Republic of Iraq

Ministry of higher education

& scientific research

Babylon University

Department of environmental engineering.

Studying the Characteristics of Two-Dimensional Flow over Spillway by Using ANSYS Fluent

Project

Submitted to the department of environmental engineering of the University of Babylon in partial fulfillment of the requirements for the degree of B.Sc. of philosophy in environmental engineering.

By:-

Haider Majid Marzouq

May 2023

Supervised by:-

Dr. Udai Adnain Jahad

بسم الله الرحمن الرحيم

وَجَعَلْنَا مِنْ الْمَاءِ كُلَّ شَيْءٍ حَيٍّ أَفَلا يُؤْمِنُونَ

صدق الله العظيم

سورة الأنبياء : الآية 30

SUPERVISOR CERTIFICATION

I certify that this project entitled **" *Studying the characteristics of two-dimensional flow over spillway by using ANSYS Fluent* "** presented by **" *Haider Majid Marzouq* "**, was prepared under my supervision as partial fulfillment for the degree of Bachelor of Science in Environmental Engineering at the Department of Environmental Engineering, College of Engineering, University of Babylon.

Signature:

Name: **Dr. Udai Adnain Jahad**

Date: / / 2023

CERTIFICATION

We certify that we have read this project entitled ***" Studying the characteristics of two-dimensional flow over spillway by using ANSYS Fluent "*** and as an examining committee, examined the students **"** ***Haider Majid Marzouq*** **"** in its content and in what is connected with it, and that in our opinion it meets the standard of a graduated project for the degree of Bachelor of Science in Environmental Engineering.

Signature	**Signature**
Name: **Asst. prof**	Name: **Asst. prof**
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Signature	**Signature**
Name: **Prof.**	Name: **Prof.**
(Member)	(Member)
Date: / / 2023	Date: / / 2023

Approval of Environmental Engineering Department

Signature

Name:

Head of the Environmental Engineering Department

Date: / / 2023

Acknowledgments

By the name of God

I would like to express our deepest thanks and sincere apperception to my supervisor Dr. Udai Adnain Jahad for his valuable guidance and his forceful encouragement throughout the preparation of this work.

To the person to who difficulties are vanquish

My father

To the person who banish sadness

My mother

To my loving sisters

To the people who have truly loved me & I have always loved them back with all my heart

My friends

I dedicated my simple work.

Haider Majid Marzouq

ABSTRACT

Spillways are structures designed to control hydraulic flow, change the direction of rivers to avoid flooding, measure discharge, and regulate navigable routes. The steps are affecting the performance of the stepped spillway regarding the dissipate energy and aeration. In the last 30 years, several studies (both experimental and theoretical) have created design guidelines and highlighted complexities of the air–water flow structure. Despite that, the optimum geometry design for stepped spillways is not known, and it is not comprehensively studied regarding the flow regimes, flow resistance and energy dissipation, velocity distributions, and pressure distributions. In the current study, CFD model has been used to solve the Reynolds-averaged Navier–Stokes equations by ANSYS-Fluent software. 2D flow model has been developed by appalling the multiphase model as a VOF model and the viscous model as the standard k-ε model to simulate the two-phase flow and the water surface profile over the stepped spillway. The CFD model verified by experimental results and then using the CFD model to conduct a parametric study with a further prediction of the stepped spillway behaviour. The results show good agreement between the CFD and the experimental results. Also, the results of CFD show the same behaviours that support the positive effect of the new modifications on the step (adding quarter-circle end sill).

TABLE OF CONTANT

Table Of Figure

NO. OF TABLE

CHAPTER ONE

INTRODUCTION

1.1 Background

Critical issues governing the performance of hydraulic structures such as spillways and chutes include the stability and safety of the structure itself. A stepped spillway aims to dissipate the energy of the water flow, thus decreasing the stilling basin volume and the risk of cavitation, and to enhance the aeration process, thus increasing the dissolved oxygen (DO) concentration. The energy dissipation is the main parameter affecting most hydraulic structural designs because the high kinetic energy of the water flow can cause scouring downstream (DS). Furthermore, hydraulic structures can improve aeration efficiency according to their geometry. One of the main purposes of aerating water is to raise the DO concentration. Hydraulic structures are of two common types: high-head flow systems and free-surface flow systems (Baylar et al. 2010). According to Chanson (2000), stepped cascades have been used in hydraulic structures to dissipate energy and reduce scouring of the water channel. Stepped cascades are included in the spillways of dams, river weirs, irrigation channels and stormwater systems, and one example is the spillway of Gold Creek dam in Brisbane, Australia, which is shown in Figure 1.1. Importantly, hydraulic structures must be designed to discharge water in a safe way and to prevent damage to the structure itself and the surrounding locations (Chanson 2001a; Felder 2013). Moreover, the flow over the stepped spillway has been characterised by free-surface aeration downstream of the inception point of air entrainment. While the energy dissipation overstepped spillway has been investigated in previous studies, the optimum design for stepped spillway regarding the aeration process is not known (Felder and Chanson, 2015). Felder and Chanson (2009) described the energy losses and aeration processes of stepped cascades with moderate slopes and found that increases in the rate of re-aeration are related to increases in the rate of energy loss. According to Aras and

Berkun (2008), hydraulic structures affect the gas transfer dynamics of white-water. The DO is the most significant parameter related to water quality in rivers and streams. In addition, Baylar et al. (2007) stated that hydraulic structures can create turbulent conditions that increase DO levels as air bubbles, especially small ones, are transported into the bulk of the flow as chute aeration. Medhi et al. (2019) described the flow over the stepped spillway as a complex flow with different characteristics from other types of spillways. The flow being complex is also a reason to obtain better performance.

In general, the geometry and configuration of stepped spillways need further examination because the optimum design for water aeration and energy dissipation may not be known. In the present study, the aeration and energy dissipation processes are investigated in a stepped spillway with a novel design, using both experiments and mathematical models. This work uses two approaches to examine these models. First, physical models are investigated via six models for three chute angles (eighteen models in total) that allow the comparison of geometry effects, aeration efficiency and energy dissipation. Second, this work performs simulations that use experimental data as input for computer-based modelling.

Figure 1.1 A Gold Creek dam (Brisbane, Australia, 1890; https://en.wikipedia.org/wiki/Gold_Creek_Dam).

1.2 Stepped spillway applications

A series of separate steps creates a stepped spillway. There are many shapes for the steps, such as horizontal, inclined upward or downward, and pooled, as illustrated in **Figure (1.2).**

Stepped cascades are utilised for many purposes and can be classified as main structures and secondary structures, as follows:

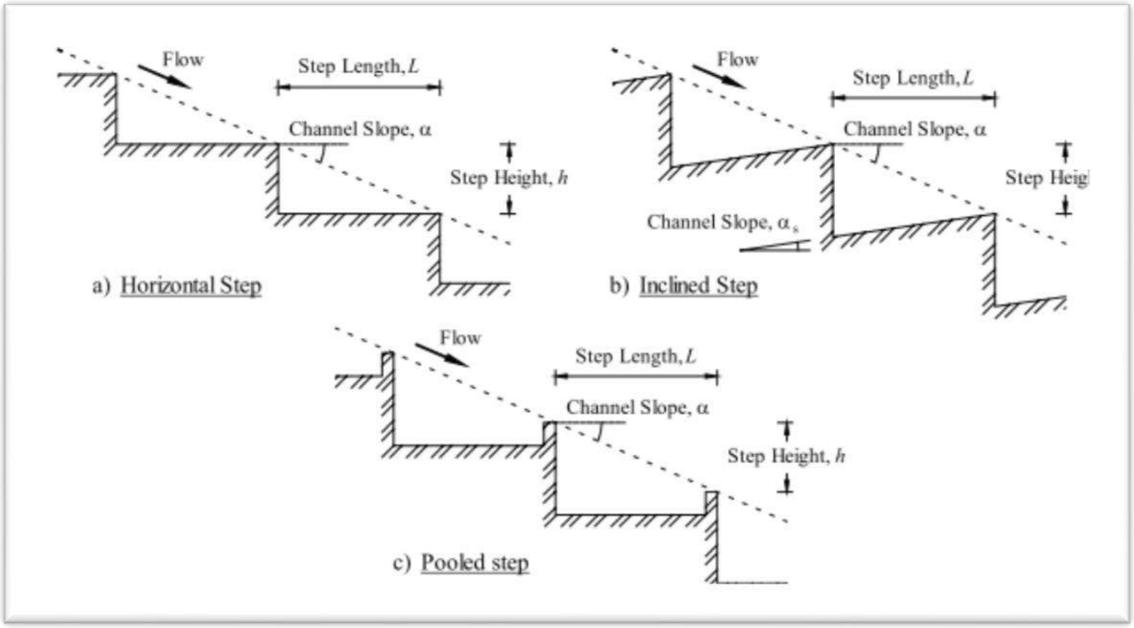


Figure 1.*2* Common geometries of stepped cascades (Toombes,

1.2.1 Main structures

A. Weirs in rivers: A weir is a small dam utilised to increase the level of water upstream (US) of the structure. In general, weirs cause a diversion of flow and have a control section. A weir with stepped cascades may function as a dam or spillway and include energy dissipation and aeration functions within the one structure, and an example is presented in **Figure (1.3).**

B. Spillways: Stepped cascades have better energy dissipation properties than smooth chutes. Leonardo Da Vinci noted that "the more rapid it (the flow) is, the more it wears away its channel" and when a waterfall "is made in deep and wide steps, after the manner of stairs, the water (…) can no longer descend with a blow of too great force" (Richter

1939; Toombes 2002). Chanson (1998 and 2000) referred to a stepped weir in Akarnania, Greece, dating from around 1300 BCE, as shown **in Figure (1.4).**

C. River control: Another use for stepped cascade structures is to distribute a waterway by using a steep gradient to the steps, which themselves have a small slope, to reduce erosion in the channel bed, as shown in **Figure (1.5).**

D. Water Treatment: The macro-roughness impact on air–water gas transfer has been common knowledge since the Roman Empire. In recent years, the design of stepped cascades has been modified for use in water treatment. Physical model studies, rather than analytical studies, have been used to design most of these cascades, and one example of these cascades is the Torrance Avenue Station No.1 in Chicago that is shown in **Figure 1.6.** There are five aeration stations built along it.

Figure 1.*4* An old stepped spillway in Akarnania, Greece, built around 1300 BCE (Chanson , 2000).

Figure 1.*3* Cunningham Weir (Texas, Qld, Australia, 1953; RJW 1999).

Figure 1. *5* River Dodder control (Dublin, Ireland; Water at TCD, 2011).

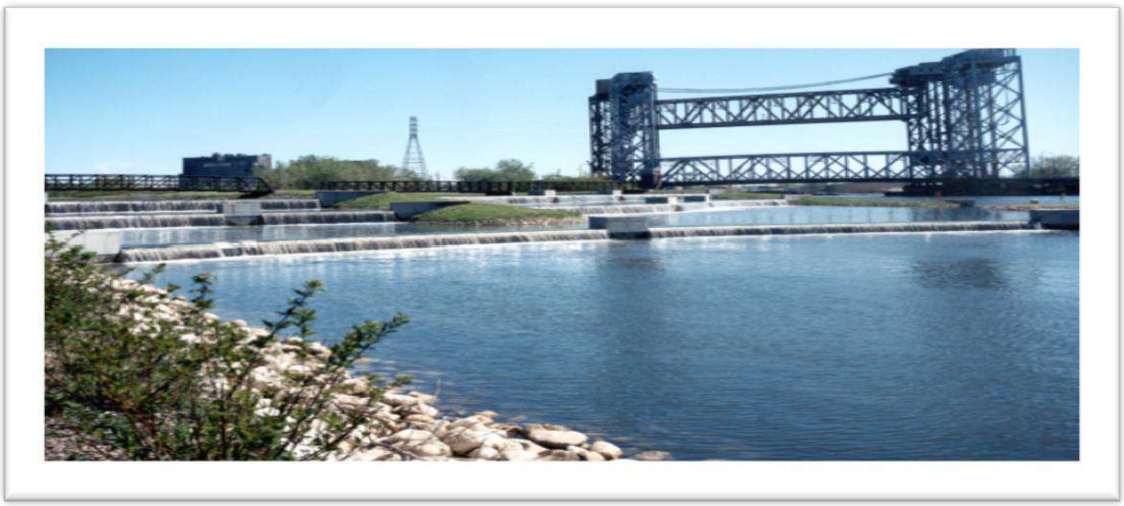


Figure 1.*6* Side stream Elevation Pool Aeration (SEPA) cascade (Chicago, USA, 1988; Toombes, 2002).

1.2.2 Secondary structures

A. Stormwater paths: Stepped cascade structures can be used in channels to dissipate the energy in stormwater channels, particularly on steep hill slopes. **Figure (1.7)** illustrates a stepped stormwater channel beneath the University of Hong Kong.

B. Dams, to prevent debris: In mountainous regions, high-velocity torrents containing debris can cause damage. The debris ranges from clay particles to large boulders, wood and trees. For example, see the Sabo works on the Kagokawa River **(Figure 1.8).**

C. Recreational spillways: Stepped cascades may be used in recreational areas for aesthetic reasons. The garden waterfalls placed around plants in the water treatment system on Chicago's Calumet River are a good example of how stepped cascades can be a successful combination of form and function. Figure 1.9 shows a stepped spillway used for recreational purposes at Al-Jadriah Lake in Baghdad, Iraq.

Figure 1.7 Stepped storm water beneath the University of Hong Kong

Figure 1.8 Stepped spillway used for recreational purposes at Al-Jadriah Lake, Baghdad, Iraq (Ministry of Water Resources Iraq 2012).

1.3 Objectives

Stepped spillways have been studied with renewed interest over the last 50 years to determine design guidelines and to understand the flow processes in complex air–water flows. Available information is still limited regarding stepped spillway characteristics and performance. The complexity of the interactions between air and water phases remain poorly characterised because of limitations in facilities, instrumentation and processing power. Also, the designs of most prototypes have been based on small scale models, which are prone to scale effects. All these factors significantly affect stepped spillway studies on energy dissipation and air entrainment mechanisms. The focus of the current study is to conduct a systematic, detailed investigation of the physical flow characteristics of stepped spillways. The current study objects are in the following:

To investigate the flow characteristics, and energy dissipation mathematically by using Computational fluid dynamics (CFD) method (based on ANSYS Fluent) with the volume of fluid (VOF) and K-ε turbulence models.

CHAPTER TWO
BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

Spillways are very significant hydraulic structure utilised in rivers, channels and dams. The dissipation of the energy of high-velocity flow is critical for the safety of structures and downstream zones. Most studies have investigated the most efficient methods of dissipation of the energy generated by the changes in head values in the upstream (US) and downstream (DS) of the hydraulic structure (stepped spillway). Energy dissipation can be accomplished by various techniques, such as 1) expelling high-velocity water nappes from a flip pail that then plunge to the DS part, 2) forcing the hydraulic jump DS by constructing a stilling basin with artificial macro-roughness, and 3) building a stepped spillway to dissipate the energy through turbulence created by the flow on the spillway face.

Stepped spillways were built by many ancient civilisations, and the remains of some of them still exist. The world's oldest stepped channels were possibly a group of stepped culverts built in Crete during 1500 BC (Chanson 2002). According to Chanson (1995), the presumed first creation stepped spillway in Arkanania, Greece, was constructed about 1300 BC. The Assyrian King Sennacherib built two dams over the Khoser River in Northern Iraq around 694 BC that included a stepped spillway arrangement. These dams (named Ajilah) were created to provide water to Nineveh (Assyrian city) in Iraq. In addition, Nabataeans, Romans and Sabaens built many stepped spillways. The remains of Roman spillways are still found in Syria and Tunisia. Furthermore, a stepped spillway was built over the Adheim Dam in Iraq (Chanson 2002). Even at the beginning of the 20th century, some stepped spillways (such as New Corton Dam, 1903) were constructed without following any definite design rules. The first contributions in stepped spillway research were by Essery and Horner (Horner 1969; Essery & Horner 1978). After the 1980s, the development of new creation techniques, such as the gabions and roller-compacted concrete, reduced costs and construction time. Since the 1990s, extensive research has been conducted on the main characteristics of stepped spillways (Diez-Cascon et al. 1992; Peyras et al. 1992; Chanson 1993; and others). Stepped spillways are defined as a series of drops that provide artificial roughness on the spillway slope (Chanson, 1994a).

Flow over stepped spillway includes three flow regimes: 1) Nappe flow (NA) regime for the low flow rates, 2) Skimming flow (SK) for large flow rates and 3) Transition flow (TR) for intermediate flow rates. Compared with smooth spillways, flow oversteps are accompanied by large amounts of air entrainment because of greater boundary layer development from macro-roughness effects. The main advantage of stepped spillways is their high energy dissipation, which can reach 99% of the total available head (Chanson 1993), reducing the need for a DS stilling basin. In addition, the higher level of aeration and higher relative depth over the spillway reduces the risk of cavitation. Stepped spillways are used for low to moderate discharges; however, for large discharges, other types of spillways and energy dissipaters can be used. Stepped spillways have many applications, as explained in Section 1.2.

2.2 Flow regimes

In the flow regimes, there are two classifications for the flow over stepped spillways. There are two flow regimes in the first classification: Nappe flow regime (NA) and Skimming flow regime (SK). Essery and Homer (1971) noted that the flow properties importantly affect the characteristics of flow regime on the stepped spillways. According to the relationship between the flow characteristics and flow regime, flow regimes are of two types: NA and SK. In NA regime, the water mass forms a series of plunges over the steps, and the flow is subcritical on most of the steps or part of it. In contrast, in the SK regime, water mass moves similar to a regular stream over all the steps and supercritical flow throughout. For the second classification, regimes of the flow are divided into three regimes. Regimes of the flow are NA (low discharges), SK (high discharges) and TR. Researchers in the hydraulic field consider the NA regime to be the highest efficiency regarding the energy dissipation and the efficiency of aeration (Pegram et al., 1999). Many researchers have examined the flow characteristics over the stepped spillway, such as Pegram et al. (1999), Chanson and Toombes (2004), Chinnarasri and Wongwises (2006), Baylar et al. (2011), Dhatrak and Tatewar (2014), Mero and Mitchell (2017), Ali and Yousif (2019).

