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SULAIMAN DAWOOD JASIM

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**OPTIMUM WEIR DESIGN FOR PREVENTING SCOUR
OCCURRENCE**

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IN
CIVIL ENGINEERING**

**BY
SULAIMAN DAWOOD JASIM
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OCCURRENCE**

Ph.D. Thesis

in

**Civil Engineering
Gaziantep University**

Supervisor

Prof. Dr. Mehmet İshak YÜCE

by

Sulaiman Dawood JASIM

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THESIS TITLE

submitted by **Sulaiman Dawood JASIM** in partial fulfillment of the requirements for the degree of Doctor of Philosophy in **Civil Engineering, Gaziantep University** is approved by,

Prof. Dr. Çiğdem AYKAÇ
Director of the Graduate School of Natural and Applied Sciences

Prof. Dr. Nildem TAYSI
Head of the Department

Exam Date: 10/1/2025

Examining Committee Members:

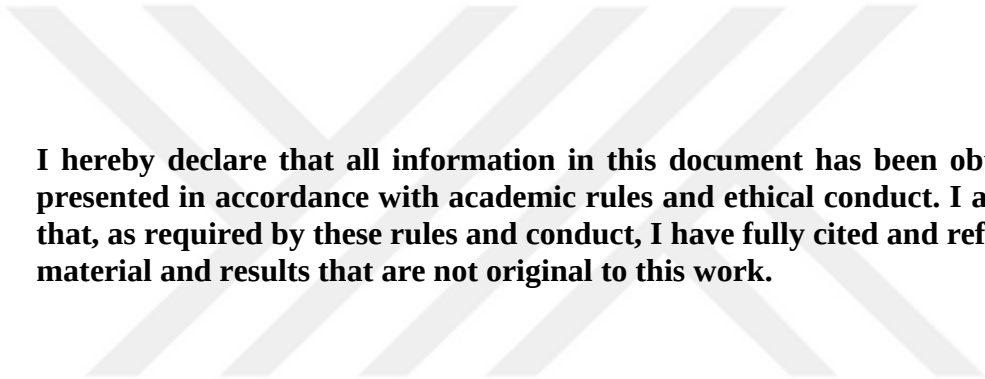
Prof. Dr. Ali AYTEK
Gaziantep İslam, Bilim ve Teknoloji universitesi

Prof. Dr. Nihat ATMACA
Gaziantep universitesi

Prof. Dr. Mehmet İshak YÜCE
Supervisor, Gaziantep universitesi

Doc. Dr. Musa ESİT
Adiyaman universitesi

Dr. Ogr, Uyesi Halil Ibrahim DEGER
Hasan Kalyoncu universitesi



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Sulaiman Dawood JASIM

ABSTRACT

OPTIMUM WEIR DESIGN FOR PREVENTING SCOUR OCCURRENCE

JASIM, Sulaiman Dawood
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Weir as a hydraulic structure with an upstream and downstream flow pattern has been of key importance to many researchers in the field of civil engineering. Energy dissipation is considered a challenge that forces researchers to make it high priority. In order to achieve the highest energy dissipation, thus, the minimum scour depth at the downstream, nine various models of different shapes of weirs were numerically and experimentally analyzed. The shapes of the weir models were optimized by numerical simulations then they were physically tested in laboratory experiments. The models have a width of 0.8m and a height of 0.59m, while their lengths range from 0.72 to 1.12m. The bottom of the channel was covered by a sand layer of 0.2 m thickness with a grain gradient rate of 0.002m. Three different discharge values of 0.015, 0.02 and 0.025m³ s⁻¹ were utilized in the experiments. The experimental and numerical simulation results showed similarities with the maximum depths of scour for all analyses were noted to be between 0.003m and 0.012m. The model SU9 was found to demonstrate the minimum scour depth ranging from 0.003 to 0.005m under all flow conditions, therefore, presenting the best performance in terms of energy dissipation.

Key Words: Weir, Energy Dissipation, Scour, CFD.

ÖZET

ÖYULMA OLUŞUMU ÖNLEME İÇİN OPTİMUM SAVAK TASARIMI

JASIM, Sulaiman Dawood
Doktora Tezi, İnşaat Mühendisliği
Danışman: Prof. Dr. Mehmet İshak YÜCE
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Yukarı ve aşağı akış modeline sahip hidrolik bir yapı olarak savak, inşaat mühendisliği alanındaki birçok araştırmacı için kilit öneme sahip olmuştur. Enerji dağılımı, araştırmacıları yüksek öncelikli hale getirmeye zorlayan bir zorluk olarak kabul edilir. En yüksek enerji yayılımını, dolayısıyla mansaptaki minimum oyulma derinliğini elde etmek için, farklı şekillerdeki dokuz farklı savak modeli sayısal ve deneysel olarak analiz edilmiştir. Savak modellerinin şekilleri sayısal simülasyonlar ile optimize edilmiş ve daha sonra laboratuvar deneylerinde fiziksel olarak test edilmiştir. Modeller 0,8 m genişlik ve 0,59 m yüksekliğe sahipken, uzunlukları 0,72 ile 1,12 m arasında değişmektedir. Kanalin dibi, 0,002 m'lik bir tane gradyan oranı ile 0,2 m kalınlığında bir kum tabakası ile kaplanmıştır. Deneylerde 0.015, 0.02 ve 0.025m³ s⁻¹ olmak üzere üç farklı deşarj değeri kullanılmıştır. Deneysel ve sayısal simülasyon sonuçları, tüm analizler için maksimum oyulma derinlikleri ile benzerlikler göstermiş ve 0.003m ile 0.012m arasında olduğu kaydedilmiştir. SU9 modelinin tüm akış koşullarında 0,003 ila 0,005 m arasında değişen minimum oyulma derinliğini gösterdiği ve bu nedenle enerji kaybı açısından en iyi performansı sunduğu bulunmuştur.

Anahtar Kelimeler: Savak, Enerji Dağılımı, Ovma, CFD.



