm
angle	θ	various	30⁰	45⁰	Degree
Radius	R	2	_	_	cm
Lateral width	W	30	_	_	cm
Upstream water depth	Y1	various	1.00	1.32	cm
Downstream water depth	Y2	various	3.40	7.28	cm
discharge	Q	various	3.11	16.41	ℓ/s

1.6. Organization of the Thesis:

The thesis is divided into the following chapters:

Chapter One (Introduction) present a basic information about spillways, stepped spillways and their benefits and drawbacks on floe regimes.

Chapter Two (Basic Conception And Literature Review):

Presents the stepped spillway defined by step geometry, flow pattern, energy dissipation, and enhancement of energy dissipation.

Chapter Three (Experiment Work And Dimensional Analysis):

describes the apparatus and models utilized in the investigations, as well as the process employed in laboratory experiments and dimensional analysis.

Chapter Four (Analysis And Discussion Of The Results):

Present the observation and results.

Chapter Five (Conclusions And Recommendation):

present the study's conclusions and suggestions for future research.

CHAPTER TWO

BASIC CONCEPTION

2.1. History Development of Stepped Spillway:

Stepped spillways have been around for at least 3,500 years **(chanson,2002).** Dam flood release facilities, drop structures in Roman aqueducts and waterways, water staircases, public fountains infamous gardens all used stepped spillways. Stepped chutes are a typical form of hydraulic structure throughout the ages; however at the turn of the twentieth century, innovations in the design of hydraulic jump stilling basins led to the abandonment of stepped spillways. The stepped spillways regained popularity in the 1980s when new, more efficient building techniques (e.g., roller compacted concrete (RCC) were developed **(Campbell et al., 2018; Chanson, 1995, 2000; Hansen & Reinhardt, 1991).** This was linked to a significant amount of study into physical modeling **(Chamani & Rajaratnam, 1999; Hubert Chanson, 2008; Gonzalez, 2005; Sorensen, 1985).** Multiple ancient civilizations independently invented the stepped channel approach. During ancient times, 16 dams with stepped spillways were built, with heights ranging from 1.4 m to 50 m, widths ranging from 3.7 m to 150 m, maximum discharges of up to 9000 m^3, step heights ranging from 0.6 m to 5 m, and the number of steps ranging from 2 to 14 **(Khatsuria, 2004).** Around 694 B.C., Assyrian King Sennacherib erected two dams on the Khosr River in northern Iraq, each with a tiered spillway (figure 2.1). These dams (dubbed the Ajilah Dams) were built to supply Nineveh, the Assyrian capital city.

Figure 2.1 : Dams on the Khosr River in Iraq were built around B.C. 694

(*www.Flickriver.com*)

2.2. Flow regime on a stepped spillway:

The flow regimes over the spillways can be classified into three types: napped, skimming, and transition flow depending on discharge for a given stepped chute geometry.

2.2.1. Napped flow regime:

Nappe flow regime is defined as that regime where the flow passes from one step to another as a free falling nappe with maintenance of air pocket beneath. The falling nappe impinging on the step, with or without formation of complete hydraulic jump.

(Chanson & Toombes, 1998) Describe nappe flow as a successive set of waves falling from one another cooling with the next followed by a hydraulic jump of two parts. The energy dissipation in the case of nappe flow occurs due to the extrusion being broken in the air by collision with the step or due to a hydraulic jump on the steps with an air space between the lower running surface and the vertical face of the step flow generally occurs at low expenses in listed facilities with high tendencies and high expenses in facilities with low tendencies and for a high step**.**

The water passes from one step to another developing a small hydraulic jump on every step, which can be observed for a small ratio ($\frac{d_c}{h}$), where h the step height and d_c the critical flow depth figure 2.2.
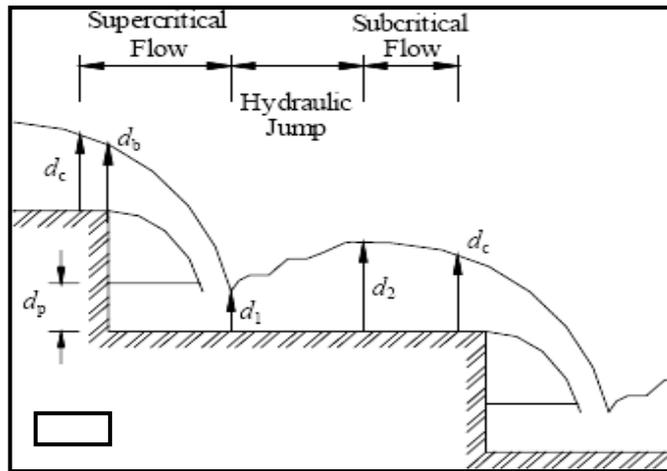
a) nappe flow with fully developed hydraulic jump
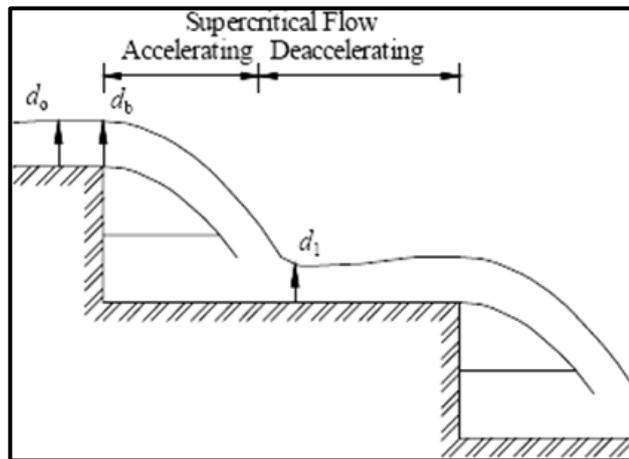
b) nappe flow with partially developed hydraulic jump
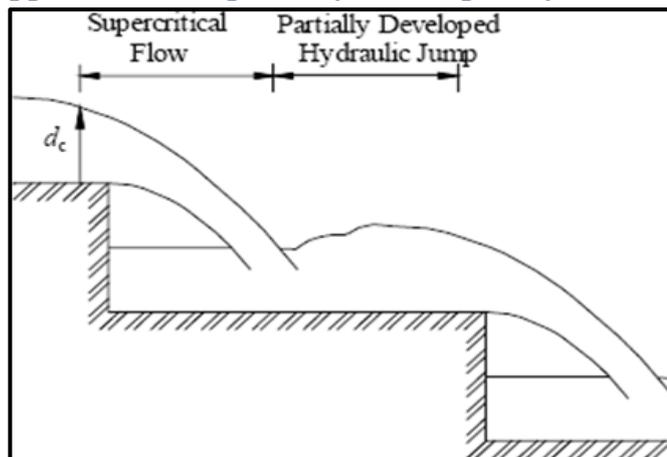
c) nappe flow without hydraulic jump

Figure 2.2: Nappe flow sub-regime above-stepped spillway **(Toombes, 2002)**

(**Chanson, 1994b**) investigated the hydraulics of napped flow regimes overstepped chutes and spillways. He established the equation (2-1) for determining the limiting parameters of napped flow patterns based on his collected data, which showed that napped flow occurs with a flat slope and a small discharge.

$$\frac{(y_c)onset}{h} = 1.057 - 0.465\frac{h}{l} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 2.1$$

Nappe flow regime occurs for $(\frac{y_c}{h}) < \frac{(y_c)onset}{h}$

Where:

y_c :the critical water depth (cm);

h :the step height (cm), and

l :the step length (cm)

(**Chanson, 1994a**) In this regime, the air is entrained at each step by a plunging jet at the intersection of the overfalling jet and the receiving waters, and the toe of a hydraulic jump. With deep pooled steps, most of the air is entrained by a plunging jet. For flat steps with shallow waters, most of the air is entrained at the toe of the hydraulic jumps.

2.2.1.1. Nappe flow occurrence:

The flow condition on the stepped chute is governed by step height, step length, and inclination of the chute with horizontal and unit discharge. Based on the result of (**Rand, 1955**) concerning flow geometry at the straight drop spillways.

(**Chanson, 1994b**) proposed the following condition for the occurrence of isolated nappe flow with developed hydraulic jump.

$$\frac{y_c}{h} \leq 0.0916 \left(\frac{h}{l}\right)^{-1.276} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.2$$

For the interval $0.2 \leq \left(\frac{h}{l}\right) \leq 0.6$

(Hubert Chanson, 2001) upper limit nappe flow regime as

$$\frac{y_c}{h} = 0.89 - 0.4\left(\frac{h}{l}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.3$$

The above relationship is valid for uniform or quasi-uniform in the range $0.05 \leq \left(\frac{h}{l}\right) \leq 1.7$

(Takahashi et al., 2001) lower limit of the step height nappe flow regime

$$\frac{h}{y_c} = 0.57\left(\frac{h}{l}\right)^3 + 1.3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.4$$

For $0.1 \leq \left(\frac{h}{l}\right) \leq 1.43 \ and \ 0 < \frac{h}{y_c} \leq 1.37$

(Chinnarasri & Wongwises, 2006) upper limit nappe flow as

$$\left(\frac{y_c}{h}\right) = 0.98 \ (0.55)^{h/l} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.5$$

2.2.2. Transition flow regime:

The transition flow intermediate flow rate, and it is a transition stage between the nappe and skimming flow. With the increase in the discharge, the jet still strikes near the edge of the step, causing a condition similar to stagnation. This regime is characterized by significant aeration, splashing, and chaotic appearance. It is also observed that flow properties vary from step to step **(Khatsuria, 2004).**

The transition flow saw extremely rapid free-surface aeration, which was much greater than the equilibrium values observed in skimming flows. For identical flow rates, the chute sidewalls must be constructed higher than in

nappe or skimming flows. Transitional conditions are unstable, resulting in variable hydrodynamic loads and possibly hydraulic structure vibrations. Several stepped spillway failures have been linked to flow conditions that coincide with the commencement of the skimming flow regime. unless a thorough hydraulic and structural analysis of the flow instabilities is performed, a stepped spillway must be developed to avoid the transition flow regime (**Chanson, 2002).**
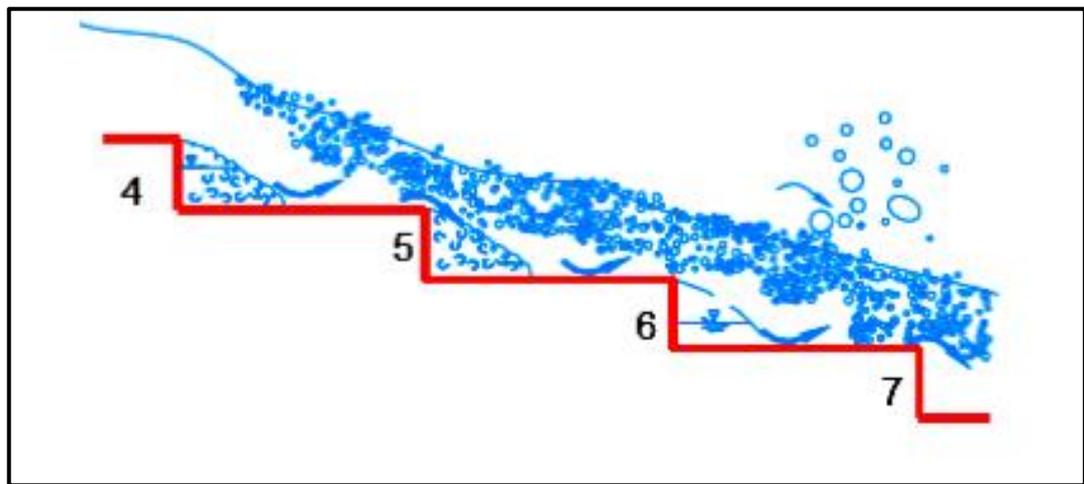
Figure 2.3 : Transition flow regime on stepped spillway (Gonzalez, 2005)

2.2.3. Skimming flow regime:

For sufficiently large discharges, the flow skims over the pseudo-bottom formed by the step edges as a coherent stream. Recirculating vortices form in the step corners beneath the main flow.

The skimming flow regime for high discharge and with decreasing step height(h) increasing flow rate (Q) and step height to step length ratio (h/l). The flow is smooth at the upstream end, and there is no air entrainment. The flow is characterized by strong air entrainment after a few steps **(Chanson, 1994a).** High levels of turbulence characterize the flow conditions above a stepped chute, and large amounts of air are entrained (**Chanson, 2001).** The majority of

the energy is lost due to momentum transfer from the mainstream to the recirculation fluid **(Chanson, 1993).**
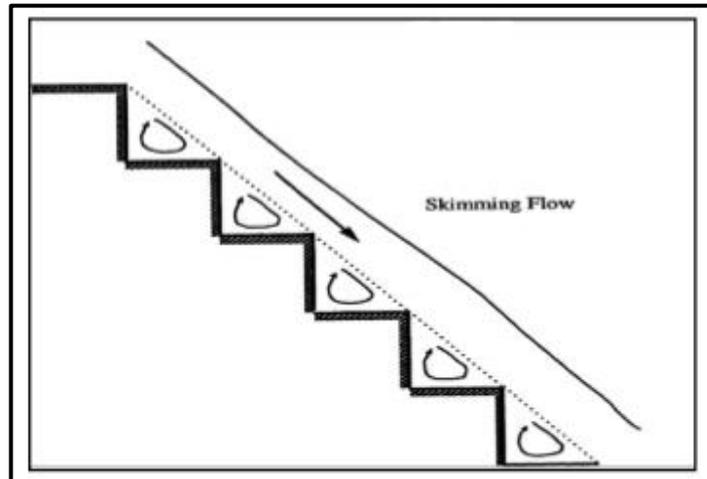
Figure 2.4 : skimming flow regime over stepped spillway (Chamani, 1993)

2.2.3.1. Skimming flow occurrence:

(Rajaratnam, 1990) $(\frac{y_c}{h}) > 0.8$ ………………………….……2.6

For 0.4< (h/l) <0.9

(Chanson, 1994b) $(\frac{y_c}{h})$=1.057-0.465$(\frac{h}{l})$ ………………………..…...2.7

For   0.2≤ $\left(\frac{h}{l}\right)$ ≤ 1.25

(Mondardo & Fabiani, 1995) $\frac{y_c}{h} > 1.1974 - 0.59501(\frac{h}{l})$ **…………...2.8**

(Boes & Minor, 2020) 0.91-0.14$(\frac{h}{l})$ ………………………..….2.9

For 0.47< $(\frac{h}{l})$ <1.43

(Chamani & Rajaratnam, 1999) cited by **(Murill, 2006)**

Studied and developed equation (2.10) to predict the onset of the skimming flow regime over the stepped spillway. The results indicate for $(\frac{h}{l})=1.7$, the onset value of $(\frac{y_c}{h}) = 0.24$ whereas for the values of $(\frac{h}{l}) < 0.8$, $(\frac{y_c}{h})$ is almost constant at 0.8.

$$\frac{h}{l} = \sqrt{0.89\left[\left(\frac{h}{l}\right) - \left(\frac{y_c}{h}\right)^{-0.34} + 1.5\right] - 1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{2.10}$$

(**Chanson, 2001**) $\frac{y_c}{h} = 1.2 - 0.352\frac{h}{l}$ $\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{2.11}$

Spillway slopes (3.4°<α<60°)

2.3. Energy dissipation:

Energy dissipation over stepped spillways is a function of discharge, spillway slope, and step geometry. Researches concerning this parameter are many and different concepts had been presented (**Sorenson, 1985; Peyras et al., 1992; Christodoulo, 1993; Chanson, 1994**).

2.3.1. Energy dissipation nappe flow regime:

(**Chanson, 1994a, 1994b**) effect of the napped flow regime on the energy dissipation in stepped chutes. The result indicates that, short chutes the napped flow dissipates higher energy. Also developed equation (2.12), to estimate the energy dissipation in a napped flow regime.

$$\frac{\Delta H}{H_{max}} = 1 - \frac{0.54*\left(\frac{y_c}{h}\right)^{0.275} + 1.715*\left(\frac{y_c}{h}\right)^{-0.54}}{\frac{3}{2} + \frac{H}{y_c}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{2.12}$$

(**Chamani, 1993**) give the relative energy losses $(\frac{\Delta E}{E_O})$ nappe flow on horizontal steppe spillway given by:

$$\frac{\Delta E}{E_O} = 1 - \frac{(1-\alpha)\left[1+1.5\left(\frac{y_c}{h}\right)\right] + \sum_{i=1}^{N-1}(1-\alpha)^i}{N+1.5\left(\frac{y_c}{h}\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{2.13}$$

Where

α: average energy losses per step horizontal steps α=-0.746

Log $(\frac{y_c}{h})$-0.5481 log $(\frac{h}{l})$-0.0455

2.3.2. Energy dissipation skimming flow regime:

(Chanson, 1994b) effect of the skimming flow regime on the energy dissipation in stepped chute the result indicated that in long chutes the skimming flow regime higher energy dissipation the equation (2.14) to estimate energy dissipation in the skimming flow regime.

$$\frac{\Delta H}{H_{max}} = 1 - \frac{\left(\frac{f}{8sin\theta}\right)^{\frac{1}{3}}*cos\alpha+0.5\left(\frac{f}{8sin\theta}\right)^{\frac{-2}{3}}}{\frac{3}{2}+\frac{H}{y_c}} \dots\dots\dots2.14$$

Where:

h=the steps height(cm)

l=is the steps length (cm)

y_c = Is the critical water depth(cm)

H=is the spillway height (cm)

H_{max} = Is the maximum kinetic energy upstream the spillway(cm)

θ=is the angle of the back surface of the spillway (degree)

f =is the frication factor =1.3

2.4. Previous Studies by Using Laboratory Experiments:

(Horner,1969) and Essery and (Horner,1978) appear to the first researchers who investigated the hydraulic of stepped spillway.

According to **(Chanson, 1994)**, substantial energy dissipation occurs on a stepped chute. Although the mechanisms of energy loss in the nappe and skimming flow regimes are significantly different, both flow regimes can waste a significant amount of the flow energy. According to Chanson, uniform flow is obtained at the toe of the spillway for lengthy chutes, and a skimming flow regime allows for greater energy dissipation than a nappe flow regime. It is thought that nappe flow circumstances would disperse more flow than skimming flow in short channels.

(Chamani & Rajaratnam, 1999) demonstrated that under a tiered spillway, jet flow occurred at lower discharges while skimming flow occurred at higher discharges.

(Chinnarasri & Wongwises, 2004) Energy dissipation in chutes with upward inclined steps was investigated. The stepped chute was 0.4 m wide and had 20 steps. As illustrated in figure (2.5), the angles of the downstream slope of spillways are 30°, 45°, and 60°. They concluded that upward inclined steps lose more energy than horizontal steps, especially in the skimming flow regime, which accounts for around 6% of total energy loss (depending on). When the number of steps is increased, the energy loss falls rapidly. The inclined steps' adverse slope raises the energy Joss ratio while lowering the output velocity by less than 10%.
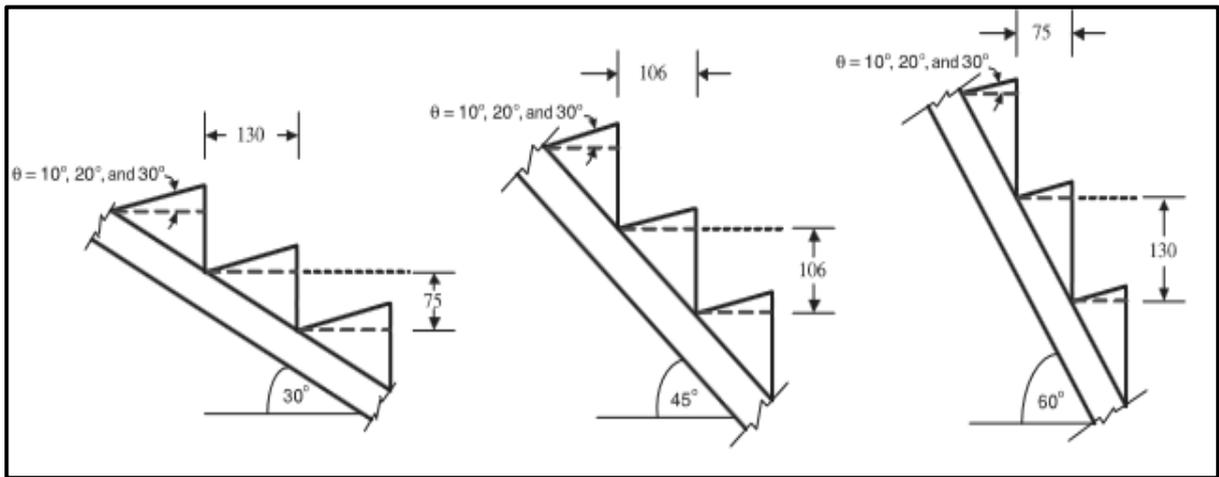
Figure 2.5 : experimental model (Chinnarasri & Wongwises, 2004)

(Barani et al., 2005) looked at how to flow energy dissipated in different sieved spillways. The model has a 41.41-degree slope, an 84-centimeter height, and 21 steps. A step measures 4 cm in height, 4.5 cm in length, and 30 cm in width. As shown in Figure (2.6) experiments included step with thicknesses of 1, 2, 3 and 4 cm, as well as steps with reverse inclined slopes of 15°, 26°, 36°, and 45°. They calculated that for small dams with a low flow rate over the spillway, a stepped-shape spillway can disperse the majority of the flow kinetic energy. For big dams with a higher flow rate over the spillway, the reverse-inclined stepped spillway can be more effective than the model with end sills on steps. End sill steps must be the same size as reverse sill steps, and reverse sill steps must be the same size as end sill steps.
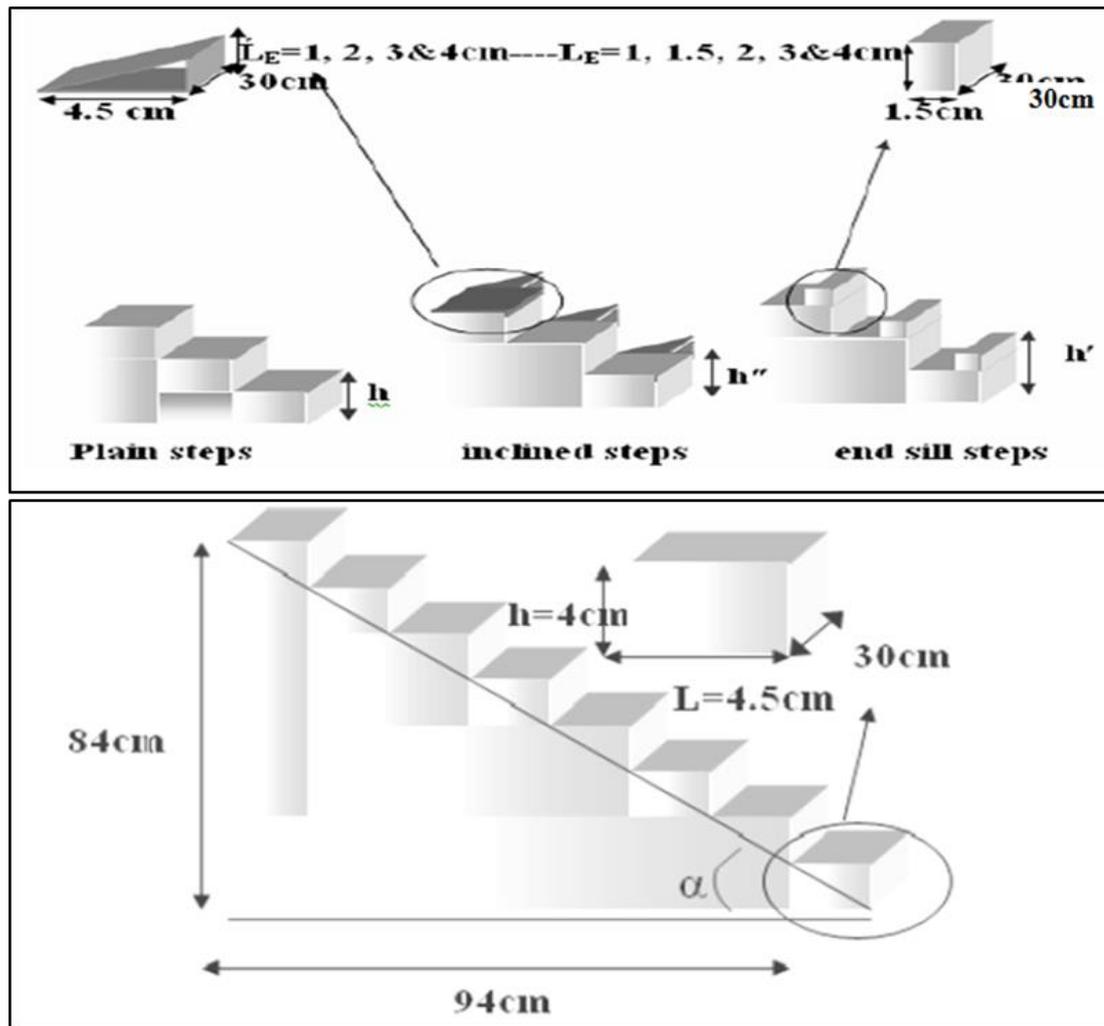
Figure 2.6 :experimental models **(Barani et al., 2005)**

(Hayawi & AL-Talib, 2009) discovered that stepped weirs were more efficient than flat-sloping weirs, with a maximum energy dissipation ratio that was roughly 10% higher in stepped weirs than in flat-sloped weirs**.**

(Chafi et al., 2010) in the stepped spillway, flow patterns, and energy dissipation were investigated experimentally. The step height (h) is 7 cm, the length (L) is 11.5 cm, and the width (B) is 24 cm. the spillway back surface slope (a) = 32° (tan α= 7/11.5). they concluded that a stepped spillway dispersed flow energy better than a smooth-profile spillway. The napped flow dissipated energy more efficiently than the skimming regime, with a dissipation rate of about 63% percent. The napped flow was also recorded with a constant value of

$\frac{y_c}{h} = 0.67$, which varied depending on the number of spillway steps and the discharge. Depending on the spillway back slope, the skimming flow was observed with a constant value of $\frac{y_c}{h} = 0.8$, while transition flow was recorded with$(\frac{y_c}{h})$between 0.67 and 0.80. investigated the effect of flow patterns on energy dissipation in a stepped spillway with reverse-inclined steps and an end sill. They discovered that using inclined steps with a reverse slope and an end sill enhances the dissipation energy rate by 15% on average for napping flow and 2% on average for skimming flow as compared to not using an end sill. The reverse slope at the end of the sill.

(Rad & Teimouri, 2010) used a numerical model to study the flow energy dissipation in simply stepped spillways and compared the results to the dissipated energy in a lengthy spillway with a constant dam height. Spillway dissipation is reduced as long as the dam's height remains constant. the experimental results of different researchers. They concluded that increasing the number of steps directly increases the simply stepped spillways, that decreasing the height of the steps reduces the slope of the spillways, and that fixing the dam height increases the energy dissipation of the spillway. In the case of a fixed number of steps, increasing step length and step height increases the amount of energy wasted down the stepped spillway.

(Felder & Chanson, 2011) investigated energy dissipation downstream of a spillway with non-uniform stepped heights. A 0.1m wide and 0.6m long road crest weir with an upstream rounded corner was tested, followed by a 0.1m wide and 1m height stepped spillway portion with a slope of 26.6°. (1v:2H). They concluded that the rate of energy dissipation was almost the same for uniform and non-uniform stepped configurations.

(**Abbasi & Kamanbedast, 2012**) studied the influence of variations in size and hydraulics of stepped spillways on energy dissipation. The stepped spillway is designed with five steps and a 45-degree slope for each group. They determined that as the number of steps increases, so does the dissipation efficiency. Furthermore, when discharge increase, energy dissipation decreases, while as discharge increases, the depth of water immediately rises and the flow changes from napped flow to skimming flow.

(**Zare & Doering, 2012a**) investigated the influence of rounded spillway margins on flow parameters in an experimental setting. The transitional phases were determined to be four. Following these four procedures, construct six identical major steps (numbered 1 to 6) with a height of h = 7.5 cm and a length of 7.5 cm apiece, with a slope of 1V: 1H of a = 45° from horizontal. The rounded radius (r) was set at 0.25 (r = 1.85 cm) as a percentage of the main step length as show in figure 2.7. They discovered that the transition from shooting to skimming flow occurred at a lower flow rate for the suggested rounded steps at the inlet or main steps than for the sharp steps. They also discovered that rounded chute steps were more effective in dissipating energy down the stepped spillway chute. Average residual education in the residual energy for rounded steps was about 3% .
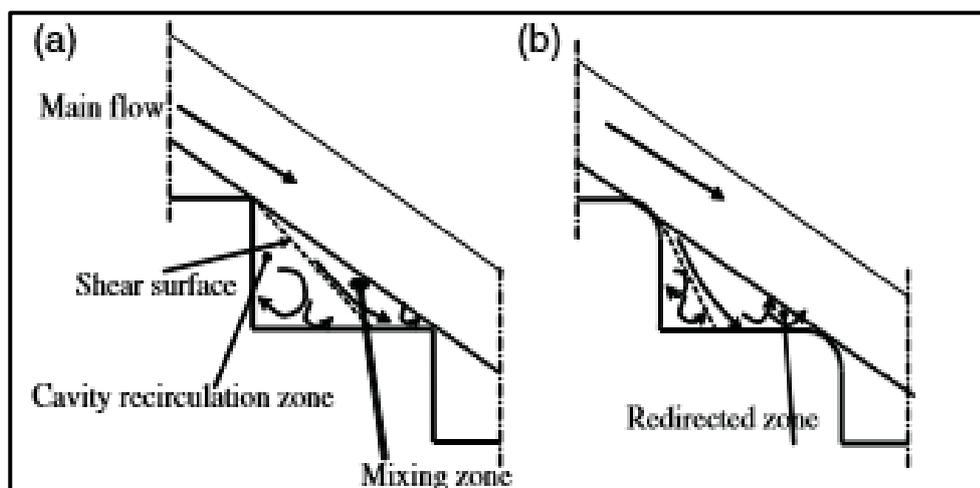
Figure 2.7 : experimental model (**Zare & Doering, 2012a**)

(Zare & Doering, 2012b) investigated the energy dissipation and flow characteristics of baffles and sills on stepped spillways in an experimental setting. The effectiveness of installing baffles and sills at step edges or shifting them from step edges of a sloping, short, sharp, or round-crested stepped spillway with an ogee inlet as shown in the figure (2.8) was evaluated using a two-dimensional physical model. They discovered that the baffled chute dissipates more energy than the sill-edged spillway. In the range of the examined discharge, relocating baffles or sills from the round-crested spillway increases energy dissipation. For the examined range of critical water depth to step height ratio (yc/h), the rounded-stepped spillway and baffled-edged stepped spillway chutes had the height energy dissipation. $(\frac{y_c}{h})$= 0.55 is required for the onset of skimming flow in the baffle-shifted rounded-stepped spillway and $(\frac{y_c}{h})$=0.65 for the rounded-stepped spillway chute.
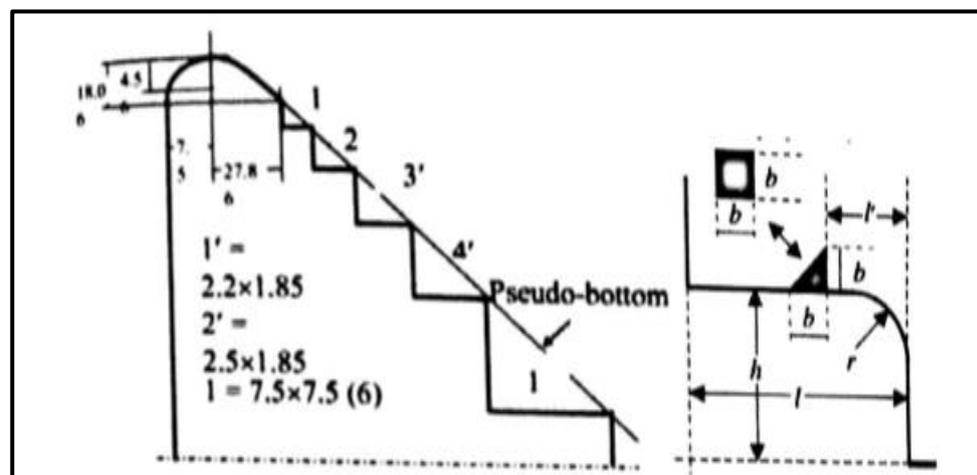
Figure 2.8: experimental model (Zare & Doering, 2012a, 2012b)

(Alghazali & Jasim, 2014) investigated flow regime restrictions using 12 stepped spillway models. They used three different downstream slope angles (25, 35, and 45) and four different numbers of steps (5, 10, 15, and 20). To investigated five different step combinations (conventional flat, pooled, porous end sills, pooled with gabions, and porous end sills with gabions). Their

findings revealed that the end sills have a significant impact on the flow regime type at the lower limits of skimming flow. Also, they found that gabions reduced the effects of end sills on the lower limit of the skimming flow regime to near the limit of flat steps. They suggested new empirical equations based on the experimental results.

(Al-Shukur et al., 2014a) investigated the flow properties and dissipation rate of energy on a twelve physical models on traditional step at angles ($\alpha = 55^0$, 45º, 40º, and 30º) to identify the ideal slopes and steps height of stepped spillway models experimentally. Three alternative the heights of step (h=3, 6 and 10 cm) were utilized to represent each angle under various flow systems (nappe, transition and skimming flow regime). The hydraulics properties of the flow across the models have been monitored during the tests, and dissipation of energy was computed. Findings indicated that at high discharge, the ideal the height of step in the skimming flow regime has been recorded as (h= 6cm, step's number N= 5); however, when discharge decreased and a trend toward the nappe flow regime emerged, the optimal the height of step decreased to (h= 3cm, N= 10). Additionally, based on the findings of the research, the significant depth to the height of step (yc/h) proportion increased with the height of step from (h= 3 cm) to (h= 6 cm & h= 10 cm), with the optimal slope of stepped spillway models rising to (= 45^0 & 55^0) in both cases.

(Abdul-Mehdi et al., 2016) carried out a laboratory study on flow and dissipation of energy in flat stepped spillways. The flume was a rectangular cross-section with a length of 5 m, wide of 30 cm, and high of 30 cm. The stepped spillway was supplied with various sizes of gravel (10-14) mm, (14 -20) mm, and (20-25) mm. Generally, the percentage of relative energy dissipation (R.E.D) was decreased with an increase in the discharge, as well as, it was increased by using coarse gravel on a surface.

(Razzak, 2015) investigated an experimental dissipation of flow energy over stepped spillways of the various shapes of steps. The various step shapes were plain steps, steps have half cut, inclined end sill steps normal to downstream slopes of stepped face, and steps have a rough surface using crushed gravel, which has been assumed. Experimental results showed that the dissipation of flow energy on inclined end sill and rough steps is more than the plain one. While the results of the experiment on the cutting steps showed that the energy dissipation is less than the plain one.

(Felder & Chanson, 2017) focused this study on embankment-stepped spillways. The investigated configurations have been examined with vertical step heights, as shown in (**Fig 2.9**). The results provided that a stepped design has been considered with a 1V:2.5H slope (θ =21.8°) may be optimum in terms of energy dissipation performances.