According to Chanson and Toombes (2004) on the stepped spillways, the flow described as an SK regime with a large enough discharge volume or be freefalling NA with a low-volume discharge. However, there is a range of TR that occurs between the NA and SK regimes. These have different properties such as troubled flow motion with strong splashing. Figure (2.1) shows examples of the NA and SK on the stepped spillways, which display significantly different flow characteristics.

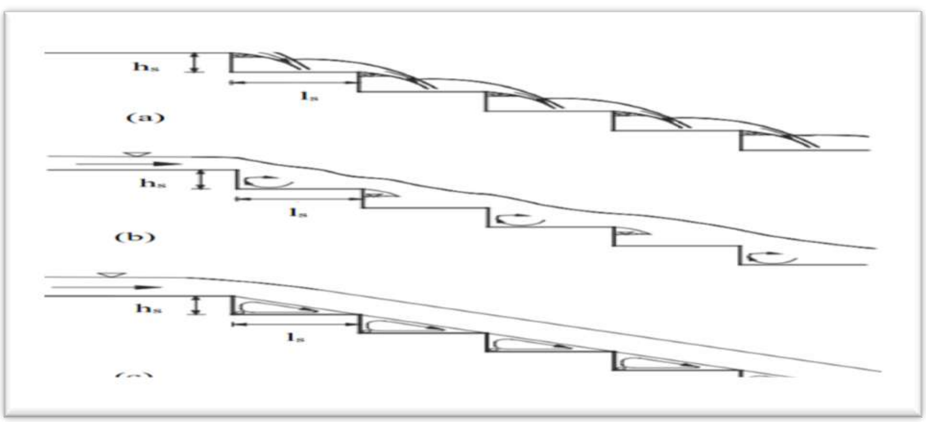


Figure 2.1 The flow regimes on stepped spillways (a) *NA* , (b) *TR*, (c)

Chinnarasri and Wongwises (2006) indicated the properties of the flow and parameters affecting the losses of the energy for the flow on the stepped spillway as the step shapes changed. The step shapes were flat shape (normal step shape), inclined shape, and flat shape with end sill; and the regimes of the flow over these steps were observed and described. The results show that the energy losses were lesser in SK flow than NA flow. Moreover, the steps with end sill were highly effective regarding the energy losses. The impact of the number of steps was clear; specifically, the energy dissipation increased as the number of steps (N_s) increased. Baylar et al. (2011) investigated the three flow regimes (NA, TR, and SK) regarding the relationship between energy dissipation and aeration performance over the stepped spillway. The results show that the aeration performance increases as the energy dissipation rate increases. In addition, the energy dissipation was higher, and the aeration performance was developed in NA when compared with the in SK.

Dhatrak and Tatewar (2014) investigated stepped spillways aeration efficiency and pressure fluctuations in the SK regime. The results show that the air concentration increased as the discharge rate and the number of steps increase. The air concentration increases along the longitudinal section of spillways. The observations showed that the bottom mean air concentration increased with the height of the step (h_s) in the US, leading to high susceptibility to cavitation. The pressure distribution exhibited a wavy shape down the stepped spillway. The pressure distribution over the step increased with the discharge, and the discharge is determined by the ratio between the critical depth of the flow and the height of the step (y_c/h_s).

Mero and Mitchell (2017) conducted research examining the flow over stepped spillways. The chute angle was (26.68°) and the discharges were up to 0.0121 m^3/s. Several step geometries were used, including inclined and horizontal curved steps, with and without reflector blocks. The flat step had a step height of h_s= 5 cm, and the flow regimes were investigated regarding the step shape with energy dissipation efficiency. The results showed that SK occurred earlier in flat steps than in steps with the horizontal curved shape and had doubled the energy dissipation.

2.3 Energy dissipation and residual energy

Energy dissipation has been studied by many researchers, especially on stepped spillways. Ideally, the high kinetic energy of flow that comes from water stored upstream of the hydraulic structure should be dissipated without any damage or erosion downstream. The traditional model for spillways designed during the 20^{th} century has been that of a flat slope (the chute is smooth) with an energy dissipation structure placed downstream. However, stepped spillways have many useful features, e.g. Their high energy dissipation allows decreased volume in the DS stilling basin (Toombes 2002). Kote and Nangare (2019) investigated an experimental model for stepped spillways with a stilling basin. These stepped spillways have a flat-step shape (traditional shape), and they presented a comparison between the stepped spillway without stilling basin and the stepped spillway with a stilling basin. The results explained that energy dissipation had a significant effect on the stepped spillway design. Christodoulou (1993) explained that the significant parameters that control energy dissipation over a stepped spillway are the non-dimensional value of the critical depth of flow to step height, y_c/h_s, and the number of steps, Ns. Energy dissipation is the greatest at small values of y_c/h_s and decreases with increasing y_c/h_s; then, for a certain y_c/h_s, the energy dissipation increases with N_s. The results were compared with those of previous investigations with a large number of steps. Parsaie et al. (2016) developed a model multivariate adaptive regression splines (MARS) to predict the dissipated energy for SK on the stepped spillway and evaluate the most effective parameters. The outcomes indicated that the significant parameters are the step height, critical depth of the flow, and drop number in the dissipated energy performance. Ashour et al. (2019) used geometry changes on the stepped spillway body to assist the energy dissipation and the aeration performance. The results showed the effect of the step number and both the step length and step height. According to Roushangar et al. (2014), the dissipation of energy in stepped spillways is significant, especially for studies related to flood control. Based on the earliest investigation obtained by Sorensen (1985), energy dissipation in spillways depends on four parameters:

1) Discharge rate.
2) Slope.
3) Step geometry.
4) Step number.

Tatewar and Ingle (1995) used a mathematical equation based on experimental data to estimate energy dissipation (Equation (2.1)):

$$\frac{\Delta E}{E_o} = \frac{1}{1+Co(\frac{y_c}{H_d})} \qquad \text{………………………. (2.1)}$$

Where ΔE represents the difference between the total heads US and DS; C is a coefficient that varies from 1.237 to 1.4; H_d is the height of the dam; E_o is the spillway total head US; and y_c is the critical depth of the flow.

Chanson (1994b) examined energy dissipation over a stepped spillway in NA and SK regimes and compared the results with experimental data. For a long, stepped, spillway chute where uniform flow conditions occur, higher energy dissipation occurs in SK. However, for short, stepped, spillway chutes, NA dissipates more kinetic energy than SK, and Figure 2.2 shows the energy dissipation variation between the NA and SK regimes. In the current study, the energy dissipation has been investigated in all the flow regimes (NA, TR, and SK) with three deferent stepped spillway lengths.

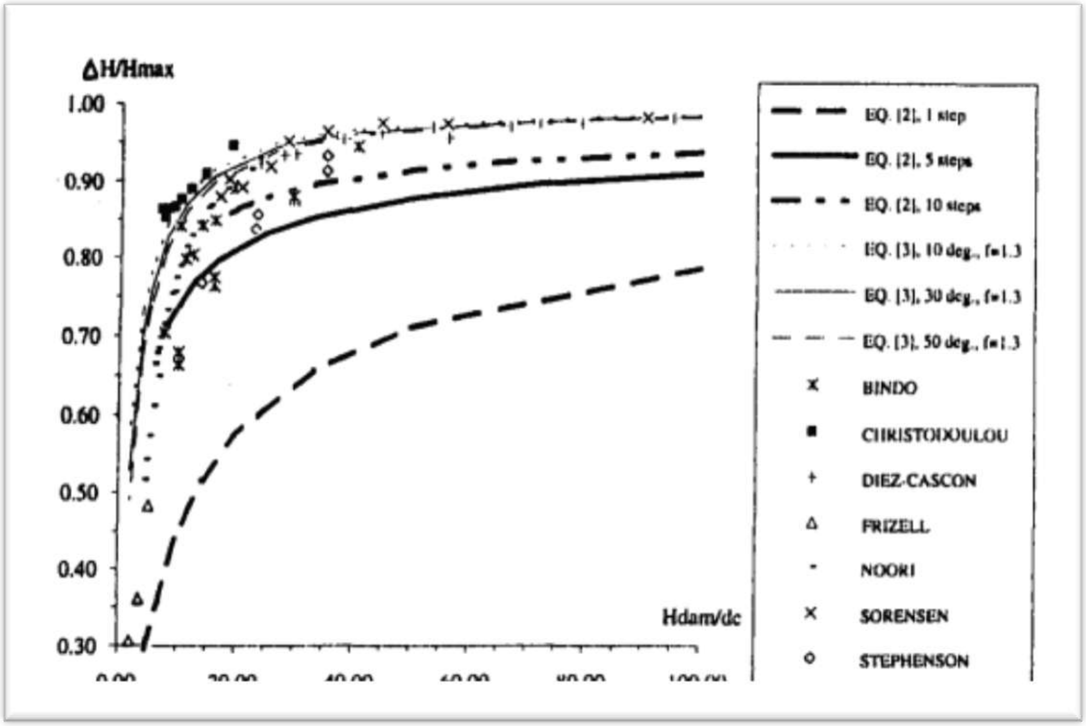


Figure 2.2 energy dissipation variation between the nappe and skimming flow regimes, Chanson (1994b).

Chinnarasri and Wongwises (2004) examined how flow and energy dissipation are affected by step geometry. The step configurations used were horizontal, inclined and end-sill steps with various step heights (h_s) and chute angles. The results illustrated a link between energy dissipation and the relative critical depth of flow in the three types of step geometry. The results show that the highest efficiency in terms of energy dissipation ratio occurred in spillways containing steps with end sills. Moreover, the results demonstrated that energy dissipation increases with the number of steps. The relationship between the ratio of energy dissipation and relative critical depth of flow was determined. The effects of step geometry were analysed to determine the effects of sills or inclined steps shape on flow characteristics and the dissipated energy.

Barani et al. (2005) determined the energy dissipation for the stepped spillways with several step configurations. Their physical model used a chute angle of 41.41°, stepped spillway height of 84 cm and 21 steps. Furthermore, the step dimensions were step height **h_s = 4 cm**, step length **l_s = 4.5 cm** and width **w = 30 cm**. Two step configurations (flat and end-sill steps) were used with chute angles of 15, 26, 36 and 45° to measure the hydraulic characteristics of the flow. The dissipated energy on the stepped spillway with end sills was greater than on the one with flat steps and increased as the thickness of the end sills increased, as shown in Figures 2.3 and 2.4. Energy dissipation decreased with increasing flow rates.

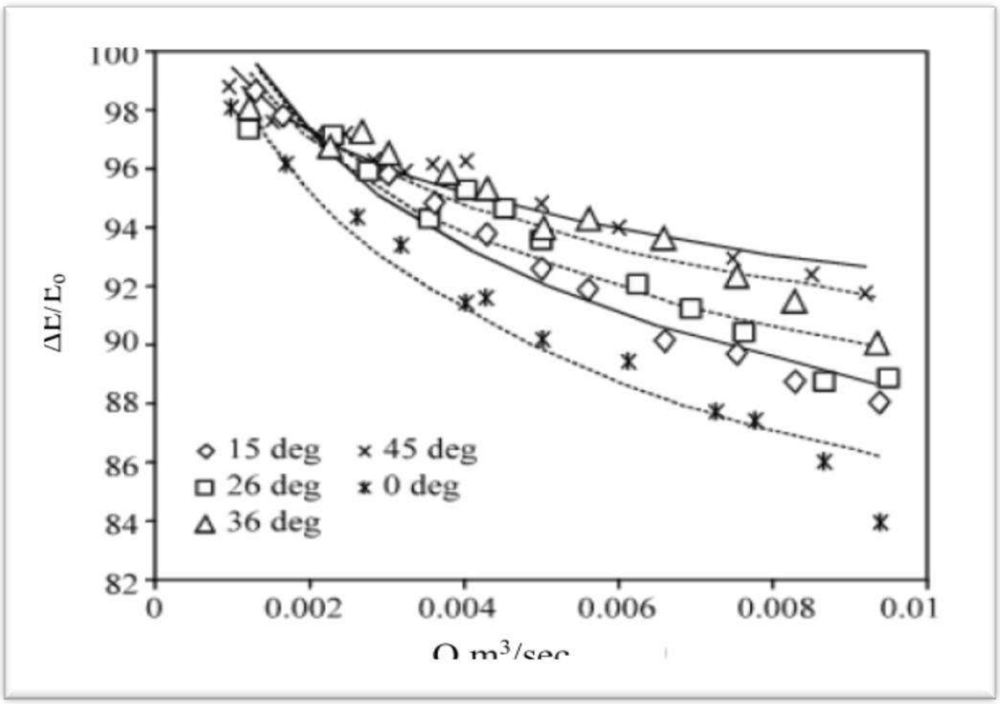


Figure 2.3 energy dissipation with flow over stepped spillway with inclined step shape for different slope chute, Barani at el. (2005).

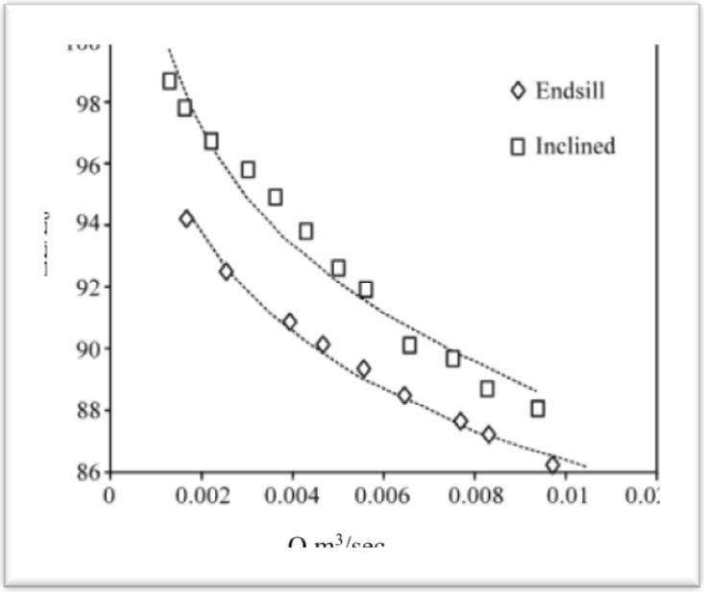


Figure 2.4 energy dissipation for the discharge over the stepped spillway with inclined and ends ill configuration for angle chute θ=15°, Barani at el. (2005).

Carosi and Chanson (2008) reported that a stepped spillway helps to increase energy dissipation according to the chute and reduces the size of the DS stilling basin required (dissipater structure). Their finding was that a stepped spillway works as a spillway and a dissipater structure at the same time. In addition, a comprehensive study was performed on the characteristics of air–water flow in SK (Figure 2.5), focusing on the properties of turbulence. A large-size facility with chute angle θ = 22° and step height h_s = 0.1 m was utilised to conduct measurements at many phase detections for intrusive probes. The integral turbulence length and time scale were estimated by correlation analysis. The results were in good agreement with previous studies about air–water flow measurements in SK regimes. Measurements had a good correlation between the intensity and length of turbulence with the timescales. Moreover, the measurements highlighted the large levels of turbulence, large turbulent times, and length scales occurring in the middle of the spray flow and bubbly flow regions. The turbulent dissipation is an important process that influences the energy dissipation.

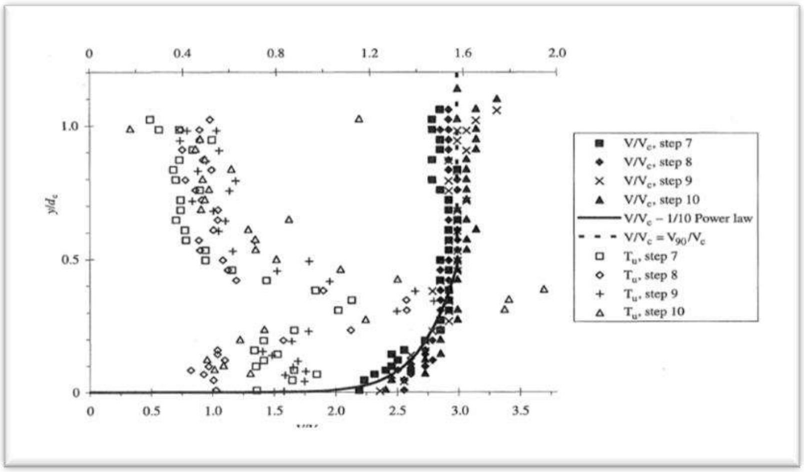


Figure 2.5 air- water velocity (V/V_c) distribution with the turbulent intensity (T_u) for d_c/h= 1.33, Carosi and Chanson (2008).

Hunt and Kadavy (2009) concluded that as the step height of a stepped spillway increases, energy dissipation is also increased. Energy losses may be defined in terms of the remaining head at the toe of the spillway or the head difference US and DS of the spillway. The latter is probably more widely used. Meireles and Matos (2009) investigated the region of air–water flow in the hydraulics of stepped spillways. The nonaerated region is significant in small embankment dam hydraulic designs that have large overtopping flows. They derived an equation for SK characteristics based on experimental data US of the air entrainment inception point with a stepped spillway slope of 1V:2H. The study focused on the nonaerated flow region that develops because of the depth of clear water, distribution of velocities and energy dissipation. The law of power gives a full description of the distribution of velocities (Figure 2.6). The depth of the clear water and the specific energy varied with the relative distance along the spillway, and the critical depth effect was very low. In conclusion, energy dissipation was small, which is good for the design of DS energy dissipaters.