“Dedicated to my family”

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LIST OF SYMBOLS

<i>SU</i>	Sulaiman weir model
<i>CFD</i>	Computational fluid dynamics program
<i>e</i>	Porosity (%)
<i>P1</i>	Height of weir in U/S (m)
<i>P2</i>	Height of weir in D/S (m)
<i>dr</i>	Diameter of the hole (m)
<i>ds</i>	Maximum depth of scour (m)
<i>L_s</i>	Length of scour hole
<i>V_s</i>	Volume of scour (m ³)
<i>R_c</i>	The radius of crest
<i>R_i</i>	The radius of main body
<i>R_{T1}</i>	The radius of the weir end
<i>R_{T2}</i>	The radius of the end of the additional part
<i>H</i>	The weir height
<i>L</i>	The total length of weir
<i>W</i>	The width of weir
<i>WSP</i>	Water surface profile
<i>L_{hs}</i>	The length of the chamber created downstream the main body of the weir
<i>L_R</i>	The length of the inclined side of ramp
<i>R_d</i>	Redaction depth of scour (%)
<i>R_v</i>	Redaction volume of scour (%)
<i>ds/Yu</i>	Maximum depth of scour to U/S water depth
<i>Y_t/Y_u</i>	Tailwater depth to U/S water depth
<i>Y_d/Y_u</i>	D/S water depth to U/S water depth
<i>θ⁰</i>	Angle of the ramp
<i>ρ</i>	Density of fluid (kg/m ³)
<i>E_o</i>	Energy
<i>E_u</i>	Energy at U/S (m)

E_t	Energy at D/S (m)
ΔE	The energy dissipation ratio between U/S and D/S (%)
$\Delta E/E_o$	Relative energy dissipation between U/S and D/S
V_a	Velocity of flow at downstream of the weir (m/s)
V_c	Critical velocity (m/s)
$TLEN$	The maximum turbulent length scale
g	Gravitational acceleration (m/s^2)
d_{50}	Median particle size (mm)
Fr	Froude number = $[v / (gh)^{0.5}]$
FD	Densiometric Froude number
R	Correlation coefficient
d_{16}	Grain size of which 16% by weight of the sediment is finer
σ_g	Geometric standard deviation
d_{84}	Grain size of which 84% by weight of the sediment is fin

CHAPTER 1

INTRODUCTION

1.1 General

While weirs are commonly used to raise water level of a river, they are also used by hydraulic engineers to measure flow discharge in the streams. When water flows over the top of the weir, it appears in the form of jets and develops a hydraulic jump. In addition, dissipating energy in channels, dam spillways and similar structures so that the excess kinetic energy does not damage them, is one of the most significant applications of the hydraulic jump. Another function the hydraulic jump inflow Froude number performs would also be the rate of energy dissipation or head loss across a hydraulic jump. Therefore, when designing a weir, one must consider partially dissipating the energy to prevent scouring that might occur in the downstream ends of the weir.



Figure 1.1 A Simple weir.

Nowadays, the investigation of the flow and the sedimentation behavior around a body has been simplified by the CFD techniques which have been the focus of many researchers [1]. Some researchers tried their studies to investigate the flow and local scour around a non-submerged spur dike based on the Navier-

Stokes equations, in order to do 3-D simulation analyses. They pointed out that the formation of the scoured surface is mainly influenced by a submerged flow and a horseshoe vortex. Few researchers studied scour downstream combined flow [5], examined the scour occurrence in non-cohesive soil below the vertical gates, after investigating them in case of simultaneous flow over and under them. After using two various bed materials of homogenous non-cohesive soil in his experiments, he initiated an empirical equation for estimating scour depth in terms of the height of water at the outlet, total discharge, head and grain size. According to Dehghani, who explored the dimensions of scour hole downstream of combined free over weir and below gate experimentally, 'the ratio of D_s/y_o increases as the H/a and w/a keep increasing, the D_s/y_o was greatest when $w/a=6$ (where a is the gate opening, H is the head over weir, w is the vertical distance between the gate top and the weir bottom and y_o is the approaching water depth) [2-11].

1.2 Scour

Scour has been given attention by researchers in hydraulic and river engineering sciences because, due to its particular condition and at the same time complexities and lack of relationship to meet all the conditions, it has been in the history of the field of hydraulics for a long time. While hydraulic structures are obstacles to flow, they also result in changing the flow pattern nearby and causing local scour to happen in the area. The importance of looking into and investigating scour lies in the possibility of the scouring depth becoming so significant that the depth reaches the river foundation structure and puts its stability at stake or even demolishes it. On that account, the applications of empirical relationships or physical models constitute the most usual method used to determine the scour depth. Notwithstanding the extensive studies on estimating local scour around various hydraulic structures, a generic and holistic correlation of calculating the local scour depth around river structures arose. In addition, despite the occasional difference between the theoretical and experimental differences of a variety of different methods, the calculated local scour does not necessarily appear to be the same or close to each other. All in all, Joolaeian and Nohani define scour as the 'eddy currents' formed by 'the erosion of channel bed and edge due to water flow or bed erosion at the downstream of hydraulic structures' caused by 'high water flow or turbulent flows'. Joolaeian and Nohani also mention that, scour comes by through the interaction of the firstly the 'driving force from the

flow which operates to separate the particles from the bed' and secondly the 'resisting force caused by the friction and weight of particles which resists the particle movement and prevents the separation of particles from the substrate' [12-15].

A particle begins to move when the drag and lift forces, which separate the particle from the substrate, prevail over the particle resistance force. Local scour in the downstream part of some hydraulic structures is shown in Figure 1.2.