(a)
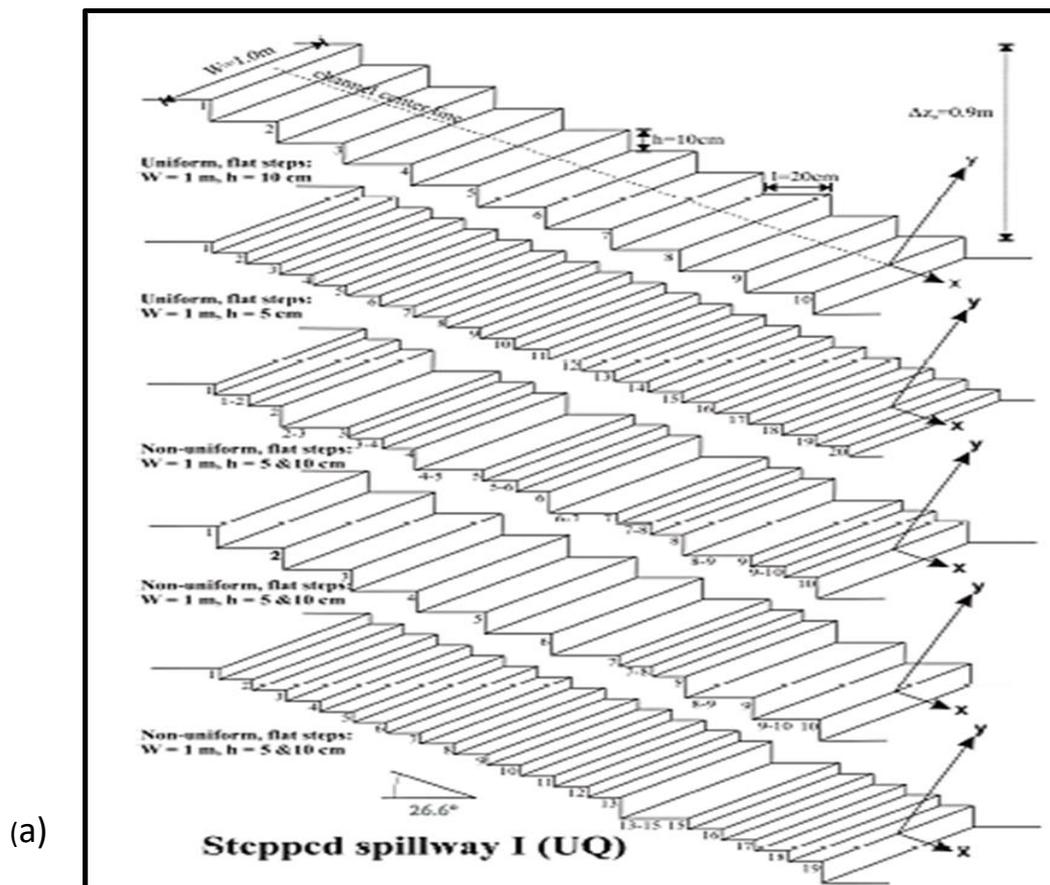
Figure 2.9: Present The investigated configurations (Felder & Chanson, 2017)

(b)

(c)
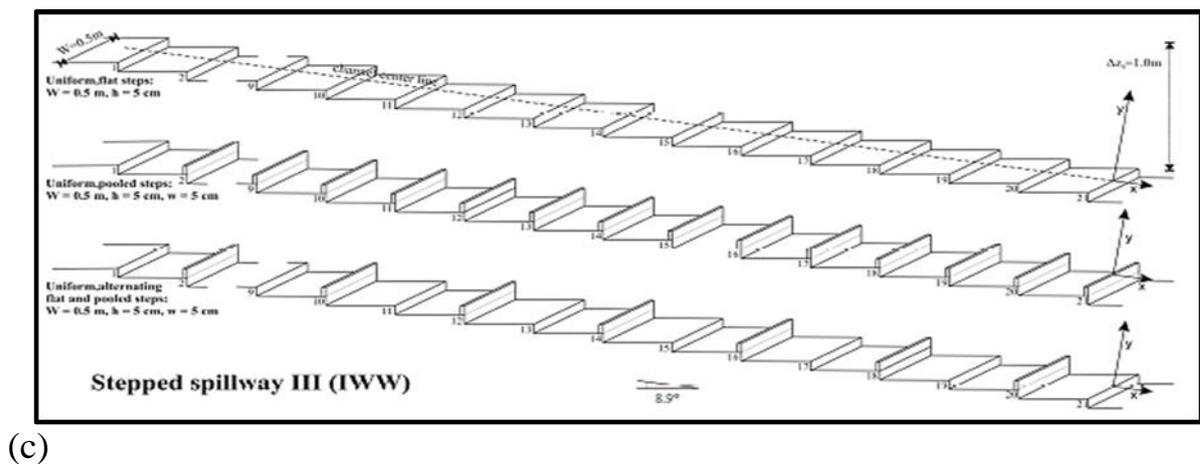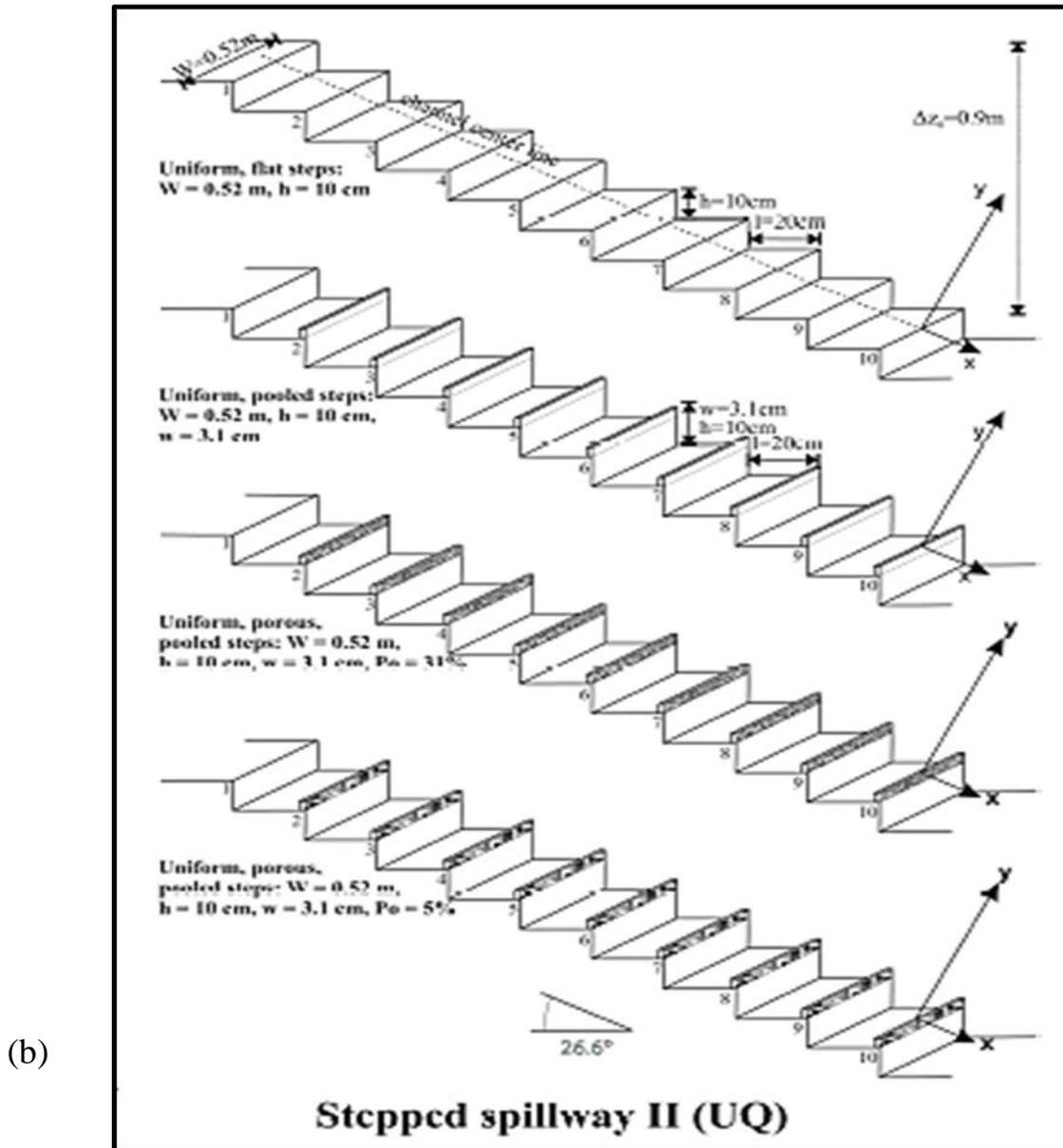
Figure 2.9follow: Present The investigated configurations (Felder & Chanson, 2017).

   (Jahad et al., 2016) studied an energy dissipation and geometry effects over Stepped Spillways. In this study present, four physical models were used to evaluate the influence of adding end sills which has a quarter circle at the edges of the step, as shown in (**Fig 2.10**). overall, the results were indicated to Nappe flow shows more heightened efficiency than both transition and skimming flows. Furthermore, model number 2 showed improved dissipation of flow energy, particularly to a nappe flow regime. The configurations of models 2 and 4 lead to positive effects for stepped spillway, compared with other models.
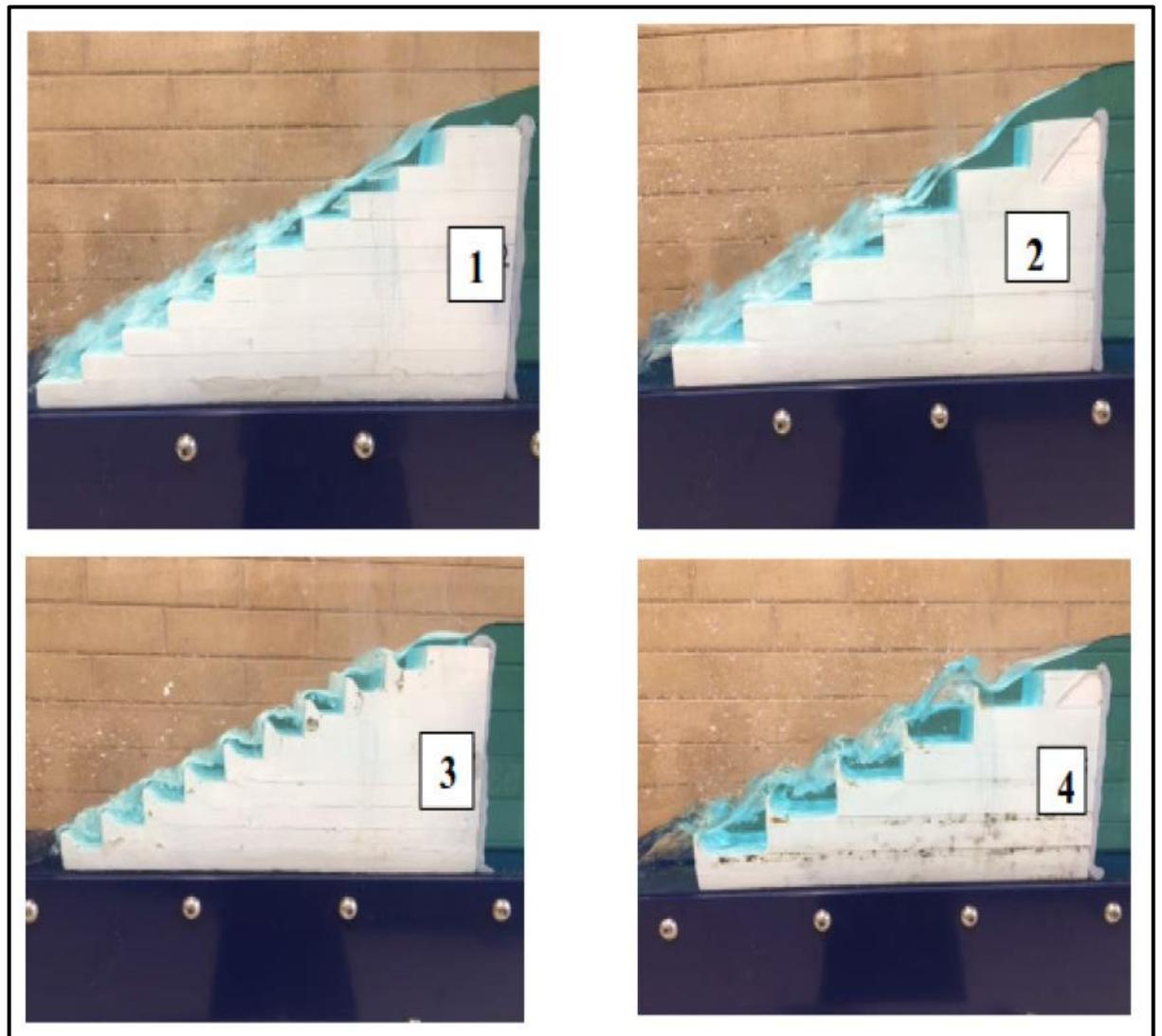
Figure 2.10:Show The configurations of a comodel (Θ =26.6°) (Jahad et al., 2016).

     (Maatooq, 2016) carried out a dissipation of kinetic energy on labyrinth Configuration Stepped Spillway. This configuration does not present formerly by researchers or in techniques of construction of dams or cascades, it is clearer in **(Fig 2.11)**. From the results, the average registered percentage yields of kinetic energy dissipation with the shape of labyrinth compared with the results of classic shape, it was ranged between (13- 44%).
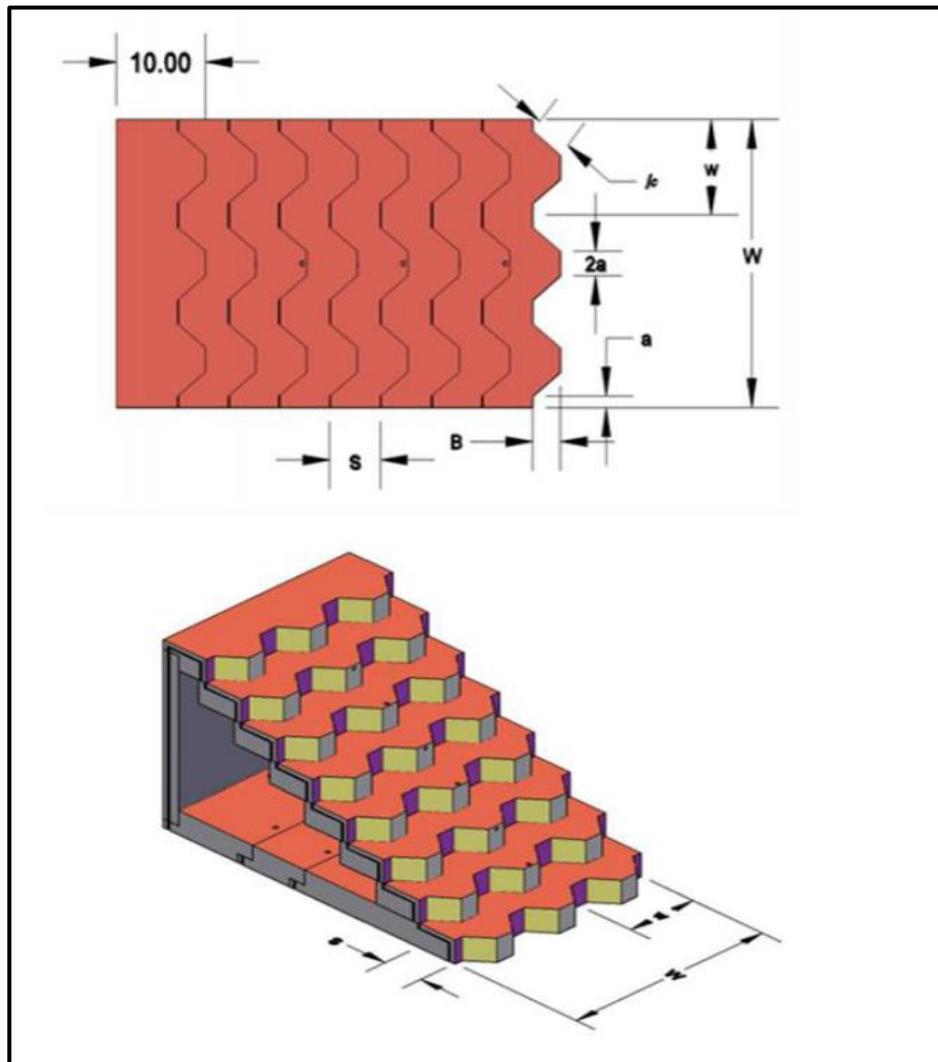
Figure 2.11: Scheme view of a physical model for configuration Labyrinth stepped spillway (Maatooq, 2016).

     (Mero & Mitchell, 2017) investigated the dissipation of flow energy over diverse forms of stepped spillways, and these configurations are clearer in (**Fig 2.12**). A series of experiments were performed in a laboratory canal on the

model of a stepped spillway with a mild slope of 26.68° for discharges up to 12.1 L/s. The results showed that The rate of the dissipation of flow energy on the curved step and horizontally inclined configurations with reflectors has approximately twice that for a configuration of a flat step.
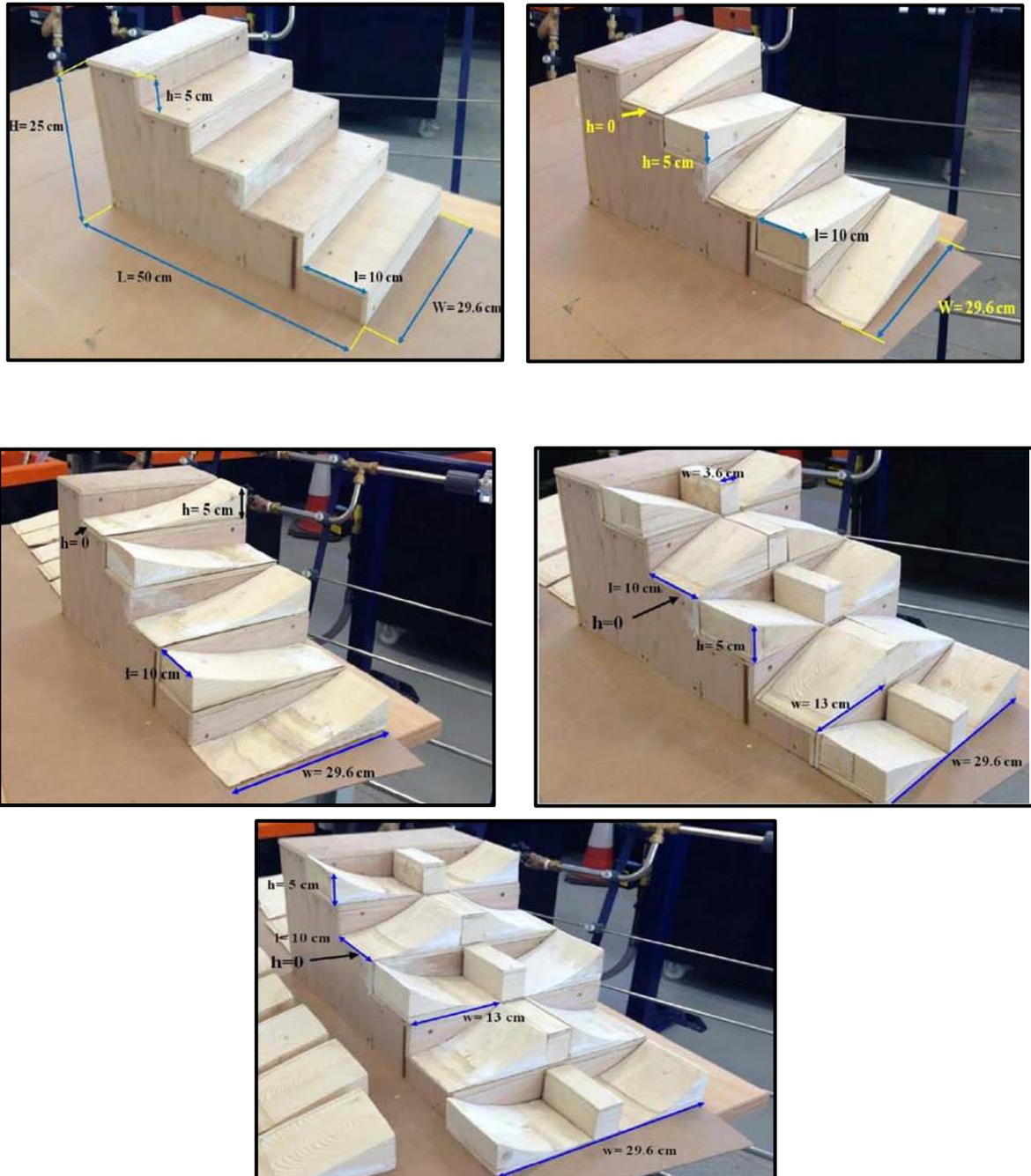
Figure 2.12: The five various configurations of the stepped spillway (Mero & Mitchell, 2017).

(Peng et al., 2019) investigated a dissipation of energy in a stepped spillway with various angles of the horizontal face. In this paper, various stepped spillways were used with five horizontal face angles of (-30°, -15°, 0°, 15°, and 30°) in the skimming flow regions. The most important results obtained, the rate of energy dissipation was increased with the absolute values of the horizontal face angles, as well as decreased with the unit discharge increases. Furthermore, the rate of energy dissipation of the simple shape of the stepped spillway has a minimum for all types of stepped spillways.

(Arjenaki & Sanayei, 2020) analyzed numerically a rate of energy dissipation in the stepped spillway with a sideways slope by using an approach of experimental model development. In this research was used the same configurations are mentioned **(Mero & Mitchell, 2017),** as well as, it was simulated by using FLOW-3D software. Results proved that the relative mean square error (RMSE) index for type a–e 0.035, 0.014, 0.021, 0.032, and 0.031, respectively, after comparing numerically with the experimental model. After this step, to develop the physical model, barriers were placed on the type (d) spillway, that has the best physical model for dissipation of energy. Results of the numerical simulation showed that having added these barriers increased the dissipation of energy by 15%.

(Ghaderi et al., 2021) studied numerically the flow properties of various pooled stepped spillways. For investigatory in this aim, various configurations of the steps were taken into account including flat steps, fully pooled steps, zig-zag pooled steps, central pooled steps, and two-sided pooled steps. Additionally, the pooled steps were used simply, with a notch configuration. The flat step configuration showed the best energy dissipation performance as compared with other configurations. With the notched pooled step configuration, the efficiency performance of the pooled structure improved by about 5.8%.

(Hamedi & Ketabdar, 2016) investigated   an experimentally and numerically to an evaluation of energy loss and simulation of flow in stepped spillways with inclined steps and end sill, and a graphic of the step is shown in (**Fig 2.13**). In this study, a series of simple horizontal steps were used, four steps (39 to 42) have been changed and provided with inclined steps and an end sill, together. As well as, end sills with diverse thicknesses and heights have been examined in three slopes reverse of stepped (7, 10 and 12°), respectively. The result proved that there has a good agreement between outcomes of the experimental results and the numerical simulation for the pattern of flow and vectors of the velocity. Moreover, results of losses of flow energy after validation have shown reasonable agreement.
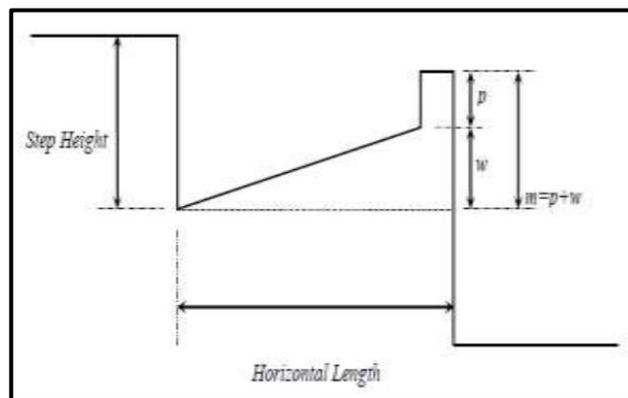
Figure 2.13. Present a graphic of the step (Hamedi & Ketabdar, 2016).

(Irzooki et al., 2016) simulated a numerically flow over the uniform of simple steps spillway by using Flow-3D software. This paper presented, three various heights of spillway were used (15, 20, and 25cm), with three steps numbers of (5, 10, and 25) and three spillway slopes of (0.5, 1 and 1.25) were applied. all runs were worked with eight various discharges range of (0.6-8.5 L/s). For validation purposes of the CFD software, the laboratory work was carried out on four samples of this spillway modeling, with five various discharges were simulated. The energy dissipation comparison in experimental and numerical modeling was showed a good agreement with an error rate up to 11.13%. Results proved that the dissipation of energy was increased with an

increase in the spillway height, and decreased a steps number and slope of the spillway. Moreover, the dissipation of flow energy decreased with an increase in the flow rate.

(Salmasi & Samadi, 2018) carried out an experimentally and numerically flow simulation over the simple uniform stepped spillways by using Fluent 6.3 software to calculated energy loss. For this objective, a physical model of the stepped spillway was created with a slope at a ratio of (2H: 1V) and experiments were conducted with ten various flow rates. Eventually, the results showed that the numerical model was reasonable after comparison between the results of the numerical model with experimental data. Furthermore, pressure and shear stress over each step was decreased with increasing the flow.

(Ghaderi & Abbasi, 2021) studied experimentally and numerically the effects of roughness element elements on energy dissipation over the stepped spillway. The trials were achieved in a rectangular flume with a length of 12 m, a width of 1.2 m, and a height of 0.8 m, for more details, the physical model is clearer in **(Fig 2.8).** The results indicated that the roughness elements on the steps have raised values of the turbulent kinetic energy (TKE), friction of Darcy–Weisbach, and the energy dissipation raised significantly. Moreover, with decreasing the roughness elements height, dissipation of energy and the TKE value was increased more significantly.
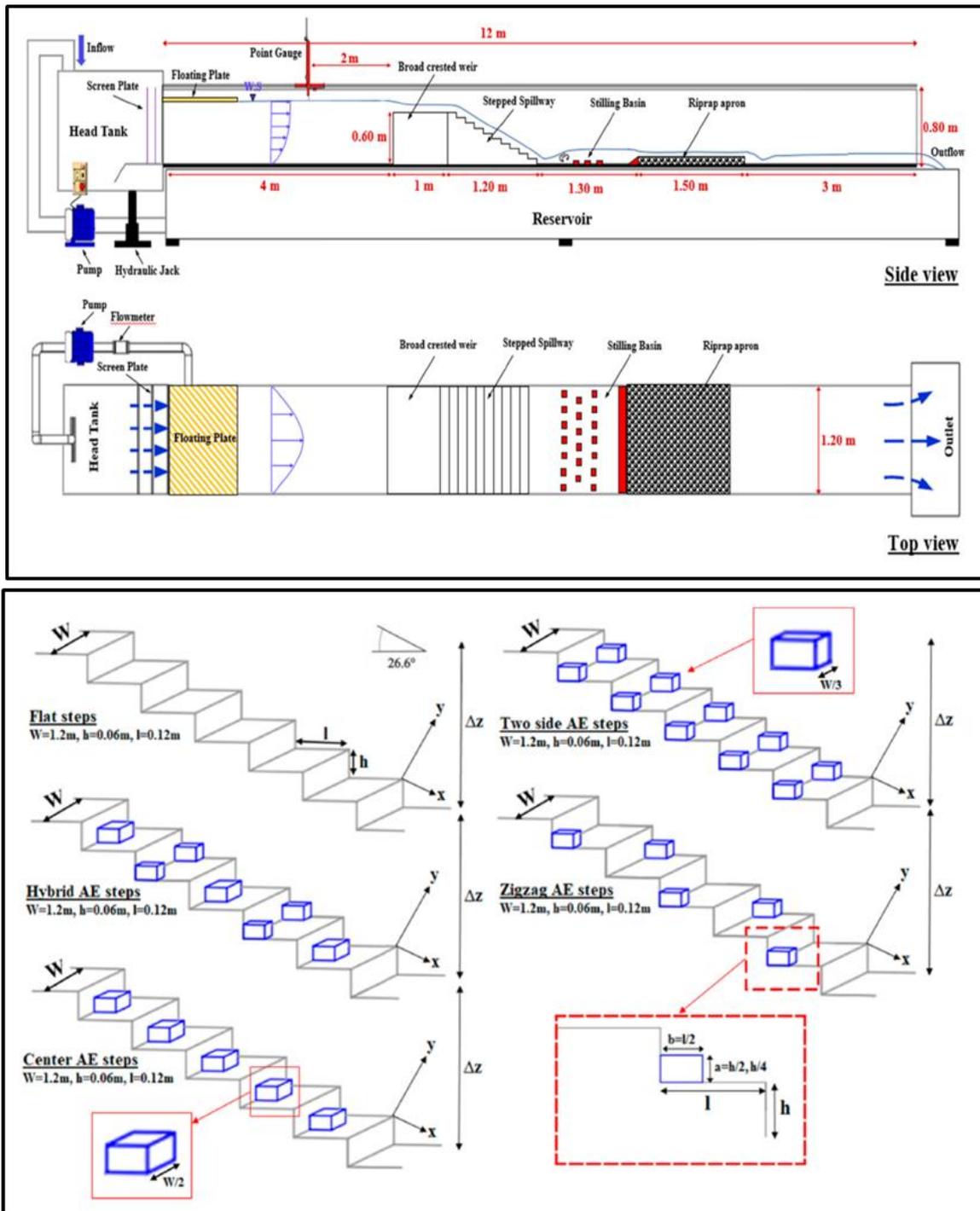
Figure 2.14 : The details of the physical model: a) Schematic view of the experimental set-up. b) Configurations of stepped spillway (Ghaderi & Abbasi, 2021).

2.5. Summary:

Energy dissipaters of dams are considered expensive structures. Therefore, the economic design of this structure was desirable. The stepped spillways may be applied as energy dissipaters to decrease the cost and size of the stilling basin. The previous studies present the details of stepped spillways and the modifications on these stepped spillways to reach an optimal model with high energy dissipation. All of the studies, as mentioned earlier, were carried out for non-uniform and uniform stepped spillways by using laboratory experiments. that most research on design stepped spillway based on a software programs.

However, the current study will be studying the flow regime characteristics ,energy dissipation and the length hydraulic jumps as a follow-up to investigate in comprehensive detail by using the experimental work for twelve models for non-uniform and uniform stepped spillways, at multi-flow conditions nappe, transition and skimming flow regime to maximize the energy dissipation and reduce hydraulic jump downstream in safety condition of designing . Moreover, identify the best stepped spillways angle from three selected angles that lead to gain the highest energy dissipation. After that placing the baffled block that contains two group the first group contains one baffled blocks on first steps and group contain two baffled blocks on first steps for model uniform and non-uniform stepped spillway in order to investigate the changing in the energy dissipation and length hydraulic jump after using baffled blokes in different distribution.

CHAPTER THREE

EXPERIMENTAL WORK AND DIMENSIONAL ANALYSIS

3.1. Description of stepped spillways models:

Twelve different models are used in the experimental work as shown in figure (3.1)and(3.2). Models were built from plywood and plated with varnish to avoid swelling and reduce the roughness coefficient of the models, with three downstream slope angles (30°,40°and 45°) and the number of steps one five and ten steps as shown in table 3.1.

To determine the dimensions for the models, it is important to strike a balance between a number of restrictions, such as the canal height requirement of (30cm) and the requirement that the step height be greater than (2cm), and making sure there is enough room above the spillway within the canal height for the various discharges that cover all flow regimes to pass.

All model have the same total height spillway (H=30cm) ,width(W=30cm) of the spillway , length of crest (Lcrest=20cm) and the radius of bending of the upstream(R=2cm) , Models are designed according to equations **(Henderson, 1966), and (chow, 1959).**

$$\frac{L_{crest}}{y_{o}-H} > (1.5-3)\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(3.1)$$

$$R = 0.2(y_{0}-H)\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(3.2)$$

where:

L_{crest} :The length of the crested spillway in the flow direction(cm).

H :The height of the spillway above the canal's bed(cm).

y_o :The upstream water depth (for maximum discharge)(cm).

R :The radius of bending upstream face edge(cm).

Table 3.1. Characteristics of the Models

Model NO.	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	-	-	Non-uniform
M3	30	3	5.19	10	Uniform
M4	30	4.39	-	10	Non-uniform
M5	40	6	7.15	5	Uniform
M6	40	7.92	7.15	5	Non-uniform
M7	40	3	3.57	10	Uniform
M8	40	-	-	10	Non-uniform
M9	45	6	6	5	Uniform
M10	45	7.15	6	5	Non-uniform
M11	45	3	3	10	Uniform
M12	45	3.8	-	10	Non-uniform
M13	45	6	6	5	Uniform with B/2 Two-baffle
M14	45	6	6	5	Uniform with B/2.5 Two-baffle
M15	45	6	6	5	Uniform with B/3 Two-baffle
M16	45	-	6	5	Non-uniform with B/2 Two-baffle
M 17	45	-	6	5	Non-uniform with B/2.5 Two-baffle
M18	45	-	6	5	Non-uniform with B/3 Two-baffle
M19	45	3	3	10	Uniform with B/2 Two-baffle
M20	45	3	3	10	Uniform with B/2.5 Two-baffle

M21	45	3	3	10	Uniform with B/3 Two-baffle
M22	45	3.8	-	10	Non-uniform with B/2 Two-baffle
M23	45	3.8	-	10	Non-uniform with B/2.5 Two-baffle
M24	45	3.8	-	10	Non-uniform with B/3 Two-baffle
M25	45	6	6	5	Uniform with B/2 One-baffle
M26	45	6	6	5	Uniform with B/2.5 One-baffle
M27	45	6	6	5	Uniform with B/3 One-baffle
M28	45	-	6	5	Non-uniform with B/2 One-baffle
M29	45	-	6	5	Non-uniform with B/2.5 One-baffle
M30	45	-	6	5	Non-uniform with B/3 One-baffle
M31	45	3	3	10	Uniform with B/2 One-baffle
M32	45	3	3	10	Uniform with B/2.5 One-baffle
M33	45	3	3	10	Uniform with B/3 One-baffle
M34	45	3.8	-	10	Non-uniform with B/2 One-baffle
M35	45	3.8	-	10	Non-uniform with B/2.5 One-baffle
M36	45	3.8	-	10	Non-uniform with B/3 One-baffle
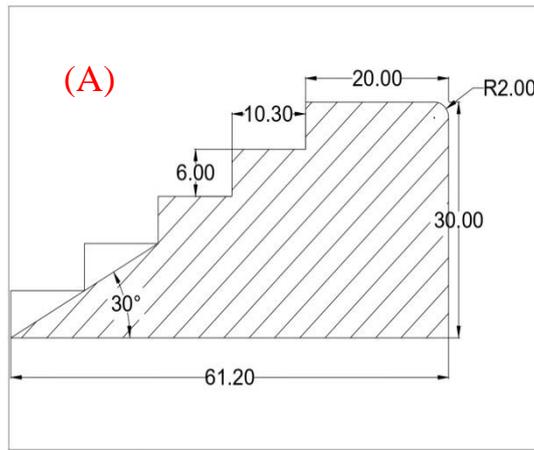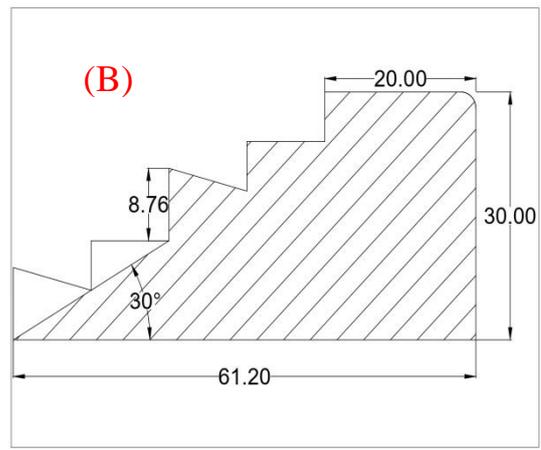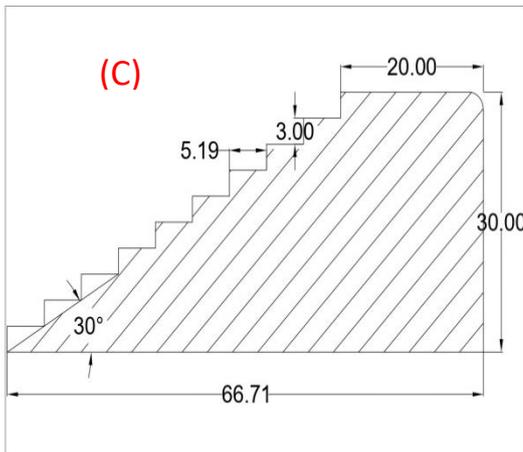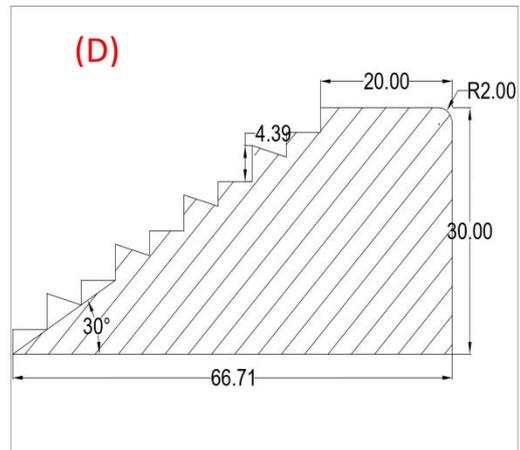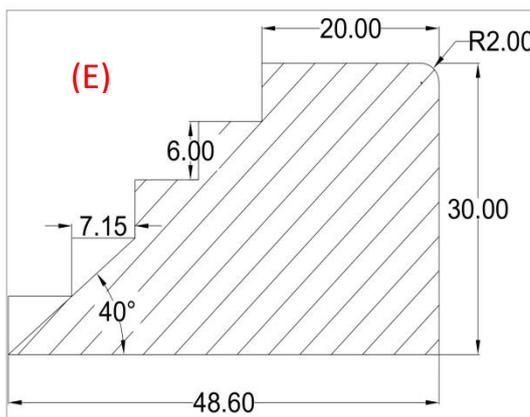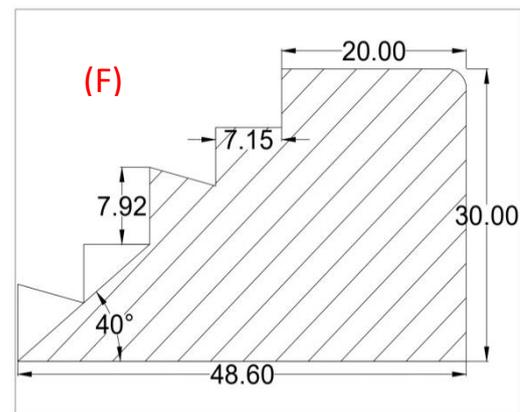
Figure 3.1. Stepped spillway models from (A-F).
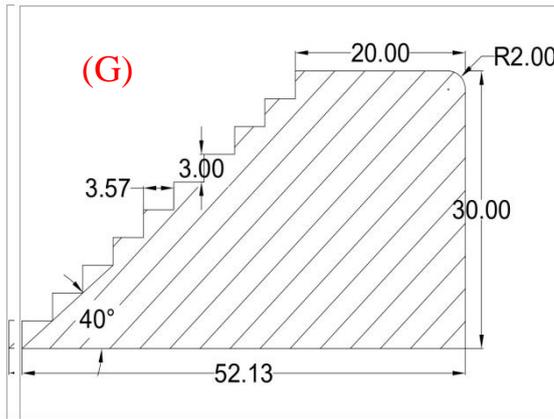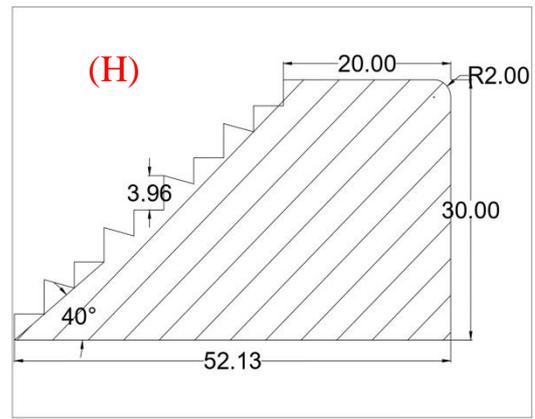
Model (7)　　　　　　　　　　　Model (8)
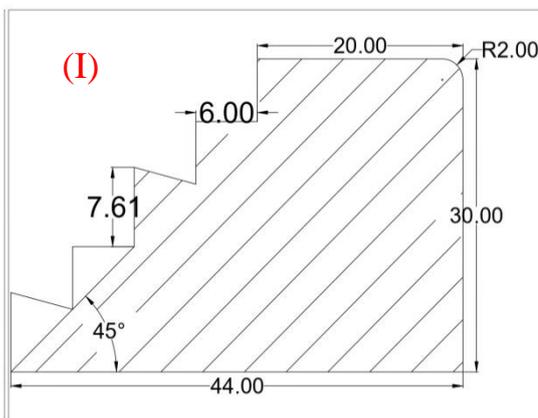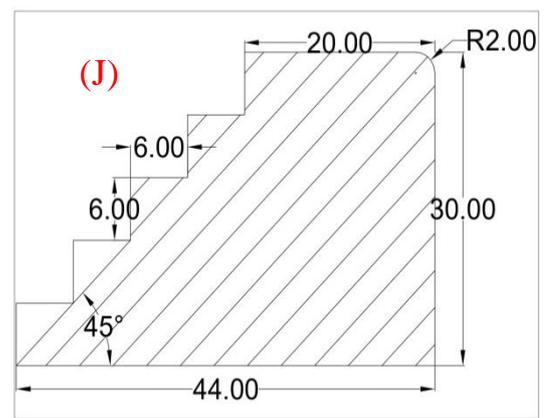
Model (9)　　　　　　　　　　　Model (10)
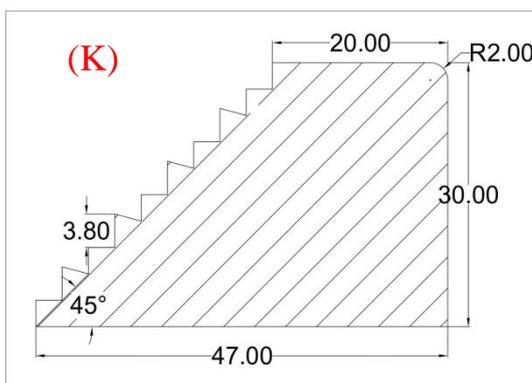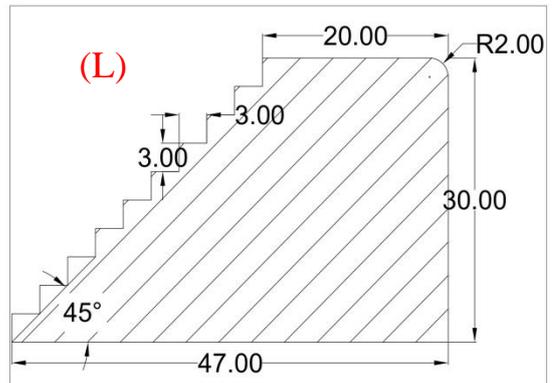
Model (11)　　　　　　　　　　Model (12)

Figure 3.2. Stepped spillway models from (G-L).