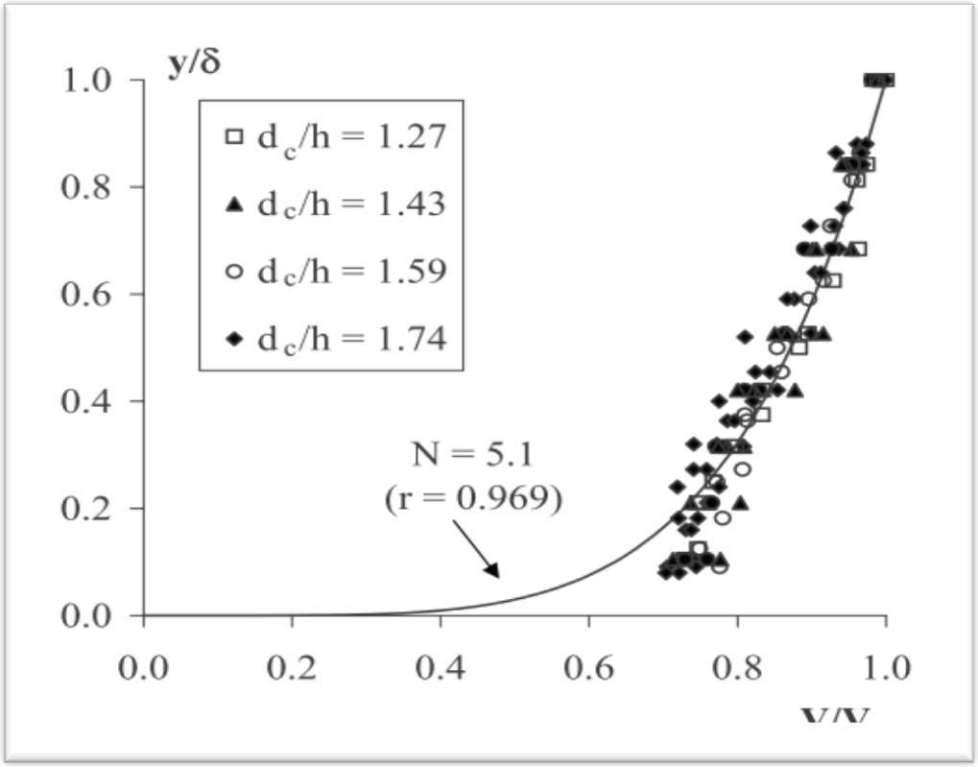


Figure 2.6 velocity distribution for the experimental data with nonaerated flow and step height h_s= 5 cm, Meireles and Matos

Hamedi et al. (2011) conducted an experimental investigation of the energy losses over stepped spillways with NA regimes. Various patterns of stepped spillways have been used, such as reverse slopes with variable angles, and with different end sills installed on the step edges. The investigated parameters were end-sill height, thickness and upper angle. The results showed that energy dissipation increases with a hybrid model and that the hybrid model is better than others in terms of estimating energy dissipation. In addition, the results inferred that energy dissipation is higher when using inclined steps with end sills than when using inclined steps only. Figure 2.7 explains the impacts of the end-sill thickness (m) on the energy dissipation. In general, using inclined steps and end sills or even inclined steps only gives higher energy dissipation than flat steps.

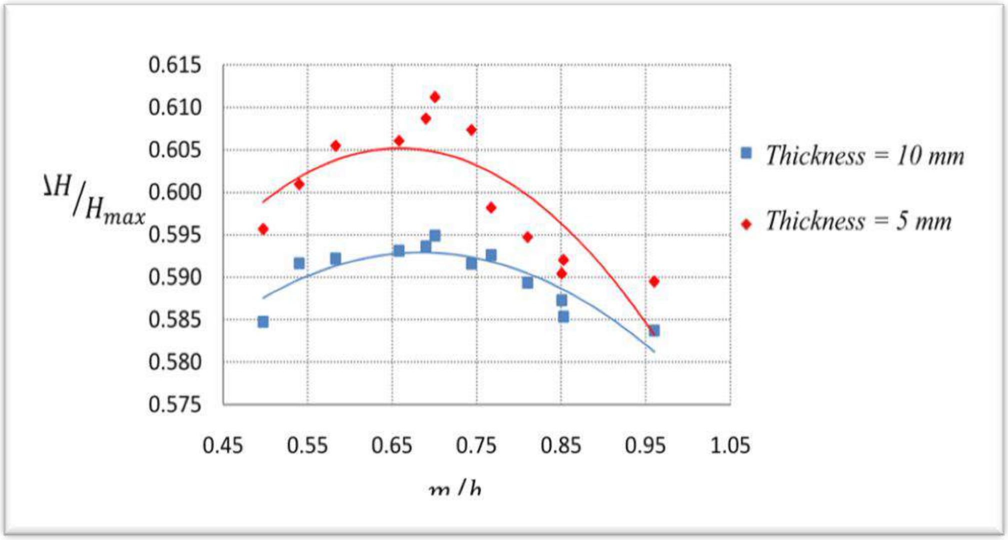


Figure 2.7 end sill thickness effect on the energy dissipation for the flow over the steeped spillway, Hamedi

Felder and Chanson (2011) investigated energy dissipation and flow characteristics over a stepped spillway. The stepped spillway slope was 1V:2H, and five step shapes were tested for $0.7 < y_c/h_s < 1.9$, where yc is the critical depth of the flow and hs is the step height, with uniform and non-uniform step heights. The results indicated only small changes in energy dissipation between the step shapes. Energy dissipation can be the same for uniform and non-uniform stepped spillways. However, observations of the non-uniform stepped spillway indicate there were unstable flow characteristics with small discharges.

Meireles et al. (2012) showed that despite previous studies examining the hydraulic characteristics of the air entrainment inception point and the aerated region, much less is known regarding flow in the non-aerated region. Moreover, the study used a huge dataset achieved over several years in a large-scale facility to highlight the properties of the non-aerated flow region. A comparison of various methods was conducted to estimate the main hydraulic characteristics of inception points. The results showed that the energy dissipation of stepped spillways is greater than that of smooth spillways, while aerated flow values at the toe point in stepped spillways are much smaller than those of smooth spillways because the steps cause high turbulence in the flow.

Zare and Doering (2012a) utilised a physical model to study the effects of baffles and sills on flow characteristics and energy dissipation. Baffles are blocks, while sills are barriers located on the steps of a stepped spillway to increase flow resistance. Baffles and sills were located at the edges of steps or were shifted from the step edges of a 1V:1H sloping, stepped spillway with a sharp or round crest. The inlet was an ogee inlet. Many shapes of baffles and sills were compared to determine their characteristics relating energy dissipation to flow. The results show that SK started at the lowest discharge rates with baffle-shifted/round-crested spillways. In addition, the dissipation of energy in the chute was greater in the baffled-edge spillway than the sill-edged spillway. The dissipation of energy was decreased by shifting baffles or sills away from the sharp edges. Within the range of discharges used in the study, energy dissipation was increased by moving baffles or sills from the round-crested spillway (Figure 2.8).

Khalaf et al. (2014) investigated the profile of water flow surface, piezometric head distribution and dissipated energy ($\Delta E/E_o\%$) on stepped and smooth spillways. Three different chute slopes for both spillways were used (V: H = 1:0.75, 1:1 and 1:125). Also, three numbers of steps (N_s = 3, 5 and 7) for each slope were used over the stepped spillways. The cross-sectional dimensions of the flume were a width of 0.5 m and a depth of 0.45 m for a wide range of discharges. On stepped spillways, the results showed that any increase in the ratio of the US water depth to the critical flow depth (y_o/y_c) and the ratio of step length to the critical flow depth (l_s/y_c) increases the value of $\Delta E/E_o\%$.

Krisnayanti et al. (2016) examined physical models for flat and pooled stepped spillways. The chute angle of the models was θ = 45° with step numbers of N_s = 20 and 40. The experimental work was conducted for ten Froude numbers (F_r) ranging between 1.117 and 9.909. The SK regime was used with a range of non-dimensional critical depth-to-step heights of $0.7 < y_c/h_s < 3.0$. Furthermore, the study investigated the relationship between energy dissipation (with Froude numbers) and step shape on various stepped spillways. The results show that energy dissipation increased as step number increased. In the pooled stepped spillway, the energy dissipation of the flow was greater than that of the flat-step spillway.

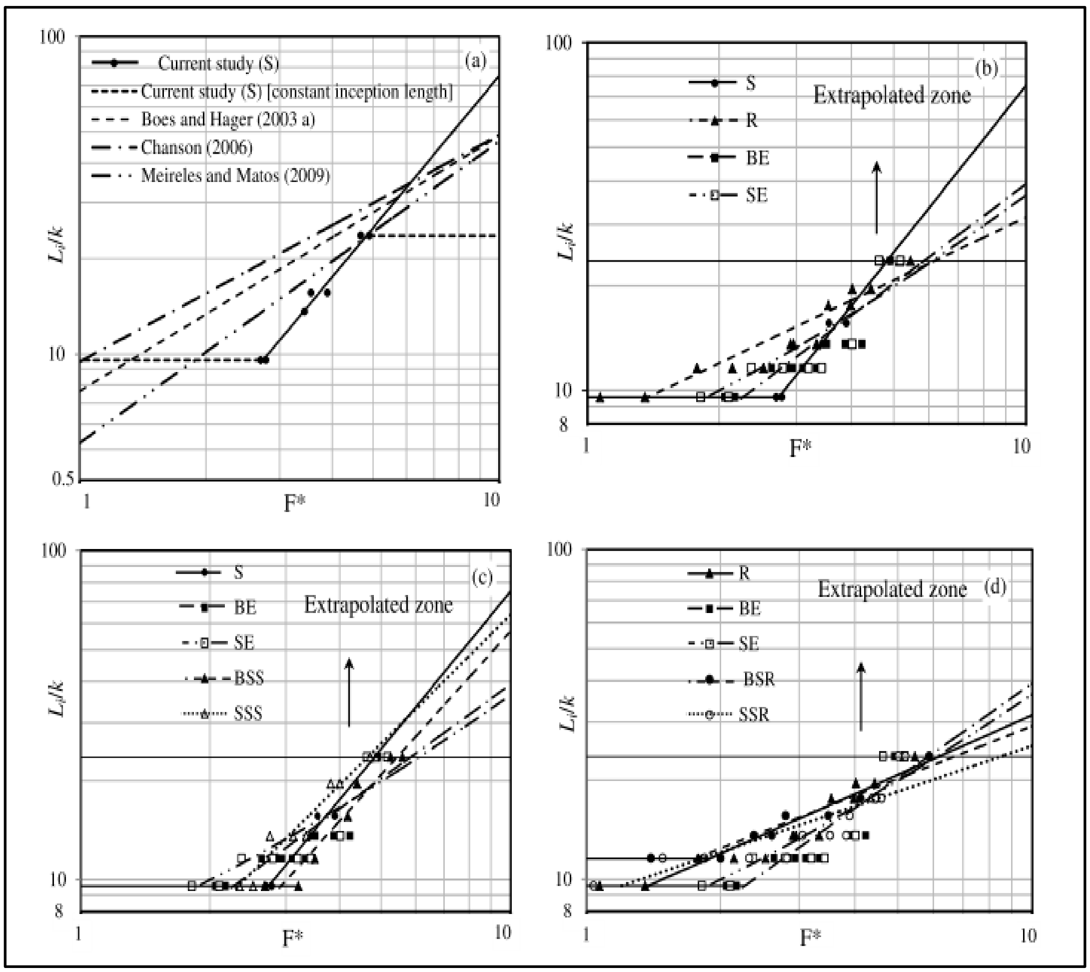


Figure 2.8 location of the inception point: (a) comparison with previous studies, (b) using baffles or sills; (c) shifting baffles or sills on sharp edges, (d) shifting baffles or sills on rounded edges, Zare and Doering (2012a).

Tabari and Tavakoli (2016) studied several parameters including step number, step height, step length and unit discharge to determine their effects on energy dissipation in spillways with flat steps. The results confirmed the findings of previous studies. Any increase in discharge led to decreased energy dissipation, as did an increase in step number and a decrease in step height. Al-Husseini (2016) investigated the energy dissipation of stepped spillways with twelve different step configurations. The step configurations were plain, half-cut, inclined end-sill steps normal to the DS slope of the stepped face, and steps with a surface roughened with crushed gravel. Three chute angles (è = 30°, 50°, and 70°) were used for each step number and step height. The results indicated that energy dissipation over inclined end-sill and rough steps was greater than for plain steps. In contrast, cut steps can have less energy dissipation than plain steps. The energy dissipation increased as the chute angle decreased. In addition, the flow types and ranges of NA, TR and SK regimes were higher for all forms of non-plain steps than with plain steps. Shen et al. (2019) examined stepped spillways regarding the hydraulic properties by the steps with end sill and the chute angles. The flow regimes were highlighted with different discharges. The results for the studied shapes showed a better performance in energy dissipation and low cavitation damage.

Many previous studies have focused on the residual energy DS (e.g. Sorensen 1985; Toombes 2002; Chanson 2002; Felder & Chanson 2009). For example, Sorensen (1985) first proposed that the residual energy at the spillway toe was on the order of 6–12% of that on a smooth chute, although scale effects were not mentioned. According to Toombes (2002), the specific energy over a stepped spillway remains constant in the equilibrium region and is equal to the residual energy DS of the spillway. The dissipater structure should be constructed separately when the residual energy is enough to cause erosion DS. In addition, Chanson (2002) suggested that it is more appropriate to consider the residual energy than energy dissipation for practical applications. On stepped spillways, a comparison of different channel slopes indicated a lower characteristic residual energy for larger moderate slopes (Felder & Chanson 2009). Felder and Chanson (2011) examined the residual energy, and their results are shown in Figure 2.9.

In general, many researchers have studied the effects of geometry on energy dissipation, focusing on DS slope and step configurations. However, there are no clear studies regarding the optimum chute angle (θ) because some researchers used chute angles of 3° < θ < 30°, while others used angles > 30°.

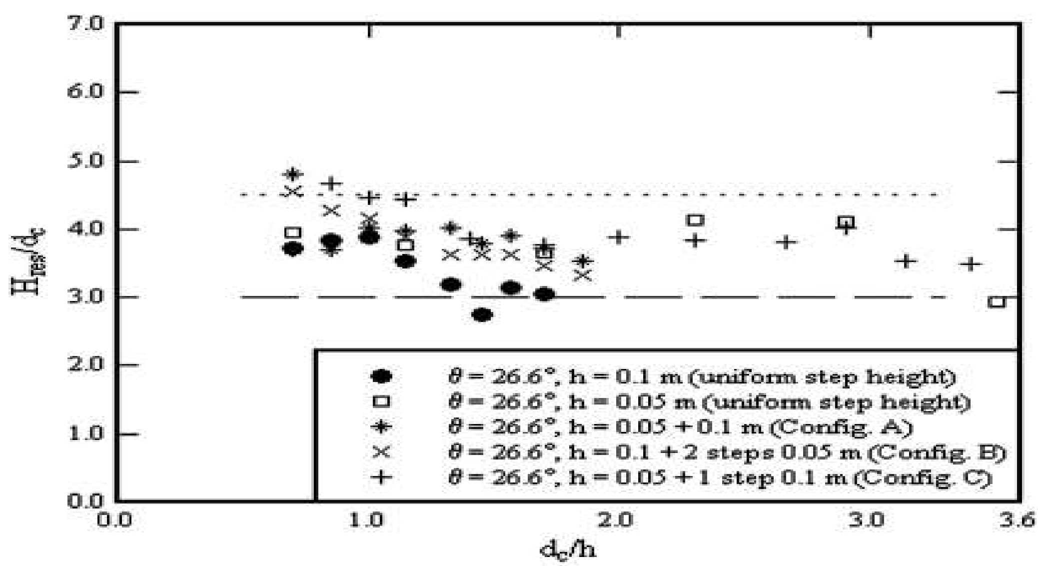


Figure 2.9 Residual energy for different step shapes, Felder and Chanson (2011).

2.7 Scale effects

Gravity can be imitated by Froude similitude in most physical models used in open-channel studies. In general, researchers have endorsed various scale ratios. Pegram et al. (1999) indicated that prototype behaviour can be represented by the scale ratio of 20:1 or more and showed that the scale ratio of 15:1 was optimal. Furthermore, Boes and Hager (2003a) stated that the scale ratio should be from 10:1 to 15:1 if smaller scale models can provide safe design information for stepped spillways with Froude models. According to

Chanson and Gonzalez (2005), from 1975 to 2005, there have been many new materials used in the construction of hydraulic structures that have improved their efficiency, especially for stepped channels and spillways. In contrast, flow regime plurality and the powerful relationships between air entrainment and turbulence are the main points that have made the hydraulics of stepped chutes very complex. Moreover, researchers have studied deformation by performing experiments from the effects of scale, and the extrapolation results show that the prototypes are invalid. In their study, two large stepped chute facilities were used, with two step heights used to measure air–water flow. Data have been obtained on air concentration, velocity and air–water flow turbulence intensity. By using Froude simulation, results have shown the scale effects observed in facilities. In addition, the selected scaling criteria have effects because they are a critical issue. For example, major differences were observed regarding bubble chord sizes and turbulence levels, although few scale effects were seen in terms of void fraction and velocity distributions in the study of Chanson and Gonzalez (2005).