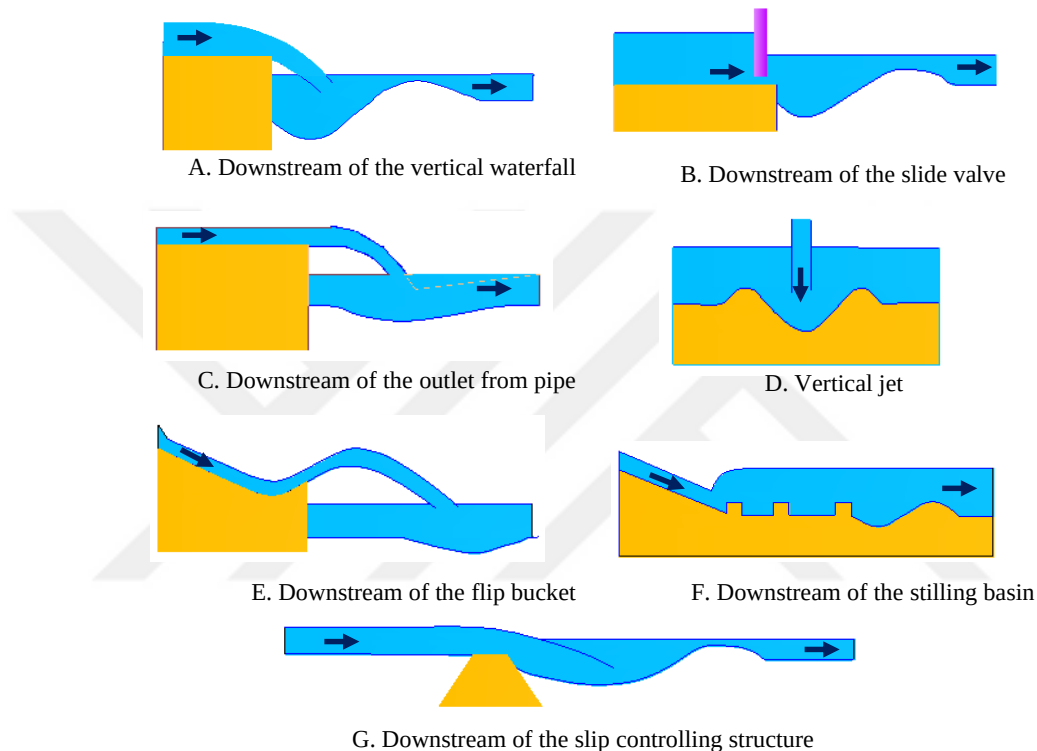


Figure 1.2 Local scour at the downstream of some hydraulic structures.

1.3 Scour types

There is a diversity of places and conditions under which scour can be created, such as contraction scour, scour at the curves and scour at confluences. Local and general scouring are, however, the two sole types of scour that can be used for bridge bases.

1.3.1 Contraction scour

This is the case of cross contraction at the flow which raises the rate and erosion power of the flow locally and it usually happens after the limiting of a river width. For instance, this type of scouring would occur after the reduction of the channel width caused by the bridge side supports and piers in the middle of the stream. (figure 1.3).

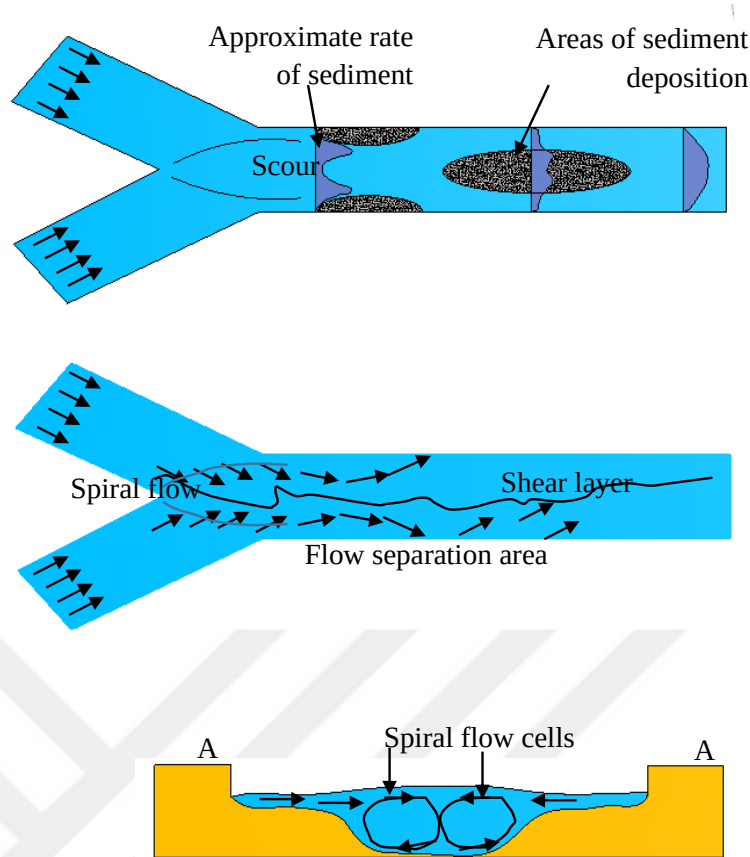


Figure 1.3 Flow patterns, sedimentation and erosion at the intersection of two rivers.

1.3.2 Local scour

Scour can be caused by water structures that may change the water flow pattern. This is the case for the reason that, changing the rate and turbulence, the flow characteristics, leads to changing the sediment transport capacity which results in an imbalance between the actual capacity of sediment transport and the capacity that carries sediment flow. When one adapts hydraulic conditions to scour a new equilibrium occurs. Although local scour is of a short temporal scale, a time-dependent and not comparable scouring process is important in the original condition. In the places where the turbulent flow intensity is increased locally, there is the occurrence of local scour, which, when happens at the downstream of hydraulic structures such as weirs, chutes, and valves, is considered a phenomenon due to its local velocity being stronger than its critical speed; what is also known as ‘threshold velocity of particle motion’. The aforementioned happens due to insufficient energy dissipation, a

formation of an unstable hydraulic jump and transferring jump out of the stilling basin bottom and the creation of torsional flows at the downstream of hydraulic structures.

1.3.3 Total scour

A total scour depth concerning a specific structure is acquired through a general scour, a contraction scour or a local scour. The bed local balance from each of these scours is taken into consideration as the initial condition to estimate the other part. Figure 1.4 shows an example of the three parts of a total scour.