3.2 Description of baffled block:

To study the enhancement increasing of energy dissipation and models of (baffled blocks) had used for uniform and non-uniform , for case contains one and two baffled blocks on first steps at different distance (B/2 ,B/2.5 and B/3) installed on a physical model at an angle (45º) , and steps number (5and10) so that   the total number of models baffled block are twenty four model these models can be shown (3.3).

uniform 5 steps   non-uniform 5 steps

uniform 10 steps   non-uniform 10 steps
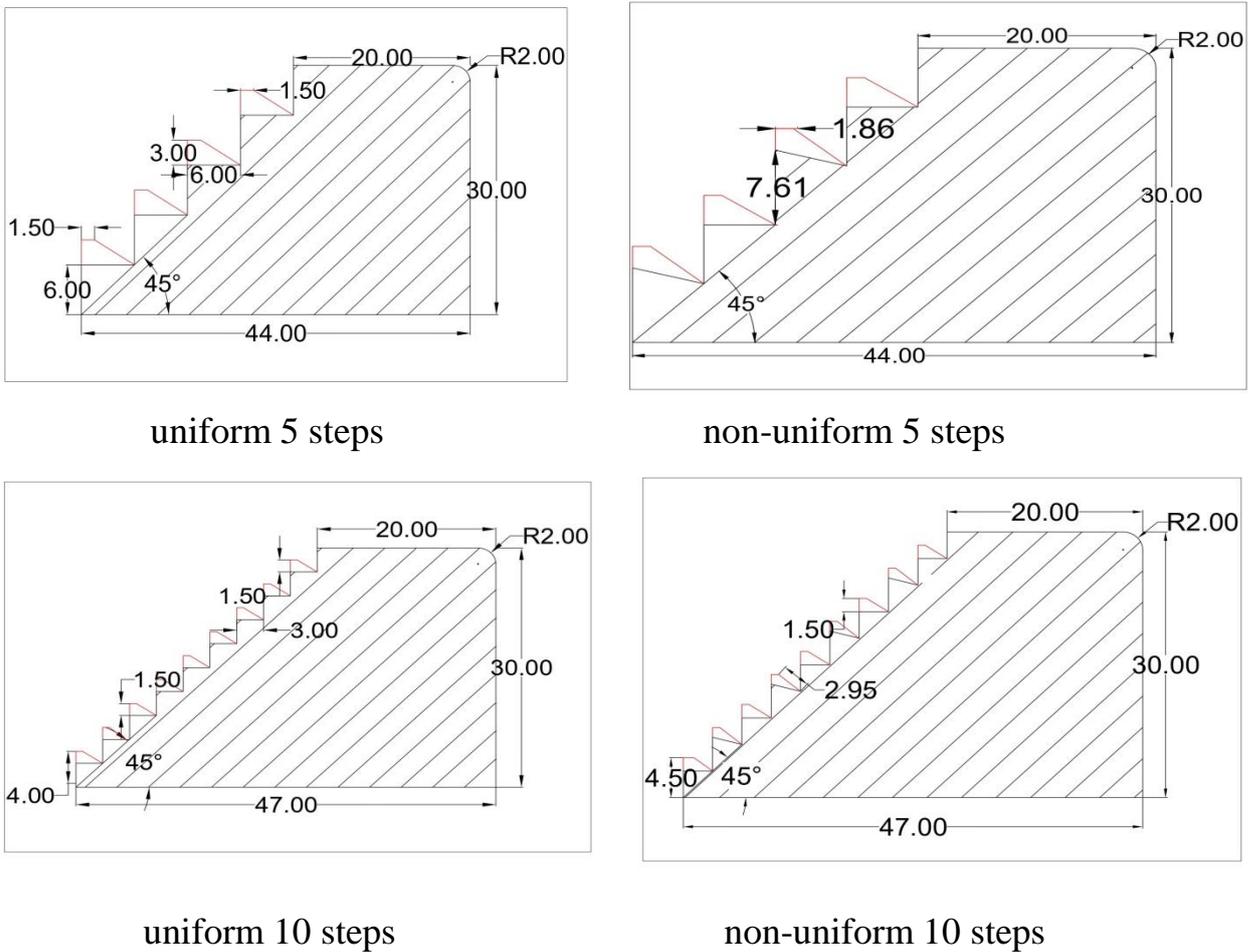
Figure 3.3 Stepped spillway with baffled blocks(side view).

Two baffled block B/2

Two baffled block B/2.5

flow

Two baffled block B/3

one baffled block B/2

one baffled block B/2.5

one baffled block B/3
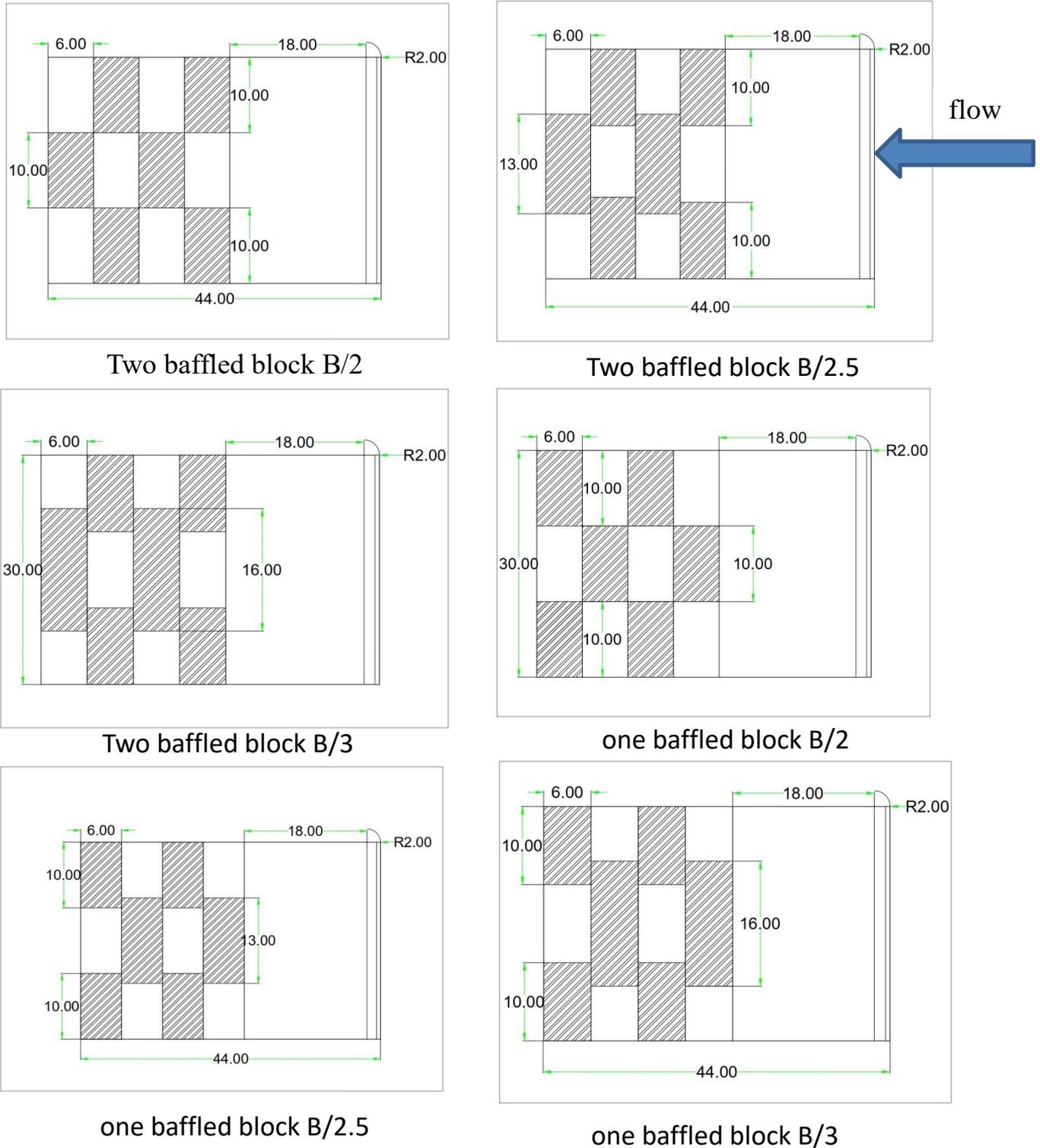
Figure 3.4 Schematic diagram showing the detail of models for case one and two baffled blocks different distance (B/2,B/2.5 and B/3) for five steps (top view).

Two baffled block B/2

Two baffled block B/2.5

flow

Two baffled block B/3

one baffled block B/2

one baffled block B/2.5

one baffled block B/3
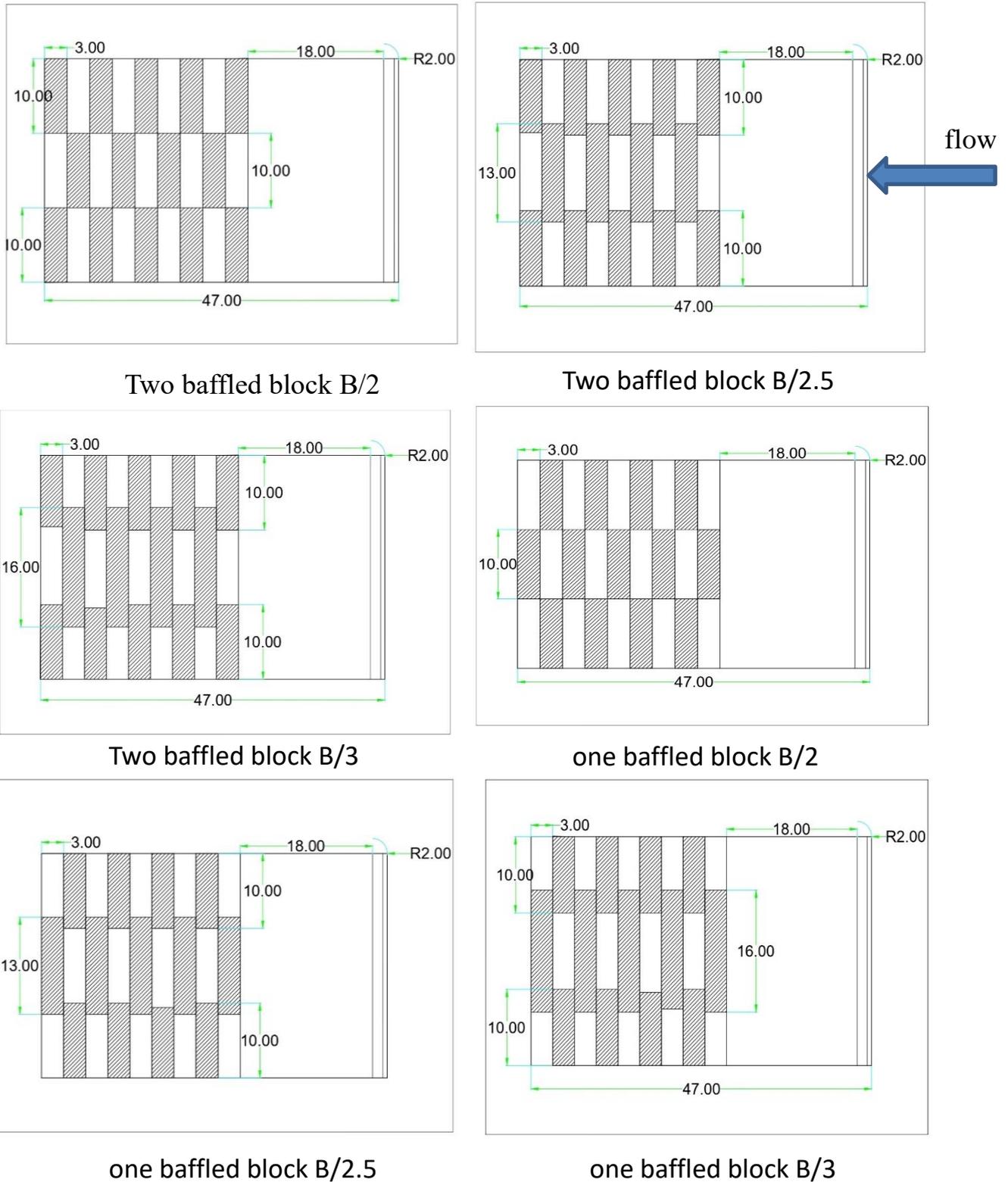
Figure 3.5   Schematic diagram showing the detail of models for case one and two baffled blocks different distance (B/2,B/2.5and B/3) for ten steps (top view).

Figure 3.6. The original experimental models without baffled blocks

B/2

B/2.5

B/3
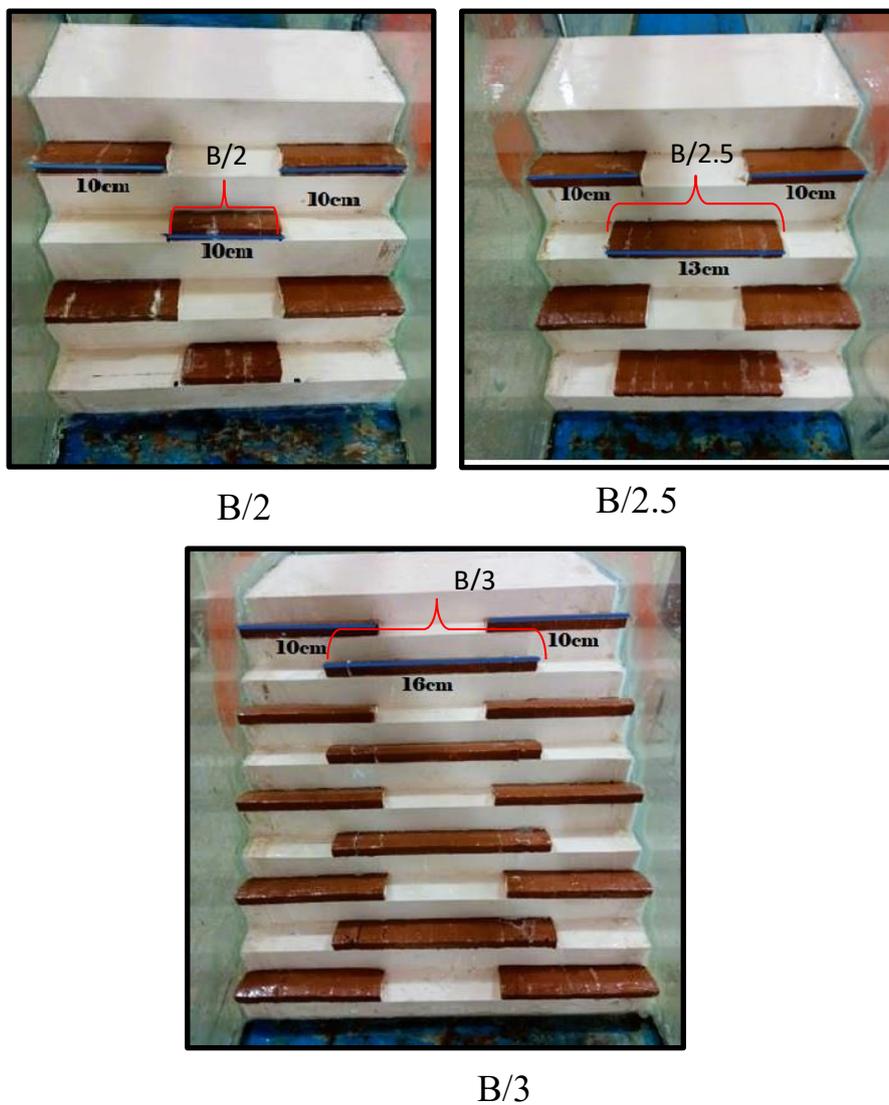
Figure 3.7. The experimental models with baffled blocks

3.3. The Canal:

The experimental works of the present study is carried out in the Irrigation and hydraulic laboratory of the Civil Engineering Department Faculty of the Engineering of the Babylon University, it is used the horizontal in the canal of the rectangular cross- section 12 m length, 0.3 m width and 0.45 m depth has been used for visual observation. The canal walls are made from glass, while the bed is stainless steel. The canal system is closed–loop water. A main tank of capacity complicated series of the straight bonded tank, at the downstream end of the canal, by means of the pump having maximum discharge (27ℓ/S).Water is carried from the main tank to an inlet tanks and the pump lies alongside the main tank in the downstream.

For the purpose of calming down the flow, two screens and a wooden board were placed horizontal and vertical to the water directly in the beginning of the canal (end of inlet tank) to develop the steady state flow condition in the canal because there was no way to dissipate and break the waves and turbulence.

Before entering the canal ,the flow passed through a pipe containg a flowmeter to measure the discharge as shown in figure (3.8).

Figure 3.8. The used canal (Civil Engineering Department, Engineering College, Babylon University).

3.4.Devices Used For Measurement:

In this paragraph we are discussed the uses of four devices and we are explained the way of work measured for each devices.

1.Electrically driven centrifugal pump:

The water was supplied into the canal a centrifugal pump in a closed system, as shown as in figure (3.9).

2.Ultrasonic Flowmeter:

It is measuring the flow rate of fluid ,When the pump feeds the water ,the ultrasonic flowmeter can measure the flow rate quality by probes put in a straight line. Also it is contains two probes and sends and receive the sight between it .Then the signal is to the device and the result appear on the screen in figure(3.9).

3. Ultrasonic level-meter:

It is used to measure the depth of water at the point that will be select by probe. First must be inter that all depth canal ,when the ultrasonic signal of the probe impacts the water surface at a selecting a point and measuring the space empty of the canal the probe will send the signal to the device to calculate the water depth as shown in figure(3.9).

4. Variable Frequency Device (V.F.D):

It is used to control the speed of the pump of water which means it controls the flow rate of water depending on the linear equation between the flow rate of water and the frequency or speed of the pump as below ;

$$\text{Selected frequency} = \frac{\text{max } frequency \; of \; water \; pump * selection \; flow \; rate}{\text{max.} flow \; rate \; of \; water} \dots\dots\dots\dots(3.3)$$

Ultrasonic Flowmeter
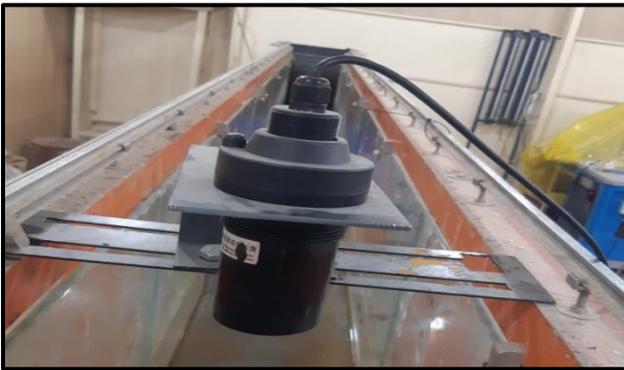
Ultrasonic level-meter

Variable Frequency Device (V.F.D)   Electrical Driven Centrifugal Pump

Figure 3.9 Types Devices Used For Measurement

3.5. The Calibration of the flow rates:

The discharge of the canal is measured by the flowmeter attaches to the pipe outside a pump .The discharge of each run can be found by dividing the volume of water (taken after 5-10 minutes) from begging of each run that passes from the flowmeter over time calculated at the same period.

A specific calibration is performed to verify the consistency of the measured discharge from the flowmeter with the actual discharge. The accumulative volume of water is measured with a known-volume container and a stopwatch, and eight different discharges are taken to strengthen the relationship's dependability (each discharge is repeated eight times and its average is obtained). The discharge measured by the flowmeter and the discharge of the canal is measured by volume container and stopwatch is plotted in figure (3.10).

$R^2 = 0.9992$
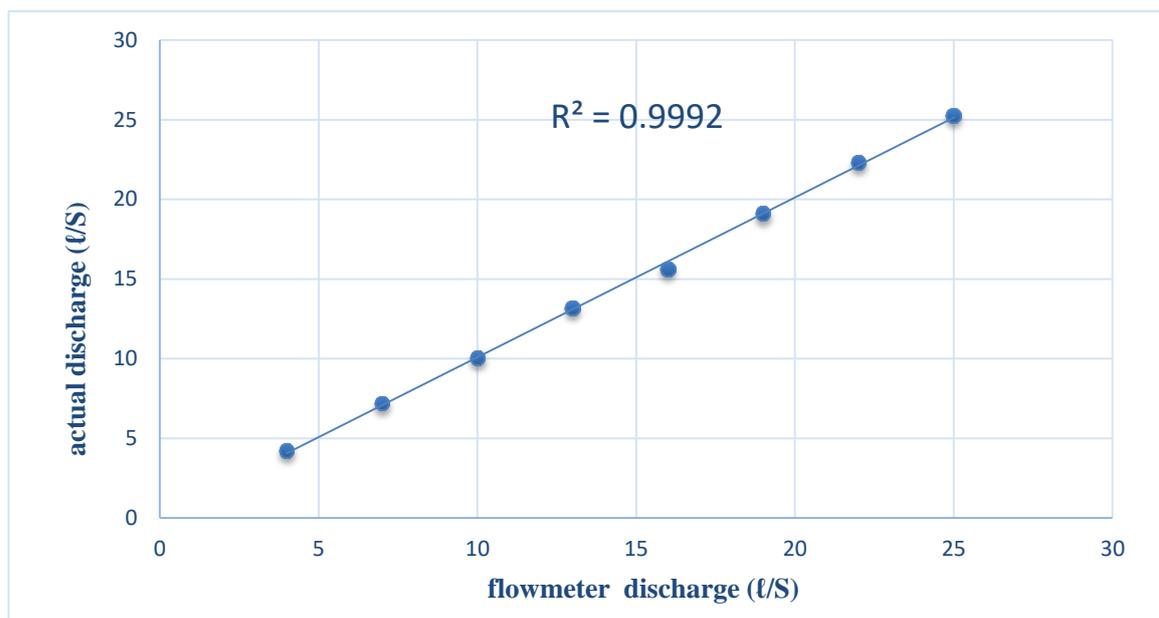
Figure 3.10 . discharge calibration curve

Whereas:
actual discharge: measured discharge by volume container and stopwatch (ℓ/sec)
flowmeter discharge : measured discharge by the flowmeter (ℓ/sec)

3.6. the calibration between the level meter and point gauge:

we have measured water depth with a levelmeter and it is attached upon the canal and it is used to measure the depth of water's after the stability flow (taking after 5-10 minutes) from begging of each run) then the results appear on the screen .

A specific calibration was performed to verify the coherence of the measured water depth's from the levelmeter and point gauge and eight different discharges are taken to strengthen the relationship's dependability (each discharge was repeated eight times and its average was obtained). The discharge measured by the   levelmeter and the depth's water   canal measured by levelmeter and point gauge are plotted on a calibration curve in figure (3.11).
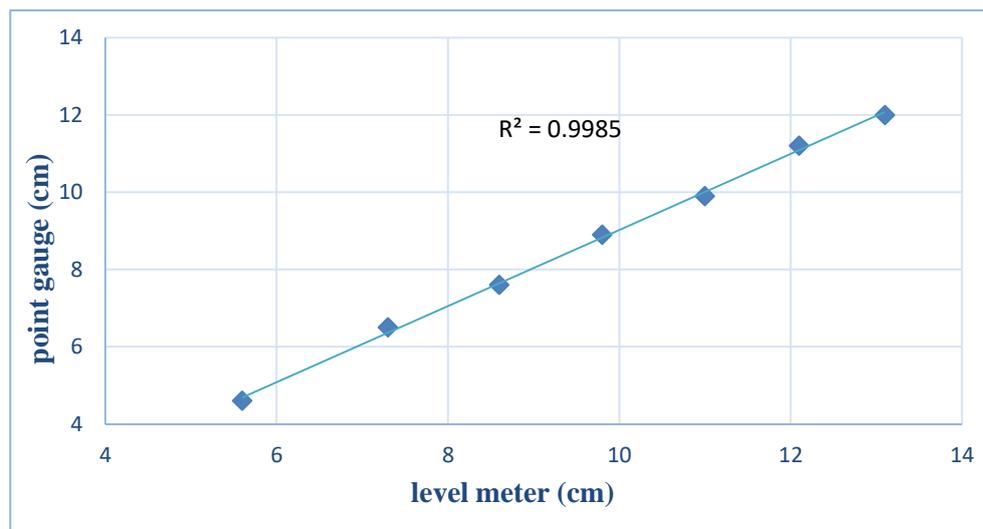
Figure 3.11. calibration between point gauge and level meter.

3.7. Limitations and procedure of the experimental work:

In this part we are discussed two parts , first part represented limitation of your steady and the second part , represented Procedure experimental work.

3.7.1.The Limitation:

The maximum height of the model stepped spillways are limited by the height of the testing canal which was (45cm). Allowing for guaranteeing free space over spillways within canal height to pass the different discharge that cover all flow regimes, the spillway height is (30 cm). then the minimum permissible height of the step is (2 cm) **(chanson, 2008)** while the data obtained with) h<2 cm) are subjected to the heights of the steps (3 cm,3.8cm,6cm and8.76cm) for geometrical like undistorted model. when testing canal, the unit discharge used ranges from (3.11 ℓ/s to 16.41 ℓ/s) according to the test canal capacity.

Table 3.2 Discharge used in the 7 runs

Run No.	Q ℓ/sec	q ℓ/s/m
1	3.11	10.33
2	5.51	18.36
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

3.7.2. The Procedure

1. Spillway models and configurations is affixed within the canal carefully by using silicon and are left for one day for complete adhesion.

2. The discharge is measurement by the flowmeter.

3. The upstream water depth is measured at a location more than ($9y_c$) upstream of the spillway model, by level meter.

4. Installing the level meter at a distance long enough to be in the non-ventilator tail water of the hydraulic jump (y_2) , at (80 cm) downstream of the toe of the model .

5. After operating the canal pump, the water depth is gradually raised till the required water depth is built ment in the run.

6. All water depth measurements are measured in the center line of the canal .

3.8. Calculation of Energy:

When the flow passes during stepped spillways and when it is in contact with the flow wall of the angled side of the spillway structures. The air rate during floods is influencing above shear stress decreasing and might be because of loss dissipating of the hydraulic structure. This event is the reason for mixing water molecules and air rate of stress which has been declined gradually .on the other side of coins , the gateway of high air out flow flux rate of flow may cause that depth of the water rising (of the spillway downstream) and estimation of the energy loss is unlike . According to recent research, the good way of loss estimation is using water depth (without air bubble). a lot of papers and journal report that use mixed depth of the water could cause overestimation of the energy dissipating **(Abbasi & Kamanbedast, 2012).**

Energy dissipation rate can be obtained by calculating the Energy upstream and downstream the spillway :

$$\Delta E(\%) = \frac{E_0 - E_1}{E_0}$$ …………………………………………………… **(3.4)**

Where:

ΔE=different between upstream and downstream Energy of the stepped spillways structure.

E_0 =is the Energy upstream the spillway .

E_1 =is the Energy downstream the spillway.

The Energy upstream the spillway is calculation at the critical section by **(Chow, 1959)**

$$E_o = 1.5y_c + H_{dam} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.\textbf{(3.5)}$$

Where:

E_o =maximum Energy of stepped spillways crest

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

The Energy downstream spillway can be calculated if the depth of water downstream the spillway (y_1)clear water depth is measured.

The flow downstream stepped spillway is highly aerated air-water flow ,so y_1 cannot be measured directly without significant error especially when the hydraulic jump located near the spillway toe . To overcome this problem many researchers **(pegram et al 1999)** used the depth after the hydraulic jump (y_2) to calculated (y_1) . If the hydraulic jump located is farther than 80cm ,it is measuring directly momentum conservation

$$y_1 = \frac{y_2}{2}\left(\sqrt{1 + 8Fr_2^2}-1\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(3.6)$$

$$Fr_{2=}\frac{v_2}{\sqrt{g\,y_2}}$$

$$E_{1=} y_1 + \alpha\frac{V_1^2}{2g}\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(3.7)$$

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 1.1 **(Chow, 1959)**

g=gravitational acceleration ;(g=9.81 $\frac{m}{s^2}$)

3.9.Flow Regime Limits:

Visual observations of flow regime types and measurements of corresponding discharges are used to determine the value at the flow regime transition flow nappe to transition and transition to skimming.

3.10.Downstream Hydraulic Jump:

Although the hydraulic jump has been studied for nearly 200 years, the interaction between the entrapped air and turbulent flow structure are not fully understood **(chanson and Wang 2013)** .

The distance of the downstream hydraulic jump measuring by grade ruler fixed on sidewall of canal , the depth upstream and downstream hydraulic jump were measure by levelmeter .

3.11.Dimensional analysis:

Geometric characteristics of the model, Flow characteristics, and Fluid properties are three groups that the discharge over stepped spillway is a function of them, these variables are shown in table (3.3) .

Table3.3. List of Abbreviation

VARIABLE	DEFINITION	DIMENSION
Fluid properties		
P	Mass flow density	ML^{-3}
μ	Dynamic viscosity	$ML^{-1}T^{-1}$
G	Gravity of acceleration	LT^{-2}
Flow characteristics		

y	the flow depth over the crest level in upstream spillway	L
y_c	Critical depth of flow	L
y_1	flow depth just downstream the spillway	L
v_1	water velocity just downstream the spillway	LT^{-1}
vc	Critical velocity over the spillway	LT^{-1}
ΔE	the total energy loss	-
Spillway geometry properties		
h	the step height	L
H	the total height of the spillway	L
l	the step length	L
B	the channel width	L
N	the number of steps	-

Effective parameters on dissipation Energy of the flow overstepped in the following:

B, and H will be constant in all experimental runs .

Energy dissipation of the stepped spillway is function of:

$\Delta E\% = f\ (\rho,\ \mu,\ g, y, y_c, y_1,\ v_1,\ v_c,\ h,\ l,\ N)$

$f\ (\ \Delta E\%, \rho,\ \mu,\ g, y, y_c, y_1, v_1, , v_c,\ h,\ l,\ N) = 0$

the number dimensionless parameter is twelve (n-m) =12-3=9

By using Buckingham's π theorem with repeated variables $(\rho,\ vc,\ y_{c,})$ the equation (3.8):

$F1(\pi_1 \pi_2 \pi_3 \pi_4 \pi_5 \pi_6 \pi_7 \pi_8 \pi_9)$ ……………………………………….(3.8)

$\pi_1 = \rho v_c\ y_c\ \Delta E\%$

$$M^0L^0T^0=(ML^{-3})^{a1}(LT^{-1})^{b1}(L)^{c1}(M^0L^0T^0)$$

For M: a1=0

For L: -3a1+b1+c1

b1+c1=0

for T: -b1+0=0

b1=0

c1=0

$\pi_1 = \Delta E\%$

The same way for the other

$\pi_2 = \rho v_c \, y_c \, \mu$, $\pi_3 = \rho v_c \, y_c \, g$, $\pi_4 = \rho v_c \, y_c \, y$

$\pi_5 = \rho v_c \, y_c \, y_1$, $\pi_6 = \rho v_c \, y_c \, v_1$, $\pi_7 = \rho v_c \, y_c \, h$,

$\pi_8 = \rho v_c \, y_c \, l$, $\pi_9 = N$

$\pi_1 = \Delta E\%$, $\pi_2 = \dfrac{\mu}{\rho v_c \, y_c}$, $\pi_3 = \dfrac{g \, y_c}{v^2}$, $\pi_4 = \dfrac{y}{y_c}$

$\pi_5 = \dfrac{y_1}{y_c}$, $\pi_6 = \dfrac{V_1}{V_c}$, $\pi_8 = \dfrac{h}{y_c}$, $\pi_9 = \dfrac{l}{y_c}$,

$\pi_{10} = N$

But:

$\pi_2 = Re$, $\pi_3 = Fr$

$\pi_4 = \dfrac{y}{y_c} = \dfrac{H_{Spillway}}{y_c}$, $\dfrac{\pi_8}{\pi_9} = \dfrac{h}{l} = tan\theta$

$\pi_{10} = N$

CHAPTER FOUR

EXPERIMENTAL RESULTS AND DISCUSSION

4.1.Flow Regime with Stepped Spillway:

In this paragraph the experimental results indicated that the type of flow regime with uniform and non-uniform stepped spillway .the boundaries between regime for twelve uniform and non-uniform stepped spillway and effect baffled blocks on flow regime type , some detailed visual observation of the flow pattern . the observation included the flow processes in nappe, transition and skimming flow regime, well effect for all angles and number of steps on flow regime types, Discharge limits for all models from $3.11\ell/s$ to $16.41\ell/s$.

4.1.1.Flow Regime for different Stepped Spillway angles:

In each case the slope of stepping is constant $(30°, 40°$ and $45°)$ and for each slope two constant number of steps is used (5 and 10) with two-step angles for each step number (acute and right angle) to present uniform and non-uniform step numbers as shown in Table 4.1.

The discharge was not completely developed at the downstream end of the spillway at the highest flow rates, which might cause the residual energy to be overestimated **(Hubert Chanson, 2002; Meireles & Matos, 2009).** The median residual energy of many experimental data sets acquired for spillway slopes less than 15.9° is shown by the upper dotted line, and the median values for stepped spillway data with slopes 21.8 and 26.6° are expressed by the bottom dashed **(Felder &Chanson, 2009)** .

From the laboratory results it was found that the nappe flow regime occurs at low discharges and when the inclination angle is low and the degree height is

high, but when the number of degrees is increased for the same angle we notice the shape of the flow regime has changed as shown in table 4.1 .

The model(M1) uniform five stepped spillway , angle is 30° and the number of step is five when the discharge was 3.11ℓ/s ,The type of flow was nappe flow regime , but when the number of steps was increased while the angle and the discharge remained the same, the type of flow changed from nappe flow regime to transition flow regime, is in which the flow is unstable at every steps. As for the angle 45° and the number of steps five(Model 9), the type of flow was transitional, but when increasing the number of steps, the shape of the flow changed from transitional to skimming flow regime, and this means that the number of steps has a great effect, changing the shape of the flow from one type to another, but increasing the discharge at the same angle becomes the shape of the flow skimming flow regime on all models For five and ten steps, the reason is that increasing the critical water depth above the model makes the water shape smooth and coherent, and the aeration decreases.

As for the non-uniform models at the angle 30° and the number of steps five and ten only, in this angle the shape of the water did not change because of the irregularity of the steps and the change in their dimensions ,However when the inclination angle of the non-uniform stepped spillway was increased from 30° to 45°, the shape of the flow changed, as shown in table 4.1 .

Table 4.1. Flow regime for different stepped spillway angles.

Run	Q (ℓ/S)	(Θ= 30°)		(Θ= 30°)		(Θ= 40°)		(Θ= 40°)		(Θ= 45°)		(Θ= 45°)	
		5 Steps		10 Steps		5 Steps		10 Steps		5 Steps		10 Steps	
		Uniform (M1)	Non-uniform (M2)	Uniform (M3)	Non-uniform (M4)	Uniform (M5)	Non-uniform (M6)	Uniform (M7)	Non-uniform (M8)	Uniform (M9)	Non-uniform (M10)	Uniform (M11)	Non-uniform (M12)
1	3.11	NA	NA	TR	NA	TR	NA	TR	TR	TR	TR	SK	TR
2	5.51	TR	TR	TR	TR	TR	TR	SK	TR	TR	TR	SK	SK
3	7.67	TR	TR	SK	TR	SK	TR	SK	SK	SK	SK	SK	SK
4	10.28	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK
5	12.52	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK
6	14.83	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK
7	16.41	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK

NA: Nappe Flow Regime   ;TR: Transition Flow Regime   ;SK: Skimming Flow Regime

A stepped spillway's flow regime may either have nappe flow or skimming flow. In nappe flows, water from each step falls as a jet onto the step below, dissipating its energy by jet breakup in the air and mixing on the step, with or without the production of a partial hydraulic leap. The vertical step wall causes the upstream-directed flow to reverse direction, creating a pool. This flow enters the downstream-directed flow at a lower velocity after being recirculate within the pool. According to **(Rajaratnam, 1990)**, nappe flow occurs when yc/h <0.8. For greater discharges, a nappe flow regime is feasible, but this requires a very flat slope. Water runs down the stepped face in a cohesive stream during the skimming flow regime, skimming over the steps and being cushioned by the recirculating fluid trapped between them. At moderate to high discharges, skimming flow occurs. The outward edges of the stairs provide a false bottom over which the flows pass without any apparent nappe. Skimming flows are characterized by the development of vortices, which convey shear loads, and significant friction losses. The fluid flow becomes uniform far downstream, where measurements would not change for a given discharge, since a layer comprising a combination of air and water spreads through the fluid downstream of the point of genesis. According to **(Chanson, 1995)**, once the skimming flow develops to its maximum potential, the tiered spillway acts much like a smooth, very abrasive surface. **(Rajaratnam, 1990)** identified the beginning of the skimming flow at ratios of yc/h > 0.80, which holds true for the whole experimental program at hand. Despite the fact that the nappe flow and skimming flow regimes have quite distinct processes for energy loss, both flows are capable of losing a significant amount of flow energy.

However, the angles of spillway stepped have no effect on flow regime in the high flow rate, while the change in the flow regime from skimming to transition flow at 3.11 ℓ/s flow discharge as well as the changing stepped

spillway from uniform to non- uniform show clearly that the change of flow regime for the same flow discharge.

Depending on steppes spillways with angle 30°, figures 4.1 to 4.4 the flow regime is changed from nappe for low flow discharges to transition flow regime and then change to skimming for 10.28 ℓ/s. From Table 4.1, it is observed that the changing in steppes number from 5 to 10 steps as well as changing the steppes from uniform to non-uniform has no significant effect on the flow regime for 30° as a declined angle, As for the rest of the angle of the models, their pictures are in the appendix(B) .

(a) Nappe flow regime ,Q=3.11ℓ/s at model (M1)

(b) Transition flow regime ,Q=5.51ℓ/s at model (M1)

Figure 4.1. flow regime for 5 uniform steps spillway at angle of 30◦.

(c) skimming flow regime ,Q=16.41ℓ/s at model (M1)

Figure 4.1 follow . flow regime for 5 uniform steps spillway at angle of 30◦.

(a) Transition flow regime ,Q=3.111ℓ/s at model (M3)

(b) Transition flow regime ,Q=16.411ℓ/s at model (M3)

Figure 4.2 . flow regime for 10 uniform steps spillway at angle of 30◦.

(a) Nappe flow regime ,Q=3.11ℓ/s at model (M2)

(b) Transition flow regime ,Q=7.67ℓ/s at model (M2)

(c) skimming flow regime ,Q=16.41ℓ/s at model (M2)

Figure 4.3. flow regime for 5 non-uniform steps spillway angle of at 30°.

(a) nappe flow regime ,Q=3.11ℓ/s at model (M4)

(b) transition flow regime ,Q=7.67ℓ/s at model (M4)

(c) skimming flow regime ,Q=16.41ℓ/s at model (M4)

Figure 4.4. flow regime for 10 non-uniform steps spillway at angle of 30⁰

According to the laboratory results, there are three types in the discharge stepped spillway , and the results showed that the nappe flow regime occurs with uniform and non-uniform stepped spillway respect to the discharge 3.11ℓ/s, while skimming flow regime it was occurring discharge 10.28 ℓ/s, Proven in this study and according to table 4.2 and table 4.3, the range of discharge limits at uniform and non-uniform stepped spillway with different angle and steps number.