In general, the results show that stepped chute physical modelling based on Froude similitude is more sensitive to scale effects than traditional flat-invert chutes, and this agrees with dimensional analysis. In addition, they suggested that better similarity can be achieved at 10:1 scale and they recommended using a step height greater than 2 cm in models. Viscosity effects should be noted in two-phase flow in practical cases for stepped spillways. Chanson et al. (2002) recommend that scale effects can be overcome with Reynolds numbers greater than 105, and this recommendation is based on their study. Markofsky and Kobus (1978) also examined the available data from spillways for two-dimensional and free overfall. Data were explained in nomograph form to try to determine the effects of model scaling. Oxygenation is determined by the primary parameters (jet Froude number and jet Reynolds number) in small streams and normal laboratory discharge ranges. The discharge per unit width was 0.2–0.5 m^3/s/m. However, in large-scale cases, the jet Froude number is the significant parameter. This applies to conditions where the plunge pool is deep, and the water temperature and other parameters are constant.

Scale effects in the current study are explained according to data from a 10:1 scale model.

2.8 Numerical modelling

There are many previous studies on stepped ways by using the numerical models (e.g. Chen et al. (2002); Tabbara et al. (2005); Ozturk and Aydin (2009); Vosoughifar et al. (2013); Peng and Tang (2015), Lopez-Egea et al. (2015), Wan et al. (2019), Mooselu et al. (2019), Parsaie and Haghiabi (2019), Medhi et al., (2019), Bentalha and Habi(2019), Saleh and Husain (2019), Dong et al.,(2019)). Numerical and experimental investigations of the flow over spillways have many applications. The analysis of flow over common hydraulic structures is an example, and the flow over spillways has been widely studied in experimental work. Most of the experimental studies were conducted to understand the flow characteristics over spillways and to obtain the coefficients of discharge under free and submerged flow conditions (Fritz & Hager (1998); Rady (2011)). Olsen and Kjellesvig (1998) and Kaouachi et al. (2019) modelled water flow over a spillway with various geometries numerically in two and three dimensions to estimate spillway capacity. Reynolds-averaged Navier–Stokes (RANS) equations were solved with k-ε turbulence models on a structured non-orthogonal grid. The estimated discharge coefficients were in good agreement with experimental results. Moreover, the pressure distributions modelled on spillways were adequately close to observations of physical models.

Kositgittiwong et al. (2012) utilised two different multiphase flow models. The first was the mixture model with multiphase flow (MMF). The second was the volume of fluid flow model (VOF) with multiphase flow. The k-ε model was applied to both models to simulate the turbulence, and the calculated outcomes were compared with experimental data (experiments were performed in a large-scale flume) at Colorado State University. The width of the spillway was 1.22 m with 25 smooth horizontal steps in the first model and 50 smooth horizontal steps in the second model. The discharges ranged from 0.20–3.28 m^3/s, and the flow, energy dissipation and velocity profiles in theoretical and practical models were compared. The acceptable simulations of flow patterns and recirculation regions were obtained for both models, and more accurate simulation of the velocity profile was achieved by the VOF model. According to Castillo et al. (2014), different models of turbulence that complement the RANS equations and two-equation models have been widely applied to many flows of engineering interest. ANSYS, CFX and Open FOAM software allow the use of two-equation turbulence models based on k-ε and k-ω. However, FLOW-3D only allows the use of two-equation turbulence models based on k-ε.

Hamedi et al. (2016) used experimental and numerical approaches to study the flow and energy dissipation characteristics of a stepped spillway with normal end sills. The finite volume method with the standard k-ε model was utilised, and the results of the experimental and numerical approaches agreed in terms of both flow regimes and energy dissipation. Toro et al. (2017) applied the detached eddy simulation (DES) to examine the three-dimensional model for the nonaerated flow on the stepped spillway at SK. The study focused on the relation between the velocity distribution and the step cavity. The outcomes showed that there were interactions between the shear force caused by the interactions between the flow and the cavity, and zones of positive and negative vorticity are carried away downstream. Ozturk and Aydin (2009) made a study to verify a 3-D numerical model of spillway aeration. Computational fluid dynamics (CFD) models were used for estimating air entrainment in spillway aerators, together with physical models. Furthermore, Peng and Tang (2015) developed a 2D numerical model that contained Navier–Stokes equations for homogeneous and incompressible flow, leading to increased understanding of the characteristics of hydraulic treatments and maintenance.

Dastgheib et al. (2012) studied the flow of several shapes for stepped spillways by utilising and developing a numerical model to compare the outcomes. The base model was calibrated with experimental data. The main features of water flow were predicted depending on two elements: (i) the CFD model, and (ii) the algorithm of surface-capturing. This algorithm contained water surface location, swirling flow development, and pressures on the steps. The VOF method was used to develop the model. In addition, comparisons were created for flow velocity at the end of the spillway and the rate of energy loss at several step heights. Moreover, eddy viscosity was computed by the RNG model of turbulence with wall functions. To accommodate the geometry of the stepped spillway, structured hybrid grids were placed US at the steps and then DS. The agreement between numerical results and experimental data showed that the RNG turbulence model and VOF method were suitable for predicting the water surface in the stepped spillway studied flow in several shapes of stepped spillways by developing a numerical model to compare the outcomes. The base model was calibrated with experimental data. The results show that a numerical model using the VOF technique is able to predict flow variables in a complex stepped spillway.

Wan et al. (2019) examined the flow on the stepped spillway with a flat step, pooled step, and rounded step using the VOF model. The result showed the rounded-step shape was more efficient. In addition, the location of the inception point was closer to the stepped spillway crest than the other shapes. Also, Roushangar et al. (2014) utilised several methods to model energy dissipation in NA and SK regimes in stepped spillways. They used experimental data from artificial neural networks (ANNs) and genetic expression programming (GEP) techniques. Furthermore, NA, SK and combined NA/SK regime data were used as input and output variables for the models. A primary test of different GEPs and operators was performed to select suitable operators. The outcomes showed that applied machine learning techniques are a reliable way to predict energy losses over stepped spillways. Parsaie and Haghiabi, (2019) studied the energy dissipation over the stepped spillway by using the M5 algorithm model. The results indicated that the drop and Froude numbers significant parameters affect the performance of the stepped spillway regarding energy dissipation.

Shahheydari et al. (2015) used numerical simulation to investigate SK characteristics and energy dissipation on stepped spillways. Some 112 numerical models were designed for this study (96 stepped and 16 smooth spillways), and four chute angles were used (15°, 30°, 45° and 60°) with a range of discharge rates. In the stepped spillway models, there were six step shapes with two step sizes. Also, the RNG k-ε model was the turbulence model used. The VOF model was applied to simulate free-surface flow, and the numerical model was verified by experimental data. The results explain that increased discharge leads to decreased energy dissipation, and the energy dissipation over the stepped spillway models was greater than that over smooth ones.

Irzooki et al. (2016) investigated the characteristics and energy dissipation of flow on stepped spillways using CFD. The stepped spillway slopes were 0.5, 1 and 1.25, and the spillway heights were H_d = 15, 20, and 25 cm. For the models, three numbers of steps, N_s = 5, 10 and 25, were used. Eight different discharges were then used, and they ranged between 600 and 8500 cm^3/s. The authors noted that energy dissipation increases with increased stepped spillway height and decreases as the step number and spillway slope increase. In addition, energy dissipation decreases with increased discharge. Tabari and Tavakoli (2016) examined a 3D Flow model and used the finite volume method to model the energy dissipation of flow at a critical depth over stepped spillways. To study the turbulence of the flow, the K-ε model was applied. The results showed good agreement with experimental work. In addition, increased discharge led to decreased energy dissipation, as did increased step number and decreased step height. Morovati et al. (2016) examined flow regimes on a stepped spillway using a numerical model of five different pool shapes. The VOF and K-ε (RNG) models were used to simulate the free-surface flow and model the turbulence, and the results of the numerical models were in good agreement with the experimental results. Also, the results showed that the flow velocity and residual energy changed significantly in the width of the stepped spillway when the pool shape changed. The pools were installed in a staggered configuration of flat and pooled steps and showed the least residual head DS and, as a result, the greatest energy dissipation.

Lopes et al. (2017) used numerical modelling to investigate two separated sub-regimes within SK over a stepped spillway, and the numerical model was validated with experimental data from a 0.5 m-wide stepped spillway. The cases were solved by using Reynolds-averaged Navier–Stokes equations together with the VOF and k-ω turbulence models. The experimental results showed that the alternating SK regime was characterised by a seesaw pattern of flow properties over consecutive steps. In addition, the numerical modelling clarified that this seesaw pattern was caused by a complex system of cross-waves along the stepped spillway. These cross-waves were also responsible for mass and momentum exchanges in the transverse direction and the formation of alternating SKs in the spillway. Bentalha and Habi (2019) used ANSYS-Fluent software with the VOF model and the k-ε turbulence standard model to describe the flow over the stepped spillway. The results indicated that ANSYS Fluent was a solid software to simulate the flow over the stepped spillway.

Alturfi et al. (2020) used CFD with the VOF method and the k-ε turbulent model to simulate the flow over the stepped spillway. The finding showed good agreement between the predicted and the experimental energy dissipation.

The presented review shows that stepped spillways have received considerable attention because of their importance in engineering practice. Most of the early work has focused on energy dissipation and was largely investigated by physically modelling. In this respect, modifications to step geometry are a promising method of increasing energy dissipation because of the many successes reported in the literature. The area of study still lacking is that of numerical modelling, as only a limited number of such studies have been reported. The motivation for this study is, therefore, to improve the performance of stepped spillways by conducting laboratory investigations using different step shapes and geometries and to numerically model the flow and energy dissipation characteristics. In conclusion, modelling used with approximate data leads to approximate results and can thus still be a useful support method. Such an approach still needs improvement, which can be achieved by collecting data from several models within the same study. In the present study, two-dimension models are be generated by utilising ANSYS-Fluent software and developed using a VOF with the k-ε turbulence model.

2.9 Summary

This chapter reviewed the current literature on stepped spillway parameters. There are the following four main points.

1) Flow regimes are one of the main things discussed in most previous studies. Different flow regimes have different impacts on energy dissipation and aeration. The knowledge gap that exists is that previous studies have investigated NA and SK regimes, while few have studied the impacts of TR on energy dissipation and aeration. The TR regime is very significant because it has high turbulence levels. The current study examines all flow regimes and focuses on the TR regime to show its advantages in terms of energy dissipation and aeration. This study also builds on previous studies by combining modified physical models, experimental work and numerical modelling.

2) Researchers have found that many geometric parameters (e.g. channel slope, height of fall, step height, step length, step number, slope angle and roughness) have significant effects on energy dissipation and aeration. There are studies on the impacts of step shape, but few on width, and researchers have not determined which of these parameters have a greater impact on energy dissipation and aeration. Step shape affects flow direction, the

length of the flow path on the spillway, time of flow over the spillway body, energy dissipation rate and aeration efficiency. In other words, it is one of the main influences on flow characteristics. In addition, the step width is very significant because it has a major effect on flow characteristics (continuity equation), thus influencing the turbulence level. The present research investigates the impacts of step shape and width on turbulence levels and establishes a new design for step surfaces that improves the energy dissipation and aeration efficiency of stepped spillways.

3) Most researchers noted in their recommendations that although the energy dissipation of stepped spillways has been studied previously, the optimum design for aeration and air–water mass transfer is not known. The current work investigates improvements to spillway designs to achieve high energy dissipation and aeration efficiency. The main reason for this is to provide better water quality and greater durability for structures and channels by increasing DO and dissipating energy.

4) In the modelling field, many models have been created to produce equations and solutions. Most of the modelling studies were used to support experimental work regarding energy dissipation. The current study applies ANSYS software because it is the newest software that is used in modelling. The modelling study investigates energy dissipation, pressure distribution and aeration processes. Furthermore, the modelling supports the experimental work, allowing the study of more shapes in a shorter time.

In summary, developments in stepped spillway design have many advantages, such as protecting the DS channel, improving water quality, decreasing the volume of the stilling basin, and having greater control over water discharges and velocities.

CHAPTER THREE

COMPUTATIONAL FLUID DYNAMICS (CFD) MODELS

3.1 Introduction

Several numerical models have been previously developed regarding stepped spillways (Ozturk and Aydin (2009), Peng and Tang (2015), and Lopez-Egea et al. (2015)). According to Castillo et al. (2014), different turbulence closure models have been implemented using the RANS equations to obtain an accurate simulation. Olsen and Kjellesvig (1998) modelled numerical water flow over a spillway in two and three dimensions for various geometries to estimate spillway capacity. The authors applied the k-ε turbulence model to solve the RANS on a structured non-orthogonal grid. The discharge coefficient and pressure distribution on the spillway obtained from the model agreed well with experimental results. Kositgittiwong et al. (2012) utilised two different multiphase flow CFD models, the mixture MMF and volume of a fluid flow model (VOF) with multiphase flow, adopting the k-ε turbulence model. The calculated results were compared with experiments conducted using a 1.22m width for spillway with smooth steps. Models with 25 and 50 horizontal steps were tested, and the discharge was from 0.20 m^3/s to 3.28 m^3/s. The simulated flow pattern and recirculation region agreed well with experimental results, although the VOF model provided more accurate simulations of the velocity profile. Hamedi et al. (2016) used the experimental and finite volume method with the standard k-ε model numerical approach to study the flow characteristics and energy dissipation for stepped spillway with normal end sills. The results showed reasonable agreement between the experimental and numerical approaches for both flow regimes and energy dissipation.

In the current study, 2D flow model has been developed by using ANSYS-Fluent software to solve the RANS equations. The solution was obtained by using the multiphase model as the VOF method for the two-phase flow to simulate the water surface profile over the stepped spillway. In addition, the viscous model as the standard k-ε model has been used to show the turbulent flow conditions. The use of the VOF method and the standard k-ε model together conduct a close simulation for the flow conditions. The CFD model is economically important to reduce effort and time. The CFD model has been used to predict the flow regime, the free-surface profile at the crest, velocity distribution, pressure distribution, and stepwise energy dissipation that has shown accurate results. In particular, it can predict all the hydraulic parameters to obtain a comprehensive flow analysis and it is easy for the designers to investigate them.

3.2 CFD model

3.2.1 Governing equations

The ANSYS Fluent v18.1 CFD package has been utilized with the VOF method in the current study. The VOF method is a multiphase numerical modelling procedure proposed by Hirt and Nichols (1981) and it is used in free-surface flow problems (Cook et al., 2002). In the VOF method, the momentum equation is solved for two phases of non-miscible fluids, and the fraction occupied by each fluid phase in a computational cell is tracked. The model solves the incompressible continuity and momentum equations for turbulent flow (Torrano et al. 2015):

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \qquad \text{.........................(3.1)}$$

$$\frac{\partial \rho u_i}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left\{\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right)\right\} + \frac{\partial}{\partial x_j}\left(-\rho u_i' u_j'\right) \qquad \text{....(3.2)}$$

Where, ρ is the density of the fluid, μ is molecular viscosity, u_i is the velocity component, x_i is the coordinate component, t is the time, and p is the pressure. The deviatoric stress component in Equation (3.2) can be expressed as the following:

$$-\rho u_i' u_j' = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}(\rho k)\delta_{ij} \qquad \text{................ (3.3)}$$

Where, μ_t is the turbulent viscosity, and the stress tensors are $\delta_{ij} = 1$ when i=j and $\delta_{ij} = 0$ when i≠ j.

3.2.2Turbulence modelling

In the CFD model, it is important to treat the turbulence of the flow. Solving RANS equations is the method that has been widely utilized in the applications of engineering. The models of this type depend on the averaging flow leading to the RANS equations. The transport equations have been added to the Navier–Stokes equations to achieve a closer mathematical flow model. In particular, the transport equations are used to represent the turbulence behavior of the flow to relate that with the turbulent viscosity, which is related to Reynolds stresses (Pope, 2000). Among the available turbulent models, the widely utilized model is the standard k-ε model (Lopez and Garcia, 2001).

Turbulence closure was solved using the k-ε model (Torrano et al. 2015):

$$\frac{\partial(\rho k)}{\partial t} + \mathrm{div}(\rho k U) = \mathrm{div}\{\left(\frac{\mu_t}{\sigma_k}\right)\mathrm{grad}k\} + 2\mu_t E_{ij}E_{ij} - \rho\varepsilon \quad \text{……………..(3.4)}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \mathrm{div}(\rho \varepsilon U) = \mathrm{div}\{\left(\frac{\mu_t}{\sigma_\varepsilon}\right)\mathrm{grad}\varepsilon\} + C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}E_{ij} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \quad \text{……….(3.5)}$$

$$\mu_t = \rho\, C_\mu \frac{k^2}{\varepsilon} \quad \text{…………….(3.6)}$$

Where, C_u = 0.09, σ_k = 1.0, σ_ε = 1.3, $C_{1\varepsilon}$=1.44 and $C_{2\varepsilon}$=1.92 (Torrano et al. 2015).

The numerical model (2D flow) has been run to steady state for all experimental conditions listed in Table 3.1. The boundary conditions used were an inlet that was separated into two parts to consider the air and water fluid components in all tested models. Velocity equal to the average velocity was specified for the water flow component, and atmospheric pressure was specified for the air layer at the inlet boundary. Then, the pressure outlet was specified as the outlet boundary condition for the water layer, and atmospheric pressure was specified for the air layer at the inlet, outlet and top boundary. The flume bade and the surfaces of the steps were defined as the wall boundary conditions.