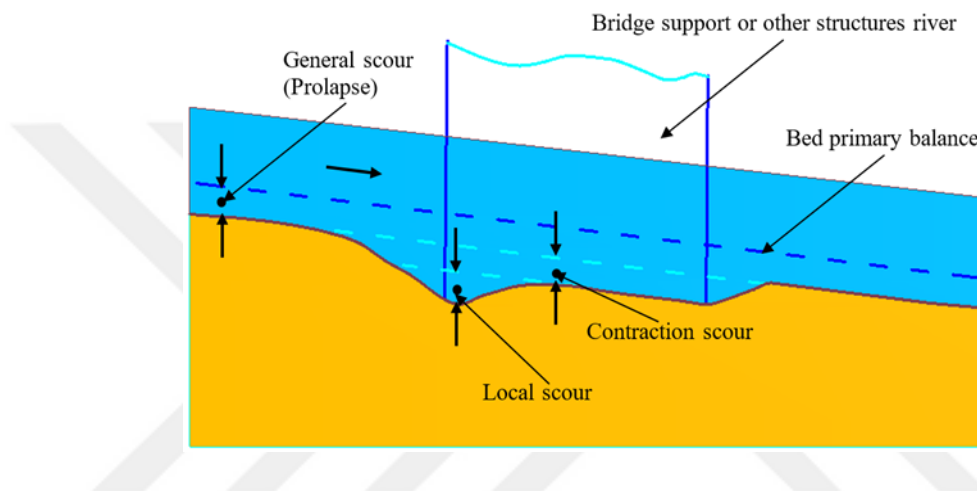


Figure 1.4 Scour components.

1.4 Scour downstream the weirs

In the dam reservoirs, the flood currents usually cause various types of agitating weirs that eventually result in an energy dissipation structure that could be in the form of a particular basin or flow at the bottom of a natural river. In the possible case of a stilling basin non-existence, scour can be caused by the flood currents following a jet collision with the river bed. What defines the scour's final shape is the bed stone place and potential non-cohesive constructive materials.

The study of these scours is generally based on three basic aims: not harming the structure stasis because of possible failure of the structure or increasing water drainage, not harming the river floor stasis at the downstream and its wings, and forming hills from eroded materials that can increase the shoal level at the downstream of dam.

1.5 Methods of preventing scour

Preventing scour can be achieved in several ways. To start with, this can be achieved by rehabilitating the stilling basin. If the depth of the downstream is not big enough to form a hydraulic jump in the basin and be subjected to scour because of the flow circumstances of the protective conditions against it, then there is a need to repair the stilling basin. When there is a supercritical water flow in the stilling basin and a hydraulic jump takes place in the downstream channel, critical scours also take place. Through building a secondary stilling basin at the downstream of the primary basin and through constructing a dam at the downstream of the river in order to deepen the water inside it, the stilling basin can also be restored. There are many ways that the secondary stilling basin can be built; however, rip rap and concrete tend to be the most functional ways.

In addition, granulated rip rap or rip rap material substitutes seem to be another good way to prevent scouring. To explain, in case the restoration of the stilling basin could not be achieved through using rip rap due to granulation issues or the high cost of the scoured parts to be fixed, there is an option to use other substitutes such as cubic concrete grout bags and tetragonal concrete blocks that have proven their usefulness in other similar constructions.

Another way to prevent scouring is aeration used a jet aeration experiment to investigate the scouring incline and the aeration effects on the water jets scouring ability. He concluded that firstly, in the stilling basin a dispersed aerated jet was a lot faster than a 'conventional jet', and secondly, the coastal depth needed to avoid erosion in the aerated jet was about half the depth needed in conventional jets having the same discharges [16-19].

All in all, one method to help in the reduction of scouring and more particularly in the downstream of weirs, is applying a submergence basin to assist in the dissipation of the flow energy. This method can vary based on the particular type of the weir. For instance, due to the decreased jump length in the submerged bucket-shaped weirs, these weirs tend to be used in areas where crating a stilling basin is not feasible. Also, grooved bucket-shaped weirs are so vulnerable to shoal depth that on one hand the reduction of their depth would result in surface deficiencies and on the other hand the increase of their depth would result in the outlet jet compression.

As previously stated, jet scouring can be affected by a variety of factors amongst which jet energy, the angle of impact of the substrate surface, the distance between the formation of the jet to bed level and the aggregation of sediments in the water and the shoal depth. The more the downstream shoal increases the more the scour reduces.

Reducing erosion in inclined jets, it is achieved by the dissipation of energy of the jet in bubbles brought about and the collision of these bubbles with the bed materials in order to get to the water surface. However, due to the fact that in the deep shoals the force brought to bear on the air bubbles causes them to most likely dissipate jet energy, the erosion is more than shallow; something that is not the case in the shallow shoals since the energy is dissolved collided with the bed and hence aeration is less required.

1.6 Weirs

Weirs are defined as barriers across a river intended to change its flow attributes. Often, weirs appear as obstructions of a smaller size than ordinary dams since water can be pooled behind them while also being able to flow in a steady way above them. Thus, a common use of the weirs is the change of the river flow in order to avoid flooding, determine discharge and assist in making rivers more traversable and clear for crossing. Also, weirs are used in the study and research of returning salmonids.

In general, weirs are considered as engineering structures that are required to function in challenging and demanding environments notwithstanding their capacity, ownership, age or state; therefore, it is crucial that the creation of brand new weirs and restoration of old ones be supervised, designed and monitored by experienced and well qualified engineering professionals.

Weirs are required to respond to three major requirements and these consist of firstly a good hydraulic performance from low flow during the summer months to flood, which covers a full range of flow conditions, secondly, they must possess structural integrity and bare any hydraulic and structural onerousness throughout their life without the necessity of further costly maintenance and thirdly, they should avoid posing health and safety risks to the public or operational staff during and after their construction stages[20-23].

1.7 Common weir types

Usually all the other types of weirs are considered as non-sharply crested weirs that are broken down to categories in terms of their cross-section shape, for example, broad-crested, triangular and trapezoidal. On the other hand, sharp-crested weirs are categorized based on their opening shape, for example, rectangular, triangular or V-notch, trapezoidal and parabolic.

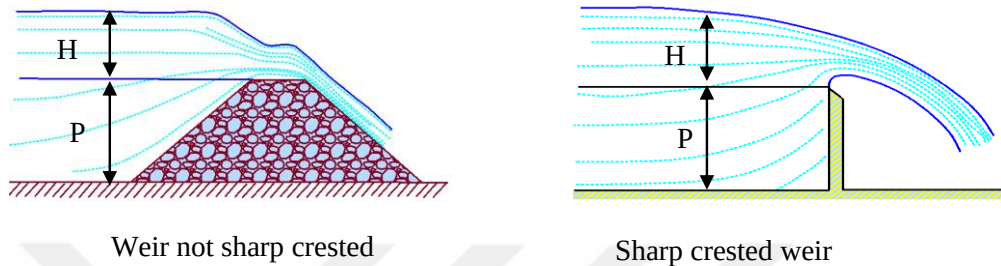


Figure 1.5 Non-sharp crested and sharp crested weirs.