Table 4.2 limitation flow regime with uniform stepped spillway.

slope	5steps	10steps
Limitation flow regime with uniform stepped spillway		
30º	- NA Q ≤ 3.11ℓ/sec - TR 5.51 ℓ/sec ≤ Q ≤7.67ℓ/sec - SK 10.28 ℓ/sec ≤ Q ≤ 16.41 ℓ/sec	- NA (-) - TR 3.11 ℓ/sec ≤ Q ≤5.51ℓ/sec - SK 7.67 ℓ/sec ≤ Q ≤ 16.41 ℓ/sec
40º	- NA (-) - TR 3.11 ℓ/sec ≤ Q ≤5.51ℓ/sec - SK 7.67 ℓ/sec ≤ Q ≤ 16.41 ℓ/sec	- NA (-) - TR Q ≤ 3.11ℓ/sec - SK 5.51 ℓ/sec ≤ Q ≤ 16.41 ℓ/sec
45º	- NA (-) - TR 3.11 ℓ/sec ≤ Q ≤5.51ℓ/sec - SK 7.67 ℓ/sec ≤ Q ≤ 16.41 ℓ/sec	- NA (-) - TR (-) - SK 3.11 ℓ/sec ≤ Q ≤ 16.41 ℓ/sec

NA: Nappe flow regime ; TR: Transition flow regime ;SK: Skimming flow regime

Table 4.2 Limitation flow regime with non-uniform stepped spillway.

slope	5steps	10steps
Limitation flow regime with non- uniform stepped spillway		
30º	- NA Q ≤ 3.11ℓ/sec - TR 5.51 ℓ/sec ≤ Q ≤7.67ℓ/sec - SK 10.28 ℓ/sec ≤ Q ≤ 16.41 ℓ/sec	- NA Q ≤ 3.11ℓ/sec - TR 5.51 ℓ/sec ≤ Q ≤7.67ℓ/sec - SK 10.28 ℓ/sec ≤ Q ≤ 16.41 ℓ/sec
40º	- NA Q ≤ 3.11ℓ/sec - TR 5.51 ℓ/sec ≤ Q ≤7.67ℓ/sec - SK 10.28 ℓ/sec ≤ Q ≤ 16.41 ℓ/sec	- NA (-) - TR 3.11ℓ/sec ≤ Q ≤ 5.51ℓ/sec - SK 7.67 ℓ/sec ≤ Q ≤ 16.41 ℓ/sec
45º	- NA (-) - TR 3.11 ℓ/sec ≤ Q ≤5.51ℓ/sec - SK 7.67 ℓ/sec ≤ Q ≤ 16.41 ℓ/sec	- NA (-) - TR Q ≤ 3.11ℓ/sec - SK 5.51 ℓ/sec ≤ Q ≤ 16.41 ℓ/sec

NA: Nappe flow regime ; TR: Transition flow regime ;SK: Skimming flow regime

4.1.2. Flow Regime for stepped spillway uniform and non-uniform at angle 45⁰ for five and ten steps with baffled blocks:

A stepped spillway's flow regime may either have nappe flow or skimming flow. In nappe flows, water from each step falls as a jet onto the step below, dissipating its energy by a jet breakup in the air and mixing on the step, with or without the production of a partial hydraulic leap. The vertical step wall causes the upstream-directed flow to reverse direction, creating a pool. depending on stepped spillways with 45° uniform and non-uniform Steps with five and ten steppes along with one and two baffled blocks with difference distance (B/2, B/2.5 and B/3), figures (4.5-4.8) show that the flow has been changed from Transition for low flow discharges to skimming flow regime. Therefore, the use of baffled blocks ony changes the flow regime for skimming to Transition for low flow discharge, but with increasing flow discharges the effect of baffled blocks on the flow regime has disappeared When comparing the flow on baffled block steps to the flow with horizontal steps, it can be seen that the baffled block steps have an impact on the lower limit of the skimming flow regime.however, it does rise slightly with baffled blocks steps at some points.Within a skimming flow regime, there is no influence at higher discharge and none at lower dischargeno significant effect on the flow regime.

(a) B/2 two baffled blocks , Q=7.67ℓ/s at model(13)
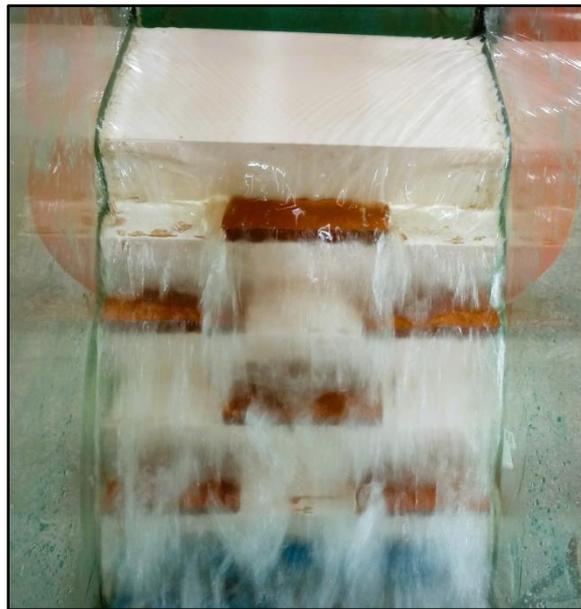

(b) B/2.5 two baffled blocks , Q=12.62ℓ/s at model(14)

(c) B/3 two baffled blocks , Q=14.83ℓ/s at model(15)

Figure 4.5. Flow regime for five uniform Steps spillway B/2 , B/2.5 and B/3 Two-baffled.

(a) B/2 one baffled blocks , Q=14.83ℓ/s at model(25)

(b) B/2.5 one baffled blocks , Q=5.51 ℓ/s at model(26)

(c) B/3one baffled blocks , Q=14.83ℓ/s at model(27)

Figure 4.6. Flow regime for five uniform Steps spillway B/2 , B/2.5 and B/3 one-baffled.

(a) B/2two baffled blocks , Q=3.11ℓ/s at model(19)

(b) B/2.5two baffled blocks , Q=7.67ℓ/s at model(20)

(c) B/3two baffled blocks , Q=5.51ℓ/s at model(21)

Figure 4.7. Flow regime for ten uniform Steps spillway B/2 , B/2.5 and B/3 two-baffled.

(a) B/2one baffled blocks , Q=3.11ℓ/s at model(31)

(b) B/2.5one baffled blocks , Q=7.67ℓ/s at model(32)

Figure 4.8. Flow regime for ten uniform Steps spillway B/2 , B/2.5 and B/3 one-baffled.

4.2. Effect discharge and number of steps for uniform and non-uniform stepped spillway on Energy dissipation with constant angle :

4.2.1. Energy dissipation for 30° spillway angles:

The relationship between discharges and $\Delta E/E0\%$ for stepped spillway at 30° angle is shown in figure (4.9) for 4 different conditions (uniform and non-uniform) 5 and 10 steps. The energy dissipations decrease when the flow discharge is increased from 3.11 to 16.41 (ℓ/s), and the influence of the number of steps reveales that a stepped spillway with 10 uniform steps have the lowest energy dissipations in comparison with other conditions.
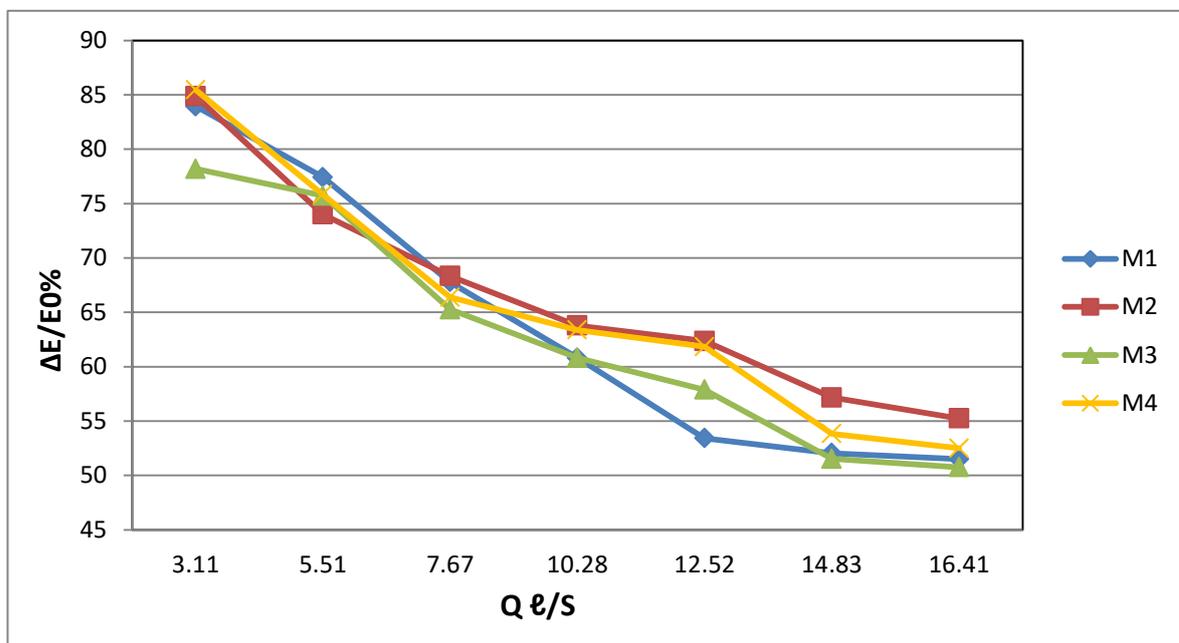

Figure 4.9 . The relationship between discharges and $\Delta E/E0$ % for Stepped Spillway at angle of 30°.

4.2.2. Energy dissipation for 40° spillway angles:

The relationship is drawn between the flow energy dissipation ($\Delta E/E0\%$) and the discharge (Q) in each of figures (4.10) From the observation of the figure, it is clear that the energy dissipation the flow rate decreases when the discharge is increased, as the increase in the discharge turns the flow into a skimming flow regime , which has less flow energy dissipation. Four different conditions (uniform and non-uniform) five and ten steps, the effect of steps

number shows that ten non-uniform steps of the stepped spillway have the lowest energy dissipations comparison with other conditions, while five non-uniform steps of the stepped spillway have the highest energy dissipation.
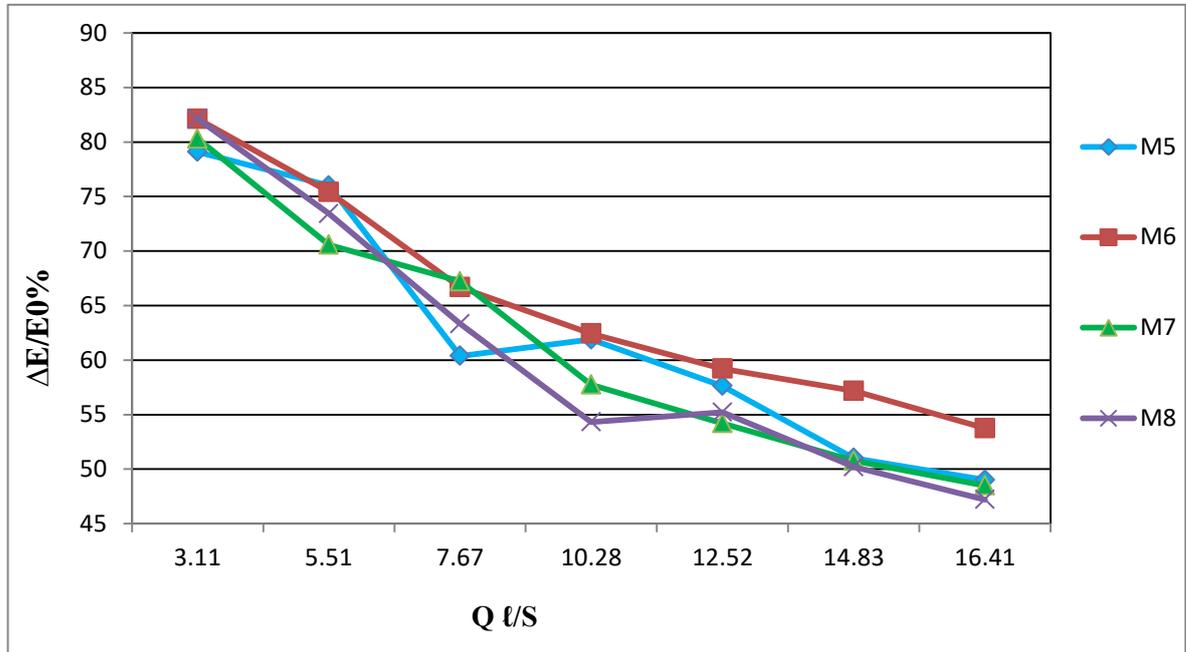

Figure 4.10 . The relationship between discharges and ΔE/E0 % for Stepped Spillway at angle of 40⁰.

4.2.3. Energy dissipation for45° spillway angles:

Relationship between discharges and (ΔE/E0 %) energy dissipation ratio is drawn as in Figure (4.11) From the observation of the figure it is seen that the energy dissipation ratio decreases when the discharge increases. In Figure (4.11) effect of the number of degrees is studied by adopting a constant slope of the gradient. It was found that the non-uniform model that contains on five steps gives the highest amount of flow energy dissipation ratio. An increase in the number of degrees leads to a decrease in the flow energy dissipation percentage as shown in ten steps of non-uniform model.
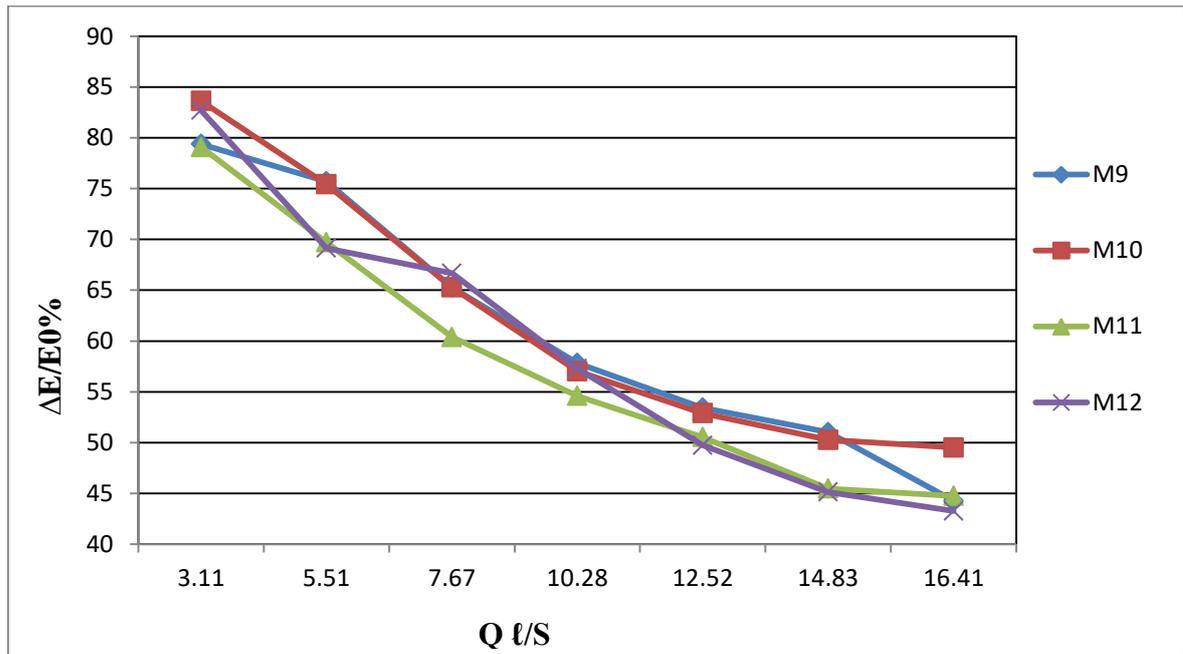
Figure 4.11 . The relationship between discharges and ΔE/E0 % for Stepped Spillway at angle of 45⁰.

4.3.The effect of different inclined angles on Energy Dissipation:

the effective of increasing the angle of models on energy dissipation rate can be show in figure(4.12-4.15) were the energy dissipation rate($\Delta E/E0$) is plotted at each design discharges as show below .According to the laboratory results, it was found that increasing the inclination angle from 30⁰ to 45⁰ degrees decreases the energy dissipation rate. It was found that the best model is at the angle of 30⁰ degrees, which is the non-uniform model at five steps when the critical water depth is yc/h=0.368 at the discharge q=10.33ℓ/s/m, as the dispersion rate was ΔE/E0%=85.45%.

Figure 4.12.the effect of the modeled angle at constant height on energy dissipation rate with uniform five steps.

Figure 4.13.the effect of the modeled angle at constant height on energy dissipation rate with uniform ten steps.
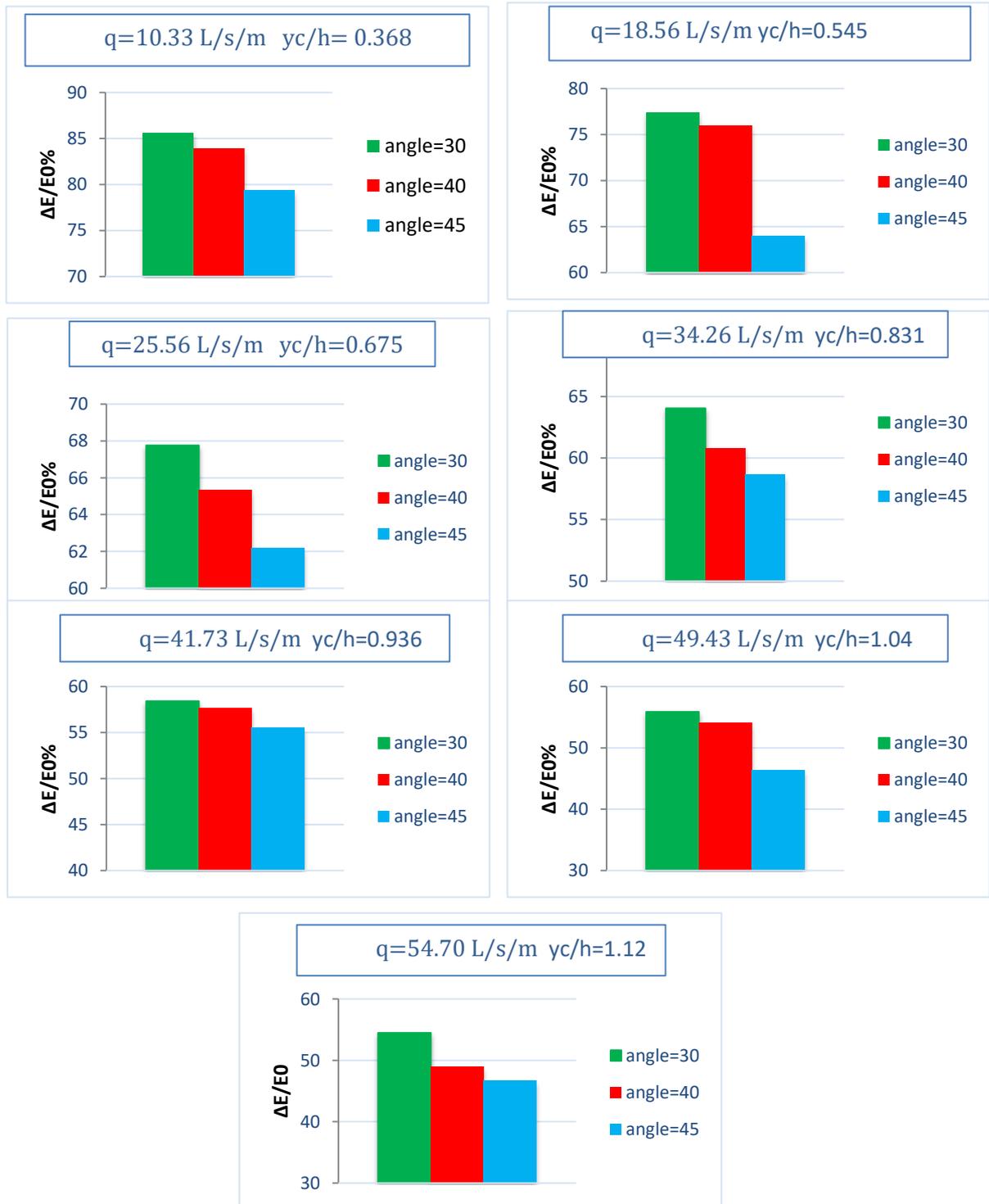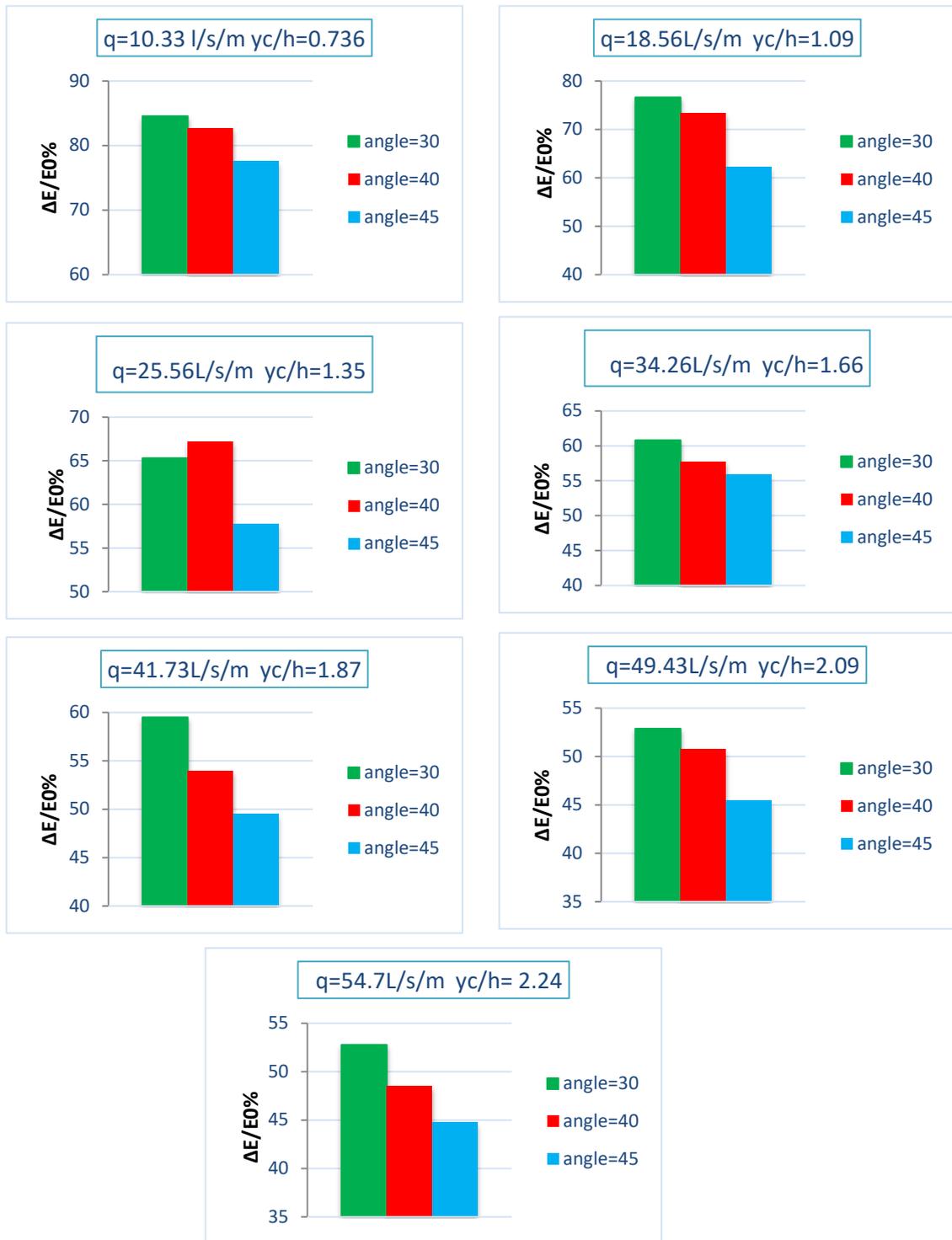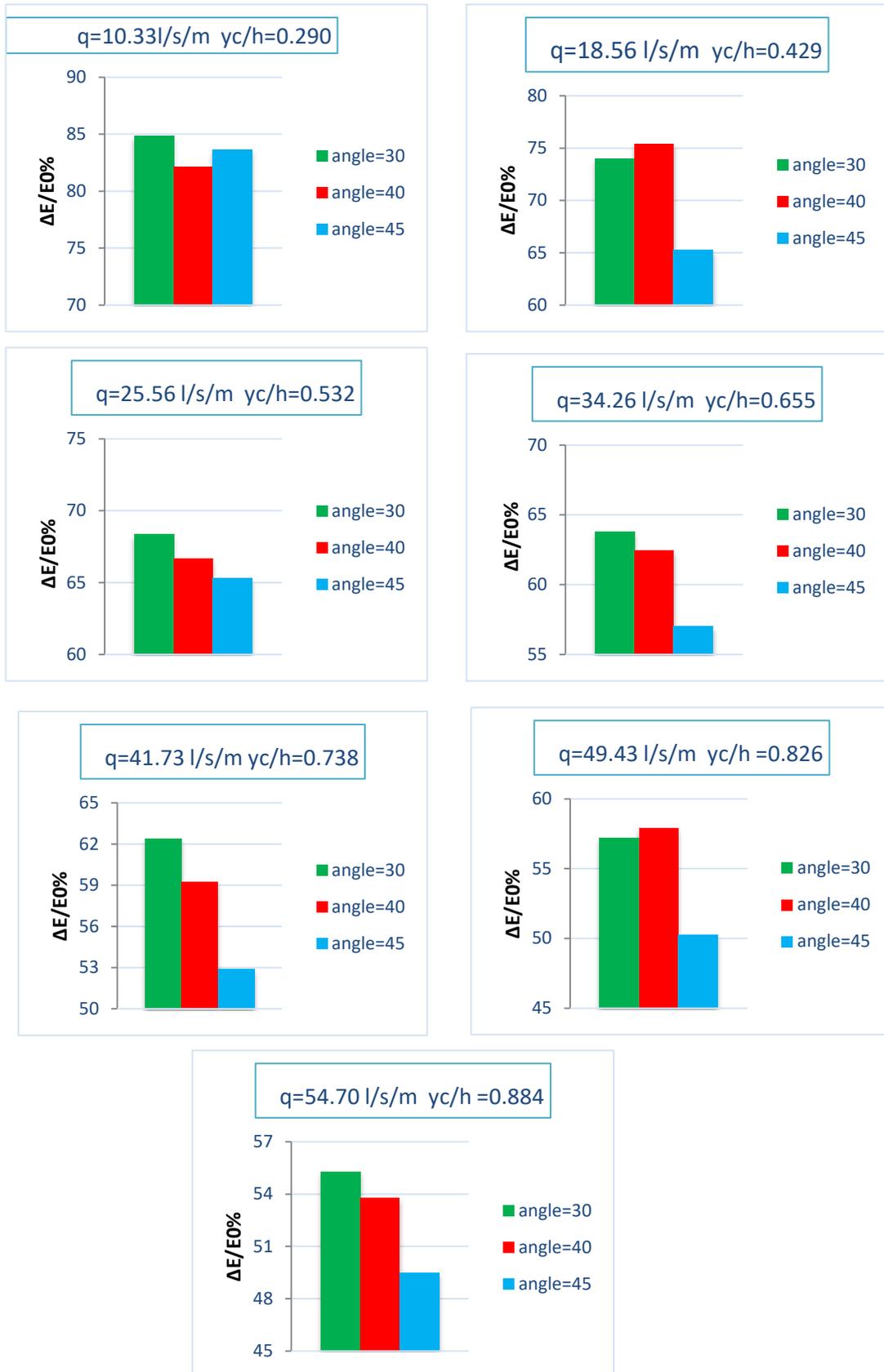
Figure 4.14.the effect of the modeled angle at constant height on energy dissipation rate with non- uniform five steps.
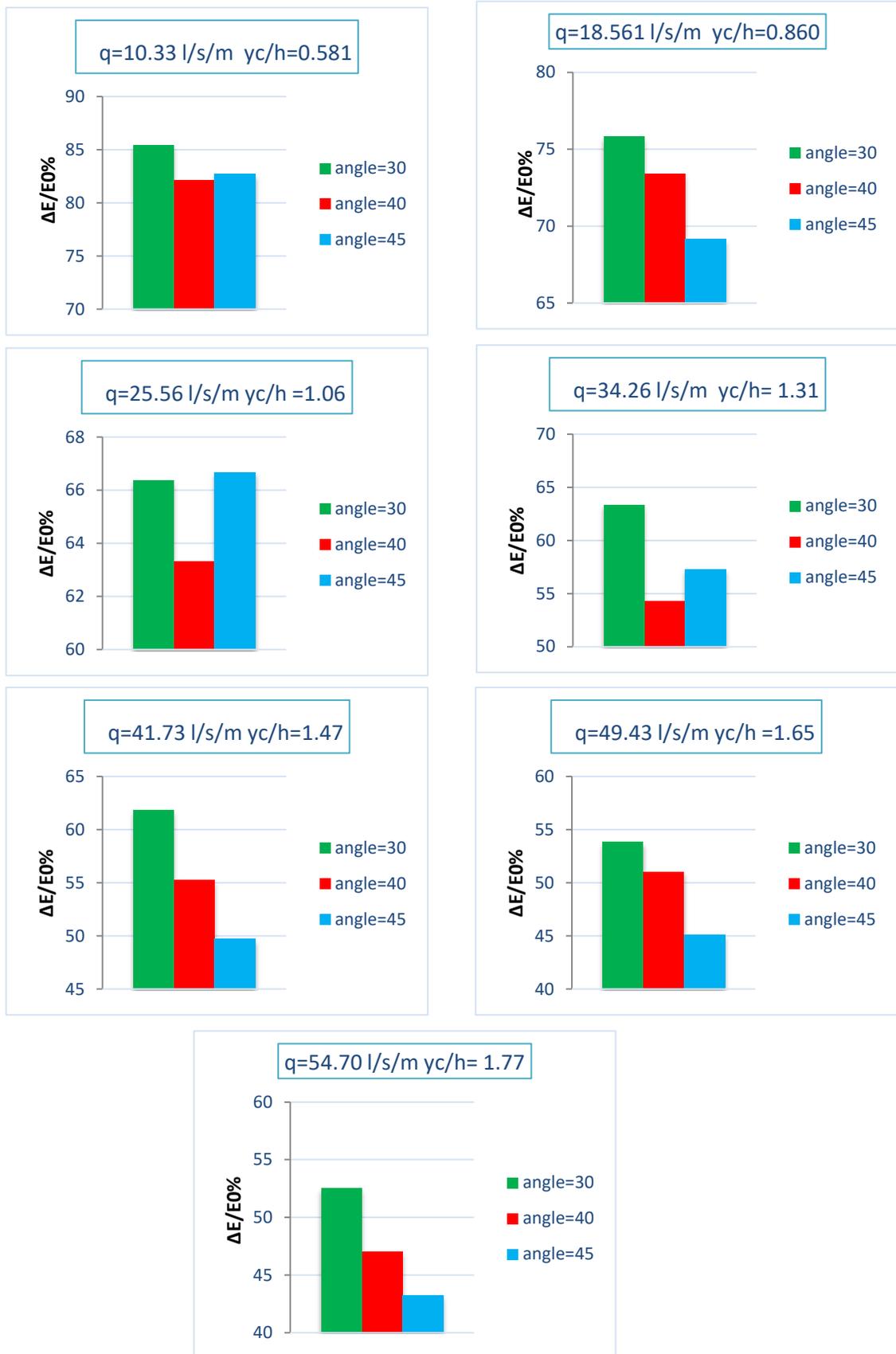
Figure 4.15.the effect of the modeled angle at constant height on energy dissipation rate with non- uniform ten steps.

4.4.Energy Dissipation for Stepped spillway with Baffled blocks:

4.4.1. Uniform 5 steps (Ө= 45°):

The relationship between ΔE/E0% and discharge for uniform 5 stepped spillway with different baffled blocks distribution is negative relationship and increasing one of them lead to decrease the other one as indicated in Figure 4.16. Also, the highest energy dissipation was recorded at low flow discharge, while increasing the flow discharge lead to reduce the energy dissipation for all selected models before and after placing different baffled blocks distribution. Sample M26 with 5 steps and uniform stepped spillway with one baffled blocks records the highest energy dissipation.
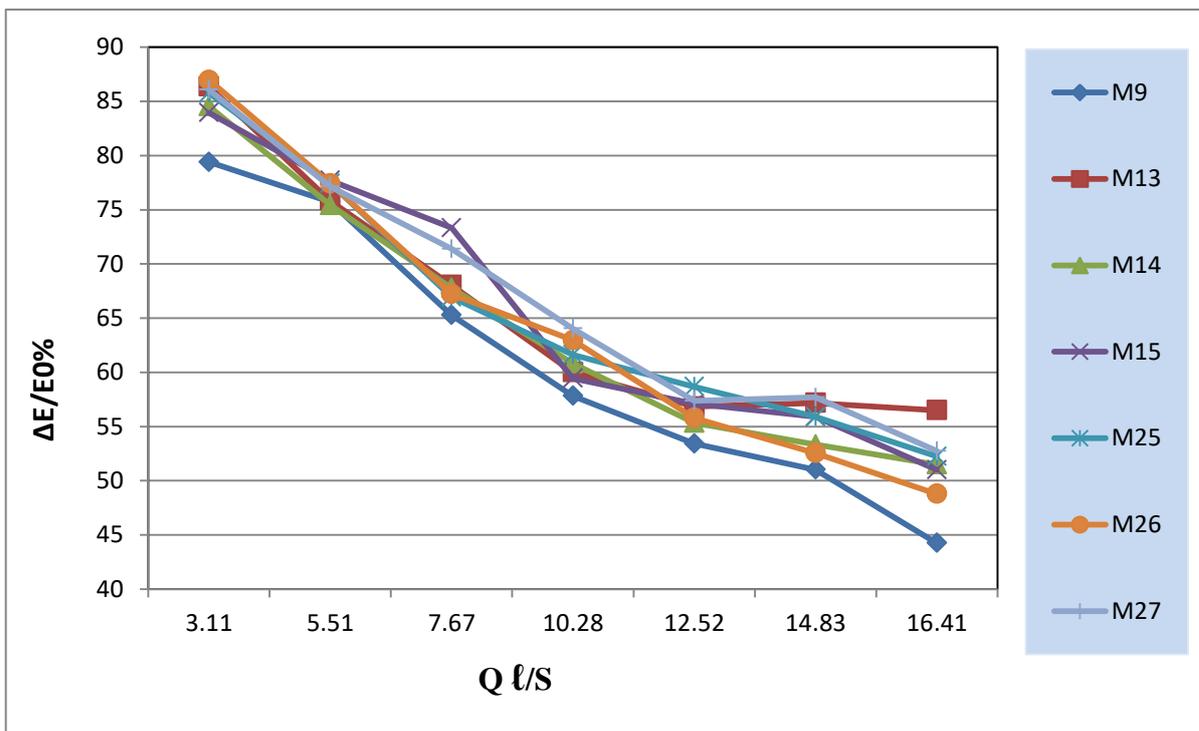

Figure 4.16. The relationship between ΔE/E0 % and discharge for uniform 5 stepped spillway with different baffled blocks distribution.

4.4.2. Non-Uniform 5 steps (⊖= 45°):

The relationship between ΔE/E0 % and discharge for non-uniform five stepped spillway with different baffled blocks distribution(B/2,B/2.5 and B/3) is negative relationship and increasing one of them lead to decrease the other one as indicated in Figure 4.17. Also, the highest energy dissipation was recorded at low flow discharge, while increasing the flow discharge lead to reduce the energy dissipation for all selected models before and after placing different baffles blocks distribution. Sample M30 with 5 steps non-uniform and one baffle with distribution (B/3) records the highest energy dissipation.

Figure 4.17. The relationship between ΔE/E0 % and discharge for non-uniform 5 stepped spillway with different baffled blocks distribution.

4.4.3. Uniform 10 steps (⊖= 45°):

The relationship between ΔE/E0 % and discharge for uniform 10 stepped spillway with different baffles blocks distribution is negative relationship and increasing one of them lead to decrease the other one as indicated in Figure 4.18. Also, the highest energy dissipation was recorded at low flow discharge,

while increasing the flow discharge lead to reduce the energy dissipation for all selected models before and after placing different baffles blocks distribution. Sample M31 with 10 steps uniform and one baffle with distribution (B/2) records the highest energy dissipation.
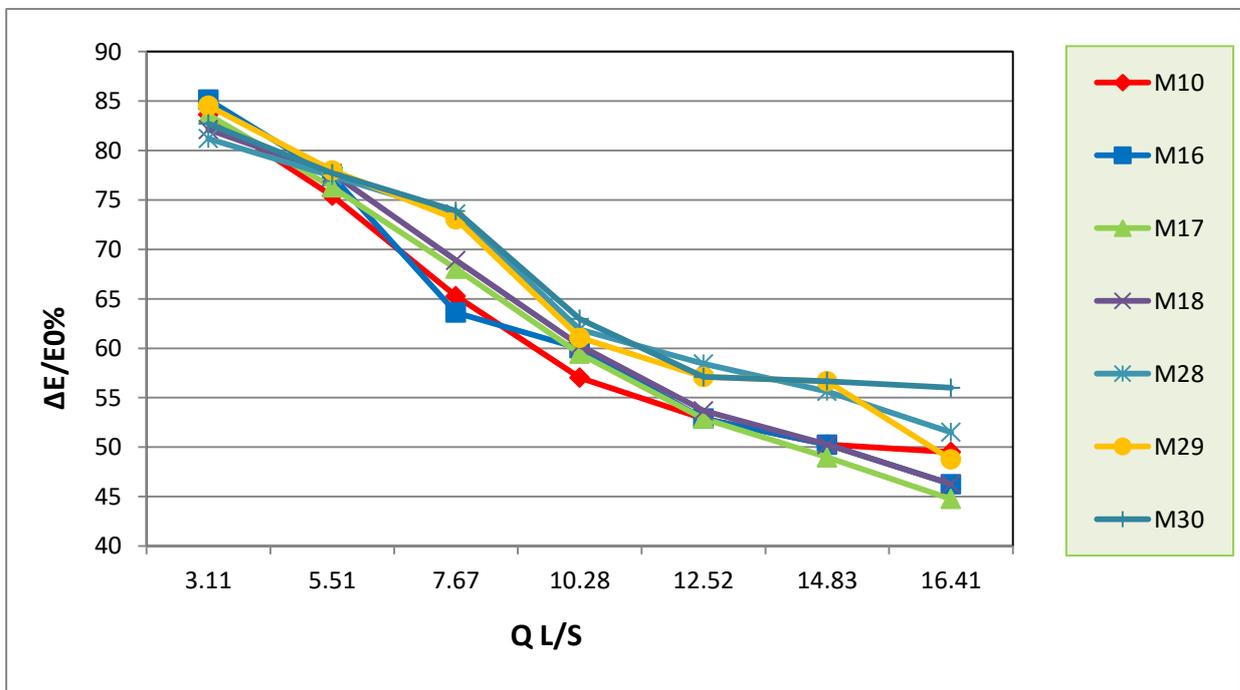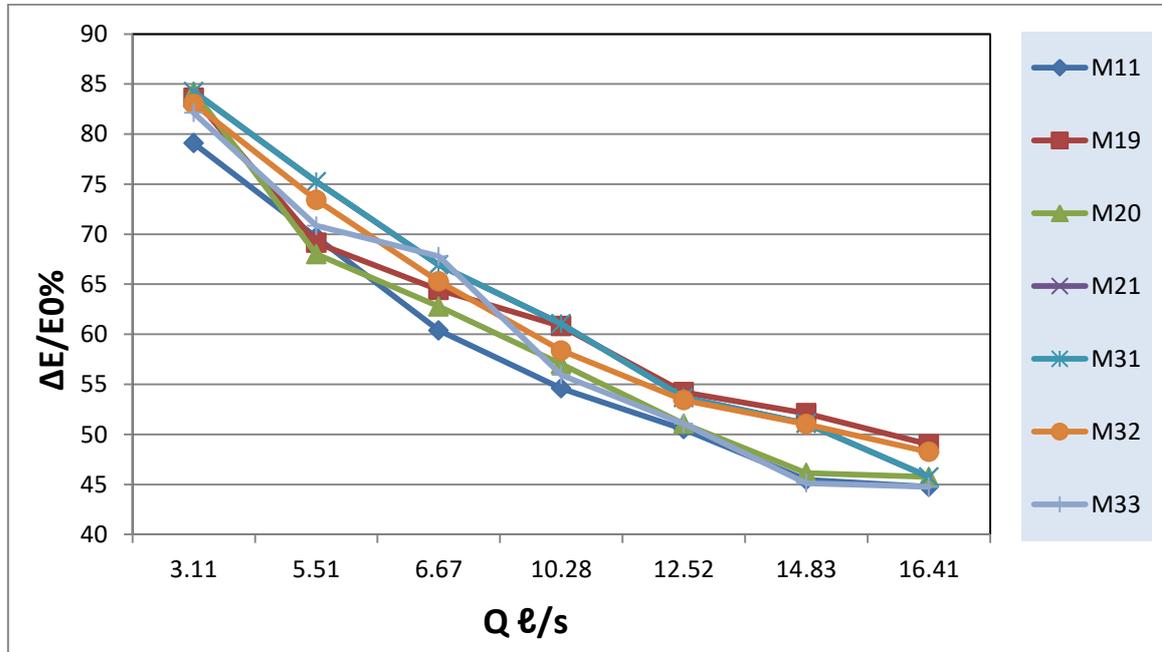

Figure 4.18. The relationship between ΔE/E0 % and discharge for uniform 10 stepped spillway with different baffled blocks distribution.