3.3 Test models

The models were 0.30 m in height and 0.50 m in width. The models have chute angle θ = 26.6°. The chute angle was chosen according to previous studies. The steps numbers are N_s= 6 and 10 with step heights of h_s= 0.05 m and 0.03 m, respectively. Three various step shapes were used, each with two different geometries. All six setups had the same chute angle and spillway height (Hd = 0.3 m). The three shapes comprised: (i) rectangular-shape steps “Step Model” (Figures 3.1a and b), where model M1-1 had ten flat steps with step height hs = 0.03 m, and M1-4 had six flat steps of hs = 0.05 m, (ii) rectangular-shape steps with end sills (Figures 3.1c and d), where M1-2 had ten steps and the end sill height was equal to the step height of hs = 0.03 m, while M1-5 had six steps (end sill height = step height hs = 0.05 m), and (iii) quarter-circle end sill steps (Figures 3.1e and f), where M1-3 had ten steps (height of the quarter circle = h_s = 0.03 m) and M1-6 had six steps (height of the quarter circle = h_s = 0.05 m). All the test setups were made from plywood and finished with a coating of marine paint. The step model was chosen as the basic shape and used to compare with previous studies that used the same chute angle. In addition, the results from the sill and quarter-circle sill models were compared with those of the step model. Details of the experimental parameters are provided in Table 3.1. All tests were repeated to test for repeatability, and a total of 432 experimental runs were conducted for unit discharges, with q ranging from 9×10^{-3} m^3/s.m to 111×10^{-3} m^3/s.m. During the experimental work, the US and DS depths and DO were measured by point gauges and a DO meter, respectively. Pressures were measured at six points on the first step, mid-step and the last step of all models.

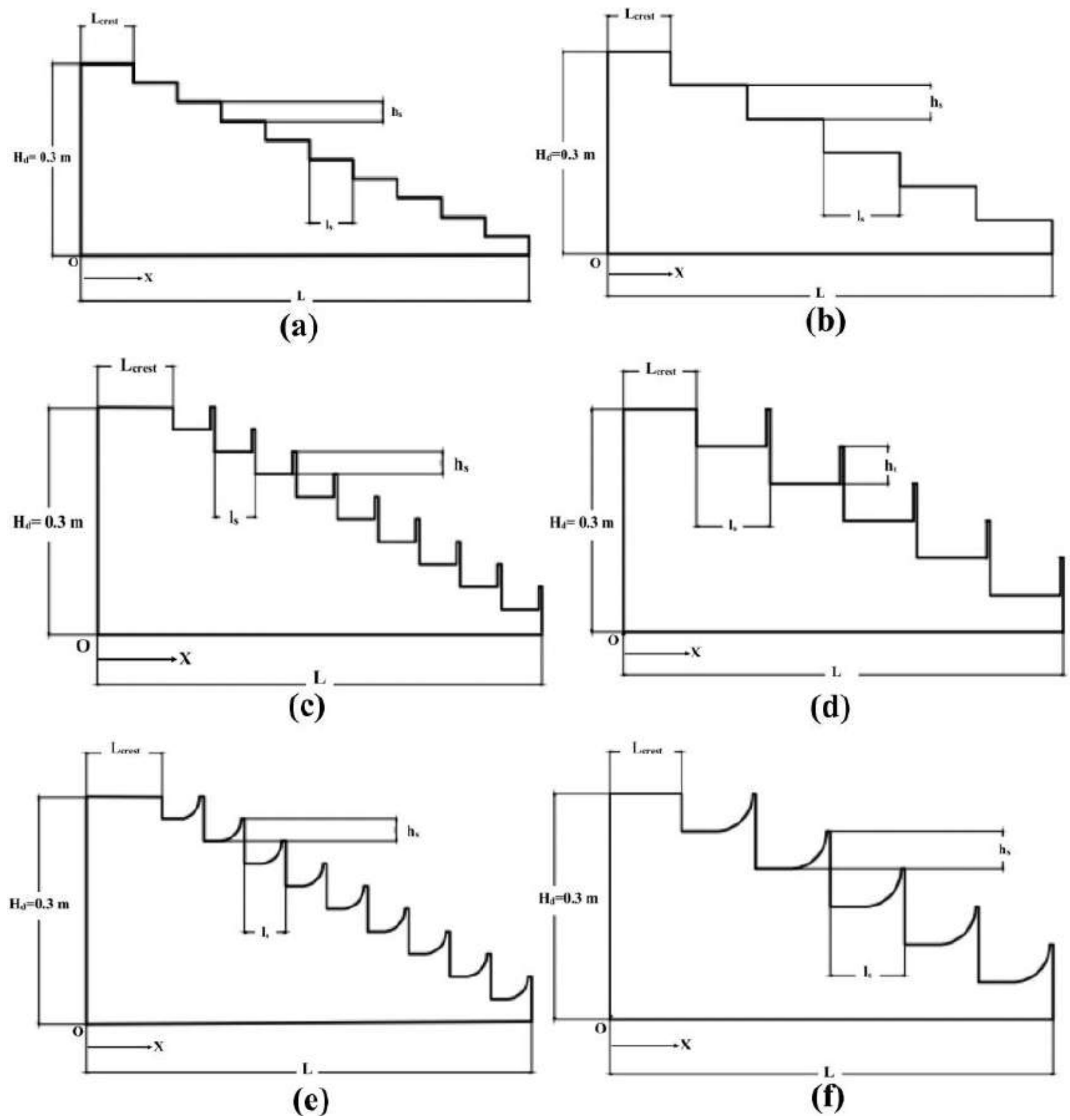


Figure 3.1 Stepped spillway geometry for chute angle θ (a) Mi-1, (b) Mi-4, (c) Mi-2, (d) Mi-5, (e) Mi-3 and (f) Mi-6.

Table 3.1 The hydraulic and geometry variables for used models in group one.

θ (°)	Model	h_s (m)	l_s (m)	End sill type	End sill height (m)	N_s
26.6		0.03	0.067	-	-	10
		0.03	0.067	normal	0.03	10
		0.03	0.067	quarter circle	0.03	10
		0.05	0.120	-	-	6
		0.05	0.120	normal	0.05	6
		0.05	0.120	quarter circle	0.05	6

3.3.1 Geometry and mesh

To represent the domain of the geometry taken by the flow of the air–water, there are two used meshing approaches. Two meshing approaches have been considered: unstructured mesh and structured mesh. None can consider which has the best performance because that depends on the specific case. According to Kim and Boysan (1999), the unstructured mesh is suitable for selective refinement to prevent the over-refinement in the zones that have expected small gradients. Also, the unstructured mesh is the best in the multi-component's geometry. This mesh has fewer closure problems, and its arbitrary topology makes automatizing the meshing process easier (Biswas and Strawn, 1998). Huang and Prosperetti (1994) highlighted that mesh non-orthogonality has no effect on the outcomes if the skewness of its elements is kept sufficiently low. However, the structured mesh has more accuracy than the unstructured mesh (Biswas and Strawn, 1998). Also, the algorithms of the structured mesh are more straightforward to implement and faster to execute. Keyes et al. (2000) indicated that the algorithms of the structured mesh show more regular access to memory, and in multiphase flow, topologically orthogonal meshes with their axis aligned with the fluid interface tend to show less numerical problems.

In some models, the mesh was slightly refined in the nearness of solid boundaries for accurately resolving the flow features in boundary layers, where larger gradients occur. This may cause the generation of very deformed elements, and it is not an actual problem if the mesh axes remain perpendicular to the solid boundaries (Hirsch, 2007). For all these reasons, a static structured rectangular hexahedral mesh is considered the best choice for the cases in the current study. Moreover, the inflation layers have been used in the mesh because they have the critical components of a good CFD.

By the geometry analysis in the current study, there are two geometry types considered: low complex geometry (the rectangular channel) and very complex geometry (the flow over the stepped spillway). For the low complex geometry, the mesh size of 2 mm and the element size of 3 mm without inflation layers were used. The very complex geometry has a mesh size of 1 mm, element size of 2 mm, and 10 inflation layers for more accuracy. Figure 3.2 presents the section of the geometry which has the same dimensions of the physical model and the mesh for M1-4 model as an example. The number of elements was 368490, and the number of nodes was 369709. The geometry details have been listed in Table 3.1.

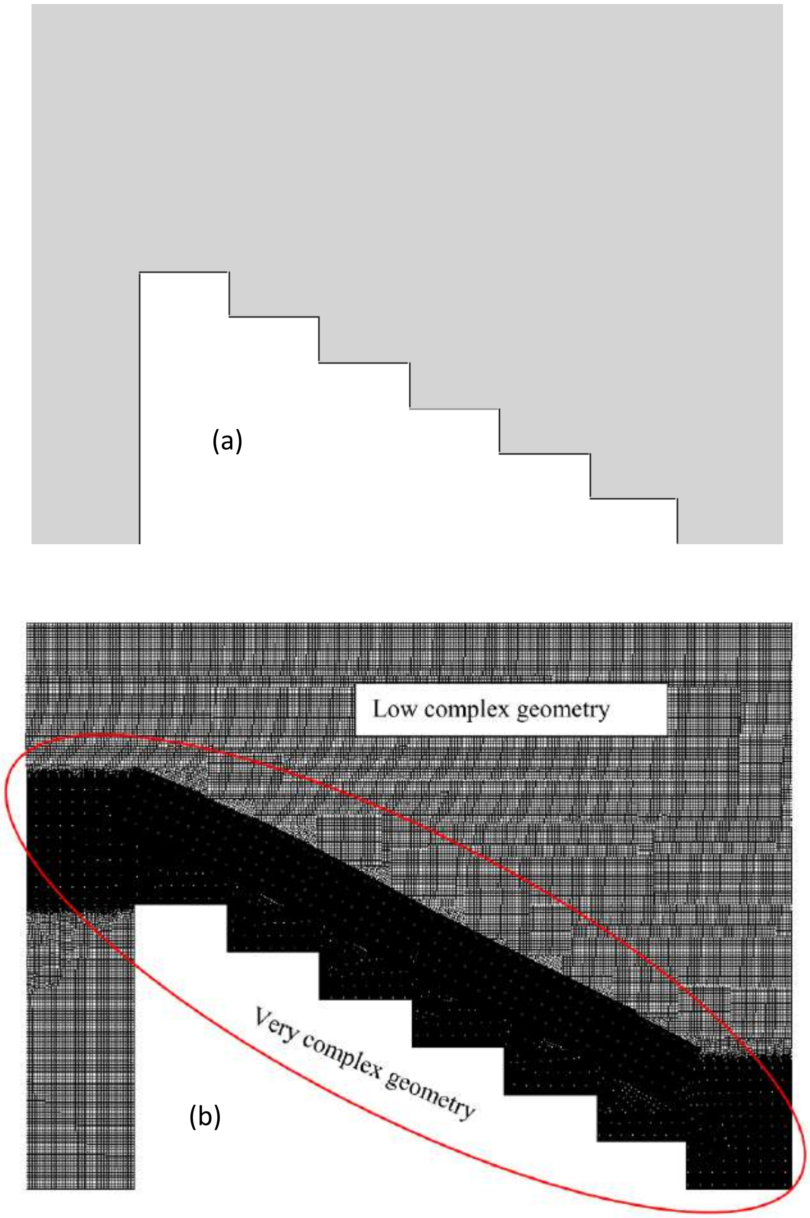


Figure 3.2 The geometry details, (a) geometry, and (b) mesh.

3.3.2 Boundary conditions

The boundary conditions do not change from one case to another except for the inlet velocity. The velocity inlet was calculated using continuity equations for five discharges (Q=4.35 L/s, 10.10 L/s, 25 L/s, 38.46 L/s, and 55.55 L/s) from experimental work. The velocity was defined as velocity magnitude and the x-direction was used as a velocity direction in the ANSYS-Fluent software. The velocity was v_o= 0.0275, 0.0605, 0.1326, 0.1895, and 0.2566 (m/s) as the data input in ANSYS-Fluent software for all the models, where v_o is the inlet velocity. The VOF model was used to simulate the two-phase flow (air and water) with the k-ε model to identify the turbulent flow turbulence in ANSYS-Fluent software. The numerical model was run to steady state for all shapes and conditions listed in Table 3.1. The boundary conditions used were an inlet that was separated into two parts to account for the air and water fluid components, where an average velocity was specified for the water flow component and the atmospheric pressure was specified for the air layer. Pressure outlet was specified as the outlet boundary condition for the water layer. In addition, atmospheric pressure was specified for the outlet air layer and top boundary. The flume bed and the surfaces of the steps were defined by the wall boundary (nonslip) condition.

Figure 3.3 illustrates the initial boundary conditions applied in the CFD model. The US boundary was separated into water and air inlets to distinguish between the two-fluid media. A velocity inlet was defined as the boundary condition for the part occupied by water flow (BC), and atmospheric pressure was defined for AB and AD boundaries. The nonslip wall boundary condition was used for the steps and flume bottom. Pressure outlet was specified in the outlet section (DE). All the dimensions in the model are similar to the physical model (spillway height =0.3 m, section length (AD line) =3.0 m, and depth (DE line) =0.6 m).

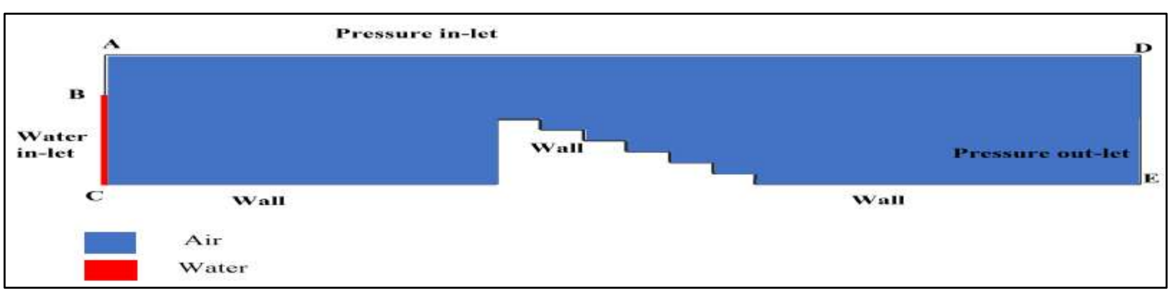


Figure 3.3 The initial boundary conditions scheme.

CHAPTER 4
CFD RESULTS

4.1 Model verification

The model has been validated by comparing the experimental data taken from previous study and the CFD results for all models. The DS velocity v_1 was selected to be the validation parameter that used a proof of the modelling ability as an example. v_1 has been selected because it is one of the main variables that have a large effect on the flow characteristics and the aeration process. Figure 4.1 presents a comparison between the experimental and CFD results by using the critical flow depth (y_c) value at x-axis and DS velocity at y-axis, where v_1 is the flow velocity at DS of the stepped spillway. When the flow rate changed, v_1 and the flow depth DS have significant effects on the hydraulic characteristics because they are the main variables in this process. The results presented the minimum and maximum errors for validation data which were 4.32%, and 8.21%, respectively. In general for Figure 4.1, The DS velocity v_1 that was obtained by the developed 2D flow model showed a close correlation within a (±6.27 %) tolerance when compared with the experimental results. It was a good agreement between the experimental work data and the simulated data. Also, the other predicted parameters can be used to validate the model because they have the same behaviour and this is further discussed in the predicted behaviour section (see Section 4.2).

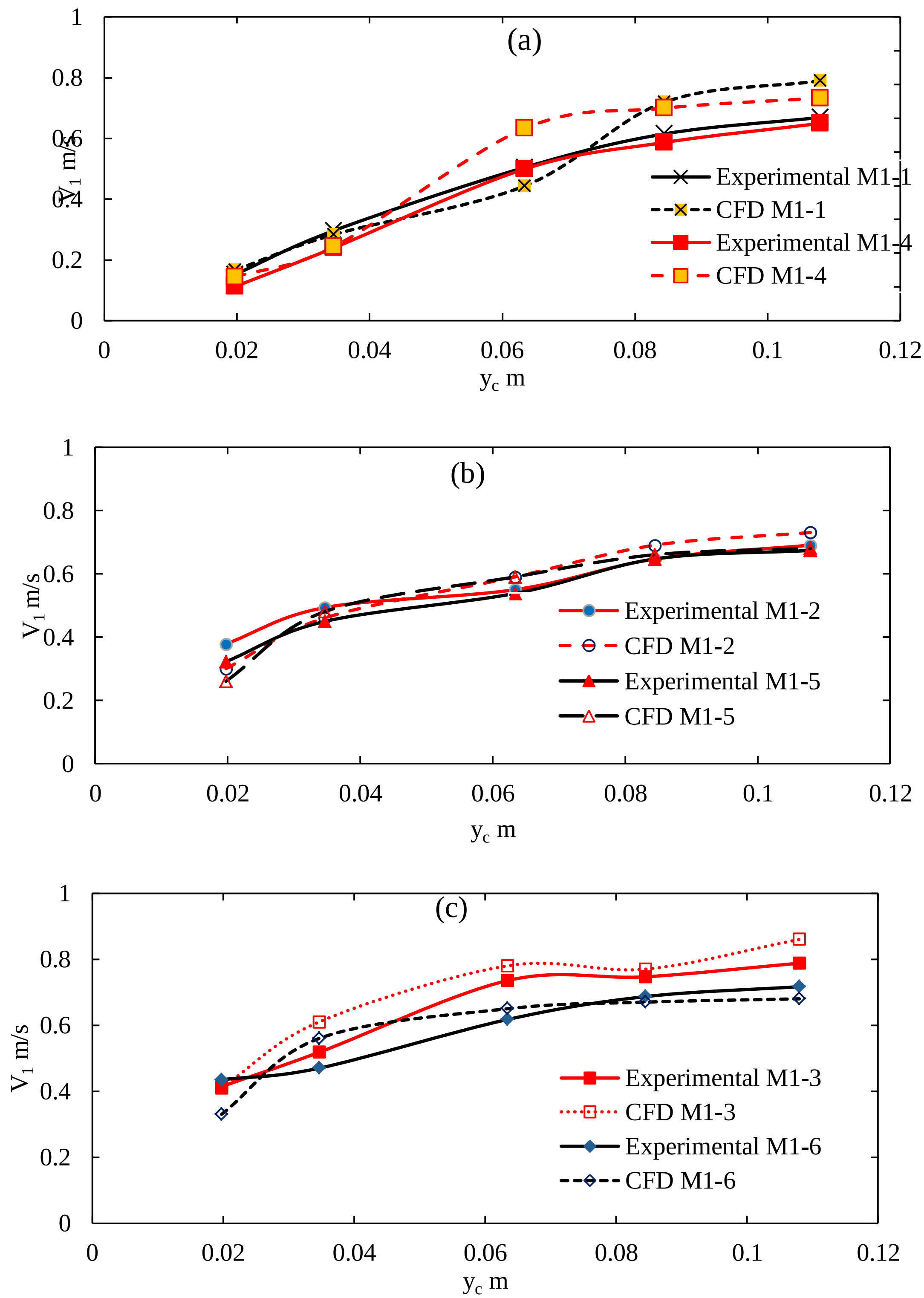


Figure 4.1 Downstream velocity for models, (a) flat step, (b) step with normal end sill, and (c) step with quarter circle end sill.