1.8 Types of weirs

The two main types of non-sharp crested weirs are gravity and non-gravity weirs.

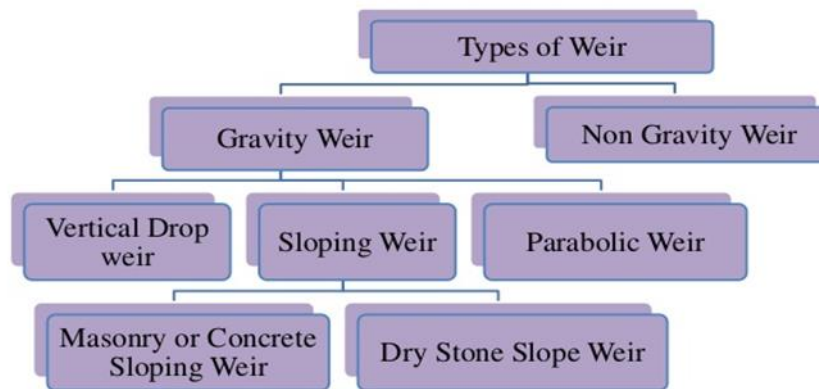


Figure 1.6 Weir types.

1.8.1 Gravity weirs

The weight of the floor resists to the uplift pressure caused by the seepage of water below the floor; that being the case gravity weirs are sub-categorized into the following types:

- a) Vertical drop weirs that as mentioned above could be explained as:
 - Vertical drop weirs or crest walls

- Upstream and downstream cut off walls at the end of impervious floor.
 - Launching apron for scouring prevention
 - Graded inverted filters at the downstream floor end to relieve the uplift pressure.
- b) Masonry or concrete slope weirs which:
- are suitable for soft sandy foundation
 - are generally used where the difference in weir crest and downstream river is limited to 3m.
 - whose sloping crest the hydraulic jump is formed on.
- c) Dry stone slope weirs that could be:
- a body or weir wall
 - an upstream and downstream rock fill laid in form of glacis, with few intervening care walls.
- d) Parabolic weirs which are:
- Similar to the spillway section of a dam
 - Body walls designed as low dams.
 - Containers to dissolve energy

1.8.2 Sharp-crested weirs types

Based upon the weir opening shape, the discharge features, the crest width and the nature of the crest. Below are some important aspects of these weir types.

1. Differentiation in terms of shape:

- Rectangular weir.
- Cippolletti (trapezoidal) weir.

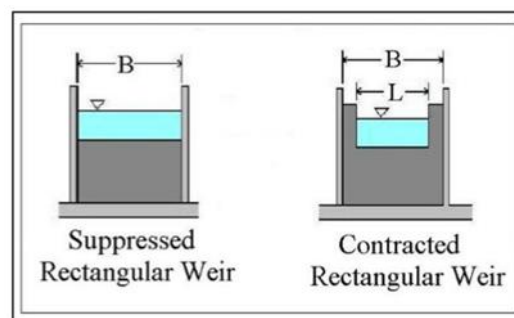


Figure 1.7 Sharp-crested rectangular weir.

2. Differentiation in terms of the discharge features:

- Ordinary weirs
- Submerged or drowned weirs.

3. Differentiation according to the crest width:

- Narrow crested weir
- Broad crested weir



Figure 1.8 Flow over broad crested weir.



Figure 1.9 Broad crested weir in the field.

4. Differentiation based on the nature of crest:

- Sharp crested weirs
- V-Notch weirs
- Oblique weirs
- Ogee weirs

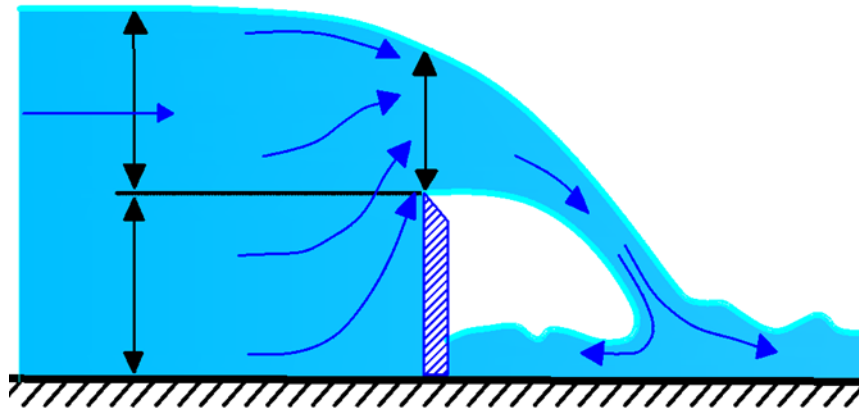


Figure 1.10 Flow over sharp crested weir.



Figure 1.11 Sharp crested weir in the field.

- V-Notch Weir

A V-notch is a sort of a sharp-crested weir which is placed perpendicularly on the sides and the bottom of a straight channel and is the most accurate discharge measuring device that can also be used for a big variety of flows. There exist two V-notch sharp-crested weirs: the partially contracted where the contraction along the sides of the weir is not fully developed because of the proximity of the walls and/or the bed of the channel nearby and the fully contracted weir where the approach channel's sides and bed are sufficiently remote from the edges of the V-notch and thus they allow a sufficiently great approach velocity component, which is also parallel to the weir face,

to fully develop contraction. A graphical view of a V-notch sharp crested weir is shown in Figure 1.12 and Figure 1.13.

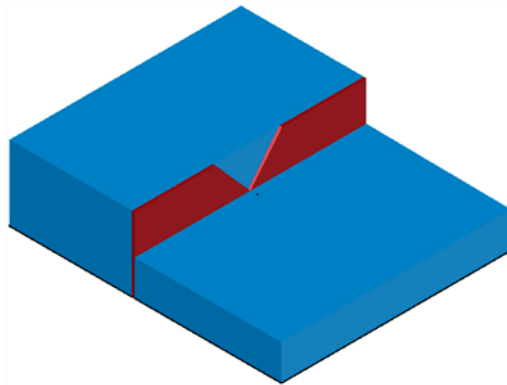


Figure 1.12 V-notch sharp crested weir.