4.4.4. Non-Uniform 10 steps (⊖= 45°).

The relationship between ΔE/E0 % and discharge for non-uniform 10 stepped spillway with different baffles blocks distribution is negative relationship and increasing one of them lead to decrease the other one as indicated in Figure 4.19. Also, the highest energy dissipation was recorded at low flow discharge, while increasing the flow discharge lead to reduce the energy dissipation for all selected models before and after placing different baffles blocks distribution. Sample M35 with 10 steps non-uniform and one baffle with distribution (B/2.5) records the highest energy dissipation.
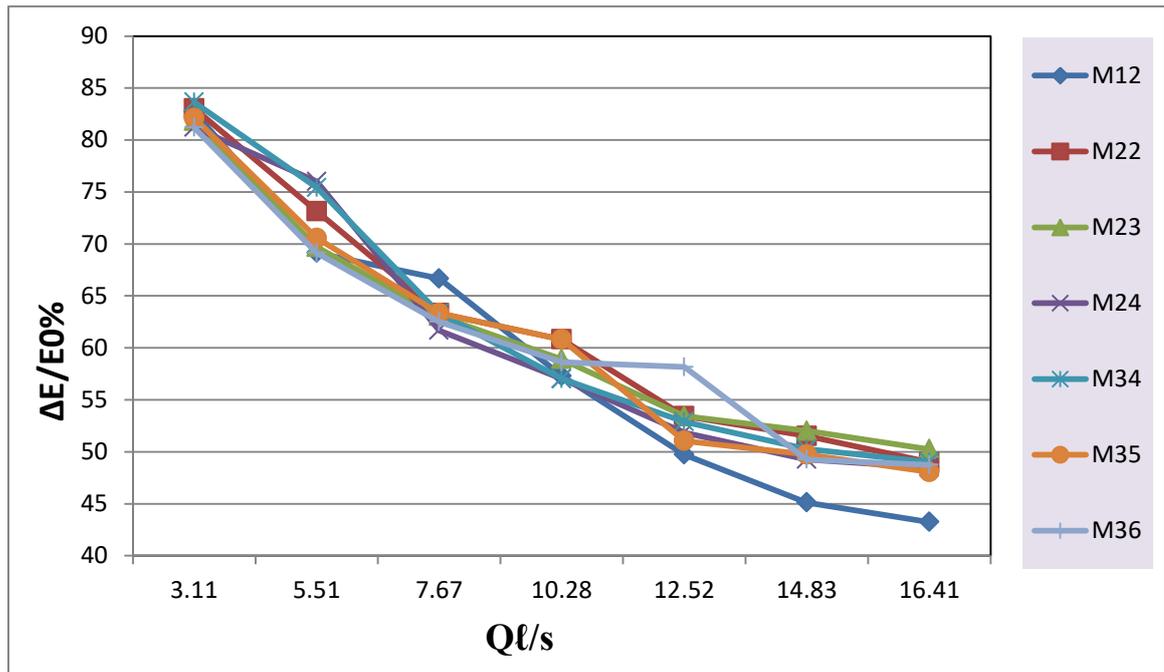
Figure 4.19. The relationship between ΔE/E0 % and discharge for non-uniform 10 stepped spillway with different baffled blocks distribution.

4.5. The effect of different distribution of baffled blocks on Energy Dissipation:

In order to enhancement the increase of Energy dissipation, we used the baffled blocks, which were proven on a physical model at the angle of 45⁰, with a different number of steps, five and ten steps, and with different distributions(B/2, B/2.5and B/3) for the uniform and non-uniform stepped spillway. The baffled blocks contain two types first case one baffled blocks and second case two baffled blocks time during the laboratory results between the effect of adding baffled blocks of the two types first case one baffled blocks and second case baffled blocks on increasing Energy dissipation compared with models without of baffled blocks and through the results was the first case one baffled blocks Better in dissipation than the second case two baffled blocks. Model 26 uniform five step one baffled (B/2.5) is the best dissipation model compared to the rest of the models as shown in figure (4.20 to 4.27).

Figure 4.20. The percentage of energy dissipation versus the dimensionless parameter (yc/h) For (N=5) uniform second case two baffled blocks.

Figure 4.21. The percentage of energy dissipation versus the dimensionless parameter (yc/h) For (N=5) uniform first case one baffled blocks.

Figure 4.22. The percentage of energy dissipation versus the dimensionless parameter (yc/h) For (N=10) uniform second case two baffled blocks.

Figure 4.23. The percentage of energy dissipation versus the dimensionless parameter (yc/h) for (N=10) uniform first case one baffled blocks.

Figure 4.24 The percentage of energy dissipation versus the dimensionless parameter (yc/h) for (N=5) non- uniform first case one baffled blocks.
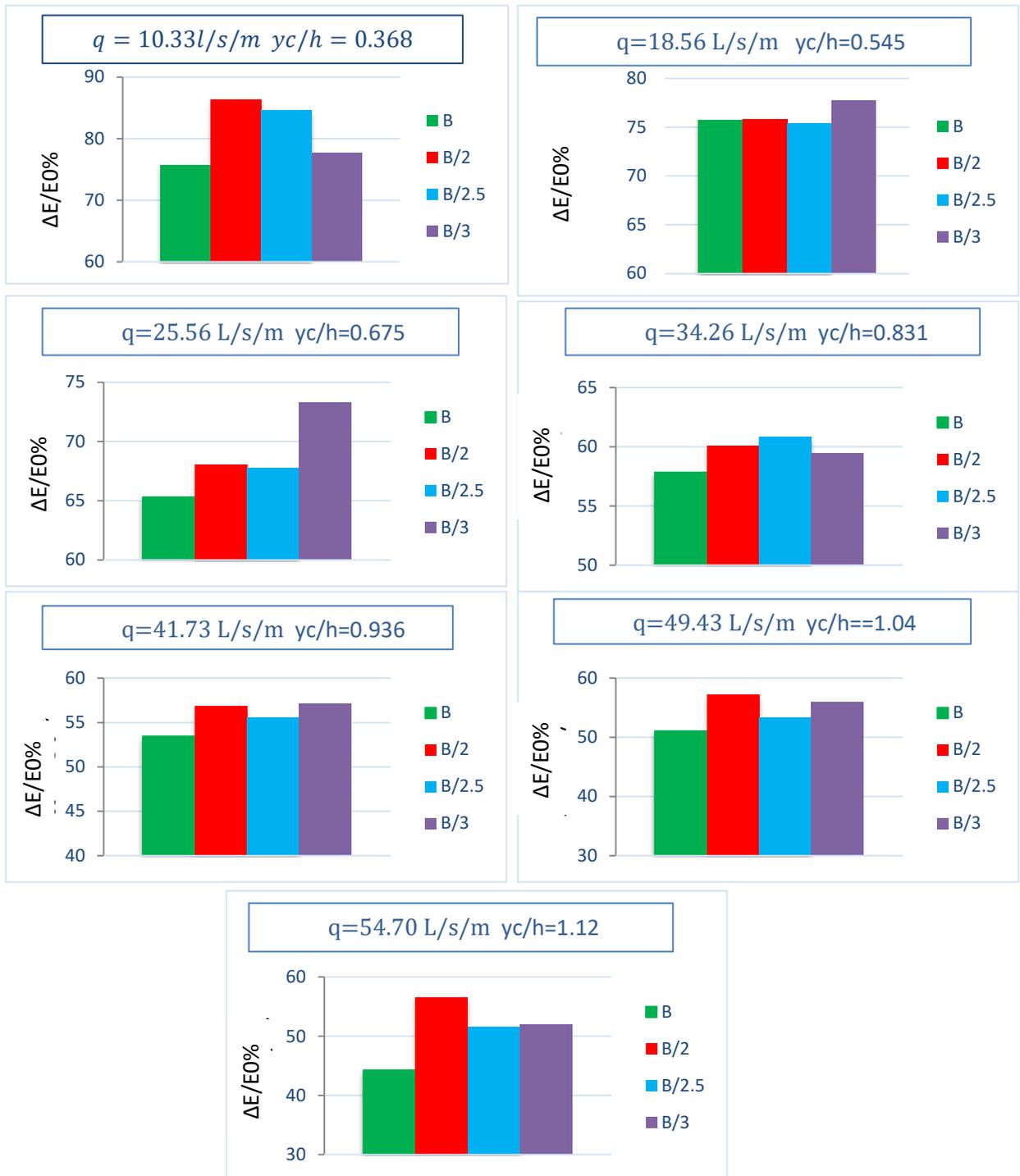
Figure 4.25. The percentage of energy dissipation versus the dimensionless parameter (yc/h) for (N=5) non uniform second case two baffled blocks.
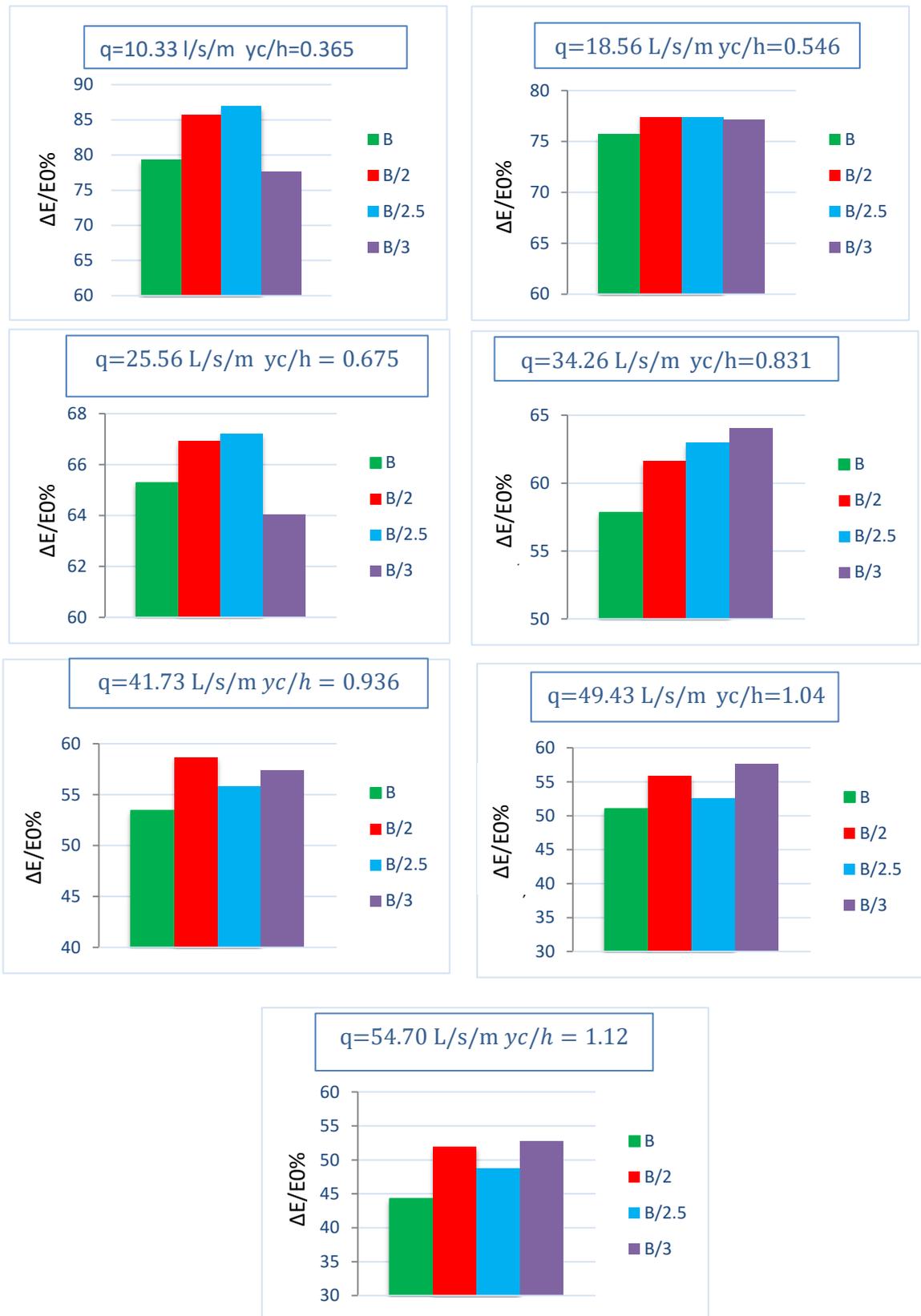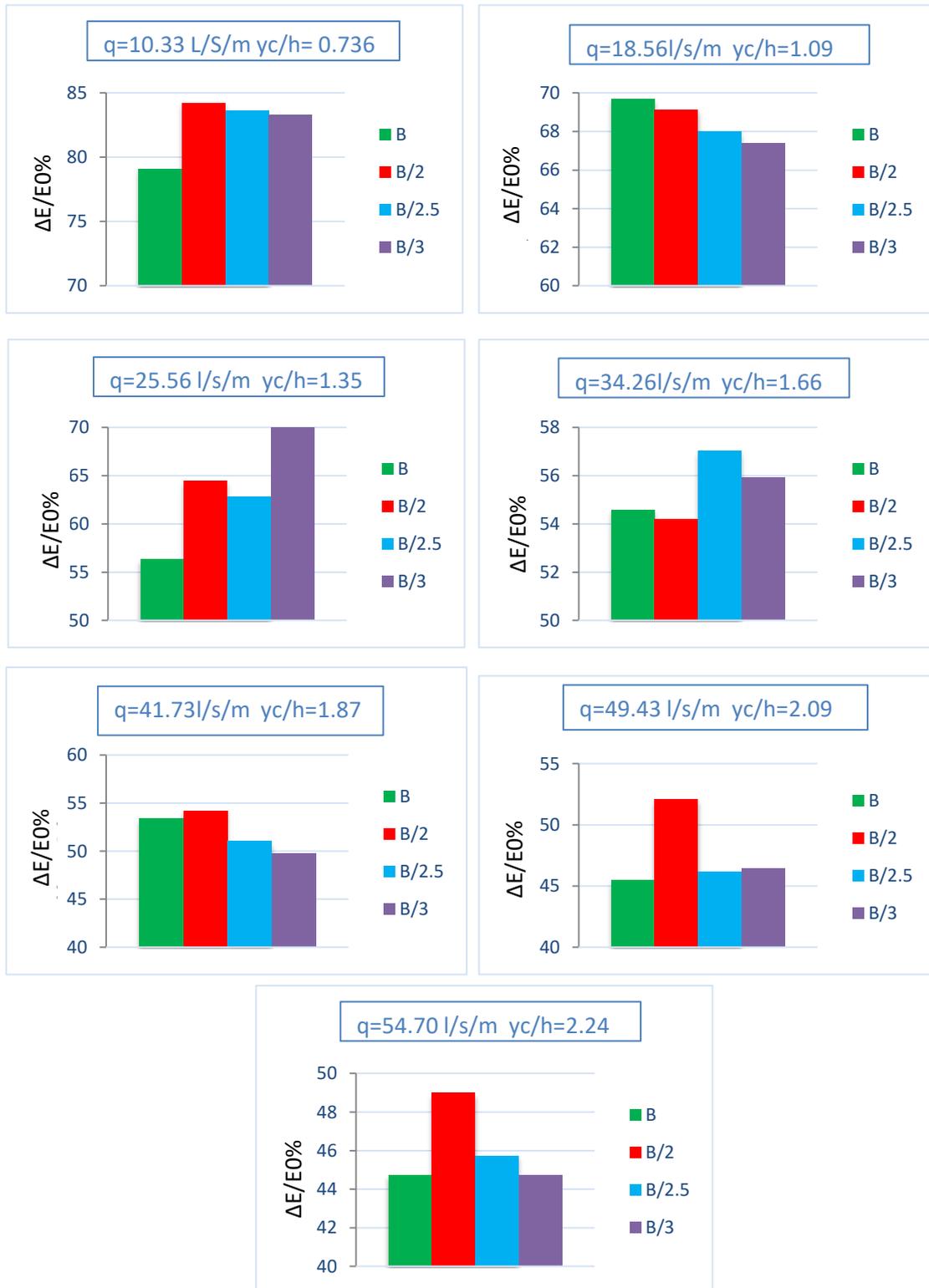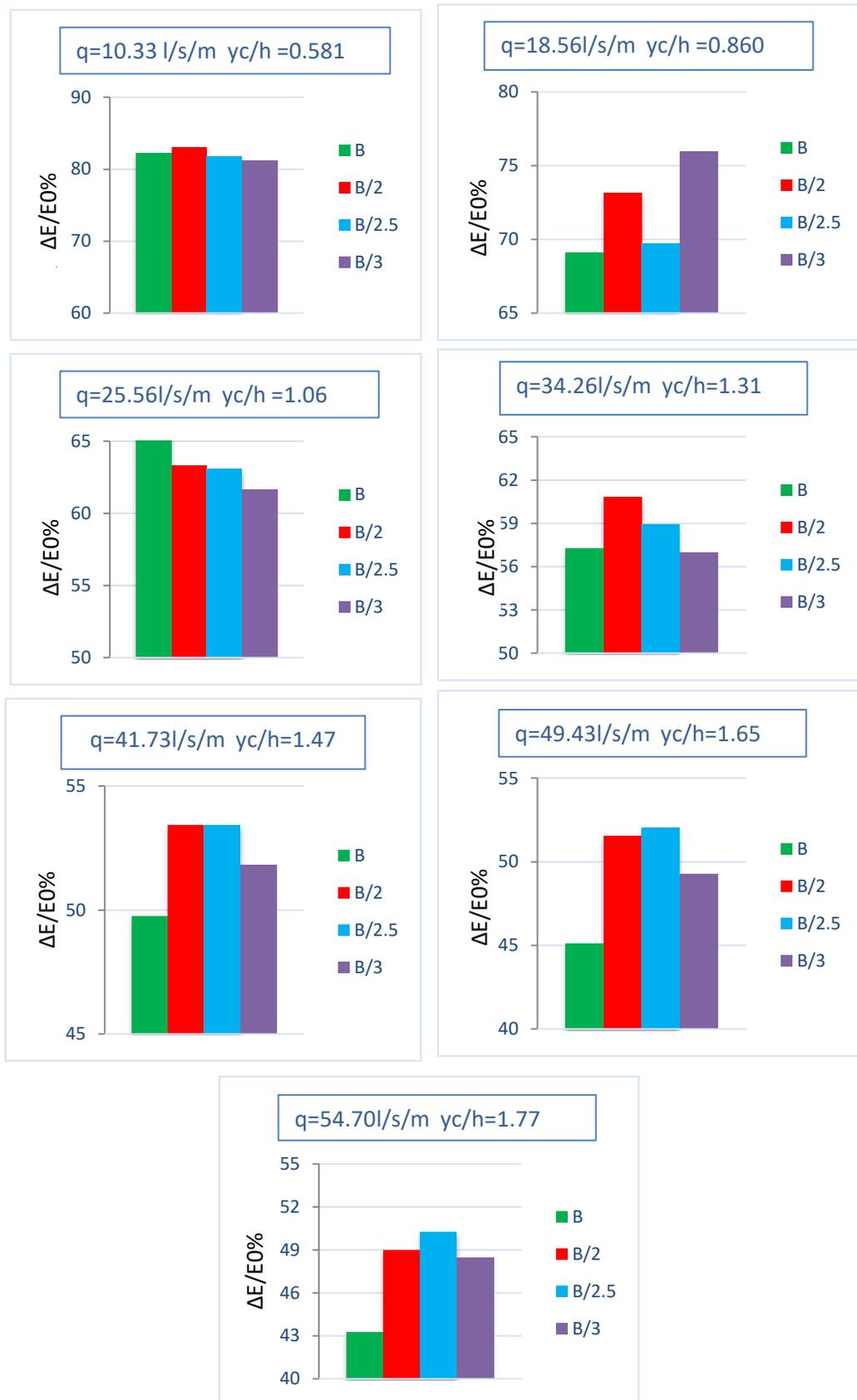
Figure 4.26.The percentage of energy dissipation versus the dimensionless parameter (yc/h) for (N=10) non- uniform second case two baffled blocks.
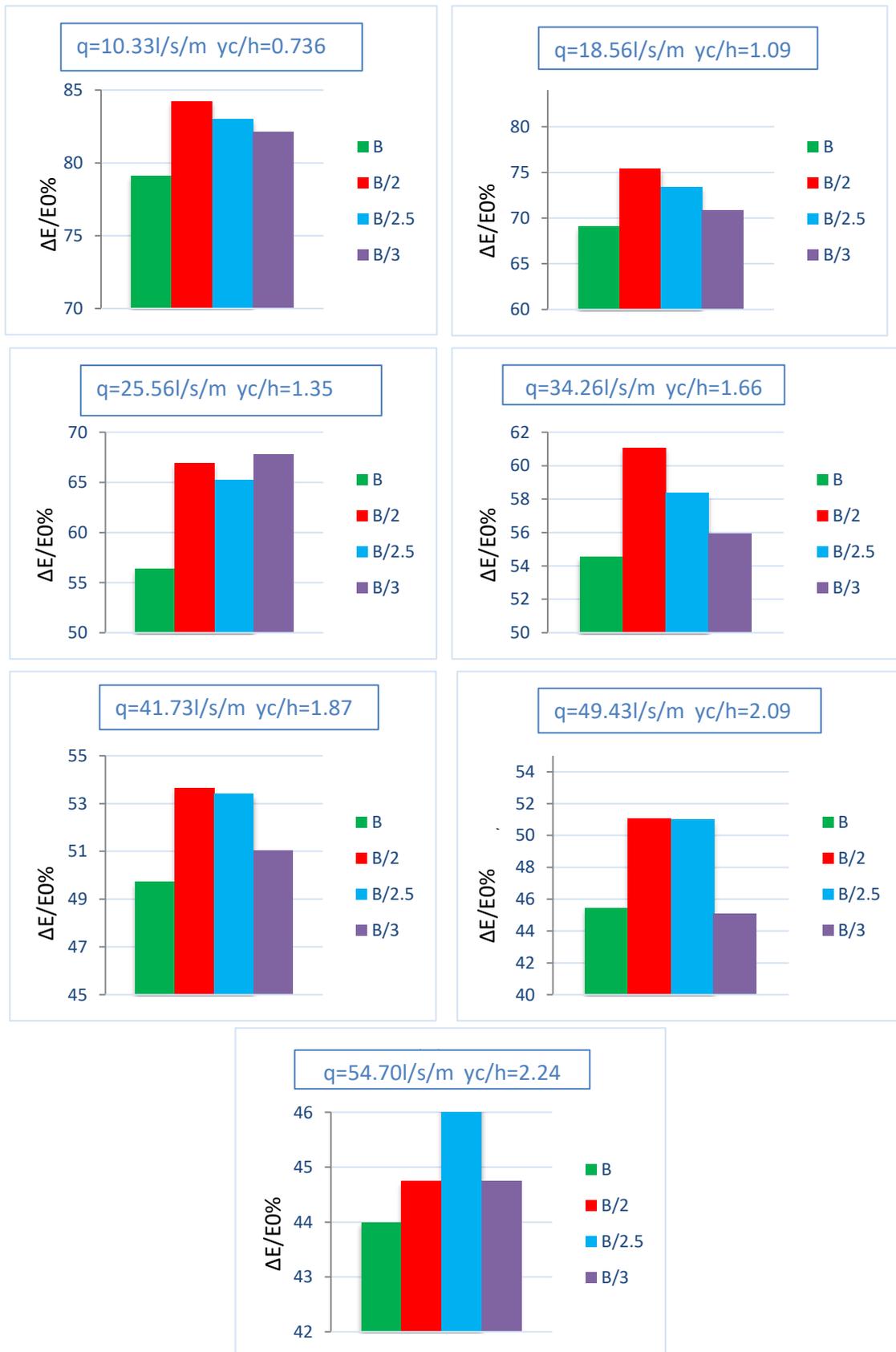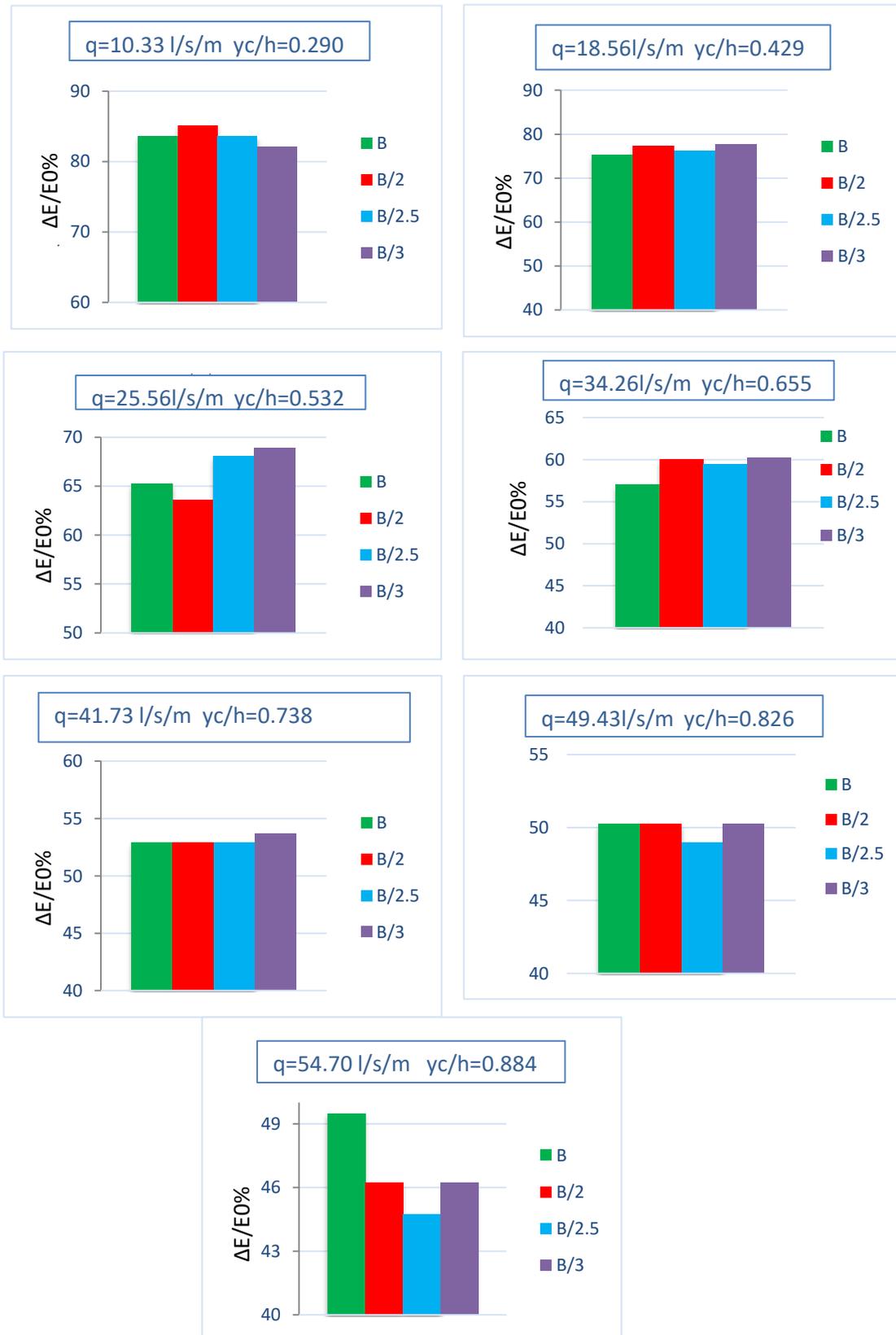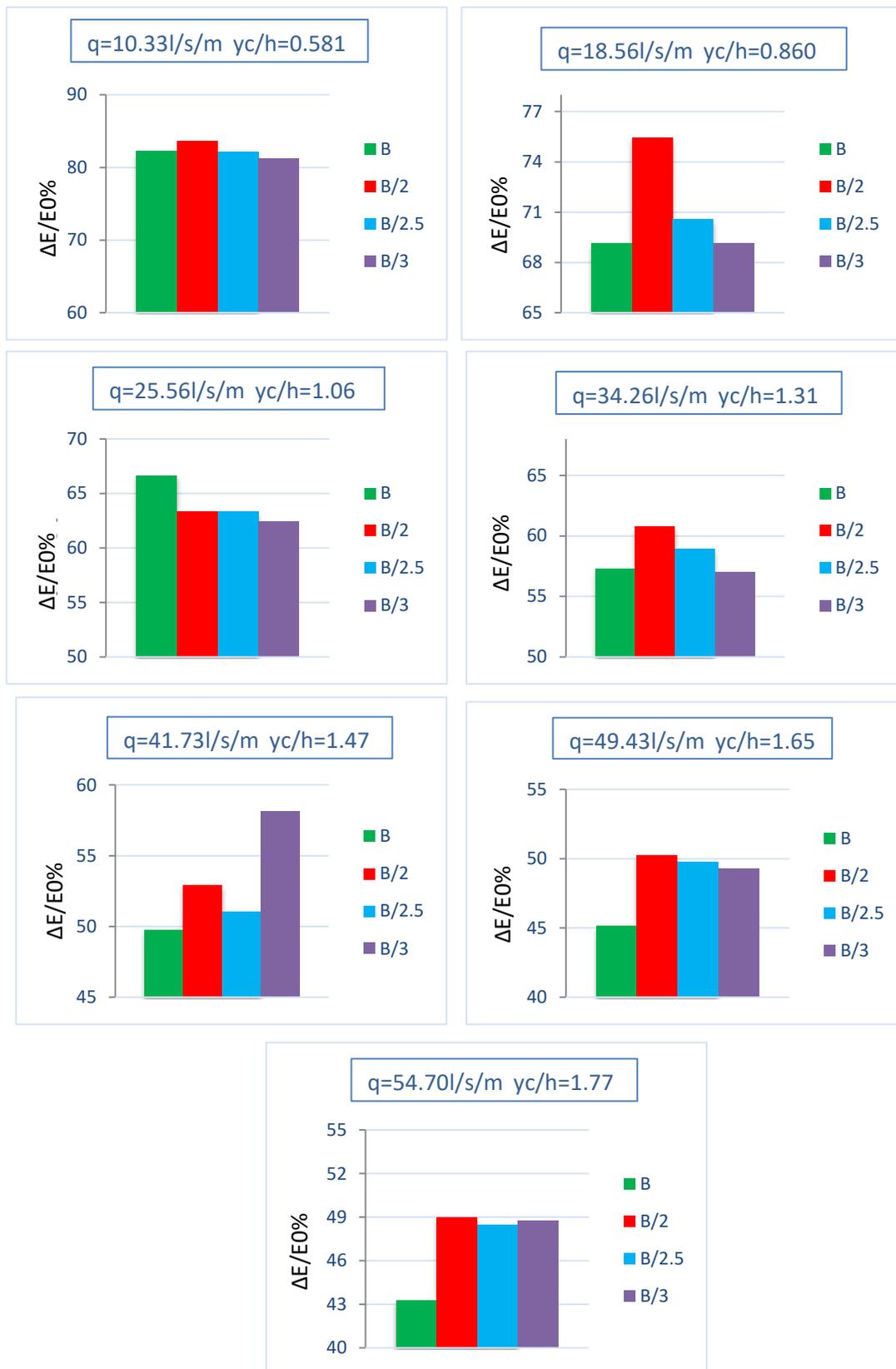
Figure 4.27. The percentage of energy dissipation versus the dimensionless parameter (yc/h) for (N=10) non- uniform first case one baffled blocks.
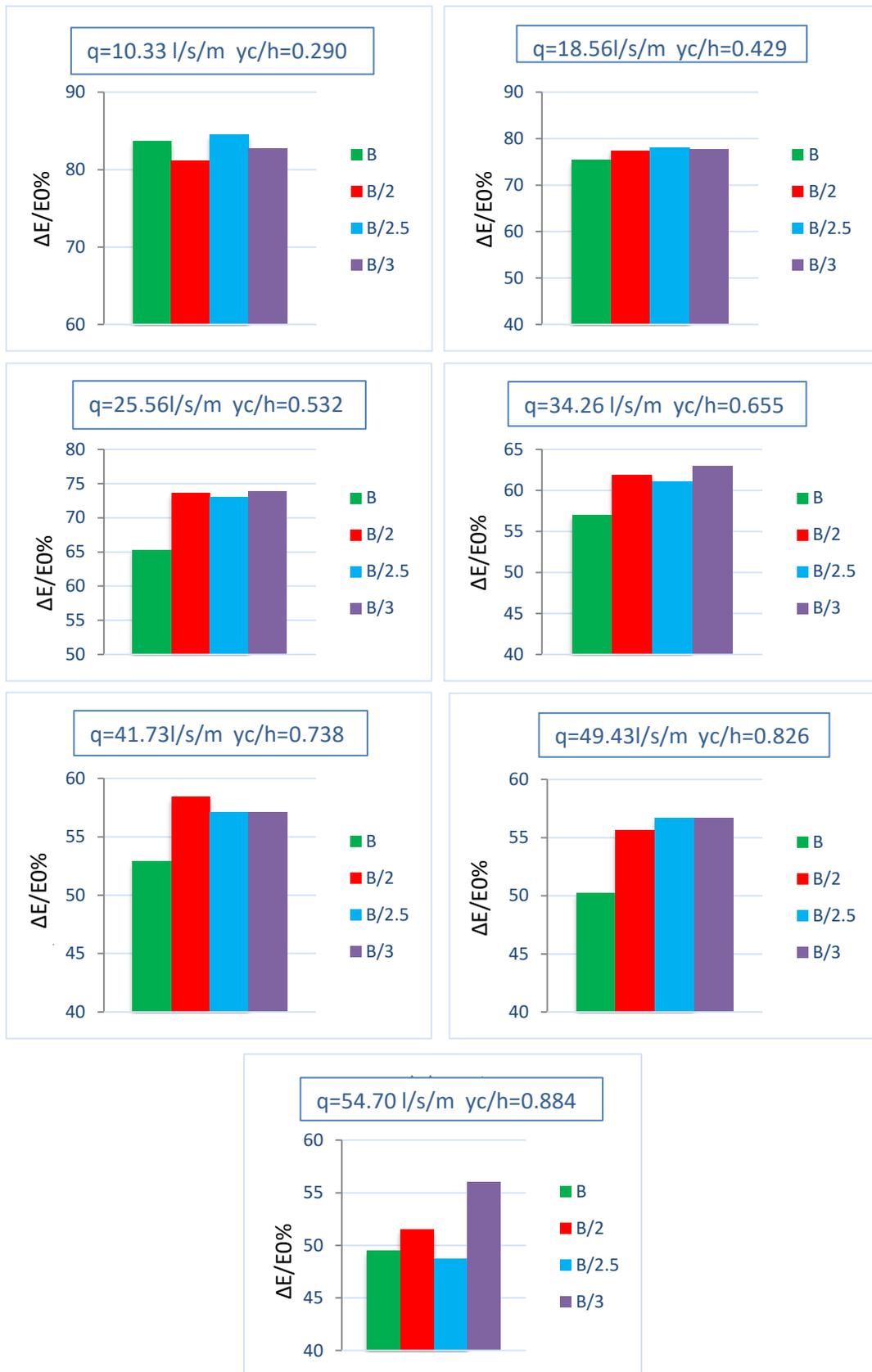
4.6. Effect of discharge and number of steps on length hydraulic jump with constant slope:

4.6.1. spillway way at 30⁰angle :

The relationship between hydraulic jump length and discharge for spillway at 30⁰ is positive relationship and increasing one of them lead to increasing the other one as indicated in Figure 4.28 When increasing the flow rate increasing hydraulic jump. Additionally model M2 which has five steps and non-uniform stepped spillway records the shortest hydraulic jump length.
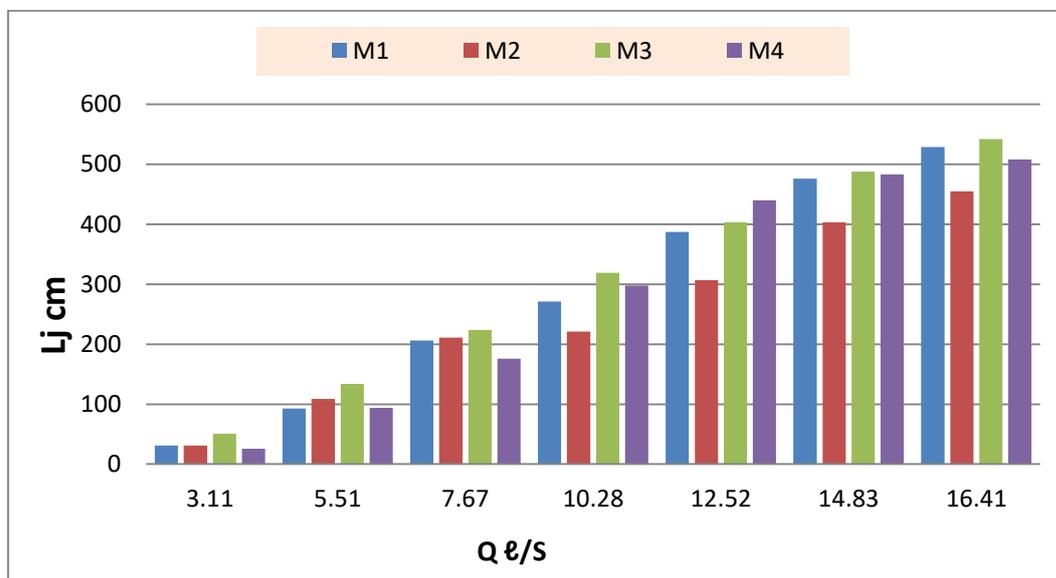
Figure 4.28. The relationship between hydraulic jump length and discharge for spillway at angle of 30⁰.