4.2 Predicted behaviour

4.2.1 Flow regime

The results of the CFD model presented by models M1-4, M1-5, and M1-6 as example. Figures 4.2 to 4.4 showed the predicted flow regimes under different flow conditions. Also, the predicted flow regimes has been compared with the experimental observations (see Figures 4.5, 4.6, and 4.7) under the same flow conditions. Nappe flow regime (NA) occurred in the experiments for q ≈ 20.0 L/s.m and is reproduced by the numerical model (Figure. 4.2a, 4.2b and 4.2c). The modelled free surface is noticed to be wavy and disturbed because of the plunging flow. In the experiments, plunging flows are accompanied by substantial amounts of air entrainment, especially for the upper steps, in the flat-step mode. This manifests as regions of white water in the experiments and low (< 1) water to air (w/a) ratios that were observed on every step, intensifying as the flow progresses down the steps.

The progress to the TR regime is also well predicted by the numerical model (Figure 4.3a, 4.3b and 4.3c). The longitudinal water surface profile is predicted to change from SK (first three steps) to NA (lower steps) when 20.0 < q (L/s.m) < 39.0. SK is predicted by the model for larger flow rates (q ≥ 39.0 L/s.m) where the flow surface appears to be relatively undisturbed, especially for the flat-step model. For the normal sill and quarter- circle sill configurations, some waviness is seen because of the obstruction to the flow by the forward end sills. Model results shown in Figures 4.4a, 4.4b, and 4.4c are except for some slight waviness of the surface, water surface profiles are relatively undisturbed, a feature of SK regime. Also, the air/water-volume fraction can be used to present the air entrainment in the CFD model. In Figures 4.2 to 4.4, the depth of the interface zone between the air and the water in M1-6 was more than the other models at SK because of the wavy surface. The wavy surface showed a new step shape (step with quarter-circle end sill) because of the high circulation flow.

An elaboration of the flow patterns is provided by the streamlines plotted in Figure 4.5 for M1-4, M1-5 and M1-6 models, where differences in step configuration help cause differences in the flow direction. In the quarter-circle sill model, the formation of a strong recirculation region is characterised by a single vortex of regular shape (Figure 4.5g, 4.5h and 4.5i). The results show significant recirculation for the quarter-circle sill model because streamlines deflected flow around the cavity space (reminiscent of flow over a cavity), generating stronger vortices than the step with normal end sill model, although the size of the vortex scales with the dimension of the cavity. However, its shape is irregular, and sometimes a second, shear-induced vortex is formed at the US corner of the sill. For the flat-step model, a single shear-induced vortex, similar to the flow over a backwards-facing step, is produced, although in backwards-facing steps, the reattachment length is approximately twice to three times, larger than the step height (h_s= 0.03m to 0.05 m) in the present experiments. The model results provide evidence that link the flow structure with $\Delta E/E_o$, which has been suggested by Felder and Chanson (2013a), showing that the quarter-circle sill and normal sill models give rise to larger and stronger vortex structures that scale with the size of the cavity, thus increasing $\Delta E/E_o$. The differences of the step configurations between the flat and pooled step have affected the residual energy and highlighted a better energy dissipation for the pooled stepped spillway (step with quarter-circle end sill). Also, the flow regimes showed some instabilities on the pooled-step configuration overstepped spillway linked with some pulses in the first pool cavity.

In general, the predicted longitudinal water surface profiles are similar to the experimental results, and the flow characteristics obtained in the model are consistent with the experimental observations. As a result, the step with quarter-circle end sill shape showed better performance regarding the flow regimes.

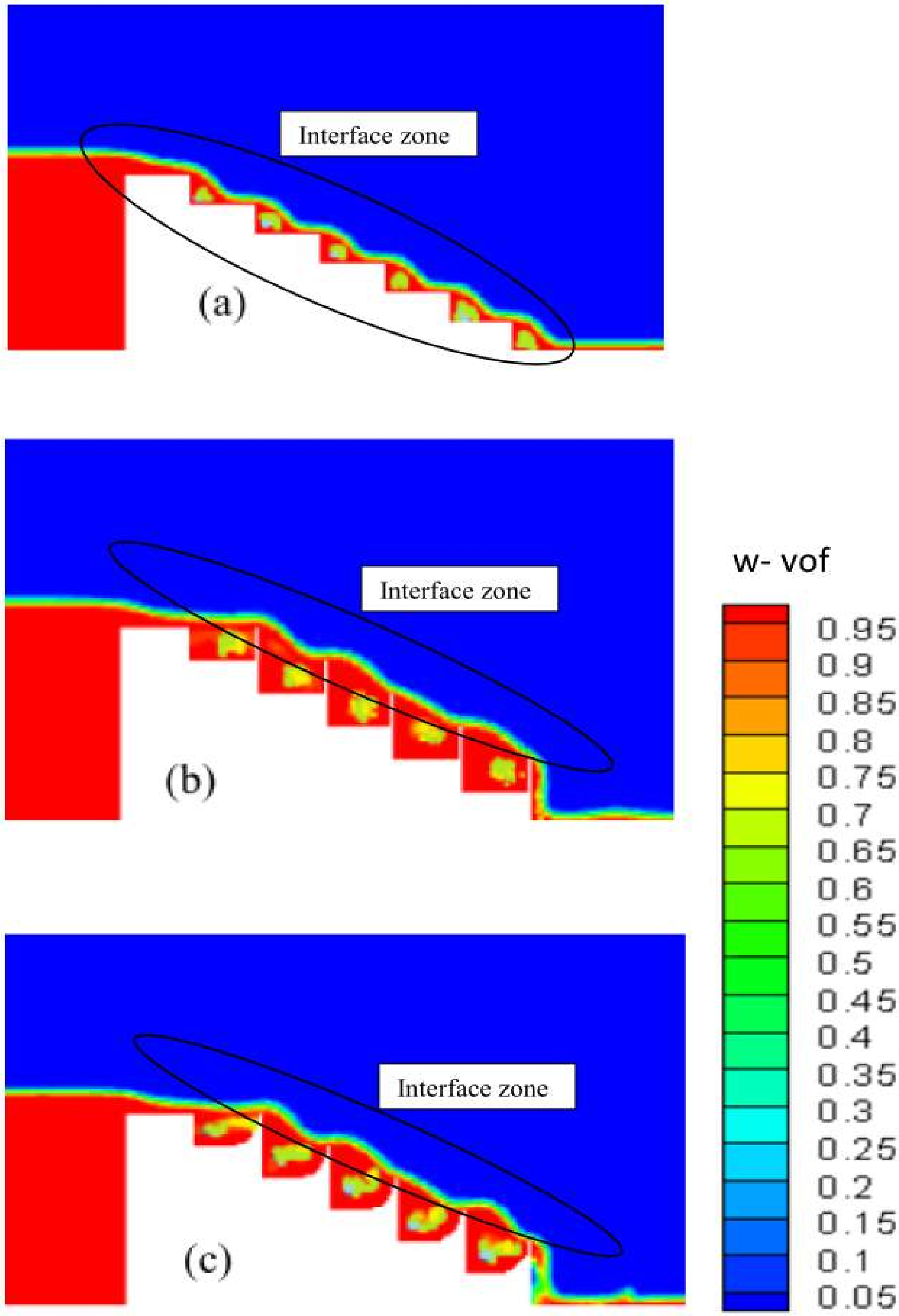


Figure 4.2 Modelled free surface and volume fraction of air. Nappe flow: (a) M1-4, (b) M1-5 and (c) M1-6, where q = 20.0 L/s.m, y_c/h_s = 0.69.

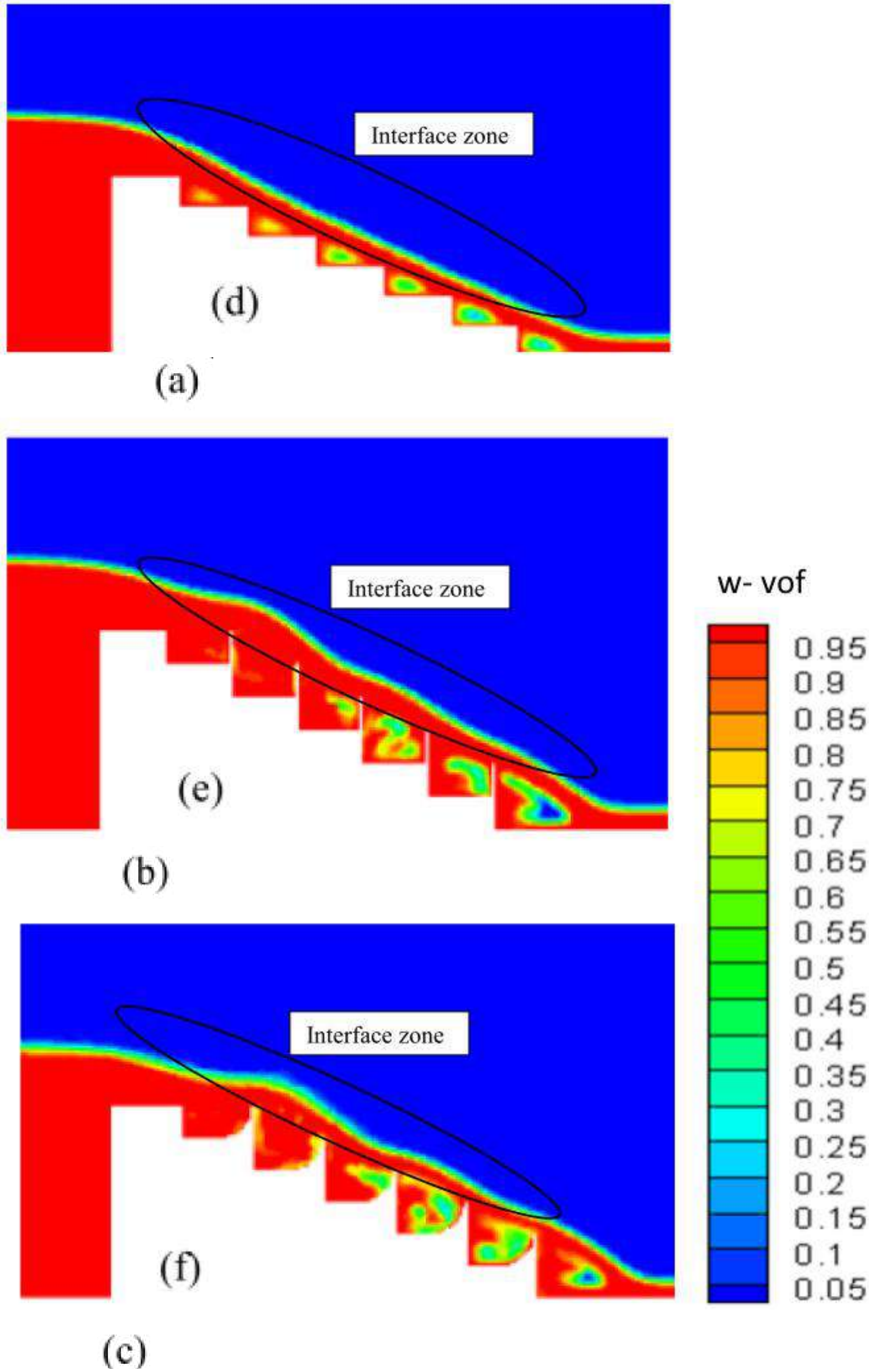


Figure 4.3 Modelled free surface and volume fraction of air, Transition flow: (a) M1-4, (b) M1-5 and (c) M1-6, where 20.0 < q < 39.0 L/s.m, 0.07 ≤ y_c/h_s ≤ 1.09.

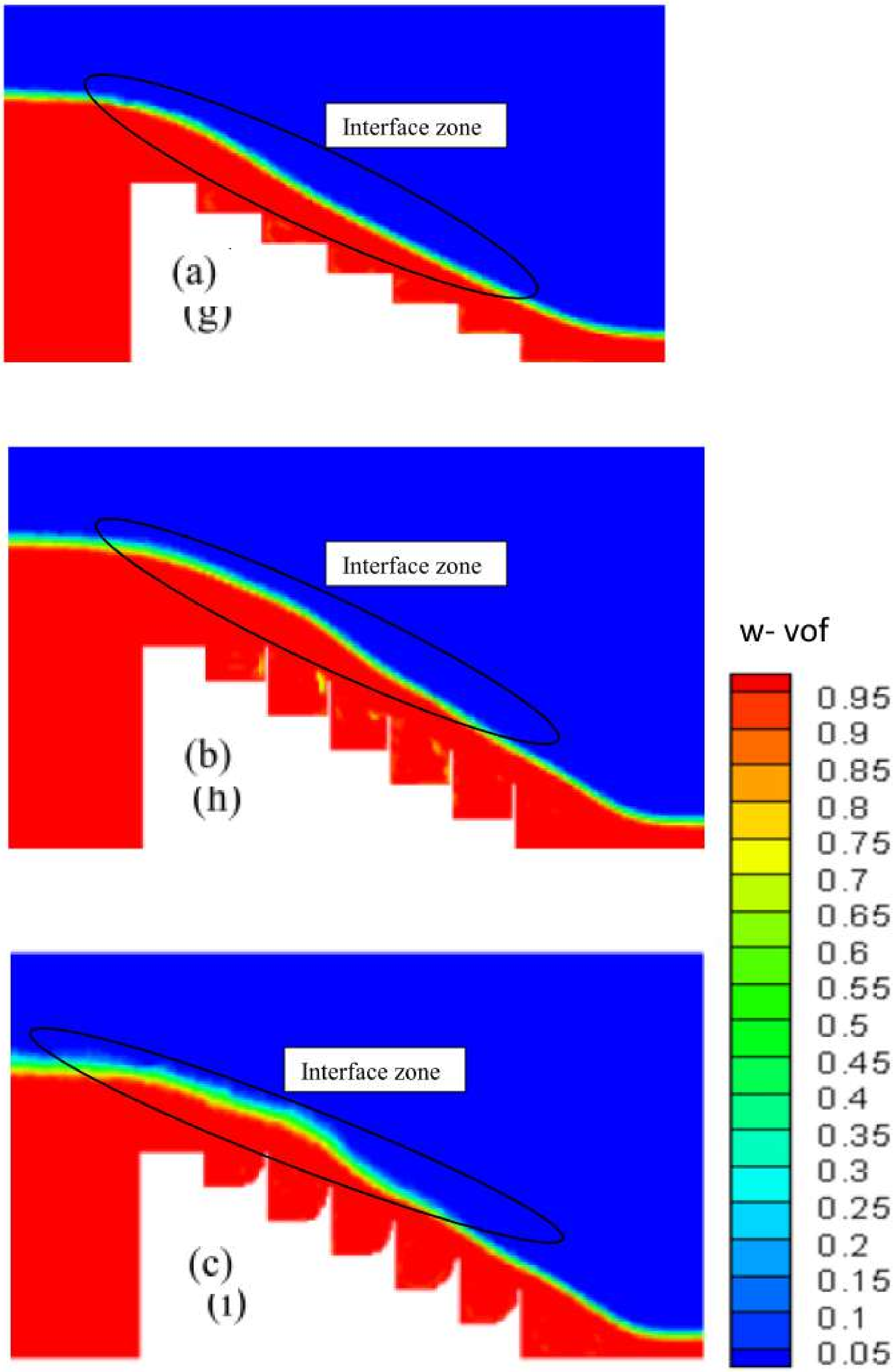


Figure 4.4 Modelled free surface and volume fraction of air, Skimming flow: (a) M1-4 (b) M1-5 and (c) M1-6, where q = 39.0 L/s.m, y_c/h_s = 1.08.