Figure 1.13 V-notch sharp crested weir.

- Oblique weirs

Several weirs, apart from the ones placed perpendicularly to the direction of the flow, are placed obliquely to the direction of the flow (Figure 1.14). In this case, the operative weir length increases beyond the channel width causing the flow of a particular water level at the upstream to increase and, at the same time, the water head at the upstream of a certain discharge to decrease. If the water passes over the weir, it flows perpendicularly towards the weir. When the flow reaches the weir, it increases

speed which it also decreases when it leaves the weir. Regarding the sharp crested oblique types of weirs, the maximum velocity is found above the crest of the weir whereas in the broad crested type of oblique weirs, the maximum velocity is found just behind the weir. In addition, due to the complexity of the oblique's downstream side flow behavior, the turbulence properties caused contribute directly to energy dissipation. Also, in the weir's rear as well as downstream side, where the circulation takes place, one can observe flow convergence and separation occurring opposite one another [23-25].

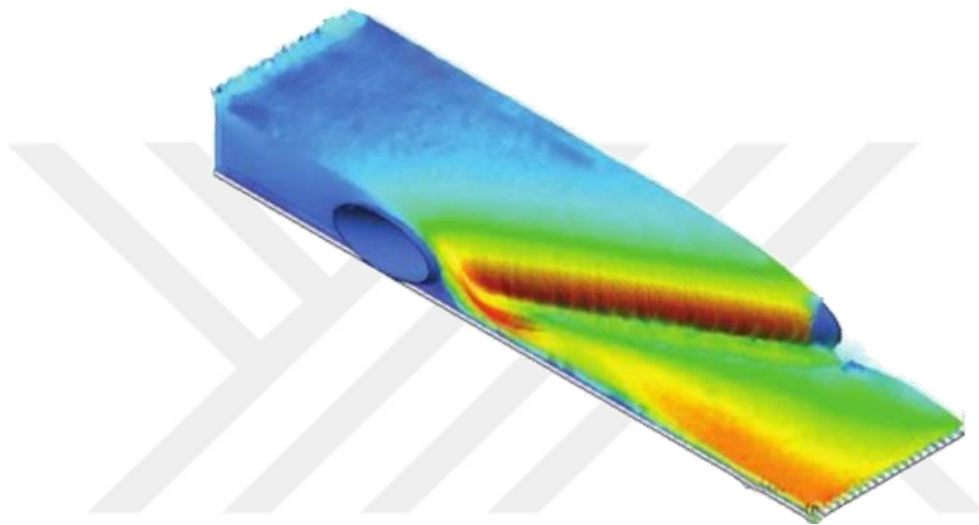


Figure 1.14 Flow behavior over and downstream cylindrical oblique weir [90].

- Ogee weirs

Ogee weirs are considered exceptional thanks to their extraordinary hydraulic features that enable them to efficiently move flow in a safe way. They are used in numerous situations in engineering as they possess great abilities in measuring flow well when properly designed. They are built in a way that prevents them from developing any unnecessary nappe, which usually is developed in weirs with the exception of sharp-crested weirs. In ogee-crested weirs, the nappe is forced to go along within a single path for discharge because of the weirs' shape; thus, the weirs are considered very consistent when it comes to measuring their flow (figure 36). Their profile adheres closely to the lower surface profile of a ventilated nappe that flows over a rectangular sharp-crested weir (Figure 35).

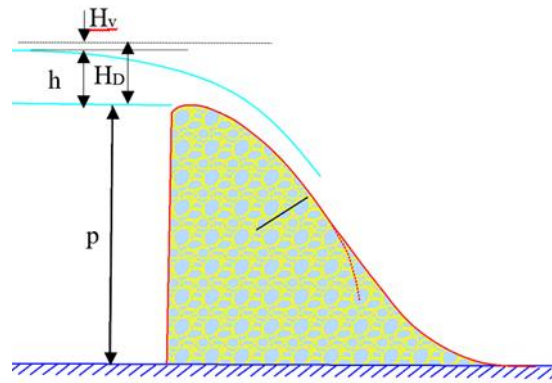


Figure 1.15 Ogee Weir.

1.8.3 Aim of the study

This study aims to examine the impact of different designed shapes of weir on the scour depth at the downstream side. The obtained results from Flow 3D program will then be validated against actual measurements.

The thesis outlines are summarized in seven chapters besides the reference menu. Chapter one includes introduction to the main subject of the study. Regarding chapter two, literature reviews of many experimental and numerical studies performed in the field of the thesis are presented in details. Chapter three presents an introduction to the numerical tool used in the simulation analyses. As for Chapter four, the numerical setup and the related analyses of the nine designed models are clarified as well. Regarding chapter five, the experimental setup, which includes defining the dimensions of the channel, the sand layer specifications and the measuring tools, is presented in attached with the method of forming the physical models. The experimental findings are presented and explained in chapter six. Whereas, the conclusion and recommendations are discussed in chapter seven.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Weirs are the initial hydraulic structures across a river or stream that raise the water level or distribution between the irrigation channels, as well as measure the water flow. Weirs are commonly used to monitor the depth of the water flow in a river or irrigation canal. Broad crest weirs are the most usual and predominant type of dams. Their studies have focused, to a high degree, on the threats against the structure foundations that scouring occurring downstream as a consequence of an increased flow velocity and turbulence can bring about [26]. Ahmed demonstrated that the practical use of the application of a physical model with holes in the downstream (double lines water jets) reduces the scour, and by comparing the results of his findings using a CFD program, he obtained the same results as the ones obtained via a laboratory model through CFD techniques. In addition, Helal used single-line floor water jets to examine the diminished scour downstream of a hydraulic structure and concluded that they reduced it by 40% to 85%. Similarly, Ghazali managed to decrease the scour hole depth and length by placing concrete semi-circular baffle blocks on local scour holes in four lines downstream [27-35].