4.6.2. spillway way at 40⁰angle :

For spillways with at angle of 40⁰ ,there is a positive correlation between hydraulic jump length and discharge, with increasing discharge leading to longer hydraulic jumps, as shown in Figure 4.29. Additionally, sample M6, which has five steps and a non-uniform stepped spillway, records the shortest hydraulic jump length.
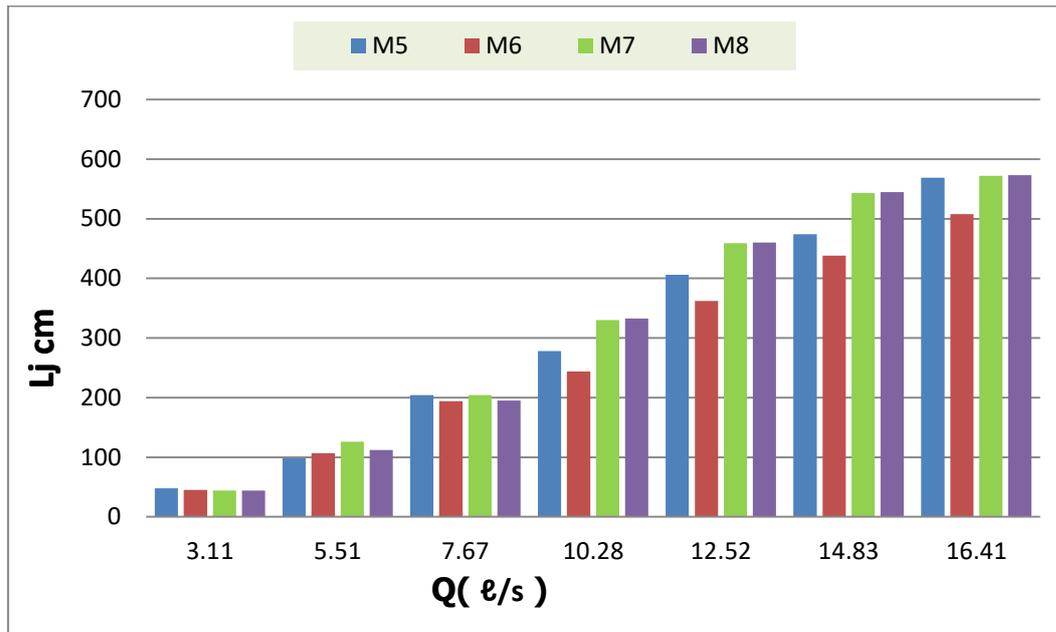
Figure4.29. The relationship between hydraulic jump length and discharge for spillway at angle of 40⁰.

4.6.3. Spillway way at 45⁰angle :

The relationship between hydraulic jump length and discharge for spillway at 45 degree is positive relationship and increasing one of theme lead to increasing the other one as indicated in Figure 4.30. Also, sample M10 with 5 steps and Non-uniform stepped spillway records the lowest hydraulic jump length with the rest of the models.
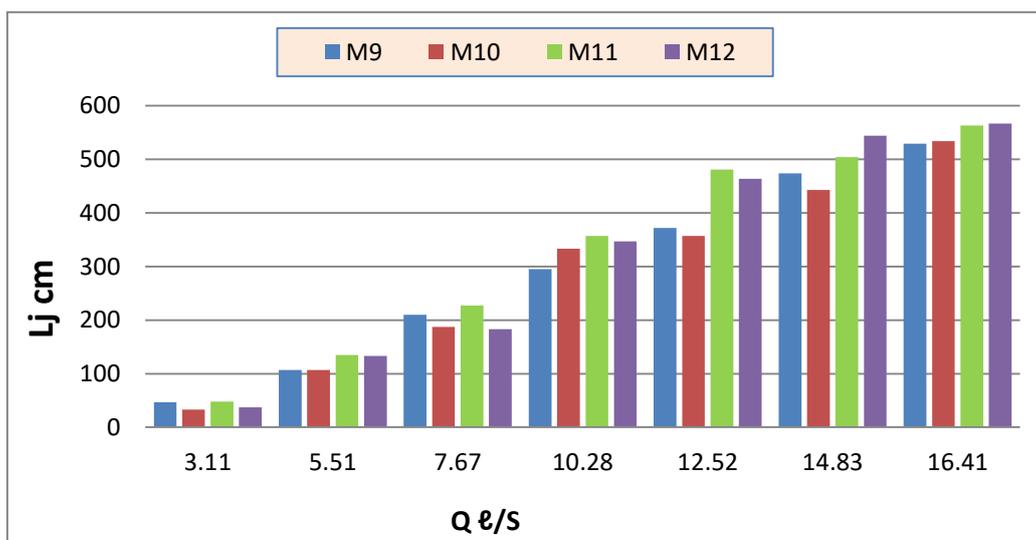
Figure4.30. The relationship between hydraulic jump length and discharge for spillway at angle of 45⁰.

4.7. Effect baffled blocks on length of hydraulic jump with constant number of steps:

4.7.1: Uniform 5 steps at angle 45° with first case one baffled blocks and second case two baffled blocks:

Figure 4.31 shows the relationship between hydraulic jump length and discharge uniform 5 stepped spillway with different baffles blocks distribution mentioned previously. All selected conditions show that the hydraulic jump length increased with increasing the flow discharge. For the current condition sample M25 with uniform 5 stepped spillway with first case B/2 one baffle recorded the shortest hydraulic jump length comparison with sample M9 without baffle block. In general, using of baffled blocks lead to reduce the length of the hydraulic jump length.

Figure 4.31. The relationship between hydraulic jump length and discharge for uniform 5 stepped spillway with different baffled blocks distribution.

4.7.2: Non-uniform 5 steps at angle 45⁰ with first case one baffled blocks and second case two baffled blocks:

The relationship between hydraulic jump length and discharge for non-uniform 5 stepped spillway with different baffles blocks distribution as shown Figure 4.32. For the selected conditions hydraulic jump length fluctuated with discharge, where in low discharge M28 with 5 steps non-Uniform and first case one baffled with distribution (B/2) has the shortest hydraulic jump length comparison with M10 without baffles block that recorded the longest hydraulic jump length. The using of baffled in different ratio reduce the hydraulic jump length in high flow discharge at the same time the flow behaviors still similar before and after placing baffled blocks in different distribution, where increasing the flow discharge lead to increase the length of hydraulic jump.

Figure 4.32. The relationship between hydraulic jump length and discharge for non-uniform 5 stepped spillway with different baffled blocks distribution.

4.7.3: Uniform 10 steps at angle 45⁰ with first case one baffled blocks and second case two baffled blocks:
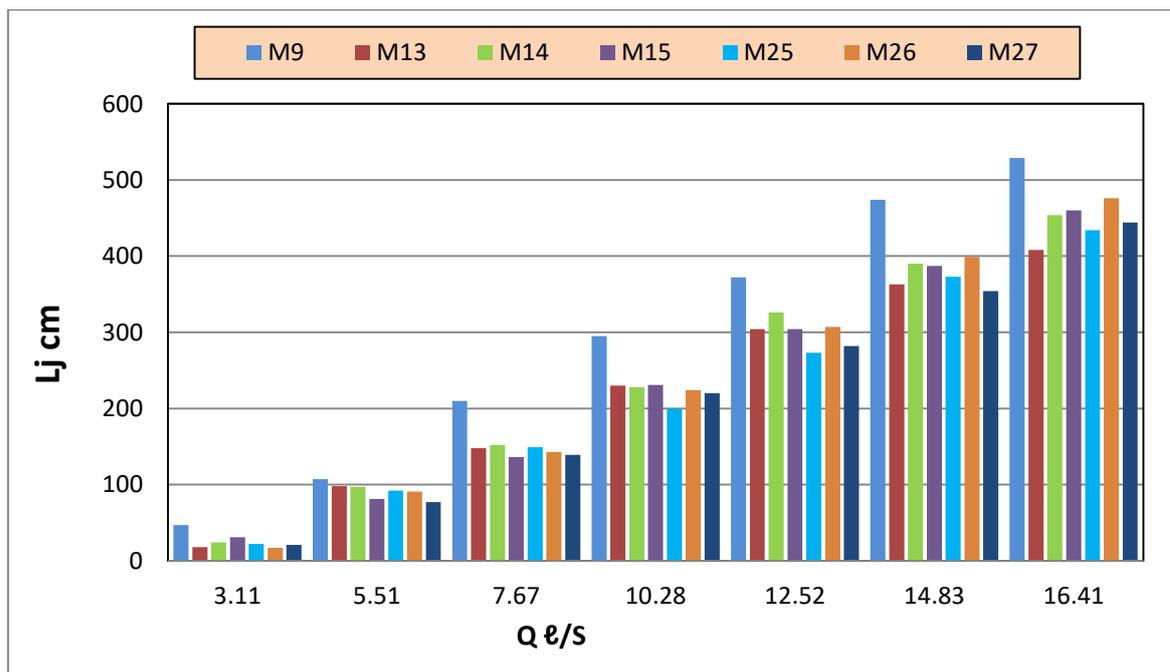
The relationship between hydraulic jump length and discharge for uniform 10 stepped spillway with different baffled blocks distribution as shown Figure 4.33. For the selected conditions hydraulic jump length fluctuated with discharge, where in low discharge M31 with 10 steps Uniform and first case one baffled with distribution (B/2) has the shortest hydraulic jump length comparison with other conditions and M11 without baffled block that recorded the longest hydraulic jump length. The using of baffled in different ratio reduce the hydraulic jump length in high flow discharge at the same time the flow behaviors still similar before and after placing baffled blocks in different distribution, where as increasing the flow discharge leads to increase the length of hydraulic jump.

Figure 4.33. The relationship between hydraulic jump length and discharge for uniform 10 stepped spillway with different baffled blocks distribution.

4.7.4: Non-uniform 10 steps at angle 45⁰ with first case one baffled blocks and second case two baffled blocks:

The relationship between hydraulic jump length and discharge for non-uniform ten stepped spillway with different baffled blocks distribution as shown Figure 4.34. For the selected conditions hydraulic jump length fluctuated with discharge, where in low discharge M34 with 10 steps non-uniform and first case one baffled with distribution (B/2) has the shortest hydraulic jump length comparison with other conditions and M12 without baffled block that recorded the longest hydraulic jump length. The using of baffled in different ratio reduce the hydraulic jump length in high flow discharge at the same time the flow behaviors still similar before and after placing baffled blocks in different distribution, where increasing the flow discharge lead to increase the length of hydraulic jump.
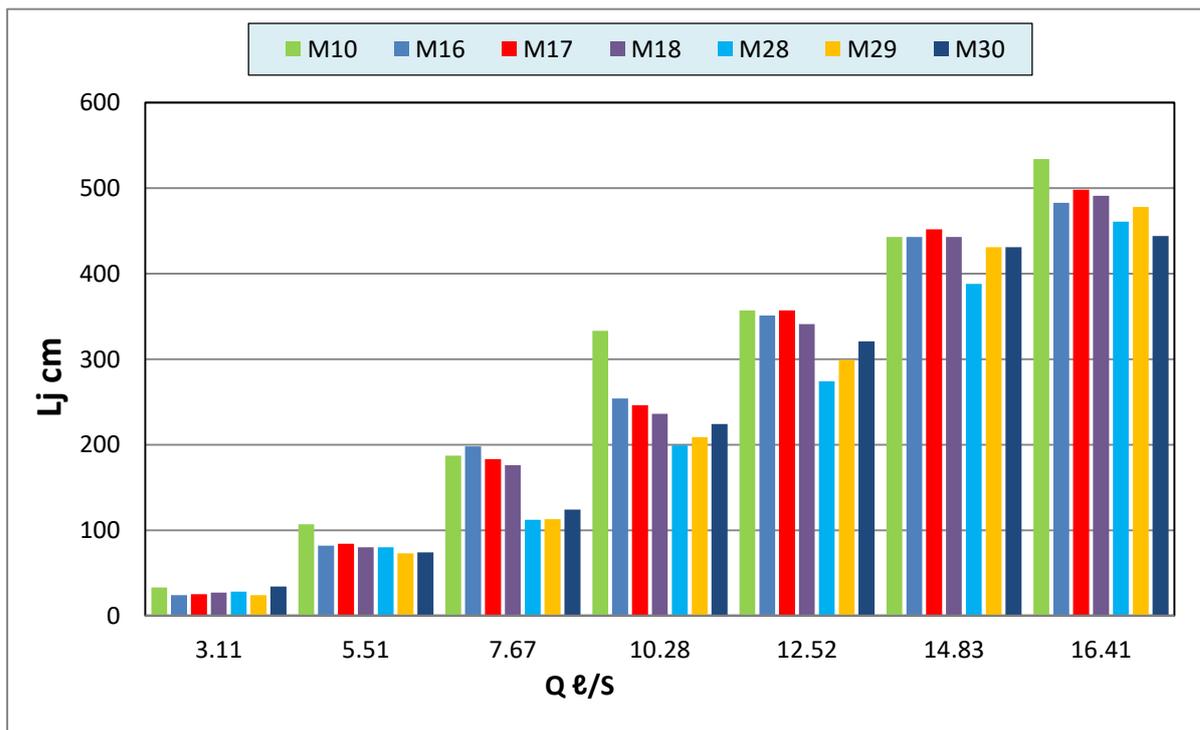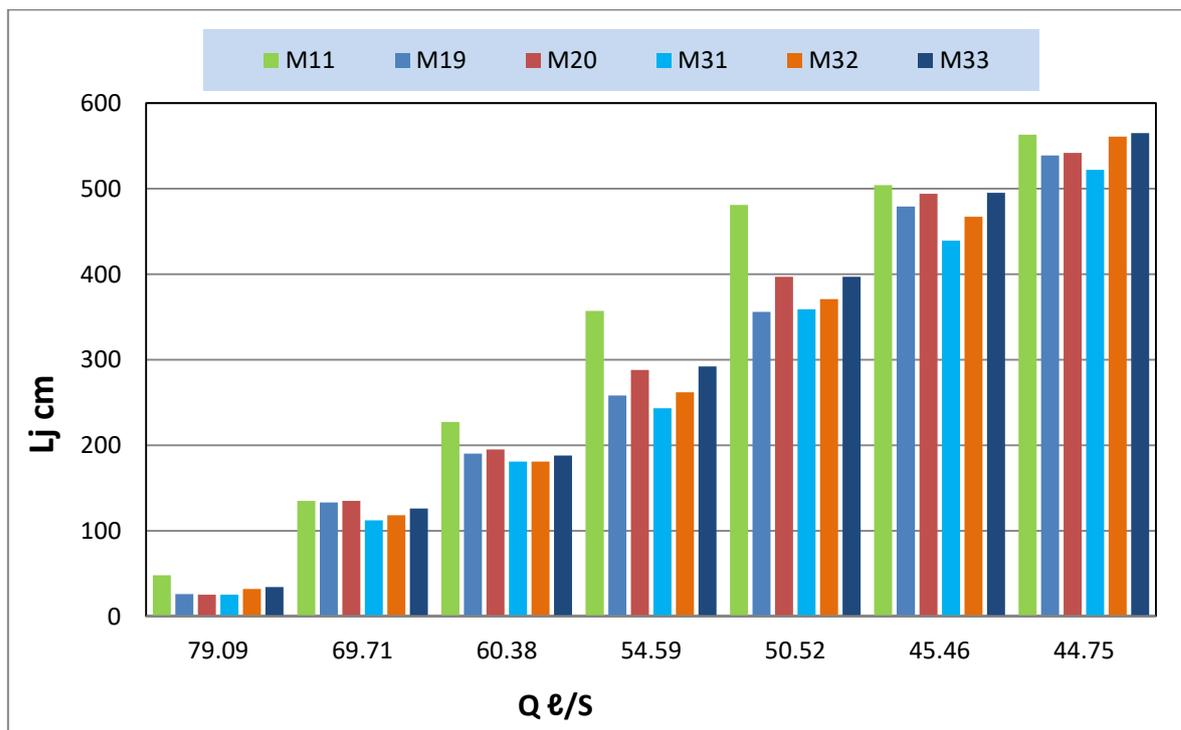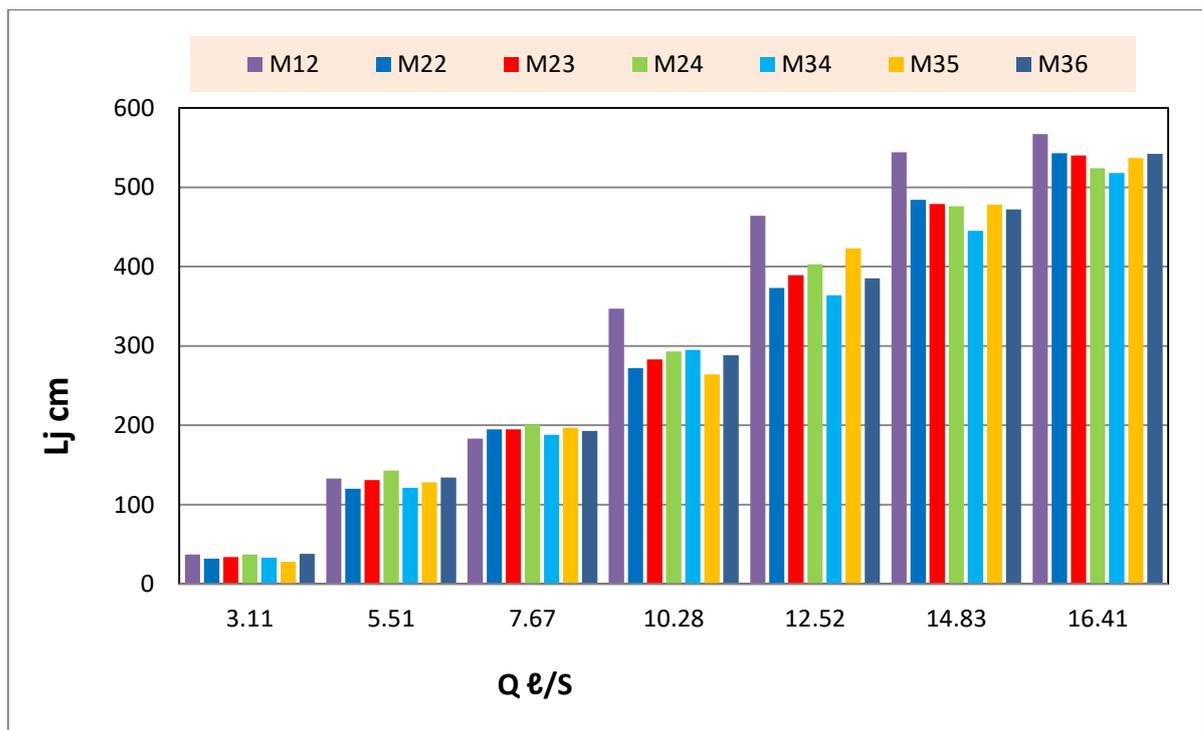

Figure 4.34. The relationship between hydraulic jump length and discharge for non-uniform 10 stepped spillway different baffled blocks distribution.

4.8. The Relationshape Of Effective Parameter On Energy Dissipation:

4.8.1. the Relationshape between critical depth and energy dissipation :

The critical depth in a rectangular canal may predict the flow rate, therefore the relative energy dissipation increases as the flow rate decreases. As the discharge lowers or implicitly as the critical depth (yc) decreases, the relative energy dissipation commonly rises. This rise is clearly visible in figure.

As previously indicated, as the river discharge grows, the critical depth rises as well, increasing the speed and flow thickness on the steppes. This lessens the flow's exposure to the roughness of the stairs, which lowers the quantity of energy lost. The flow changes from nappe to skimming flow as the critical depth rises regime and energy dissipation decrease as observed in figure (4.35 to 41).
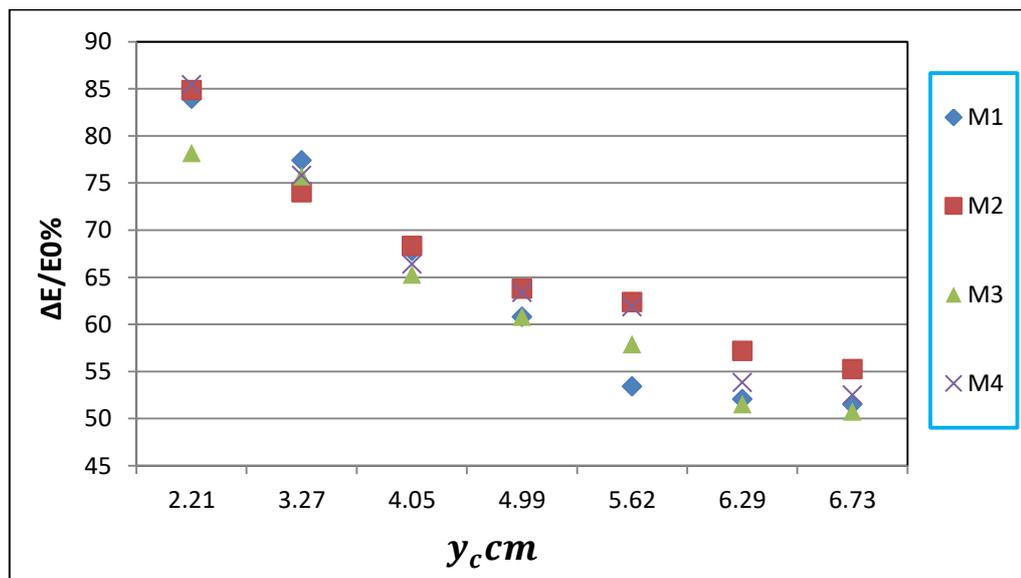
Figure 4.35. The relationship between $\Delta E/E0$ % and y_c for Stepped Spillway at angle of 30^0.
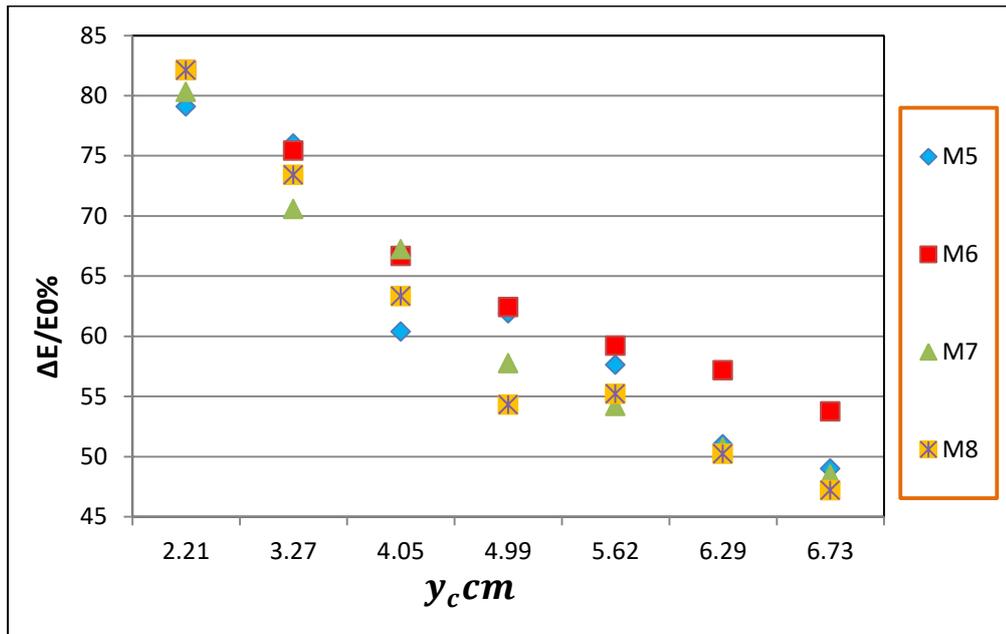
Figure4.36. The relationship between ΔE/E0 % and y_c for Stepped Spillway at angle of 40⁰.
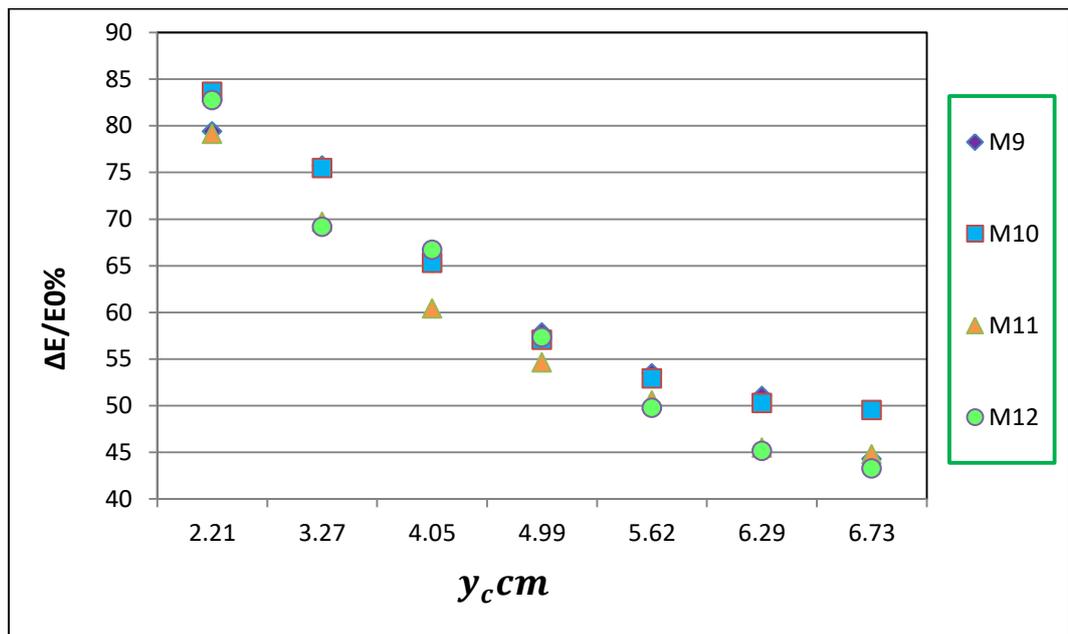
Figure4.37. The relationship between ΔE/E0 % and y_c for Stepped Spillway at angle of 45⁰.
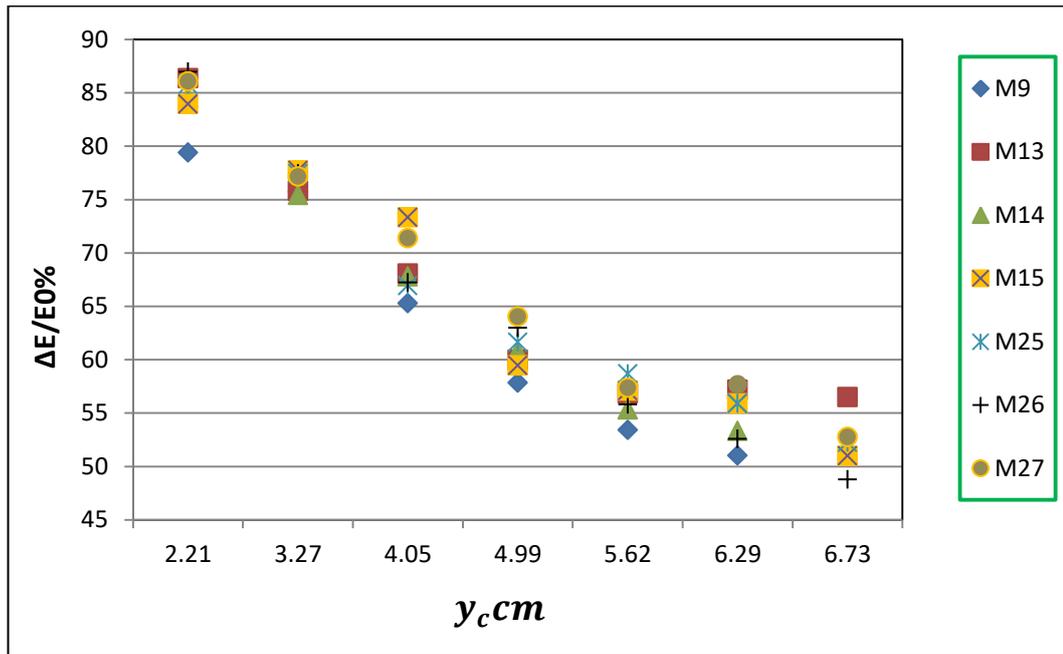
Figure 4.38. The relationship between $\Delta E/E0$ % and y_c for Stepped Spillway for uniform 5 stepped spillway at angle of 45º with different baffled blocks distribution.

Figure 4.39. The relationship between $\Delta E/E0$ % and y_c for Stepped Spillway at angle of 45º for non-uniform 5 stepped spillway with different baffled blocks distribution.

Figure 4.40. The relationship between ΔE/E0 % and y_c for Stepped Spillway at angle of 45º for uniform 10 stepped spillway with different baffled blocks distribution.

Figure 4.41. The relationship between ΔE/E0 % and y_c for Stepped Spillway at angle of 45º for uniform 10 stepped spillway with different baffled blocks distribution.

4.8.2 Relationshape between Froude number and energy dissipation rate:

The relationship between %ΔE/E0 and Froude's number for a stepped spillway at angle of 30⁰,40⁰ and 45⁰ is shown in Figure 4.42 to 4.48 for 4 different conditions (uniform and non-uniform) five and ten steps and with first case one baffled and second case two baffled blocks . All of the chosen conditions behave identically, with the exception of the flow on the stepped spillway with the non-uniform five steps. A stilling basin structure of some sort that has been utilized to dissipate energy is built into the spillway's foundation. All selected conditions show fluctuated behavior and changeable depending on both Froude's numbers and changing in energy dissipations. The change in discharge is most likely to explain a change in the type of flow from one type to another. The velocity changes when the discharge changes. This is why we draw the relationship between energy dissipation and the Froude number It will become a dissipation of energy and it will become a change flow regime.

The stilling basin may take a variety of shapes, from a simple concrete apron to a more intricate design that may incorporate rows of chute blocks, baffle piers, and a plain or dentate end-sill, depending on the anticipated Froude Number Fr_1 of the incoming flow. If the basin needs all three elements, the entire cost may increase substantially. Consequently, it would be wise to look into other potential remedies to the issue. At the base of the spillway, there is some kind of stilling basin construction that was utilized for energy dissipation.

Dynamic similitude demands keeping the Froude and Reynolds numbers constant if both gravitational and viscous forces are significant. As a result, the modeling exercise loses one degree of freedom, and the length ratio is no longer random but rather dependent on the choice of the fluid viscosity. In order to get around this problem, the Reynolds number is kept constant in the

same flow domain as the prototype and the Froude number is remained constant since gravitational forces are the dominating force.
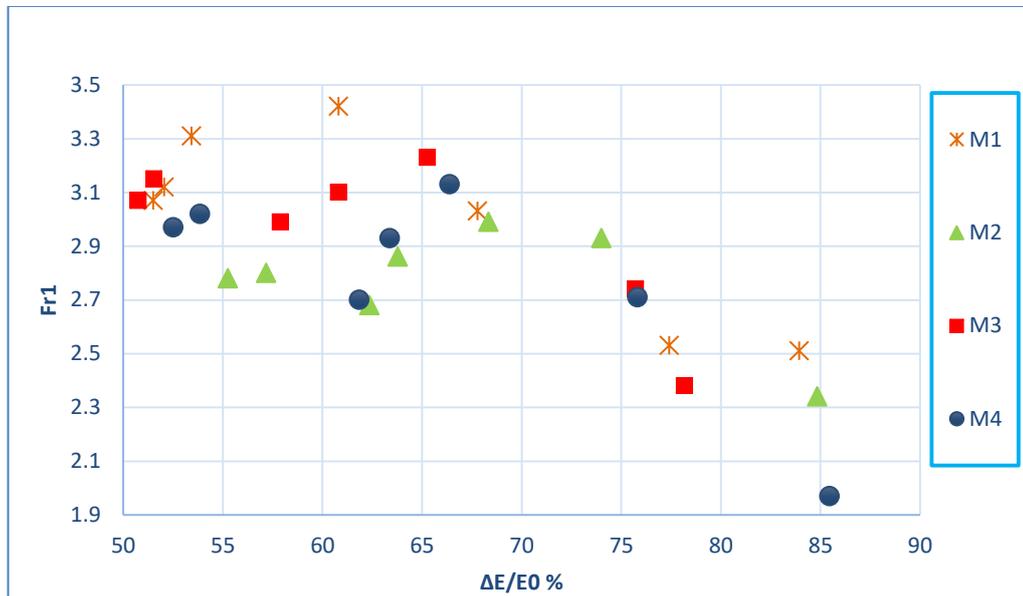
Figure 4.42. The relationship between Froude number and %ΔE/E0 for Stepped Spillway at angle of 30⁰.

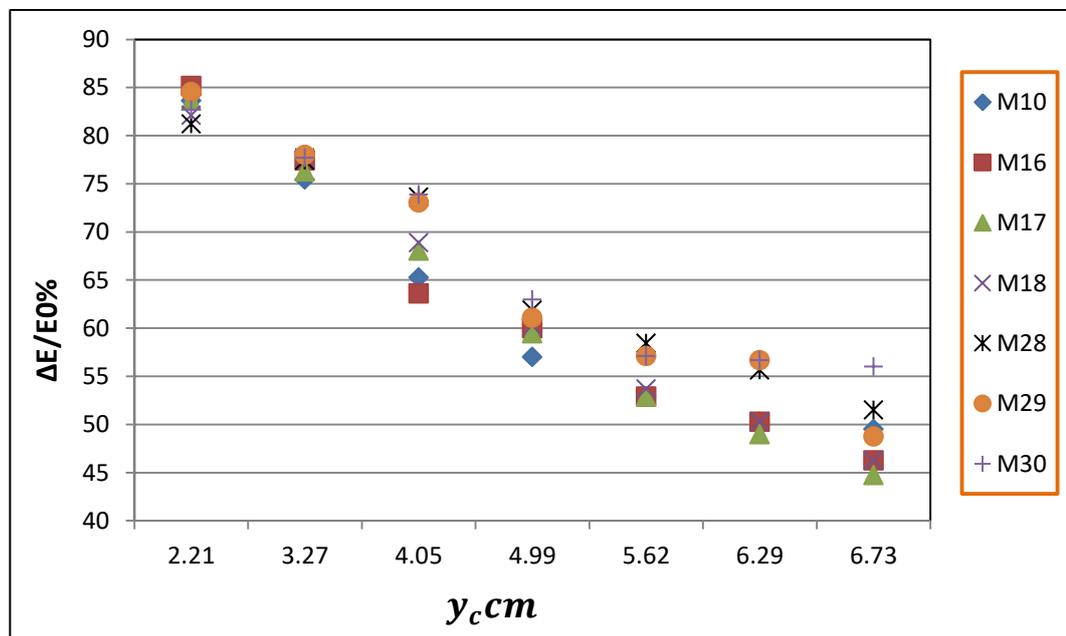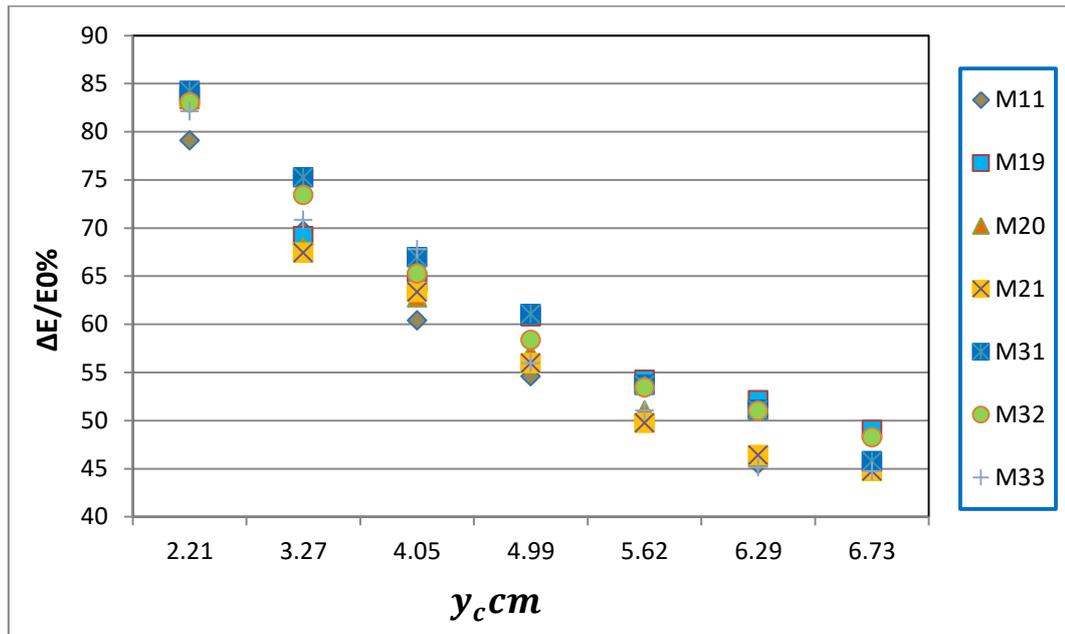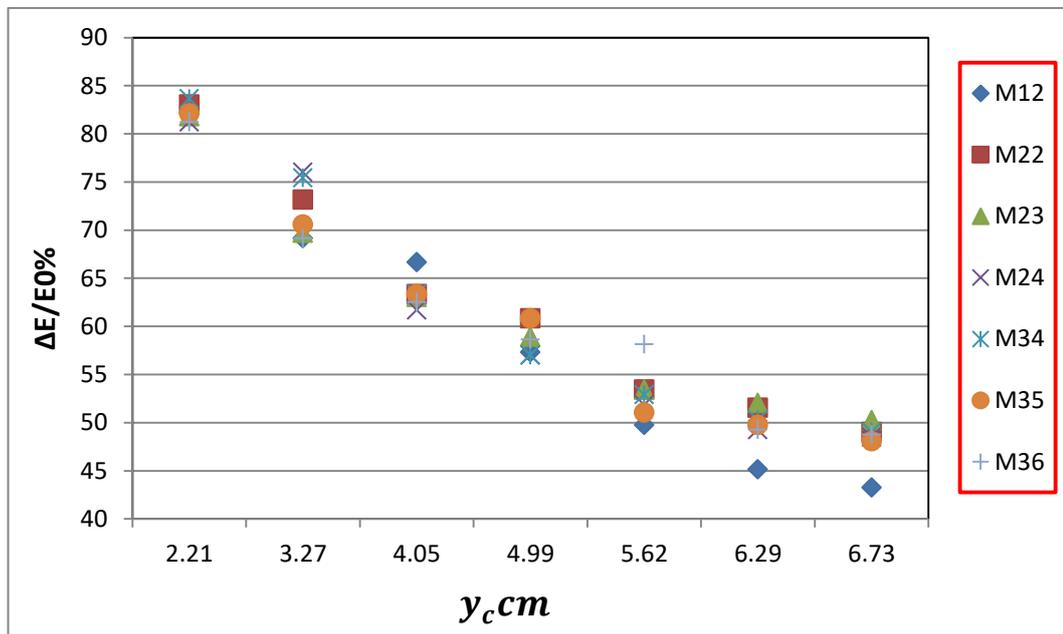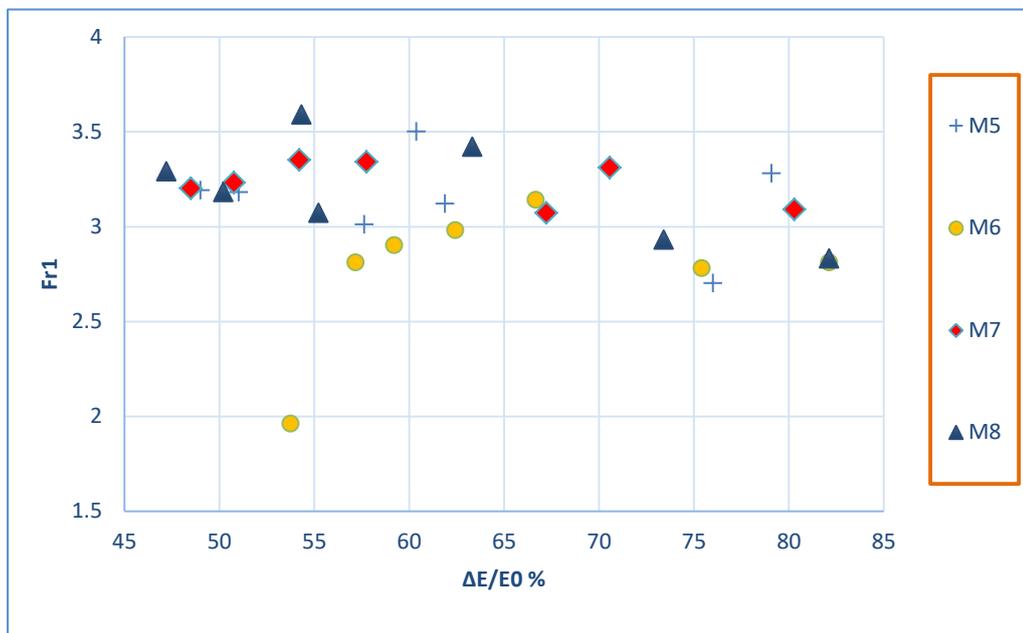**Figure 4.43.**The relationship between Froude number and ΔE/E0 % for Stepped Spillway at angle of 40⁰.
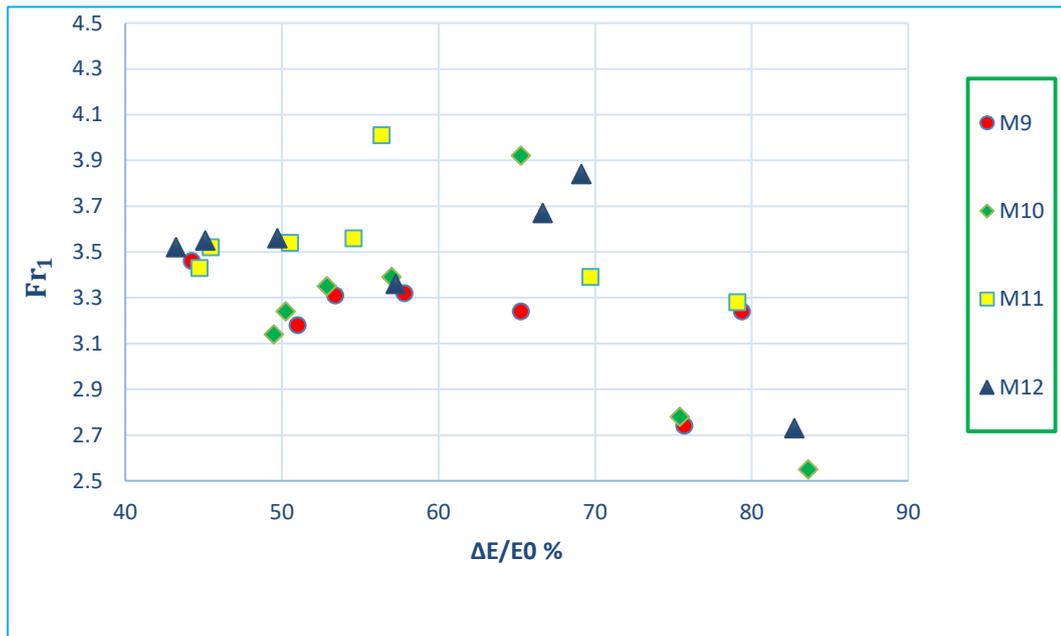
Figure 4.44. The relationship between Froude number and ΔE/E0 % for Stepped Spillway at angle of 45⁰.
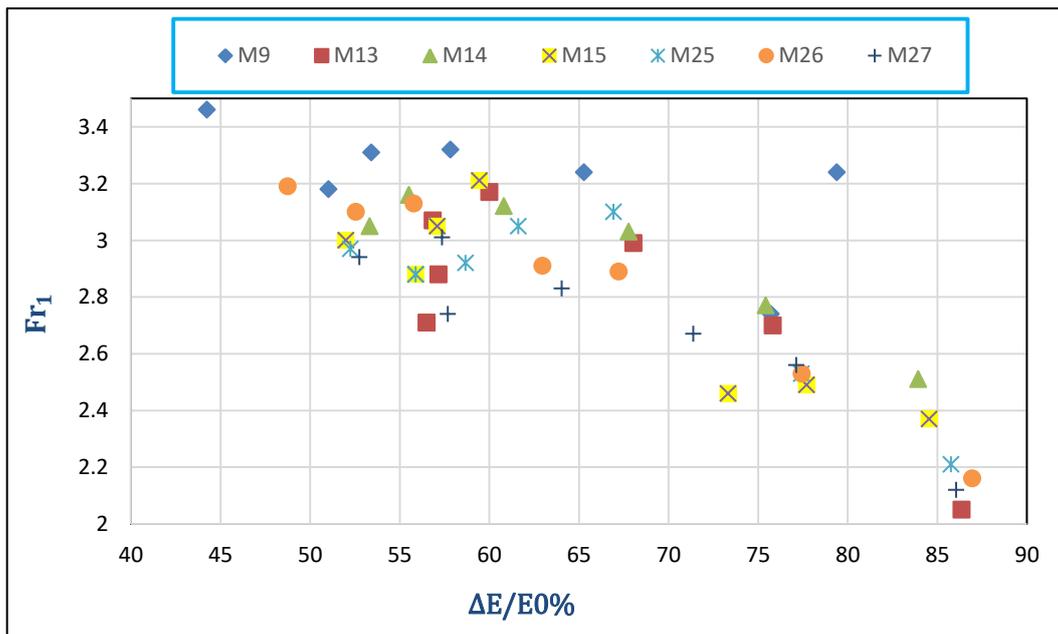
Figure 4.45. The relationship between Froude number and ΔE/E0 % for uniform 5 stepped spillway at angle of 45⁰ with different baffled blocks distribution.