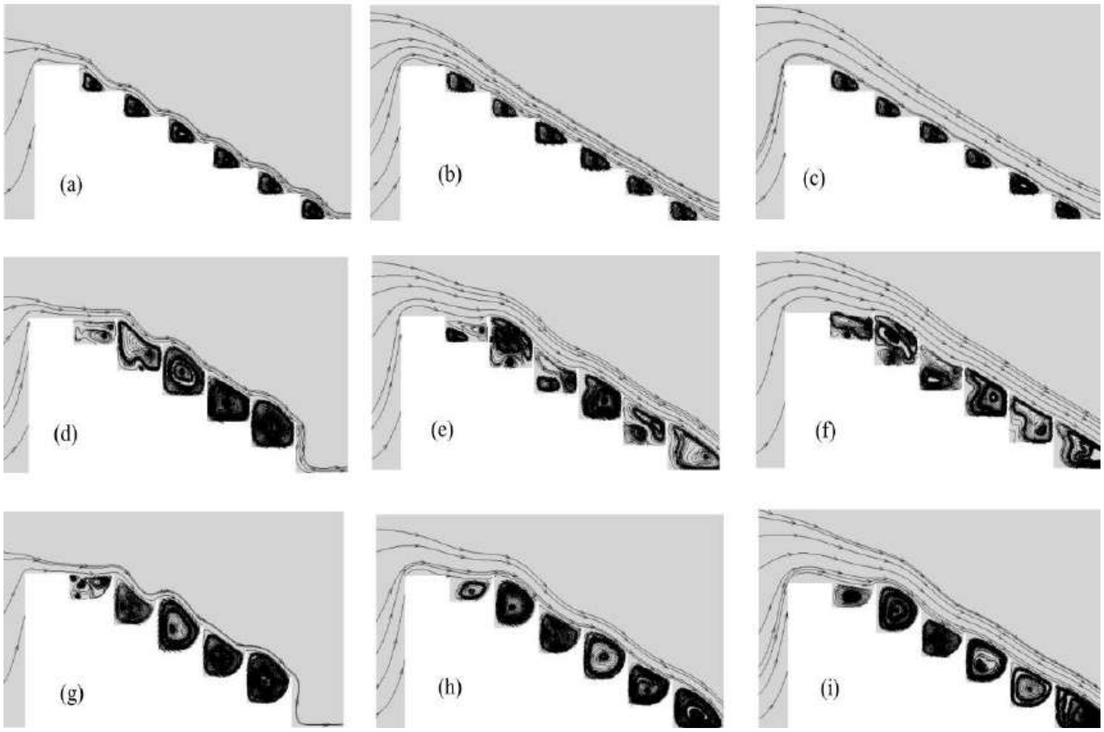


Figure 4.5 Flow streamlines. Nappe flow: (a) M1-4, (d) M1-5 and (g) M1-6, where q = 20.0 L/s.m, y_c/h_s = 0.69. Transition flow: (b) M1-4, (e) M1-5 and (f) M1-6, where 20.0 < q < 39.0 L/s.m, 0.07 ≤ y_c/h_s ≤ 1.09. Skimming flow: (c) M1-4 (f) M1-5 and (i) M1-6,

4.2.2 Crest- free-surface profiles

This section presents the results of the investigation of the conditions of the inflow for five discharges (q= 20.0 L/s.m with y_c/h_s=0.69 to q=39.0 l/m.s with y_c/h_s=1.08) by using the simulation. The free surfaces shape US and above the crest of the stepped spillway were smooth. Figure 4.6 shows the free-surface profiles obtained by the CFD for M1-1 model in group one as an example. The data highlighted that the water surface profile was a curvature profile and not a horizontal profile, as indicated by (Woodburn, 1932), especially at low discharges. However, for high discharges, the water surface profile has a wavy shape because of the effect of the interactions of the developing boundary layer with the main flow, as explained by Isaacs (1981). The results agreed with the experimental data including the water surface profiles (CFD data) above the crest.

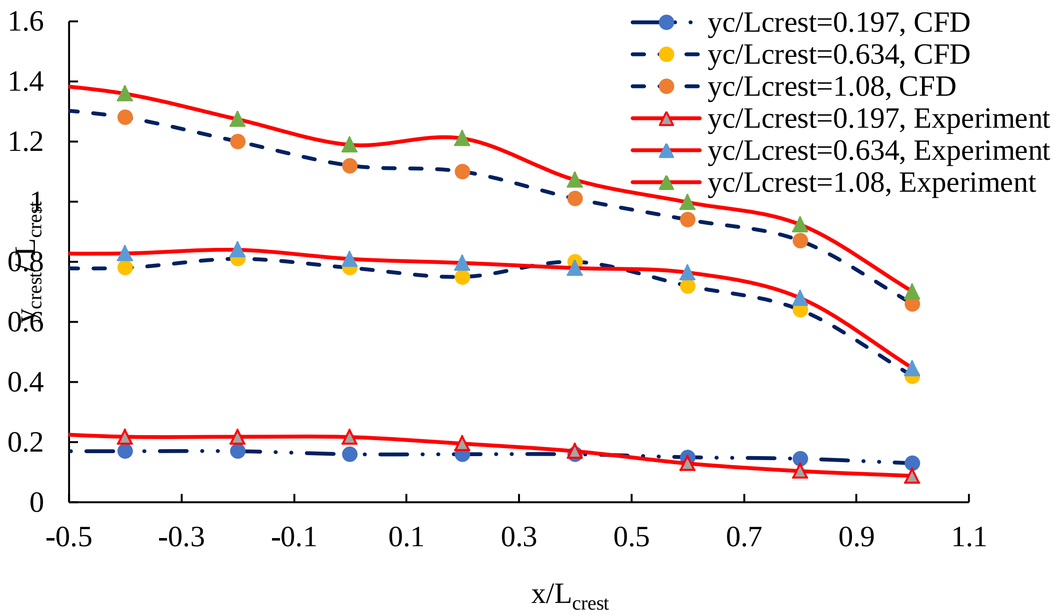
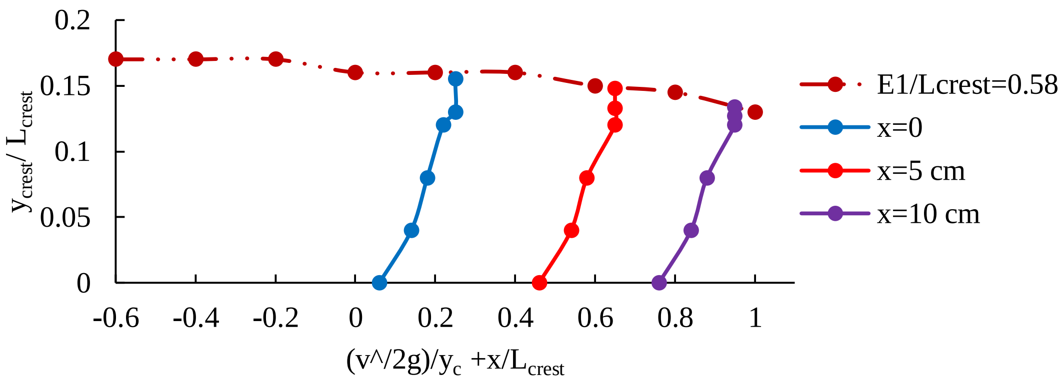


Figure 4.6 Free surface flow profiles over the broad crest for M1-1 model (CFD and Experimental data).

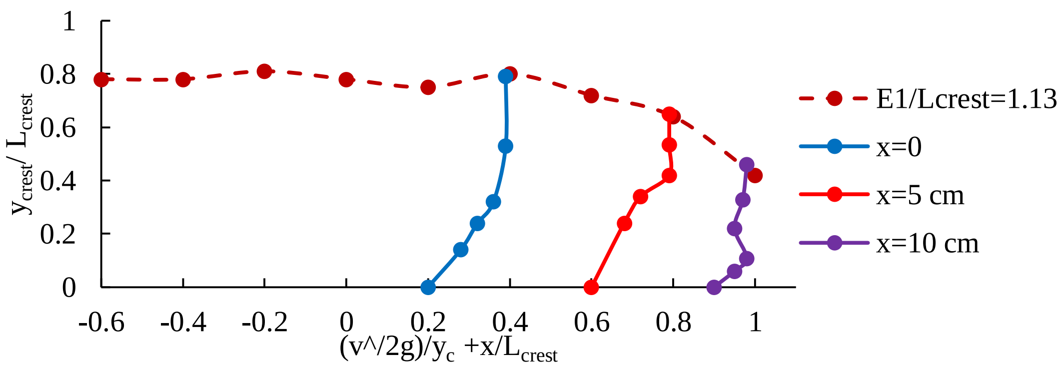
4.2.3 Velocity distribution

The velocity of the flow over the stepped spillway is one of the main hydraulic parameters that affecting on the structure design. The velocity profiles over the stepped spillway have been predicted using CFD and compared with the experimental results. Figure 4.7 presents, as an example, the CFD results at the three locations at the crest that were at x=0, 5 cm, and 10 cm for the M1-1 model in group one. The discharge was low in the NA regime in Figure 4.7a and high in the SK regime in Figure 4.7c. Figure 4.7b presents the velocity distribution over the crest at TR regime. The CFD profiles of the velocities had a shape like the flow of the ideal fluid theory at x=0 and 5 cm. However, the distributions of the velocity presented a behaviour similar to the velocity profile of free overfalls at the DS of the crest (x=10 cm) (Henderson 1966). The velocity distribution at the crest can be used as the index to the flow regime DS of the crest especially crest edge.

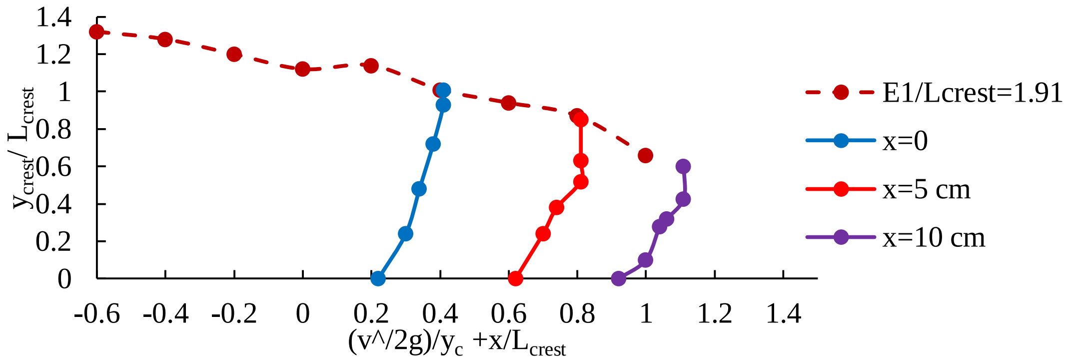
Figure 4.8 explains the differences between the CFD and experimental results of the velocity distribution at the DS for M1-1 model in group one. All the measurements depended on the input data of Section (5.2.3), and Figure 7.14 presents the typical velocity distributions at the last step edge. The line of the best fit yielded N = 5.4 (R = 0.955), which was close to the line proposed by Chanson (2001a) for the stepped spillway with small changes from the suggestions by Amador et al. (2009) and Meireles et al. (2012), which were the N = 3.0 and 3.4, respectively.



a- Velocity distributions for E_1/L_{crest} = 0.58, from



b- Velocity distributions for E_1/L_{crest} = 1.13, from CFD.



c- Velocity distributions for E_1/L_{crest} = 1.91, from CFD.

Figure 4.7 Dimensionless distributions of velocity at the crest and corresponding free-surface profile over stepped spillway.

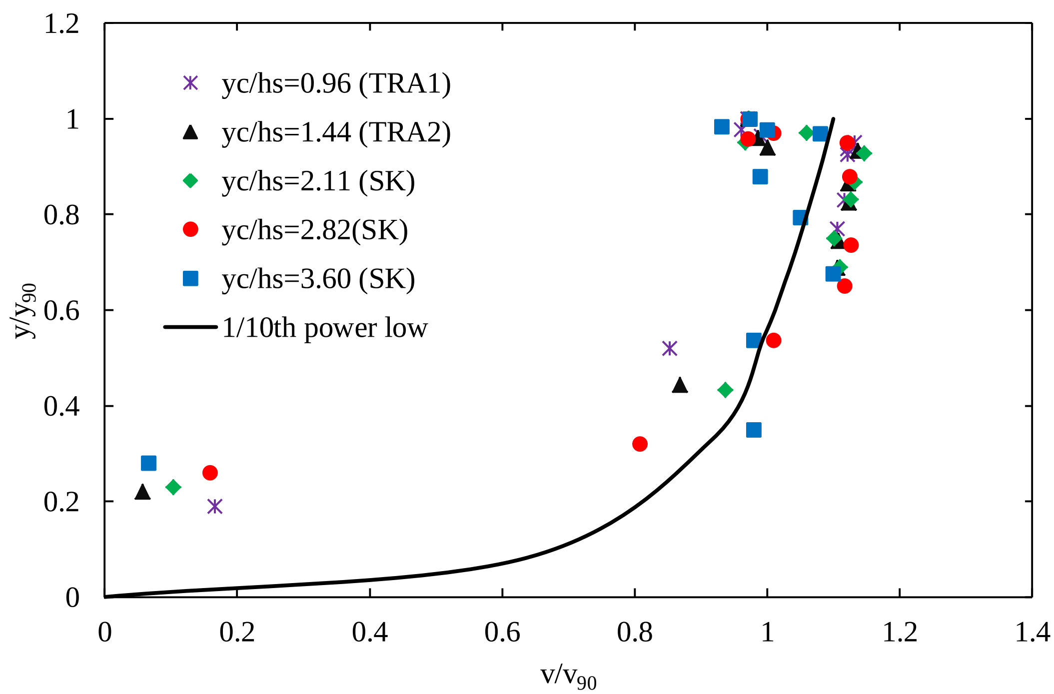


Figure 4.8 Dimensional velocity distributions at last step edge in the Transition and Skimming flows in M1-1 for CFD data.

4.2.4 Pressure distributions

The pressure distribution is one of the significant parameters affecting the stepped spillway designed. In this section, the results showed the predicted pressure distributions on the first, mid, and last step in group one with chute angle θ=26.6°. The same locations for the spot measurements over the step as presented in Section 5.2.5 were used.

Figure 4.9 to 4.11 present the contour of pressure distribution over the stepped spillway for flow regimes with all the step shapes. In the NA regime, the contour showed the negative pressure at the flat step shape referring to air pockets (Figure 4.9). The negative pressure also should be controlled by changing the step designed. Furthermore, Figures 4.10 and 4.11 illustrate the differences between the contour that indicate that the pressure was higher in the step with normal end sill and the step with quarter-circle end sill because of the trapped water over the steps. The contours of the CFD show all the flow characteristics regarding the pressure. In general, the contour of the pressure shows all the pressure details on the stepped spillway in different cases with different flow conditions.

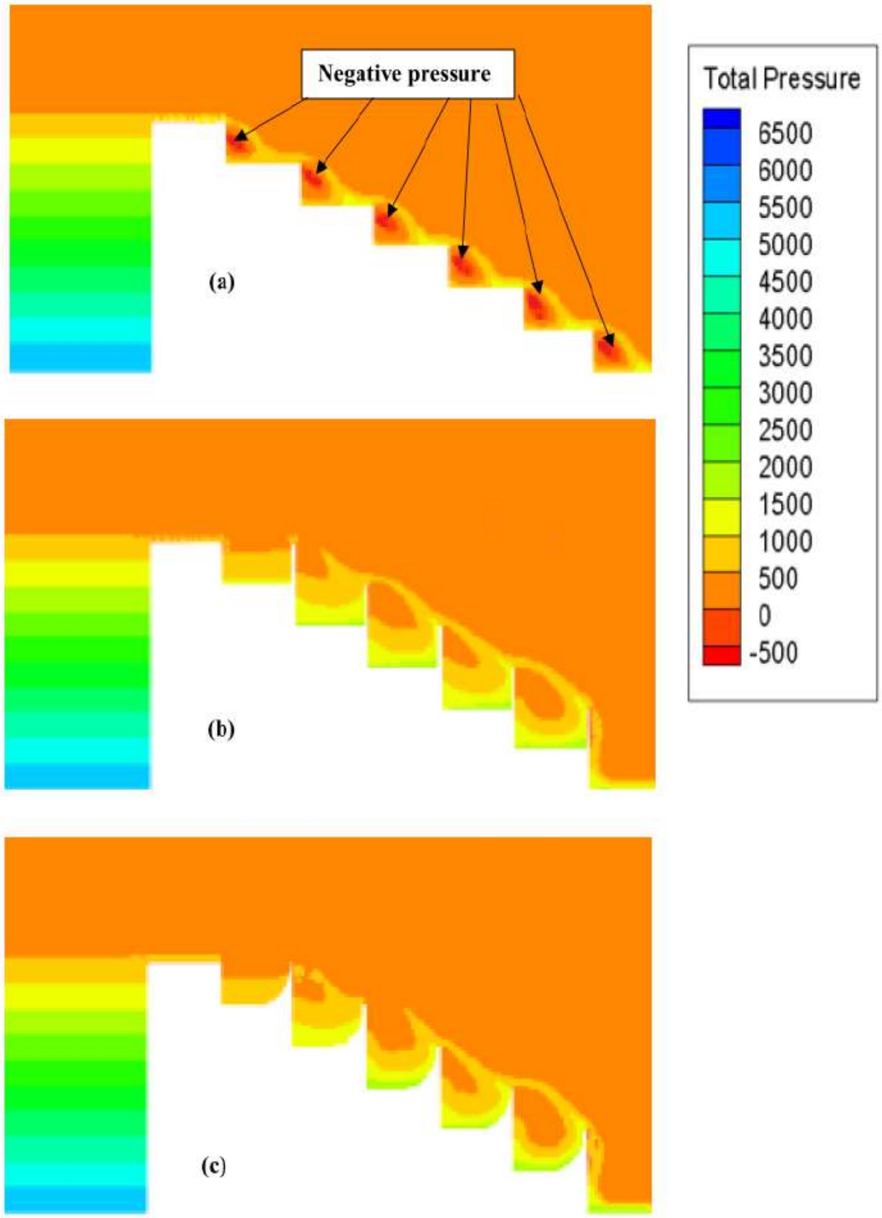


Figure 4.9 Modelled total pressure distribution, Nappe flow: (a) M1-4, (b) M1-5 and (c) M1-6, where q = 20.0 L/s.m, y_c/h_s = 0.69.