Chen investigated the scour downstream clear-overfall weirs and discovered a close link between the Froude number and the water levels above and below the submerged dam; additionally, he highlighted that materials found at the bottom, the flow depth and the submerged dam type can affect the scouring. The holes found in the weir's body can also reduce the scouring [36-41], according to Sobeih and Al Talib, also studied the effect of the weir slope, the radius of the crest weir [13], and the type of gradient in the weir body on the scour downstream of the weir by using a semi-crest weir with three different gradations [41]. According to Ahmed's calculations, after using three different height obstacle models, the most effective obstacle height was 24 centimeters because as he concluded, it allowed less scouring in the downstream of the weir. He also added that the obstacle's gradation and shape had a

great effect on the coefficient runoff and the energy dissipation percentage (E%). Finally, when comparing the efficient results of the CFD techniques (Flow 3D program) to the laboratory experiments, the Flow 3D program is admittedly far more superior as it outperforms any other program thanks to its capability to measure the flow as it is in real life [42-46].

2.2 The evolution of weir forms and their uses

Many have been the studies regarding the evolution of the forms of weirs and their applications. To begin with, Siti and Yee, assessed an empirical modeling on sediment loss of disturbed land via the use of MUSLE and gauging weirs, and a sharp crested rectangular weir for runoff measurements [47]. Next, Younis extensively explored the influence of side weirs lip slope on flow characteristics and found that by altering the end lip slope of a weir from three angles (0, 30 and 60) to go towards the opposite flow direction, the performance of the side weirs improves, bearing in mind the Froude number and the slope of the side weir end lip; an equation of the coefficient of discharge of the side weir was therefore also defined [51]. The results of their research showed that the side weir which was inclined at 30 degrees reduced the water head above it by 8%, the horizontal lip of the side weir which was inclined at 60 degrees reduced the water head by 12%; these results indicated that the discharge was increased when passing over the side weir while the slope of the side weir end lip was increased flowing in the opposite direction. This meant that this type of weir could be used as a good getaway of the surplus discharge and be more economical compared to the horizontal lip side weir, especially with regards to horizontal channels and subcritical flows [47-51].

Moreover, Noori and Hayawi researched experimentally the stability of rockfill weirs safeguarded by gabions and subjected to overflowing rates in a laboratory study aiming to protect the downstream slope of these rockfill weirs using stepped gabions. They constructed and tested five weir models with different downstream slopes: 1V:2.5H, 1V:3H, 1V:4H, 1V:5H, and 1V:7.5H. There were fifty-eight experiments carried out in five different cases of stepped gabions placed on the downstream slope via the use of three gravel diameters: 11.11mm, 15.9 mm and 22.25 mm. More particularly, the first type of gabion was the 'M-1', which was one-layered and without connections, the second gabion type was the 'M-H' in which the gabions were connected laterally

sideways, the third type was the 'M-V' where the gabion connections were longitudinal, the fourth type was the two-layered 'M-2' and finally, the fifth type was the 'M-3' which were the three layered gabions. In their data analysis, Noori and Hayawi, brought about a set of equations to estimate the failure of the discharge unit bearing in mind the equivalent gravel diameter, the relative submerged intensity of the gabions, the solidity of the gabions' layers and the gabions' internal friction angle per each gabion type. They also demonstrated a straightforward technique as to the design of rockfill weirs supported by stepped gabions, bearing in mind the maximum failure discharge illustrated in charts. The characteristics of the physical model of each slope determined a mathematical model in which failure unit discharge values matched well with the values derived from the experiments. The combination of the results of their study and those of other researchers proved that rockfill weirs protected by gabions are subjected to a greater chance of failure of the discharge unit than the earth weirs protected by gabions [52-55].

Adhau et al. focused their research on the design of a mini hydro-power plant on a weir of a limited size, since the hydropower generation can be planned in a small scale on small rivers, canals, weirs and so on. The planning of a hydropower project on canal waters must adhere to the Independent Power Producers Policy and be built as an independent power generation plant. In order to decide on the capacity of the plant, a number of different fundamental parameters need to be taken into consideration, for example, the selection of the site and the hydrological and topographical analysis survey. A river has to contain sufficient water flow to provide the necessary hydrological data and a feasibility report including all the required parameters should be prepared per each proposed hydroelectric project. These parameters are also included in the report to prevent the project from having any negative environmental and ecological consequences. Overall, a well-planned hydro-power plant could potentially be used in the planning and irrigation of the inner and surrounding land of rural areas. Overall, Adhau et al. showed the details of the design of a mini hydro project; for instance, its designed head, designed discharge, machine ratings, power house dimensions, and so on.

In addition, Khalaf et al. also studied the flow hydraulic characteristics, the flow energy dissipation over stepped spillways, the profile of water surfaces, the

piezometric head distribution and energy dissipation (E/E_0) % with regards to a semi-circular crest's stepped spillway. In his research, he used three types of d/s spillway slopes ($\alpha=V: H=1:0.75, 1:1$ and $1:125$) and three numbers of steppes ($N_s= 3, 5$ and 7) per slope. He performed seventy-two experiments in laboratory horizontal channel of 12m length, 0.5m width and 0.45m depth to achieve a greater variety of discharge. The results of the stepped spillway experiment showed that a rise in (d_0/d_c) and (L/d_c) value causes a rise in ($\Delta E/E_0$) %, and a rise in the roughness of the Froude number (F^*) and number of steps (N_s) value causes a drop in the ($\Delta E/E_1$) % value in every stepped model. Khalaf et al. also came up with an empirical equation to calculate the energy dissipation, as shown below.

$$E_o = d_o + \frac{v_o^2}{2g} \quad (2.1)$$

$$E_1 = d_1 + \frac{\alpha_1 v_o^2}{2g} \quad (2.2)$$

$$\Delta E = (E_o - E_1) \quad (2.3)$$

$$\frac{\Delta E}{E_o} \% = \left[\frac{E_o - E_1}{E_o} \right] * 100\% \quad (2.4)$$

The functional relationship for ($\Delta E/E_o$ %) with the main flow parameters for stepped spillway.

$$f_6 \left\{ \frac{\Delta E}{E_o} \%, q, d_o, L, d_c, K_s, g, v, N_s \right\} = 0 \quad (2.5)$$