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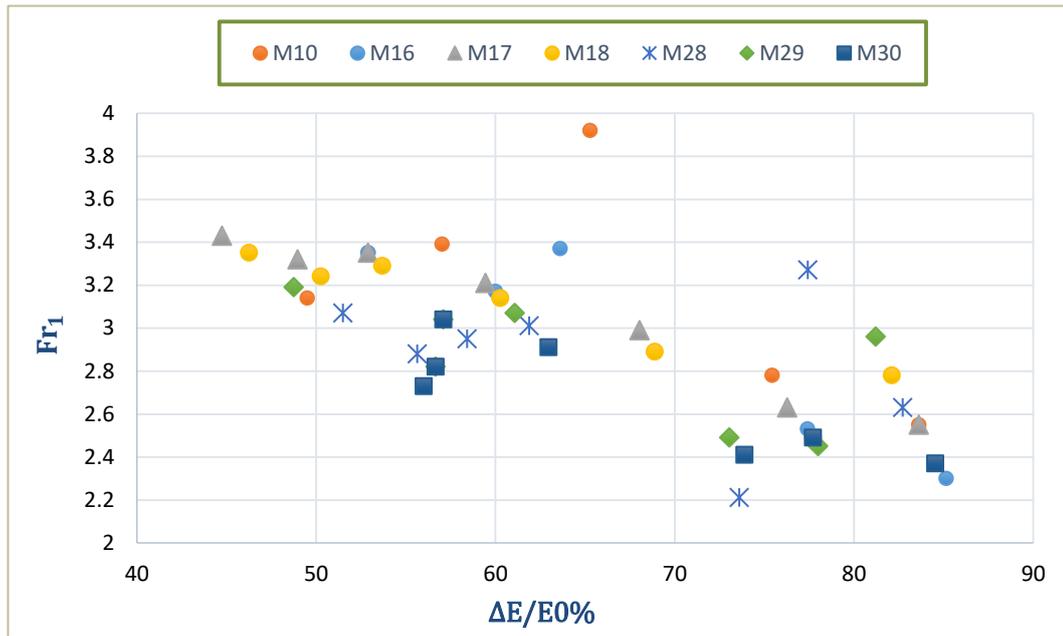
Figure 4.46. The relationship between Froude number and ΔE/E0% for non-uniform 5 stepped spillway at angle of 45⁰ with different baffled blocks distribution.
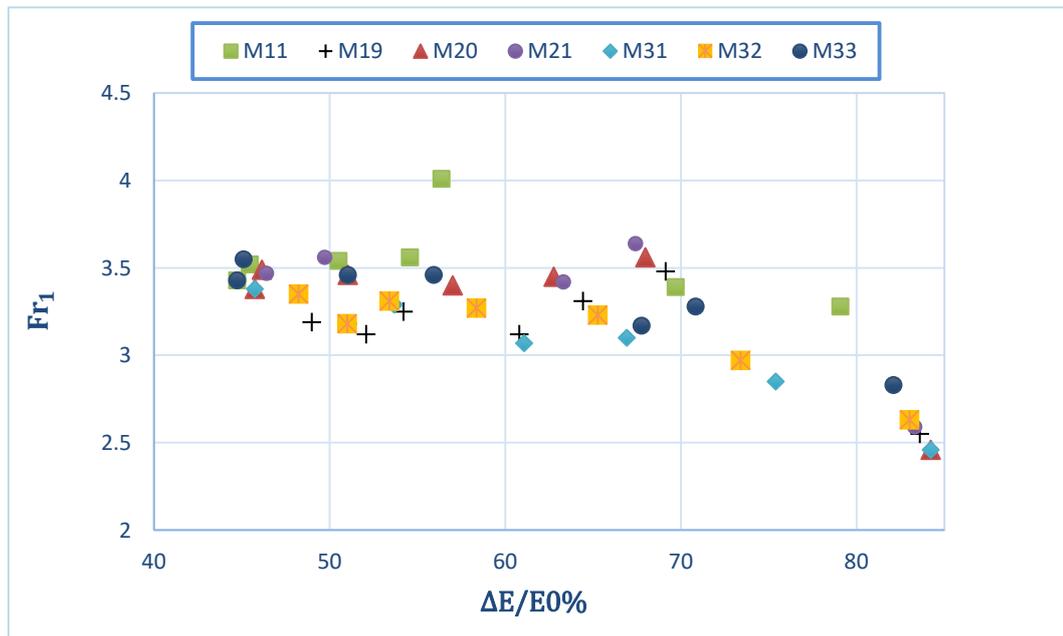
Figure 4.47. The relationship between Froude number and ΔE/E0%for uniform 10 stepped spillway at angle of 45⁰ with different baffled blocks distribution.
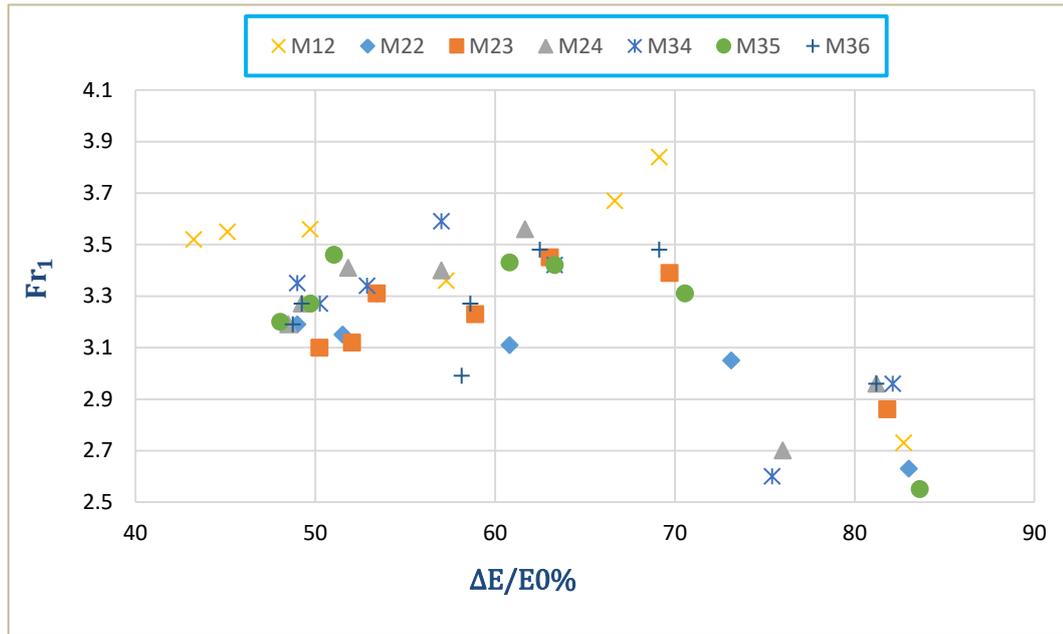
Figure 4.48. The relationship between Froude number and $\Delta E/E0\%$for non-uniform 10 stepped spillway at angle of 45⁰ with different baffled blocks distribution.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1.Conclusions

1.The model with 30° angle has the highest energy dissipation, while 45° angle records the lowest energy dissipations. As well as increasing the number of steps leads to a decrease in the energy dissipations for the same spillway angle.

2. The ratio of Energy dissipation for the stepped spillway decreases with increasing the slope of the step, the number of steps, and the percentage of the depth of the critical water to the height of the discharge degree, where the weir with several degrees (n=5) and a slope of its stepped ($\theta = 30^{o}$) is the best model in terms of energy flow dissipation.

3.The flow energy dissipation rate increases at the nappe flow and decreases as the flow turns into a skimming flow, as it reached the most significant amount of the flow energy dissipation at the nappe flow (85.45%), at the transitional flow (79.09%), and the skimming flow (75.71%).

4. Changing the stepped spillway angles lead to a change in the flow regimes from transition or nappe to skimming due to the effect of slope angle on the fluid flow system, where increasing the angle of the steeped spillway from 30° to 45° angle lead to a change in the flow regime from transition to skimming, which is the most dangerous case.

5.The effect of slope on energy dissipation depends on the flow regimes and height of steps. In the skimming flow regime at (h=3cm h=3.8cm ,h=6cm and h=8.76), the relative energy dissipation shows an increase with a decrease in the slope of the spillway.

6.The hydraulic jump length was reduced significantly for uniform 5 stepped spillway after using baffles comparison with other conditions.

7.Sample M26 with uniform 5 stepped spillway one baffled block with B/2.5 at 45º angle baffle recorded the highest energy dissipation comparison with all other samples with and without baffles block.

8.Increasing the discharge leads to an increase in the length of the hydraulic jump for all selected conditions, and the using of a baffled blocks in all identified condition lead to a decrease the length, but these decrease are more clearly in high flow discharges.

5.2.Recommendations

The reduction of applied energy from water drops on the hydraulic structure cause a series of problems; therefore, it should be decrease to its lower limits and the following suggestion could be taken into consideration:

1. Using more angles ranges between 40° and 45° such as 41°, 42°, 43°, 44° to investigate the critical angle value that lead to decrease the energy dissipation while the experimental was be worked using of baffles block lead to increase the energy dissipation, therefore, the baffles blocks could be improved by using more complicated shapes such as using circular edges instead of straight one.

2.Using similar work procedure numerically in order to investigate the differences between the experimental results that conducted in unideal conditions and the numerical results with ideal conditions as well as The changing in flow regime happened in flow discharge ranges from10.33 and 34.26, therefore take more fluid flow discharges values between two ranges to investigate the changes in the flow regime

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Appendix A

| | | | | | | **M1=⊖= 30° (5 step) Uniform** | | | | | | | | | |

Run	Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 cm	y2 cm	cm Lj	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	ΔE% E0
1	3.11	10.33	33.3	2.21	1.19	3.4	31	3.5	0.28	0.47	0.86	2.51	0.33	0.053	83.94
2	5.51	18.56	35.04	3.27	1.75	4.69	93	5.04	0.37	0.58	1.05	2.53	0.35	0.079	77.42
3	7.67	25.56	36.12	4.05	1.93	5.1	206	6.12	0.5	0.7	1.32	3.03	0.36	0.116	67.78
4	10.28	34.26	37.42	4.99	2.3	5.83	271	7.42	0.67	0.88	1.48	3.42	0.37	0.145	60.81
5	12.52	41.73	38.6	5.62	2.52	6.16	387	8.6	0.71	0.91	1.65	3.31	0.38	0.177	53.42
6	14.83	49.43	39.16	6.29	3.94	6.52	476	9.16	0.75	0.94	1.68	3.12	0.39	0.187	52.05
7	16.41	54.7	40	6.73	3.2	7.0	529	10	0.77	0.95	1.7	3.07	0.4	0.194	51.5

Run	Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 cm	y2 cm	cm Lj	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	ΔE% E0
										M2=⊖= **30°** (5 step) Non-uniform					
1	3.11	10.33	33.3	2.21	1.32	3.55	31	3.5	0.29	0.41	0.82	2.34	0.33	0.05	85.45
2	5.51	18.56	35.04	3.27	1.6	4.64	109	5.04	0.38	0.55	1.116	2.93	0.35	0.091	74
3	7.67	25.56	36.12	4.05	1.95	5.57	211	6.12	0.45	0.61	1.31	2.99	0.36	0.114	68.33
4	10.28	34.26	37.42	4.99	2.44	6.3	221	7.42	0.54	0.68	1.4	2.86	0.37	0.134	63.78
5	12.52	41.73	38.6	5.62	2.9	6.86	307	8.6	0.6	0.73	1.43	2.68	0.38	0.143	62.36
6	14.83	49.43	39.16	6.29	3.15	7.32	403	9.16	0.67	0.79	1.56	2.8	0.39	0.167	57.17
7	16.41	54.7	40	6.73	3.4	7.35	455	10	0.72	0.83	1.61	2.78	0.4	0.179	55.25

Table title: **M2=⊖= 30° (5 step) Non-uniform**

M3=⊖= 30° (10 step) Uniform														
Run	Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 cm	y2 cm	cm Lj	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	ΔE% E0
1	3.11	10.33	33.30	2.21	1.23	3.6	51	3.3	0.29	0.48	1.06	2.38	0.33	0.072	78.18
2	5.51	18.56	35.20	3.27	1.67	5.12	134	5.2	0.36	0.51	1.11	2.74	0.35	0.085	75.71
3	7.67	25.56	36.12	4.05	1.85	5.32	224	6.12	0.48	0.66	1.38	3.23	0.36	0.125	65.27
4	10.28	34.26	37.42	4.92	2.31	5.86	319	7.42	0.58	0.77	1.48	3.1	0.37	0.145	60.81
5	12.52	41.73	38.60	5.62	2.71	6.23	403	8.6	0.67	0.85	1.54	2.99	0.38	0.160	57.89
6	14.83	49.43	39.16	6.29	2.92	6.79	488	9.16	0.72	0.88	1.69	3.15	0.39	0.169	51.53
7	16.41	54.7	40.00	6.73	3.18	6.89	542	10	0.75	0.89	1.72	3.07	0.4	0.197	50.75

							M4=⊖= **30°** (10 step) Non-uniform								
Run	Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 Cm	y2 cm	cm Lj	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	ΔE% E0
1	3.11	10.33	33.3	2.21	1.29	4.08	26	3.5	0.25	0.39	0.8	1.97	0.33	0.048	84.85
2	5.51	18.56	35.04	3.27	1.68	4.24	94	5.2	0.43	0.67	1.1	2.71	0.35	0.084	75.82
3	7.67	25.56	36.12	4.05	1.89	5.23	176	6.12	0.48	0.67	1.35	3.13	0.36	0.121	66.38
4	10.28	34.26	37.42	4.99	2.40	5.88	298	7.42	0.58	0.76	1.42	2.93	0.37	0.135	63.37
5	12.52	41.73	38.6	5.62	2.88	6.29	440	8.6	0.66	0.84	1.44	2.7	0.38	0.145	61.84
6	14.83	49.43	39.16	6.29	3	6.78	483	9.16	0.72	0.88	1.64	3.02	0.39	0.18	53.84
7	16.41	54.7	40.00	6.73	3.2	7.37	508	10	0.74	0.87	1.68	2.97	0.4	0.19	52.5

M5=Ө= 40° (5 step) Uniform														
Run	Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 cm	y2 cm	Lj cm	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	ΔE% E0
1	3.11	10.33	33.30	2.21	1.00	4.12	48	3.3	0.25	0.39	1.03	3.28	0.33	0.069	79.09
2	5.51	18.56	35.20	3.27	1.68	4.6	98	5.2	0.4	0.59	1.10	2.7	0.35	0.084	76.00
3	7.67	25.56	36.12	4.05	1.7	5.23	204	6.12	0.48	0.68	1.43	3.5	0.36	0.143	60.38
4	10.28	34.26	37.42	4.92	2.35	5.87	278	7.42	0.58	0.76	1.48	3.12	0.37	0.141	61.89
5	12.52	41.73	38.60	5.62	2.69	6.22	406	8.6	0.67	0.86	1.55	3.01	0.38	0.161	57.63
6	14.83	49.43	39.16	6.29	2.99	6.6	474	9.16	0.74	0.91	1.70	3.18	0.39	0.191	51.02
7	16.41	54.7	40.00	6.73	3.10	6.95	569	10	0.79	0.83	1.76	3.19	0.4	0.204	49.0

M6=⊖= 40° (5 step) Non-uniform														
Run	Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 cm	y2 cm	Lj cm	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	ΔE% E0
1	3.11	10.33	33.30	2.21	1.11	3.72	45	3.5	0.27	0.44	0.93	2.81	0.33	0.059	82.12
2	5.51	18.56	35.04	3.27	1.65	4.88	107	5.2	0.38	0.55	1.12	2.78	0.35	0.086	75.42
3	7.67	25.56	36.12	4.05	1.88	5.25	194	6.12	0.48	0.68	1.35	3.14	0.36	0.12	66.67
4	10.28	34.26	37.42	4.99	2.37	5.9	244	7.42	0.58	0.76	1.44	2.98	0.37	0.139	62.43
5	12.52	41.73	38.60	5.62	2.75	6.42	362	8.6	0.65	0.82	1.51	2.90	0.38	0.155	59.21
6	14.83	49.43	39.16	6.29	3.15	6.69	438	9.16	0.73	0.9	1.56	2.81	0.39	0.167	57.17
7	16.41	54.7	40.00	6.73	3.30	7.2	508	10.00	0.75	0.91	1.65	1.96	0.4	0.185	53.75

								M7=⊖= 40° (10 step) Uniform						
Run	Q	q	yo	yc cm	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%
	L/Sec	L/Sec/m	cm		cm	cm	cm	cm	m/s		m/s				E0
0	3.11	10.33	33.3	2.22	1.04	3.92	44	3.3	0.26	0.4	0.94	3.09	0.33	0.065	80.3
2	5.51	18.56	35.04	3.27	1.47	4.45	26	5.2	0.41	0.62	1.26	3.31	0.35	0.103	70.57
3	7.67	25.56	36.12	4.05	1.91	5.5	204	6.12	0.46	0.63	1.33	3.07	0.36	0.118	67.22
4	10.28	34.26	37.42	4.92	2.2	5.62	330	7.42	0.6	0.8	1.55	3.34	0.37	0.157	57.75
5	12.52	41.73	38.6	5.62	2.58	6.05	459	8.6	1260	0.82	1.63	3.35	0.38	0.174	54.21
6	14.83	49.43	39.16	6.29	2.89	6.7	543	9.16	0.73	0.9	1.72	3.23	0.39	0.192	50.76
7	16.41	54.7	40	6.73	3.08	6.92	572	10	0.78	0.94	1.77	3.2	0.4	0.206	48.5

							M8=⊖= 40° (10 step) Non-uniform							
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				E0
1	3.11	10.33	33.3	2.21	1.1	3.98	44	3.5	0.26	0.42	0.93	2.83	0.33	0.059	82.12
2	5.51	18.56	35.04	3.27	1.58	4.4	112	5.2	0.38	0.55	1.16	2.93	0.35	0.091	73.42
3	7.67	25.56	36.12	4.05	1.78	5.26	195	6.12	0.48	0.66	1.43	3.42	0.36	0.132	63.33
4	10.28	34.26	37.42	4.99	2.1	5.45	333	7.42	0.62	0.84	1.63	3.59	0.37	0.169	54.32
5	12.52	41.73	38.6	5.62	2.6	6.25	460	8.6	0.66	0.85	1.6	3.07	0.38	0.164	55.226
6	14.83	49.43	39.16	6.29	2.91	6.72	545	9.16	0.73	0.89	1.7	3.18	0.39	0.191	50.212
7	16.41	54.7	40	6.73	3.04	6.73	573	10	0.79	0.95	1.8	3.29	0.4	0.212	47.211

						M9=Ɵ= 45° (5 step) Uniform								
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				E0
1	3.11	10.33	33.3	2.21	1.01	4.16	47	3.3	0.24	0.38	1.02	3.24	0.33	0.065	79.39
2	5.51	18.56	35.2	3.27	1.67	4.96	107	5.04	0.38	0.55	1.11	2.74	0.35	0.085	75.71
3	7.67	25.56	36.12	4.05	1.84	5.33	210	6.12	0.48	0.66	1.38	3.24	0.36	0.125	65.28
4	10.28	34.26	37.42	4.92	2.21	5.75	295	7.42	0.59	0.79	1.55	3.32	0.37	0.156	57.83
5	12.52	41.73	38.6	5.62	2.52	6.39	372	8.6	0.65	0.82	1.65	3.31	0.38	0.177	53.42
6	14.83	49.43	39.16	6.29	2.9	6.69	474	9.16	0.75	0.9	1.7	3.18	0.39	0.191	51.02
7	16.41	54.7	40	6.73	2.94	6.95	529	10	0.78	0.94	1.86	3.46	0.4	0.223	44.25

M10=θ= 45° (5 step) Non-uniform															
Run	Q	q	yo	Yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				E0
1	3.11	10.33	33.3	2.21	0.18	3.58	33	3.5	0.28	0.47	0.87	2.55	0.33	0.054	83.63
2	5.51	18.56	35.04	3.27	1.65	4.84	107	5.2	0.38	0.55	1.12	2.78	0.35	0.086	75.43
3	7.67	25.56	36.12	4.05	1.85	5.3	187	6.12	0.48	0.66	1.38	3.92	0.36	0.125	65.27
4	10.28	34.26	37.42	4.99	2.18	5.75	333	7.42	0.59	0.78	1.57	3.39	0.37	0.159	57.02
5	12.52	41.73	38.6	5.62	2.50	6.60	357	8.6	0.62	0.77	1.66	3.35	0.38	0.179	52.89
6	14.83	49.43	39.16	6.29	2.86	6.91	443	9.16	0.71	0.86	1.72	3.24	0.39	0.194	50.26
7	16.41	54.7	40.00	6.73	3.13	7.3	534	10	0.74	0.87	1.74	3.14	0.4	0.196	49.5

Run	Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 cm	y2 cm	Lj cm	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	ΔE% E0
1	3.11	10.33	33.3	2.21	1.00	4.12	48	3.5	0.25	0.39	1.03	3.28	0.33	0.069	79.09
2	5.51	18.56	35.2	3.27	1.45	4.96	135	5.04	0.37	0.54	1.28	3.39	0.35	0.106	69.71
3	7.67	25.56	36.12	4.05	1.6	5.2	227	6.12	0.49	0.68	1.59	4.01	0.36	0.157	56.38
4	10.28	34.26	37.42	4.99	2.15	5.56	359	7.42	0.62	0.83	1.62	3.56	0.37	0.168	54.59
5	12.52	41.73	38.6	5.62	2.4	6.13	481	8.6	0.68	0.87	1.7	3.54	0.38	0.198	50.52
6	14.83	49.43	39.16	6.29	2.71	6.6	504	9.16	0.74	0.92	1.82	3.52	0.39	0.212	45.46
7	16.41	54.7	40	6.73	2.95	6.92	563	10	0.79	0.95	1.85	3.43	0.4	0.221	44.75

Table title: **M11=Θ= 45° (10 step) Uniform**

								M12=⊖= 45° (10 step) Non-uniform						
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				E0
1	3.11	10.33	33.3	2.21	1.13	3.8	37	3.5	0.27	0.44	0.91	2.73	0.33	0.057	82.73
2	5.51	18.56	35.04	3.27	1.36	4.93	133	5.2	0.38	0.55	1.3	3.84	0.35	0.108	69.14
3	7.67	25.56	36.12	4.05	1.88	5.16	183	6.12	0.49	0.68	1.35	3.67	0.36	0.12	66.67
4	10.28	34.26	37.42	4.99	2.19	5.45	347	7.42	0.62	0.84	1.56	3.36	0.37	0.158	57.29
5	12.52	41.73	38.6	5.62	2.4	6.14	464	8.6	0.67	0.86	1.73	3.56	0.38	0.191	49.73
6	14.83	49.43	39.16	6.29	2.7	6.6	544	9.16	0.74	0.91	1.83	3.55	0.39	0.214	45.12
7	16.41	54.7	40	6.73	2.9	6.87	567	10	0.79	0.96	1.88	3.52	0.4	0.227	43.25

Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	$\frac{\Delta E\%}{E0}$
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				
1	3.11	10.33	33.3	2.21	1.36	3.30	18	3.5	0.30	0.52	0.75	2.05	0.33	0.045	86.36
2	5.51	18.56	35.04	3.27	1.68	4.81	98	5.20	0.38	0.55	1.10	2.70	0.35	0.084	75.82
3	7.67	25.56	36.12	4.05	1.95	5.46	148	6.12	0.46	0.62	1.31	2.99	0.36	0.115	68.05
4	10.28	34.26	37.42	4.99	2.28	5.72	230	7.42	0.59	0.78	1.50	3.17	0.37	0.148	60.00
5	12.52	41.73	38.6	5.62	2.65	6.31	304	8.60	0.66	0.83	1.57	3.07	0.38	0.164	56.84
6	14.83	49.43	39.16	6.29	3.15	6.68	363	9.16	0.73	0.90	1.56	2.88	0.39	0.167	57.17
7	16.41	54.70	40.00	6.73	3.45	6.87	408	10.0	0.79	0.96	1.58	2.71	0.40	0.174	56.50

M13=$\ominus$= 45° (5 step) Uniform Two baffled (B/2)

	M14=Θ= 45° (5 step) Uniform Two baffled (B/2.5)													
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	$\frac{\Delta E\%}{E0}$
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				
1	3.11	10.33	33.3	2.21	1.24	3.60	24	3.5	0.28	0.48	0.86	2.51	0.33	0.051	84.54
2	5.51	18.56	35.04	3.27	1.66	4.82	97	5.20	0.38	0.55	1.12	2.77	0.35	0.086	75.42
3	7.67	25.56	36.12	4.05	1.93	5.48	152	6.12	0.46	0.62	1.32	3.03	0.36	0.116	67.78
4	10.28	34.26	37.42	4.99	2.30	5.70	228	7.42	0.60	0.80	1.48	3.12	0.37	0.145	60.81
5	12.52	41.73	38.6	5.62	2.60	6.42	326	8.60	0.65	0.81	1.60	3.16	0.38	0.169	55.52
6	14.83	49.43	39.16	6.29	2.98	6.96	390	9.16	0.71	0.85	1.65	3.05	0.39	0.182	53.33
7	16.41	54.70	40.00	6.73	3.21	7.33	454	10	0.74	0.87	1.70	3.02	0.40	0.194	51.50

M15=⊝= 45° (5 step) Uniform Two baffled (B/3)																

Run	Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 cm	y2 cm	Lj cm	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	$\frac{\Delta E\%}{E0}$
1	3.11	10.33	33.3	2.21	1.19	3.60	31	3.5	0.28	0.47	0.86	2.37	0.33	0.053	83.94
2	5.51	18.56	35.04	3.27	1.77	4.82	81	5.20	0.39	0.57	1.04	2.49	0.35	0.078	77.71
3	7.67	25.56	36.12	4.05	2.21	5.43	136	6.12	0.47	0.64	1.15	2.46	0.36	0.096	73.33
4	10.28	34.26	37.42	4.99	2.26	5.78	231	7.42	0.59	0.78	1.51	3.21	0.37	0.150	59.45
5	12.52	41.73	38.6	5.62	2.66	6.31	304	8.60	0.66	0.83	1.56	3.05	0.38	0.163	57.10
6	14.83	49.43	39.16	6.29	3.10	6.94	387	9.16	0.71	0.86	1.59	2.88	0.39	0.172	55.89
7	16.41	54.70	40.00	6.73	3.23	7.28	460	10	0.75	0.88	1.69	3.00	0.40	0.192	52.00

M16=⊖= 45° (5 step) Non-Uniform Two baffled (B/2)														
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				$\overline{E0}$
1	3.11	10.33	33.3	2.21	1.26	3.58	24	3.5	0.29	0.49	0.81	2.30	0.33	0.049	85.15
2	5.51	18.56	35.04	3.27	1.76	4.67	82	5.20	0.39	0.57	1.05	2.53	0.35	0.079	77.42
3	7.67	25.56	36.12	4.05	1.80	5.48	198	6.12	0.46	0.62	1.42	3.37	0.36	0.131	63.61
4	10.28	34.26	37.42	4.99	2.28	5.72	254	7.42	0.59	0.78	1.50	3.17	0.37	0.148	60.00
5	12.52	41.73	38.6	5.62	2.51	6.53	351	8.60	0.64	0.79	1.66	3.35	0.38	0.179	52.89
6	14.83	49.43	39.16	6.29	2.86	6.91	443	9.16	0.71	0.86	1.72	3.24	0.39	0.194	50.26
7	16.41	54.70	40.00	6.73	3.00	7.38	483	10.00	0.74	0.87	1.82	3.35	0.40	0.215	46.25

M17=Θ= 45° (5 step) Non-Uniform Two baffled (B/2.5)														
Run	Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 cm	y2 cm	Lj cm	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	ΔE% — E0
1	3.11	10.33	33.3	2.21	1.18	3.70	25	3.5	0.**28**	0.46	0.87	2.55	0.33	0.054	83.63
2	5.51	18.56	35.04	3.27	1.72	4.70	84	5.20	0.39	0.**57**	1.08	2.63	0.35	0.083	76.28
3	7.67	25.56	36.12	4.05	1.95	5.16	183	6.12	0.49	0.68	1.31	2.99	0.36	0.115	68.05
4	10.28	34.26	37.42	4.99	2.26	5.78	246	7.42	0.59	0.78	1.51	3.21	0.37	0.150	59.45
5	12.52	41.73	38.6	5.62	2.50	6.60	357	8.60	0.62	0.77	1.66	3.35	0.38	0.179	52.89
6	14.83	49.43	39.16	6.29	2.82	7.10	452	9.16	0.69	0.**82**	1.75	3.32	0.39	0.199	48.97
7	16.41	54.70	40.00	6.73	2.95	7.30	498	10.00	0.**74**	0.87	1.85	3.43	0.40	0.221	44.75

Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%/E0
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				
1	3.11	10.33	33.3	2.21	1.12	3.75	27	3.5	0.27	0.44	0.92	2.78	0.33	0.059	82.12
2	5.51	18.56	35.04	3.27	1.78	4.67	80	5.20	0.39	0.57	1.04	2.49	0.35	0.078	77.71
3	7.67	25.56	36.12	4.05	2.00	5.12	176	6.12	0.50	0.70	1.28	2.89	0.36	0.112	68.89
4	10.28	34.26	37.42	4.99	2.30	5.70	236	7.42	0.60	0.80	1.49	3.14	0.37	0.147	60.27
5	12.52	41.73	38.6	5.62	2.54	6.65	341	8.60	0.63	0.78	1.64	3.29	0.38	0.176	53.68
6	14.83	49.43	39.16	6.29	2.86	6.91	443	9.16	0.71	0.86	1.72	3.24	0.39	0.194	50.26
7	16.41	54.70	40.00	6.73	3.00	7.24	491	10.00	0.78	0.90	1.82	3.35	0.40	0.215	46.25

Table title: **M18=⊖= 45° (5 step) Non-Uniform Two baffled (B/3)**

							M19=⊖= 45° (10 step) Uniform Two baffled (B/2)								
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	$\frac{\Delta E\%}{E0}$
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				
1	3.11	10.33	33.3	2.21	1.18	3.70	26	3.5	0.28	0.46	0.87	2.55	0.33	0.054	83.63
2	5.51	18.56	35.04	3.27	1.42	4.93	133	5.20	0.38	0.55	1.30	3.48	0.35	0.108	69.14
3	7.67	25.56	36.12	4.05	1.82	5.63	190	6.12	0.45	0.61	1.40	3.31	0.36	0.128	64.44
4	10.28	34.26	37.42	4.99	2.30	5.88	**258**	7.42	0.58	0.76	1.48	3.12	0.37	0.145	60.81
5	12.52	41.73	38.6	5.62	2.56	6.54	**356**	8.60	0.63	0.78	1.63	3.25	0.38	0.174	54.21
6	14.83	49.43	39.16	6.29	2.94	6.63	**479**	9.16	0.74	**0.91**	1.68	3.12	0.39	0.187	52.10
7	16.41	54.70	40.00	6.73	3.10	6.88	**539**	10.00	0.79	0.96	1.76	3.19	0.40	0.204	49.00

M20=⊖= 45° (10 step) Uniform Two baffled (B/2.5)														
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE% / E0
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				
1	3.11	10.33	33.3	2.21	1.21	3.65	25	3.5	0.28	0.47	0.85	2.46	0.33	0.052	84.24
2	5.51	18.56	35.04	3.27	1.28	5.13	135	5.20	0.36	0.51	1.32	3.56	0.35	0.112	68.00
3	7.67	25.56	36.12	4.05	1.78	5.50	195	6.12	0.46	0.62	1.44	3.45	0.36	0.134	62.78
4	10.28	34.26	37.42	4.99	2.17	6.16	288	7.42	0.56	0.72	1.57	3.40	0.37	0.159	57.02
5	12.52	41.73	38.6	5.62	2.45	6.65	397	8.60	0.62	0.76	1.70	3.46	0.38	0.186	51.05
6	14.83	49.43	39.16	6.29	2.73	6.74	494	9.16	0.73	0.89	1.81	3.49	0.39	0.210	46.15
7	16.41	54.70	40.00	6.73	2.98	7.10	542	10.00	0.77	0.92	1.83	3.38	0.40	0.217	45.75

Run	Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 cm	y2 cm	Lj cm	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	ΔE%/E0
							M21=⊖= 45° (10 step) Uniform Two baffled (B/3)								
1	3.11	10.33	33.3	2.21	1.17	3.67	26	3.5	0.28	0.46	0.88	2.59	0.33	0.055	83.33
2	5.51	18.56	35.04	3.27	1.38	5.26	137	5.20	0.35	0.48	1.34	3.64	0.35	0.114	67.42
3	7.67	25.56	36.12	4.05	1.78	5.51	195	6.12	0.46	0.62	1.43	3.42	0.36	0.132	63.33
4	10.28	34.26	37.42	4.99	2.15	6.20	293	7.42	0.55	0.70	1.59	3.46	0.37	0.163	55.94
5	12.52	41.73	38.6	5.62	2.40	6.71	405	8.60	0.62	0.76	1.73	3.56	0.38	0.191	49.73
6	14.83	49.43	39.16	6.29	2.74	6.75	493	9.16	0.73	0.89	1.80	3.47	0.39	0.209	46.41
7	16.41	54.70	40.00	6.73	2.95	7.15	528	10.00	0.76	0.90	1.85	3.43	0.40	0.221	44.75

Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				E0
1	3.11	10.33	33.3	2.21	1.16	3.65	32	3.5	0.28	0.46	0.89	2.63	0.33	0.056	83.03
2	5.51	18.56	35.04	3.27	1.55	4.87	120	5.20	0.38	0.55	1.19	3.05	0.35	0.094	73.14
3	7.67	25.56	36.12	4.05	1.78	5.51	195	6.12	0.46	0.62	1.43	3.42	0.36	0.132	63.33
4	10.28	34.26	37.42	4.99	2.30	5.89	272	7.42	0.58	0.76	1.48	3.11	0.37	0.145	60.81
5	12.52	41.73	38.6	5.62	2.52	6.40	373	8.60	0.65	0.82	1.65	3.31	0.38	0.177	53.42
6	14.83	49.43	39.16	6.29	2.92	6.68	484	9.16	0.74	0.91	1.69	3.15	0.39	0.169	51.53
7	16.41	54.70	40.00	6.73	3.10	6.83	**543**	10.00	0.80	0.97	1.76	3.19	0.40	0.204	49.00

Table title: **M22=⊖= 45° (10 step) Non-Uniform Two baffled (B/2)**

M23=Ө= 45° (10 step) Non-Uniform Two baffled (B/2.5)														
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	$\dfrac{\Delta E\%}{E0}$
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				
1	3.11	10.33	33.3	2.21	1.10	3.70	34	3.5	0.27	0.44	0.94	2.86	0.33	0.066	81.82
2	5.51	18.56	35.04	3.27	1.45	4.83	131	5.20	0.38	0.55	1.28	3.39	0.35	0.106	69.71
3	7.67	25.56	36.12	4.05	1.77	5.51	195	6.12	0.46	0.62	1.44	3.45	0.36	0.133	63.05
4	10.28	34.26	37.42	4.99	2.25	6.10	283	7.42	0.56	0.72	1.52	3.23	0.37	0.145	58.91
5	12.52	41.73	38.6	5.62	2.52	6.37	389	8.60	0.65	0.82	1.65	3.31	0.38	0.177	53.42
6	14.83	49.43	39.16	6.29	2.94	6.63	479	9.16	0.74	0.91	1.68	3.12	0.39	0.187	52.05
7	16.41	54.70	40.00	6.73	3.15	6.91	**540**	10.00	0.79	0.95	1.73	3.10	0.40	0.199	50.25

Run	Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 cm	y2 cm	Lj cm	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	ΔE% / E0
							M24=⊖= 45° (10 step) Non-Uniform Two baffled (B/3)								
1	3.11	10.33	33.3	2.21	1.07	3.88	37	3.5	0.28	0.42	0.96	2.96	0.33	0.062	81.21
2	5.51	18.56	35.04	3.27	1.68	4.78	143	5.20	0.38	0.55	1.10	2.70	0.35	0.084	76.00
3	7.67	25.56	36.12	4.05	1.73	5.61	201	6.12	0.45	0.61	1.47	3.56	0.36	0.138	61.67
4	10.28	34.26	37.42	4.99	2.17	6.23	293	7.42	0.54	0.69	1.57	3.40	0.37	0.159	57.02
5	12.52	41.73	38.6	5.62	2.48	6.69	403	8.60	0.62	0.76	1.68	3.41	0.38	0.183	51.84
6	14.83	49.43	39.16	6.29	2.85	6.70	467	9.16	0.73	0.90	1.72	3.27	0.39	0.196	49.26
7	16.41	54.70	40.00	6.73	3.08	6.85	**524**	10.00	0.79	0.96	1.77	3.19	0.40	0.206	48.50

																		M25=⊖= 45° (5 step) Uniform One baffled (B/2)																	

Run	Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 cm	y2 cm	Lj cm	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	$\frac{\Delta E\%}{E0}$
1	3.11	10.33	33.3	2.21	1.30	3.35	22	3.5	0.30	0.52	0.79	2.21	0.33	0.047	85.76
2	5.51	18.56	35.04	3.27	1.75	4.69	92	5.20	0.37	0.58	1.05	2.53	0.35	0.079	77.42
3	7.67	25.56	36.12	4.05	1.90	5.48	149	6.12	0.47	0.64	1.34	3.10	0.36	0.119	66.94
4	10.28	34.26	37.42	4.99	2.34	5.67	200	7.42	0.60	0.80	1.46	3.05	0.37	0.142	61.62
5	12.52	41.73	38.6	5.62	2.75	6.25	273	8.60	0.66	0.84	1.52	2.92	0.38	0.157	58.68
6	14.83	49.43	39.16	6.29	3.10	6.94	375	9.16	0.71	0.86	1.59	2.88	0.39	0.172	55.89
7	16.41	54.70	40.00	6.73	3.25	7.24	434	10.00	0.75	0.89	1.68	2.97	0.40	0.191	52.25

Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				E0
1	3.11	10.33	33.3	2.21	1.32	3.20	17	3.5	0.32	0.57	0.72	2.16	.33	0.043	86.96
2	5.51	18.56	35.04	3.27	1.76	4.69	91	5.20	0.39	0.57	1.05	2.53	0.35	0.079	77.43
3	7.67	25.56	36.12	4.05	2.00	5.48	143	6.12	0.47	0.64	1.28	2.89	0.36	0.118	67.22
4	10.28	34.26	37.42	4.99	2.42	5.67	224	7.42	0.60	0.80	1.42	2.91	0.37	0.137	62.97
5	12.52	41.73	38.6	5.62	2.62	6.25	307	8.60	0.65	0.81	1.59	3.13	0.38	0.168	55.79
6	14.83	49.43	39.16	6.29	2.95	6.94	399	9.16	0.69	0.83	1.67	3.10	0.39	0.185	52.56
7	16.41	54.70	40.00	6.73	3.10	7.24	476	10.00	0.74	0.87	1.76	3.19	0.40	0.205	48.75

Table title: **M26=⊖= 45° (5 step) Uniform One baffled (B/2.5)**

Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				$\overline{E0}$
1	3.11	10.33	33.3	2.21	1.32	3.25	21	3.5	0.31	0.54	0.78	2.12	0.33	0.046	86.06
2	5.51	18.56	35.04	3.27	1.74	4.70	77	5.20	0.39	0.57	1.06	2.56	0.35	0.080	77.14
3	7.67	25.56	36.12	4.05	2.10	5.43	139	6.12	0.47	0.64	1.21	2.67	0.36	0.103	71.39
4	10.28	34.26	37.42	4.99	2.45	5.64	220	7.42	0.61	0.82	1.39	2.83	0.37	0.133	64.05
5	12.52	41.73	38.6	5.62	2.70	6.30	282	8.60	0.66	0.84	1.55	3.01	0.38	0.162	57.37
6	14.83	49.43	39.16	6.29	3.21	6.61	354	9.16	0.75	0.93	1.54	2.74	0.39	0.165	57.69
7	16.41	54.70	40.00	6.73	3.28	7.28	444	10.00	0.75	0.88	1.67	2.94	0.40	0.167	52.75

M27=Θ= 45° (5 step) Uniform One baffled (B/3)

							M28=Θ= 45° (5 step) Non-Uniform One baffled (B/2)							
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%⁄E0
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				
1	3.11	10.33	33.3	2.21	1.07	3.90	28	3.5	0.26	0.42	0.96	2.96	0.33	0.062	81.21
2	5.51	18.56	35.04	3.27	1.77	4.67	80	5.20	0.39	0.58	1.05	3.27	0.35	0.079	77.43
3	7.67	25.56	36.12	4.05	2.23	4.94	112	6.12	0.52	0.75	1.14	2.21	0.36	0.095	73.61
4	10.28	34.26	37.42	4.99	2.36	5.67	199	7.42	0.60	0.80	1.45	3.01	0.37	0.141	61.89
5	12.52	41.73	38.6	5.62	2.73	6.30	274	8.60	0.66	0.84	1.53	2.95	0.38	0.158	58.42
6	14.83	49.43	39.16	6.29	3.10	6.94	388	9.16	0.71	0.86	1.59	2.88	0.39	0.173	55.64
7	16.41	54.70	40.00	6.73	3.20	7.30	461	10.00	0.74	0.87	1.70	3.07	0.40	0.194	51.50

						M29=⊖= 45° (5 step) Non-Uniform One baffled (B/2.5)								
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				E0
1	3.11	10.33	33.3	2.21	1.24	3.60	24	3.5	0.28	0.48	0.91	2.37	0.33	0.051	84.54
2	5.51	18.56	35.04	3.27	1.80	4.63	73	5.20	0.40	0.59	1.03	2.45	0.35	0.077	78.00
3	7.67	25.56	36.12	4.05	2.20	5.10	113	6.12	0.50	0.70	1.16	2.49	0.36	0.097	73.05
4	10.28	34.26	37.42	4.99	2.33	5.71	209	7.42	0.60	0.80	1.47	3.07	0.37	0.144	61.08
5	12.52	41.73	38.6	5.62	2.67	6.35	299	8.60	0.65	0.82	1.56	3.04	0.38	0.163	57.10
6	14.83	49.43	39.16	6.29	3.15	6.80	431	9.16	0.72	0.88	1.57	2.82	0.39	0.169	56.67
7	16.41	54.70	40.00	6.73	3.10	7.36	478	10.00	0.74	0.89	1.76	3.19	0.40	0.205	48.75

M30=⊖= 45° (5 step) Non-Uniform One baffled (B/3)														
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	$\frac{\Delta E\%}{E0}$
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				
1	3.11	10.33	33.3	2.21	1.16	3.62	34	3.5	0.**28**	0.46	0.89	2.37	0.33	0.057	82.72
2	5.51	18.56	35.04	3.27	1.78	4.66	74	5.20	0.**39**	0.**57**	1.04	2.49	0.35	0.078	77.71
3	7.67	25.56	36.12	4.05	2.25	5.43	124	6.12	0.47	0.64	1.13	2.41	0.36	0.094	73.89
4	10.28	34.26	37.42	4.99	2.42	5.68	224	7.42	0.60	0.80	1.42	2.91	0.37	0.137	62.97
5	12.52	41.73	38.6	5.62	2.67	6.38	321	8.60	0.65	0.82	1.56	3.04	0.38	0.163	57.10
6	14.83	49.43	39.16	6.29	3.15	6.80	431	9.16	0.72	0.**88**	1.57	2.82	0.39	0.169	56.67
7	16.41	54.70	40.00	6.73	3.44	6.87	**444**	10.00	0.79	0.96	1.59	2.73	0.40	0.176	56.00

M31=⊖= 45° (10 step) Uniform One baffled (B/2)															
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				E0
1	3.11	10.33	33.3	2.21	1.21	3.65	25	3.5	0.28	0.47	0.85	2.46	0.33	0.052	84.24
2	5.51	18.56	35.04	3.27	1.62	4.96	112	5.20	0.37	0.53	1.14	2.85	0.35	0.086	75.42
3	7.67	25.56	36.12	4.05	1.90	5.66	181	6.12	0.45	0.60	1.34	3.10	0.36	0.119	66.94
4	10.28	34.26	37.42	4.99	2.33	5.84	243	7.42	0.58	0.76	1.47	3.07	0.37	0.144	61.08
5	12.52	41.73	38.6	5.62	2.53	6.63	359	8.60	0.62	0.76	1.64	3.29	0.38	0.176	53.68
6	14.83	49.43	39.16	6.29	2.90	6.70	439	9.16	0.73	0.90	1.70	3.18	0.39	0.191	51.09
7	16.41	54.70	40.00	6.73	2.98	7.10	522	10.00	0.77	0.92	1.83	3.38	0.40	0.217	45.75

M32=⊖= 45° (10 step) Uniform One baffled (B/2.5)
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%/E0
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				
1	3.11	10.33	33.3	2.21	1.09	3.62	32	3.5	0.28	0.46	0.89	2.63	0.33	0.056	83.03
2	5.51	18.56	35.04	3.27	1.58	4.87	118	5.20	0.38	0.55	1.17	2.97	0.35	0.095	73.42
3	7.67	25.56	36.12	4.05	1.85	5.67	181	6.12	0.45	0.66	1.38	3.23	0.36	0.125	65.28
4	10.28	34.26	37.42	4.99	2.23	5.89	262	7.42	0.58	0.76	1.53	3.27	0.37	0.154	58.37
5	12.52	41.73	38.6	5.62	2.52	6.58	371	8.60	0.63	0.78	1.65	3.31	0.38	0.177	53.42
6	14.83	49.43	39.16	6.29	2.90	6.72	467	9.16	0.73	0.89	1.70	3.18	0.39	0.191	51.02
7	16.41	54.70	40.00	6.73	3.00	7.20	561	10.00	0.75	0.89	1.82	3.35	0.40	0.215	48.25

						M33=⊖= 45° (10 step) Uniform One baffled (B/3)								
Run	Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 cm	y2 cm	Lj cm	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	ΔE% E0
1	3.11	10.33	33.3	2.21	1.10	3.69	34	3.5	0.27	0.44	0.93	2.83	0.33	0.059	82.12
2	5.51	18.56	35.04	3.27	1.48	5.12	126	5.20	0.36	0.51	1.25	3.28	0.35	0.102	70.85
3	7.67	25.56	36.12	4.05	1.93	5.73	188	6.12	0.44	0.58	1.32	3.17	0.36	0.116	67.78
4	10.28	34.26	37.42	4.99	2.15	6.20	292	7.42	0.55	0.70	1.59	3.46	0.37	0.163	55.94
5	12.52	41.73	38.6	5.62	2.45	6.65	397	8.60	0.62	0.76	1.70	3.46	0.38	0.186	51.05
6	14.83	49.43	39.16	6.29	2.70	6.78	495	9.16	0.72	0.88	1.83	3.55	0.39	0.214	45.12
7	16.41	54.70	40.00	6.73	2.95	7.15	565	10.00	0.76	0.90	1.85	3.43	0.40	0.221	44.75

M34=⊖= 45° (10 step) Non-Uniform One baffled (B/2)															
Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	ΔE%/E0
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				
1	3.11	10.33	33.3	2.21	1.01	3.58	33	3.5	0.27	0.40	0.87	2.55	0.33	0.054	83.63
2	5.51	18.56	35.04	3.27	1.58	4.62	121	5.20	0.40	0.59	1.17	2.60	0.35	0.095	75.42
3	7.67	25.56	36.12	4.05	1.78	5.71	188	6.12	0.45	0.60	1.43	3.42	0.36	0.132	63.33
4	10.28	34.26	37.42	4.99	2.17	6.28	295	7.42	0.54	0.68	1.57	3.59	0.37	0.155	57.02
5	12.52	41.73	38.6	5.62	2.51	6.67	364	8.60	0.62	0.76	1.66	3.34	0.38	0.179	52.89
6	14.83	49.43	39.16	6.29	2.86	6.77	445	9.16	0.70	0.85	1.72	3.27	0.39	0.194	50.26
7	16.41	54.70	40.00	6.73	3.10	7.10	518	10.00	0.77	0.92	1.76	3.35	0.40	0.204	49.00

Run	Q	q	yo	yc	y1	y2	Lj	hw	v2	Fr2	v1	Fr1	E0	E1	$\frac{\Delta E\%}{E0}$
	L/Sec	L/Sec/m	cm	cm	cm	cm	cm	cm	m/s		m/s				
1	3.11	10.33	33.3	2.21	1.07	3.75	28	3.5	0.27	0.44	0.92	2.96	0.33	0.059	82.12
2	5.51	18.56	35.04	3.27	1.47	4.69	128	5.20	0.39	0.57	1.26	3.31	0.35	0.103	70.57
3	7.67	25.56	36.12	4.05	1.78	5.53	197	6.12	0.46	0.62	1.43	3.42	0.36	0.132	63.33
4	10.28	34.26	37.42	4.99	2.30	6.35	264	7.42	0.53	0.67	1.48	3.43	0.37	0.145	60.81
5	12.52	41.73	38.6	5.62	2.45	6.38	423	8.60	0.65	0.82	1.70	3.46	0.38	0.186	51.05
6	14.83	49.43	39.16	6.29	2.85	6.65	478	9.16	0.74	0.91	1.72	3.27	0.39	0.196	49.74
7	16.41	54.70	40.00	6.73	3.08	7.10	537	10.00	0.77	0.92	1.77	3.20	0.40	0.204	48.05

Table title: **M35=$\ominus$= 45° (10 step) Non-Uniform One baffled (B/2.5)**

Q L/Sec	q L/Sec/m	yo cm	yc cm	y1 cm	y2 cm	Lj cm	hw cm	v2 m/s	Fr2	v1 m/s	Fr1	E0	E1	$\frac{\Delta E\%}{E0}$
3.11	10.33	33.3	2.21	1.07	3.88	38	3.5	0.28	0.42	0.96	2.96	0.33	0.062	81.21
5.51	18.56	35.04	3.27	1.36	5.10	134	5.20	0.38	0.55	1.30	3.48	0.35	0.108	69.14
7.67	25.56	36.12	4.05	1.76	5.34	193	6.12	0.47	0.64	1.45	3.48	0.36	0.135	62.50
10.28	34.26	37.42	4.99	2.23	6.15	288	7.42	0.56	0.72	1.53	3.27	0.37	0.153	58.64
12.52	41.73	38.6	5.62	2.70	6.34	385	8.60	0.65	0.82	1.54	2.99	0.38	0.159	58.15
14.83	49.43	39.16	6.29	2.85	6.67	472	9.16	0.74	0.91	1.72	3.27	0.39	0.196	49.26
16.41	54.70	40.00	6.73	3.10	7.15	542	10.00	0.76	0.90	1.76	3.19	0.40	0.205	48.75

M36=⊖= 45° (10 step) Non-Uniform One baffled (B/3)

Appendix B

B.1 Flow Regime over stepped spillway with variable angle:

(a)Transition flow regime ,Q=5.51ℓ/s

(b)Skimming flow regime ,Q=14.83ℓ/s

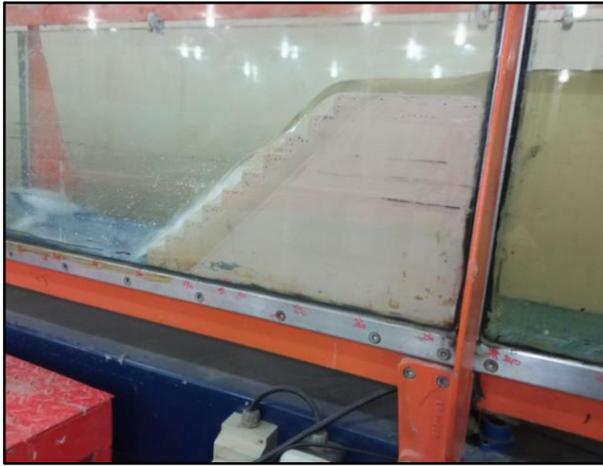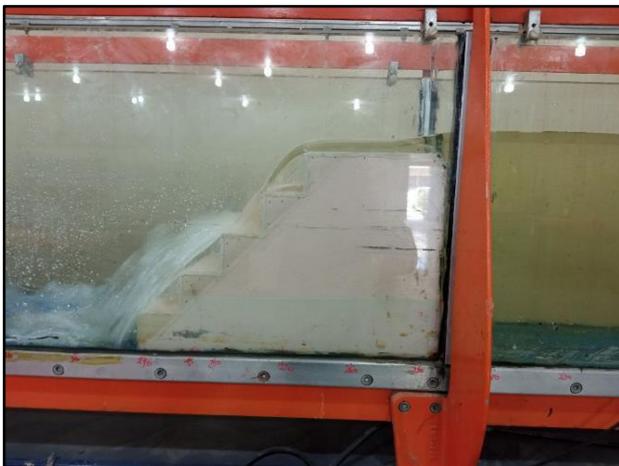Figure B.1. flow regime for 5 uniform steps spillway at angle of 40∘.
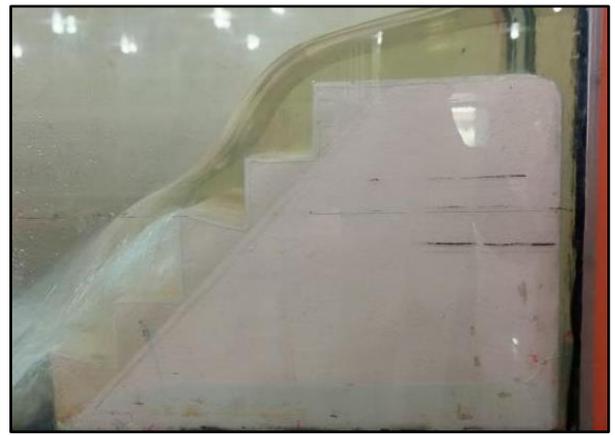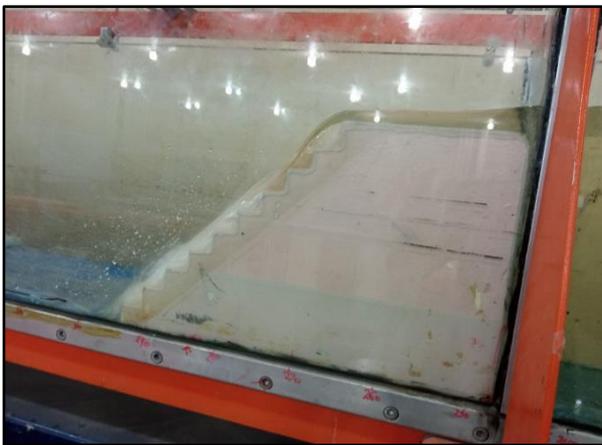

(a)Transition flow regime ,Q=7.67ℓ/s

(b)Skimming flow regime ,Q=16.41ℓ/s

Figure B.2. flow regime for 5 non-uniform steps spillway at angle of 40∘.

(a)Transition flow regime ,Q=3.31ℓ/s   (b)Skimming flow regime ,Q=10.28ℓ/s

Figure B.3. flow regime for 10 uniform steps spillway at angle of 40∘.


(a)Transition flow regime ,Q=7.67ℓ/s   (b)Skimming flow regime ,Q=16.41ℓ/s

Figure B.4. flow regime for 10 non-uniform steps spillway at angle of 40∘.

(a)Transition flow regime ,Q=3.11ℓ/s   (b)Skimming flow regime ,Q=16.41ℓ/s

Figure B.5. flow regime for 5 uniform steps spillway at angle of 45∘.

(a)Transition flow regime ,Q=5.51ℓ/s   (b)Skimming flow regime ,Q=12.52ℓ/s

Figure B.6. flow regime for 5 non-uniform steps spillway at angle of 45∘.

(a)skimming flow regime ,Q=3.11ℓ/s   (b)Skimming flow regime ,Q=7.67ℓ/s

Figure B.7. flow regime for 10 uniform steps spillway at angle of 45∘.
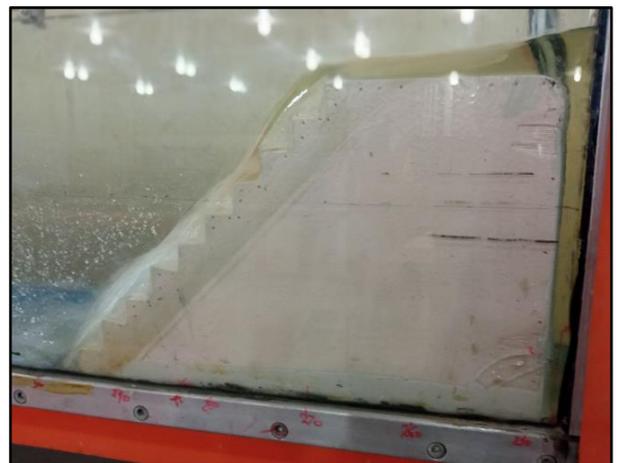
(a)Transition flow regime ,Q=3.11ℓ/s   (b)Skimming flow regime ,Q=7.67ℓ/s

Figure B.8. flow regime for 10 non-uniform steps spillway at angle of 45∘.

(a) B/2 Two-baffled blocks

(b) B/2.5 Two-baffled blocks

(c) B/3 Two-baffled block

Figure B.9. flow regime for 5 non-uniform Stepped spillway at angle of 45⁰ with baffled blocks.
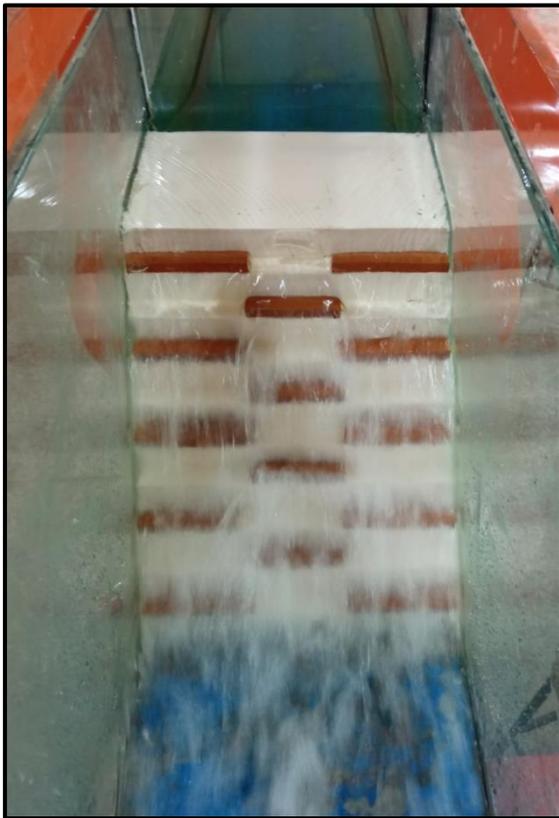
(a) B/2 Two-baffled blocks
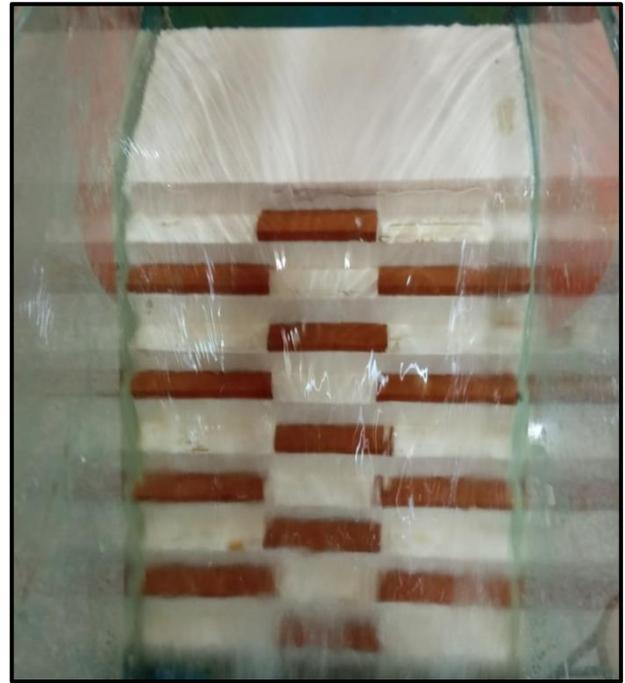

(b) B/2.5 Two-baffled blocks
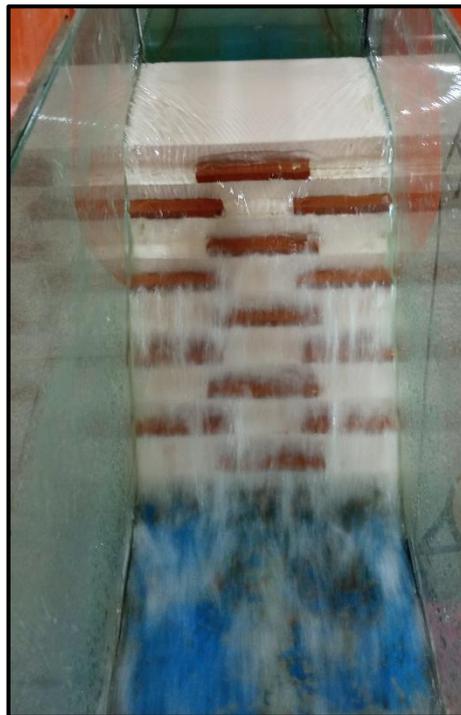

(c) B/3 Two-baffled block

Figure B.10. flow regime for 10 non-uniform Stepped spillway at angle of 45⁰ with baffled blocks.
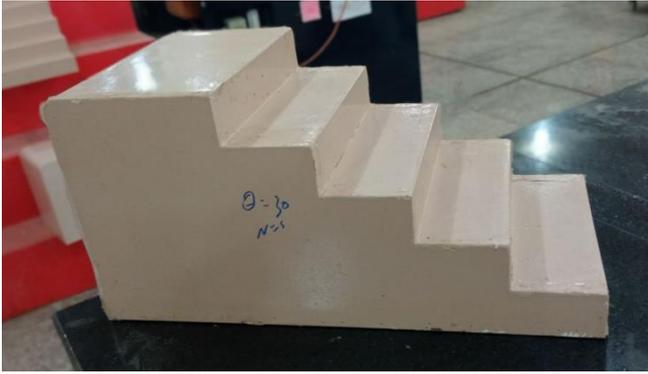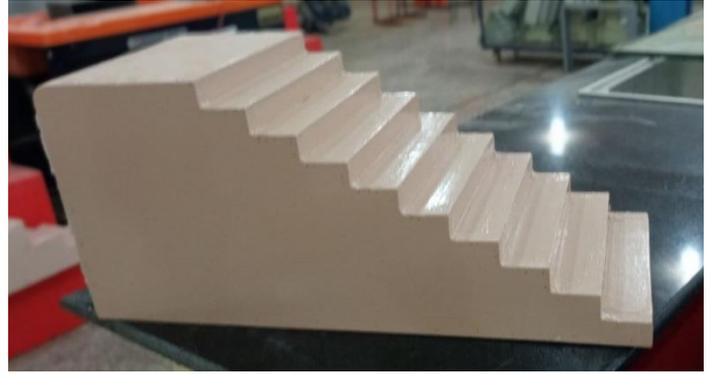
(a) B/2one-baffled blocks

(b) B/2.5 one-baffled blocks

(c) B/3 one-baffled block

Figure B.11. flow regime for 10 non-uniform Stepped spillway at angle of 45⁰ with baffled blocks.
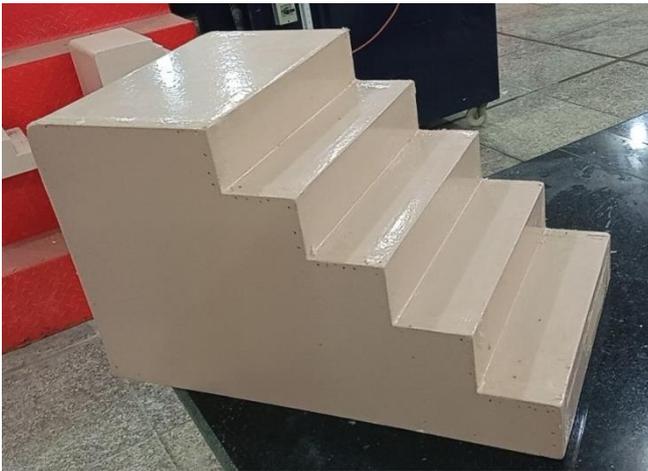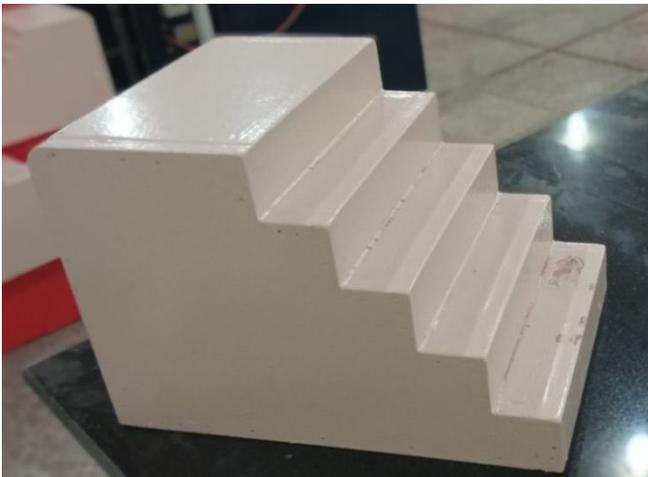
5steps

10steps
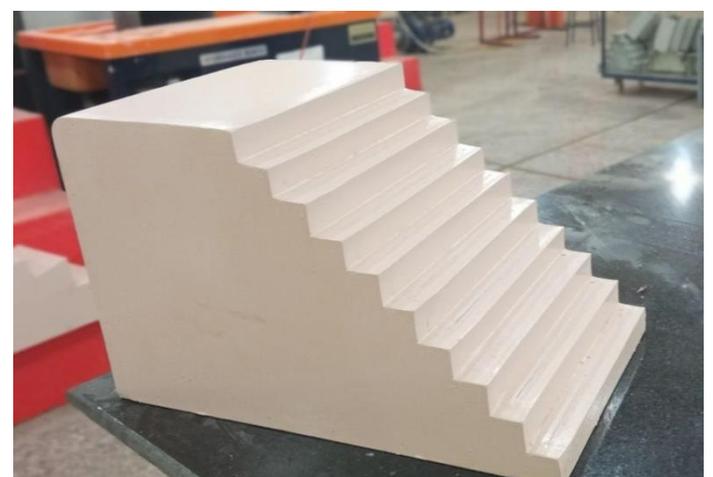

5steps

10steps

5steps

10steps

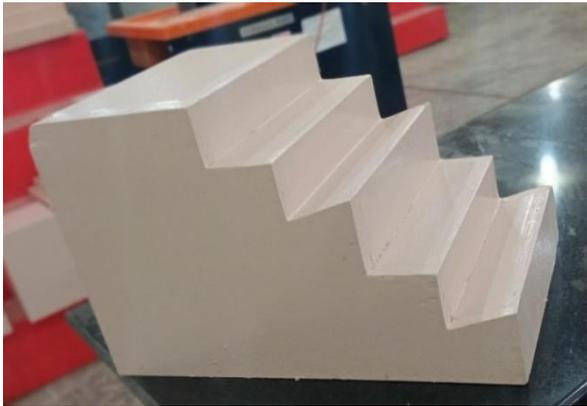Figure. B.12 Manufactured models and dimension of the uniform models

5steps

10steps

5steps

10steps

5steps

10steps

Figure. B.13 Manufactured models and dimension of the non- uniform models

الخـــلاصـــة

المسيل المائي منشأ مائي يستخدم للسيطرة على منسوب المياه في السد من خلال تصريف المياه وتحويلها من مقدم المجرى المائي إلى مؤخر المجرى المائي وهو بمثابة صمام الامان للسد . يسمح بتصريف السيول قبل أن تعلو الحد التصميمي المسموح لذلك السد وذلك تجنبا للمشاكل الهندسية التي تنشأ نتيجة علو المياه على السد والتي قد تسبب انهيار السد وتهدمه. ولأجل زيادة تبديد الطاقة وتقليل المشكلات الناشئة منها تم زياده طول المسيل المائي و وضع بداخله مطافح بأشكال متنوعة وضيفتها تقصير طول القفزة الهيدروليكية وزيادة تبديد الطاقة الناشئة من الجريان المائي في القنوات او داخل المنشاءات الهيدروليكية.

الهدف من هذه الدراسة وعلى اساس العمل المختبري التحقق في خصائص الجريان وتبديد الطاقة وطول القفزة الهيدروليكية لأثنا عشر نموذجا من المطافح باستخدام ماده خشب مقاومه للماء وتم اختبارها للمقارنة بين المطافح المدرجة المنتظمة والغير منتظمة . تم استخدام ثلاث زوايا 30 و 40 و 45 درجة وعدد درجات مختلفة 5 و10 والتي اما ان تكون ذات ارتفاع منتظم او غير منتظمة.

اضافه الى 24 نموذج من الكتل الحاجزة استخدمت للنماذج المنتظمة والغير منتظمة حيث تكونت من مجموعتين مجموعه الاولى تحتوي على واحدة من الكتل الحاجزة فوق الدرجة الاولى والنوع الثاني يحتوي عل اثنين من الكتل الحاجزة فوق الدرجة الاولى ذات مسافات مختلفة B/2 وB/2.5 وB/3 تم تثبيتها على موديل فيزيائي بزاوية (45) درجه وعدد درجات 5 و10 وبذلك اصبح العدد الكلي للنماذج 36 نموذج مرر فوق كل نموذج من النماذج اعلاه سبع تصاريف مختلقة تتراوح ما بين (3.11-16.41 لتر/ثانية) .

بينت النتائج تشتيت الطاقة يزداد مع نقصان الميل وعدد الدرجات وايضا ان نسبه تبديد طاقه الجريان تكون اكبر عند التصاريف القليلة اي عند الجريان المتدرج وتقل كلما زاد التصريف ويتحول الى الجريان الانسيابي حيث بلغت اكبر قيمة لنسبه تبديد طاقه لجريان المتدرج 85.45% وعند الجريان الانتقالي79.09% وعند الجريان الانسيابي 75.71% من خلال ملاحظه شكل الماء فوق المطافح عند الجريان المتدرج فأنه يأخذ مظهرا متموجا وبزياده التصريف تتحول تلك الموجات بسيطة ومتباعدة وعندها يسمى بالجريان الانتقالي اما بالنسبة للجريان الانسيابي يأخذ مظهرا انسيابيا ومتماسكا واظهرت النتائج العملية ان النموذج الغير منتظم اكثر كفاءه من النموذج المنتظم في تبديد الطاقة وتقريب القفزة الهيدروليكية للمؤخر وبذلك يقلل من حجم احواض التهدئة في المؤخر وتشير النتائج ان افضل نموذج لتبديد الطاقة هو النموذج عند الزوايا 30 وعدد درجات 5 وتظهر النتائج المستحصل عليها لزوايا النماذج المختارة ان النموذج ذو 30 درجه لدية اعلى تبديد للطاقة بينما يسجل 45 درجة اقل تبديد

للطاقة. أكدت الدراسة ان المطافح التي تحتوي على الكتل الحاجزة اكثر كفاءه في تبديد الطاقة من المطافح الاعتيادية ,النماذج التي تحتوي على المجموعة الاولى من الكتل الحاجزة فوق الدرجة الاولى هي الاعلى في تشتيت الطاقة وتقريب طول القفزة الهيدروليكية من النوع الثاني الذي يحتوي على اثنين من الكتل الحاجزة فوق الدرجة الاولى . حيث كانت النماذج التي تحتوي عل النوع الاول من الكتل الحاجزة عند 5 درجات اعلى نسبة لتشتيت الطاقة عند المسافة (B/2.5) اما عند 10 درجات اظهرت النتائج عند المسافة (B/3) بينما في المجموعة الثانية الذي يحتوي على اثنين من الكتل الحاجزة عند5 و10 درجات تزداد نسبه تبديد الطاقة كلما قلت مسافة التوزيع .

فحص الهيدروليكي للمجرى المائي المتدرج مع درجات منتظمة وغير منتظمة

رسالة

مقدمة الى كلية الهندسة ، جامعة بابل وهي جزء من متطلبات نيل درجة الماجستير علوم في الهندسة/ الهندسة المدنية/هندسة الموارد المائية

من قبل:

حســن جــاسم محـــمد حسن

بكالوريوس علوم في الهندسة المدنية 2018

بأشراف:

أ. د. عبد الحسن خضير الشكر

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