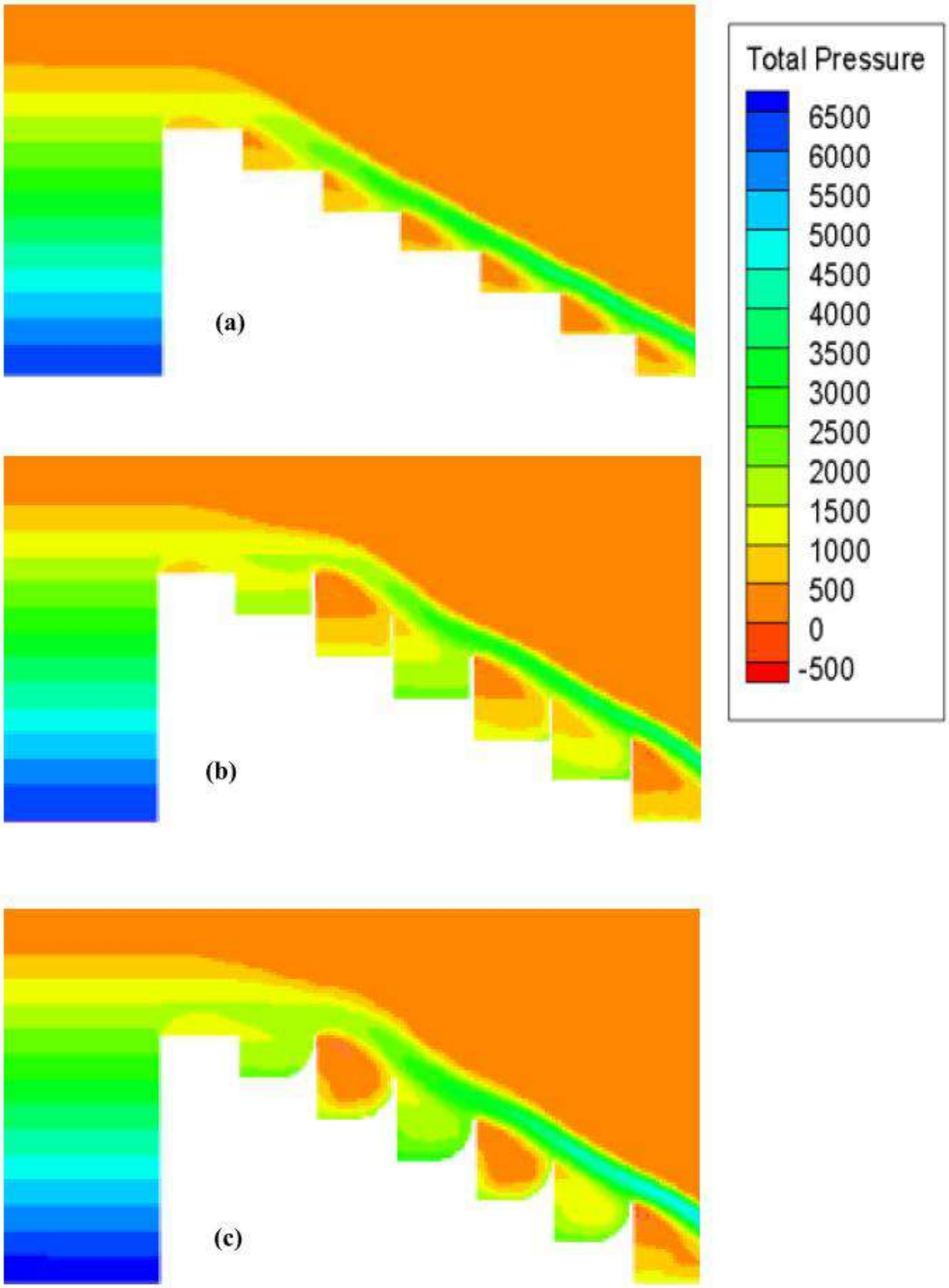


Figure 4.10 Modelled total pressure distribution, Transition flow: (a) M1-4, (b) M1-5 and (c) M1-6, where $20.0 < q < 39.0$ L/s.m, $0.07 \leq y_c/h_s \leq 1.09$.

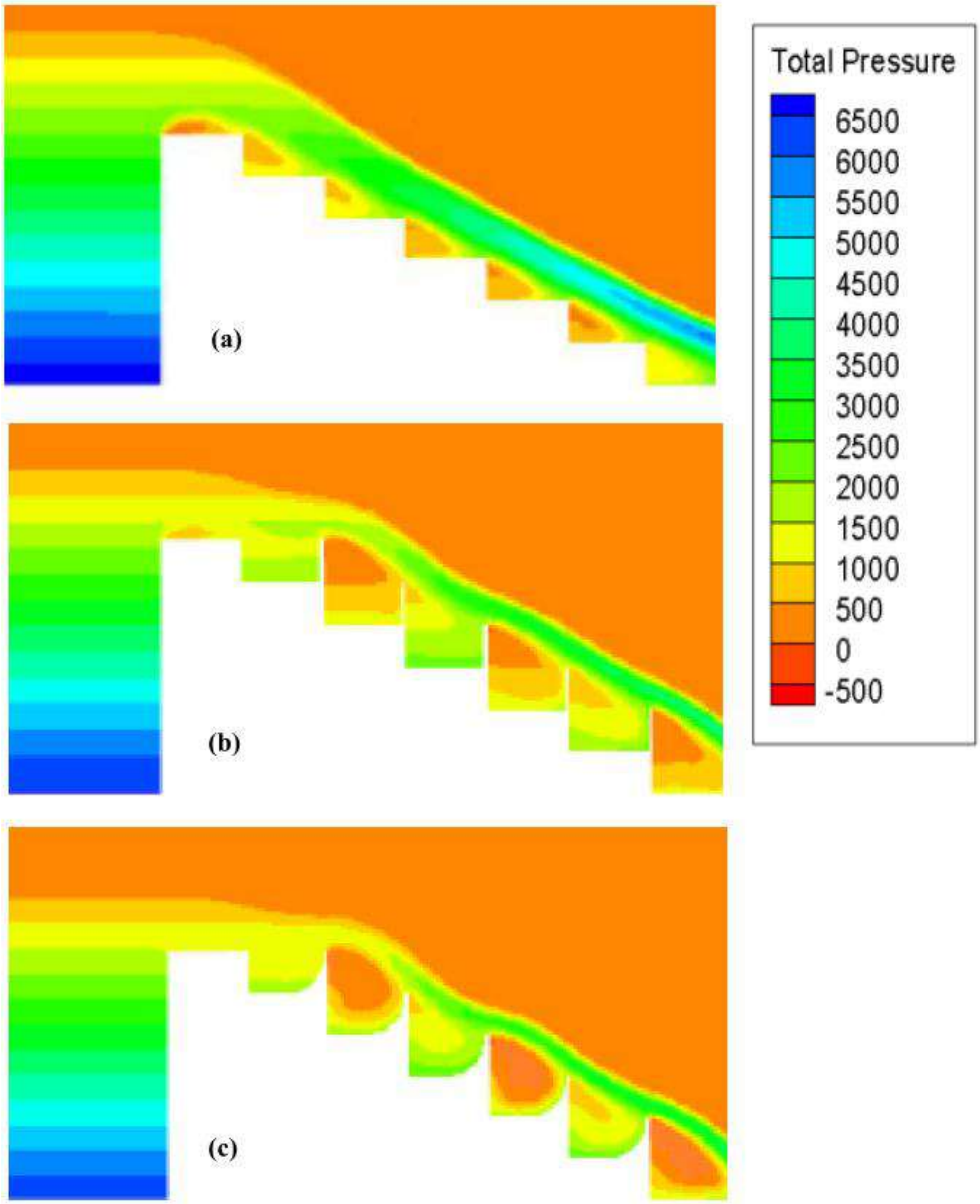


Figure 4.1 Modelled total pressure distribution, Skimming flow: (a) M1-4 (b) M1-5 and (c) M1-6, where q = 39.0 L/s.m, y_c/h_s = 1.08.

4.2.5 Stepwise energy dissipation

The modelled energy dissipation rate was examined by the predicted velocity and flow depth on each step edge to calculate the energy dissipation. Values of $\Delta E_x/E_o$ were calculated at the edge of each step, and the relationship between $\Delta E_x/E_o$ and the distance X for step height (h_s) is shown in Figure 4.12. The dimension X is the horizontal distance from the original point where the original point is at the starting face of the stepped spillway. ΔE_x is the difference between the US energy E_o and the energy E_x at distance X. Also, the data in Figures 4.12, 4.13, and 4.14 examined all flow regimes (NA, TR, and SK). Figure 4.12 presents the predicted energy dissipation at NA regime for all the step configuration for group one. ΔE_x values increased with X, and the step height h_s=0.05 m has higher energy dissipation than with h_s=0.03 m for the single step. Figure 4.13 showed ΔE_x for TR. ΔE_x values were height at the first steps and then became low at the last steps because the flow was close to the NA and SK properties at the first steps and last steps, respectively. Moreover, in Figure 4.14, the flow regime was SK and ΔE_x values were the lowest at the single step. Overall, the ΔE_x value increased with increasing step height h_s for each separate single step, and ΔE_x values were the highest with the NA regime. Figures 4.12, 4.13, and 4.14 can be used as a non-dimensional chart to determine the energy dissipation over stepped spillways with a chute angle θ of 26.6°. In addition, the result of the energy dissipation for the new step shape (step with quarter- circle end sill) was the highest for the same location and same step height. This positive change showed one of the main contributions of the current study.

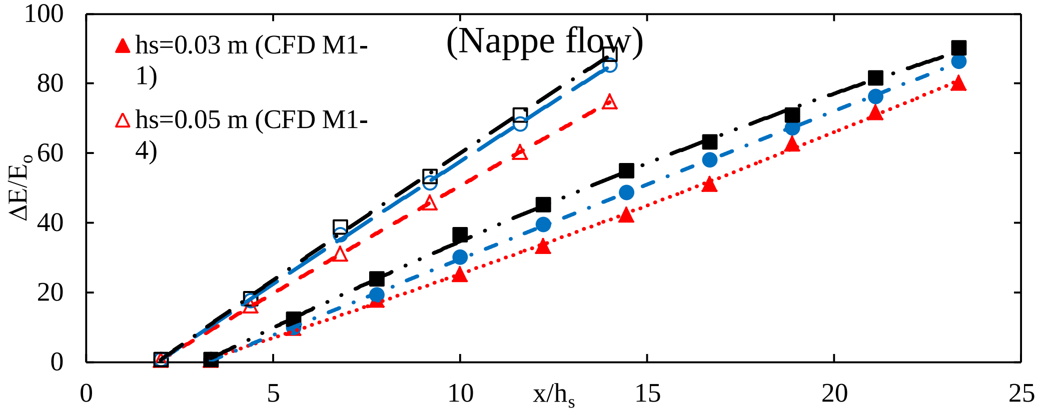


Figure 4.12 Energy dissipation over the stepped spillway for group one at Nappe flow.

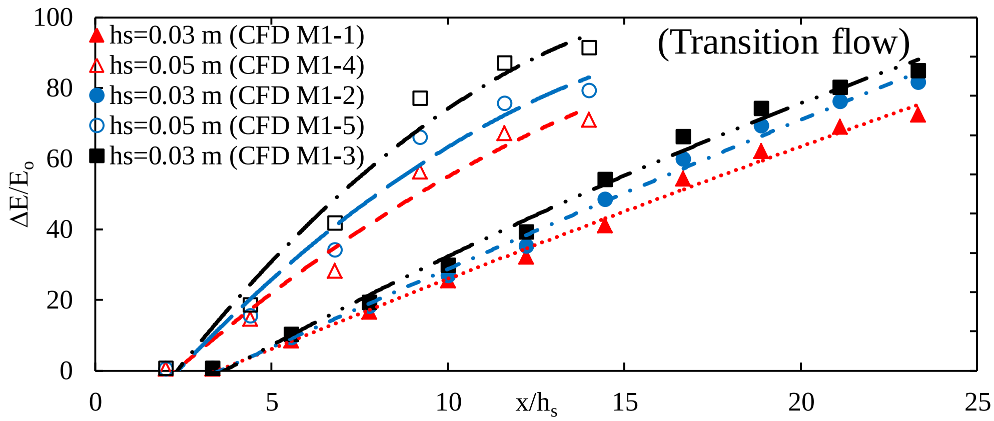


Figure 4.13 Energy dissipation over the stepped spillway for group one at Transition flow.

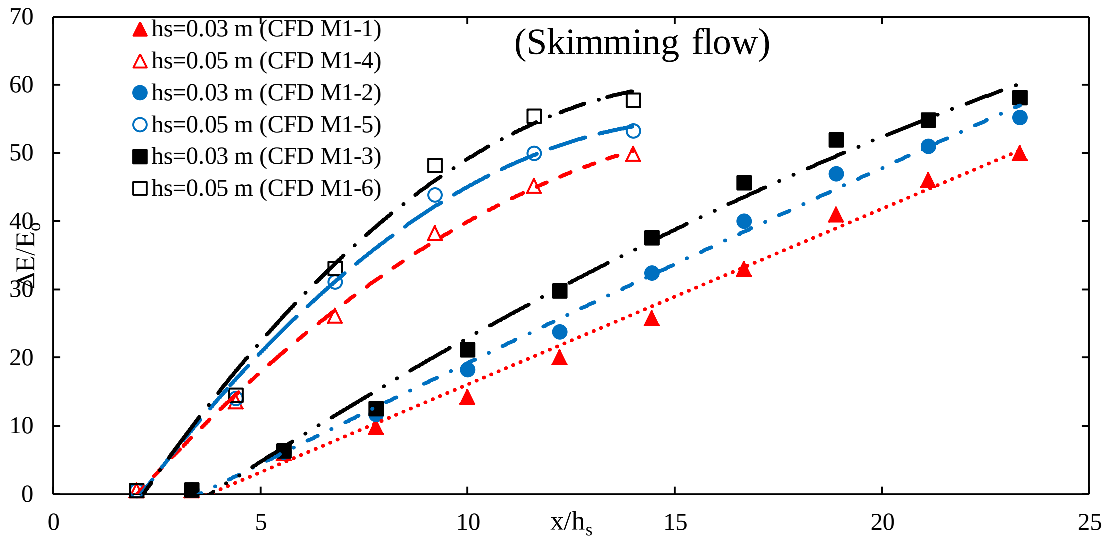


Figure 4.14 Energy dissipation over the stepped spillway for group one at Skimming flow.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This chapter demonstrated a 2D flow model to simulate the flow over stepped spillway. The 2D flow model had the same scale of the real experimental models of the current study. In addition, six step configurations with three chute angles were used to investigate the flow characteristics. The experimental work was performed in the lab for a range of discharges, and same these conditions were applied in the CFD approach. Then, the results show that the flow regimes and the energy dissipation efficiency depend on the discharge and step shape. Rather than utilising a flat step, the designers consider the possibility of utilising the step with quarter-circle end sill to address unpredictable flow conditions. The highlighted points are as follows:

•As the discharge increases on the stepped spillway, the critical depth of the flow increases. Also, the flow regime changes from NA to TR and to SK can be observed experimentally and numerically.

•The different flow regimes formation overstepped spillway is a function of flow rate and spillway geometry including the step shape that showing the delay in the flow regimes for the new step shape when compare with flat step.

•It was a clear change in the energy dissipation values among the used step shapes, especially for steps with quarter-circle configuration.

•Any increase in discharge leads to decreased energy dissipation for all step shapes used in this study, and it is consistent with the previous studies.

•The model has the same behaviours regarding the velocity distribution as the experimental results.

5.2 Recommendations

The present study investigated a 2D flow model by using the VOF method with K-ε models to illustrate the flow characteristics and shows the predicted stepwise energy dissipation. The results showed good agreement between the experimental and CFD data. Future research will change the VOF method by using the mixture method with different turbulent models to compare and obtain more details about the CFD models regarding the flow characteristics, energy dissipation, and aeration efficiency.

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الخلاصة

الهدارات هي هياكل مصممة للتحكم في التدفق الهيدروليكي ، وتغيير اتجاه الأنهار لتجنب الفيضانات ، وقياس التصريف ، وتنظيم الطرق الصالحة للملاحة. تؤثر الدرجات على أداء المجرى المتدرج فيما يتعلق بتبديد الطاقة والتهوية. في الثلاثين عامًا الماضية ، وضعت العديد من الدراسات (التجريبية والنظرية) إرشادات التصميم وسلطت الضوء على تعقيدات بنية تدفق الهواء والماء. على الرغم من ذلك ، فإن التصميم الهندسي الأمثل لمجرى المياه المتدرج غير مكتمل الدراسه ، ولم يتم دراسته بشكل شامل فيما يتعلق بأنظمة التدفق ، ومقاومة التدفق وتبديد الطاقة ، وتوزيعات السرعة ، وتوزيعات الضغط. في الدراسة الحالية ، تم استخدام نموذج CFD لحل معادلات Navier-Stokes التي يبلغ متوسطها رينولدز بواسطة برنامج ANSYS-Fluent. تم تطوير نموذج الجريان ثنائي الأبعاد من خلال استخدام النموذج متعدد الأطوار كنموذج VOF و k-القياسي لمحاكاة لجريان ثنائي الطور ومظهر سطح الماء فوق مجرى تصريف المياه. تم التحقق من نموذج CFD من خلال النتائج التجريبية ثم استخدام نموذج CFD للحصول على مزيد من التنبؤ بسلوك مجرى التدفق المتدرج. تظهر النتائج توافق جيد بين CFD والنتائج التجريبية. أيضًا ، تُظهر نتائج CFD نفس السلوكيات التي تدعم التأثير الإيجابي للتعديلات الجديدة على الخطوة (إضافة عتبة نهاية ربع دائرة). "

جمهورية العراق

وزارة التعليم العالي

و البحث العلمي

جامعة بابل / كلية الهندسة

قسم هندسة البيئية

دراسة خصائص الجريان ثنائي الأبعاد فوق هدار باستخدام الانسس فلونت

المشروع

مشروع مقدم إلى قسم الهندسة البيئية في جامعة بابل كجزء من متطلبات نيل شهادة البكالوريوس في علوم هندسة البيئية.

من قبل:-

حيدر ماجد مرزوق

آيار 2023

بإشراف:-

د. عدي عدنان جهاد