Then equation (5) becomes as:

$$\frac{\Delta E}{E_o} \% = f_7 \left\{ \frac{d_o}{d_c}, \frac{L}{d_c}, F^*, R_e, N_s \right\} \quad (2.6)$$

Reynolds number (Re) which has very large values and hence its effect on ($\Delta E/E_o$ %) will be very little, therefore, Re will be neglected in this study then equation (6) can be rewritten as:

$$\frac{\Delta E}{E_o} \% = f_7 \left\{ \frac{d_o}{d_c}, \frac{L}{d_c}, F^*, N_s \right\} \quad (2.7)$$

Where:

E_0 = U/S energy (m), E_1 =D/S energy (m), $(\Delta E/E_o \%)$ %= Relative energy dissipation between U/S and D/S of stepped and traditional spillway, V_0 = velocity at sec. 0(m/sec), α = Spillway slope, V_1 = velocity at sec.1 (m/sec), L =Horizontal step (m), h =Vertical step (m), N_s = Number of steps. q = discharge over the spillway per unit width (m²/s/m), d_c = critical depth over spillway (m), d_1 = D/S depth of water at toe of stepped and traditional spillway (m), d_0 = U/S depth of water (m) [56-60],

Furthermore, Julien investigated the bendway weirs' optimal design criteria via numerical simulations and physical models. As bendway weirs have a normal position in the downstream direction, the flow streamlines get redirected towards the center of the channel, reducing the chances for bank erosion and assisting in navigation. Figure 2.1 illustrates the flow near a submerged weir [61].

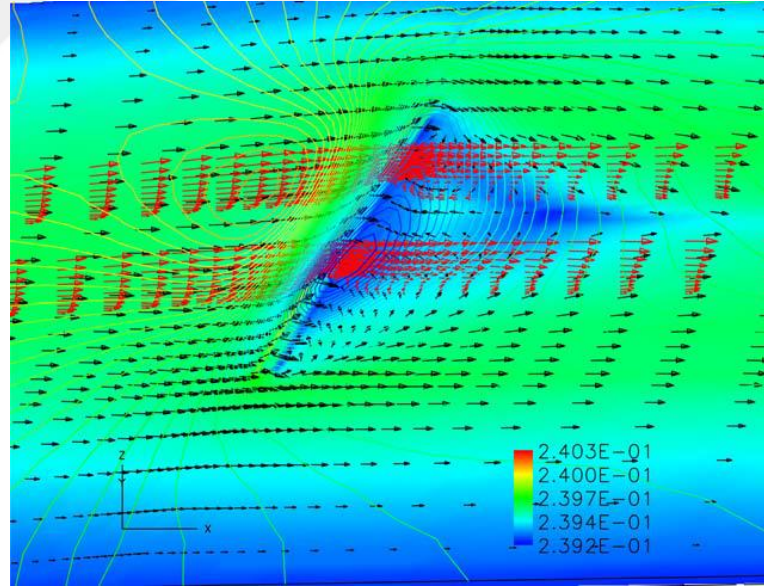


Figure 2.1 Oblique view of flow around a submerged weir [88].

2.3 Attempts to reduce scour:

Elnikhely, carried out an experimental study to explore the effect of a single curved vertical sill use on the scour hole dimensions downstream of a spillway with various flow conditions, where he also added a case of flat floor without a sill. His findings showed that the suggested curved vertical sill gave a reduction of 20% to 43% in

maximum scour depth and 45% to 66% in scour length compared to the case of the flat floor. His findings also demonstrated that the best location of sill was in the first one-third of the floor with a relative diameter of 0.122 of spillway height. He also came up with simple formulae to estimate the scour parameters and he applied a dimensional analysis aiming at the correlation of the different variables affecting the scour depth in the downstream of the spillway. The variables used were as following: b = sill width, B = channel width, ds = maximum scour depth, dso = maximum scour depth in case of flat floor, D = Diameter of sill, $d50$ = mean size of bed material, g = gravitational acceleration, h = sill height, H = spillway height, L = distance between sill and the toe of the spillway, L_f = floor length, L_s = maximum scour length, L_{so} = maximum scour length in case of flat floor, S_o = bed slope of the channel, t = time at maximum scouring, y_1 = initial water depth of the hydraulic jump, y_2 = sequent water depth of the hydraulic jump, y_t = tail water depth, and y_{up} = upstream water depth, ρ = density of water, ρ_s = density of bed material, and μ = dynamic viscosity of water. The functional relationship of the maximum scour depth could be indicated below:

$$ds = f(b, ds, dso, B, D, d50, g, h, H, L, L_f, L_s, L_{so}, S_o, t, y_1, y_2, y_t, y_{up}, \rho, \rho_s, \mu) \quad (2.8)$$

Since b , B , $d50$, g , H , L_f , S_o , ρ , ρ_s , and the effect of viscosity μ can be neglected, the time of balance for the scour hole parameters was also fixed to be 5 hr. for all experiments. The sill height was considered equal to the sill diameter ($h=D$); then, eq. (1) will be reduced as following:

$$ds = (Ft, L_s/y_t, y_2/y_t, D/H, L/L_f) \quad (2.9)$$

Where, Ft = tail Froude number [62-65]. In a comprehensive research of the scour downstream curved weirs, Ashour, M.A, measured the efficiency wiers to pass water via their capacity of passing high discharges on the level of their crest with minimal acting heads. The curved weirs were proven to have a large capacity of passing water compared to the straight ones, because of the expansion of their crest length in the same channel width. He predicted the scour downstream curved weirs and compared it with the straight ones in the downstream. The influence of different flow parameters, bed materials, instant drop in the bed behind the weir and the use of downstream sills on the scour were tested experimentally. He built five models of weirs with different

crest lengths and different downstream face across a trapezoidal channel that took place in a Hydraulic Laboratory. The channel bed slope was constant at 0.0001, while the discharge changed with a normal flow depth in the downstream of the weir. In addition, the bed materials changed from fine to coarse sand. His findings showed that, the curved weir type-3 was exposed to minimum scour dimensions compared to the other types. Thus, in order to reduce the minimum scour, two groups of sills were placed on the solid apron in the downstream and this is how the scour was examined. Finally, he developed empirical equations to predict the scour length, the maximum depth and its location [66-69].

2.4 Applications of CFD Techniques for different purposes:

Afzal investigated a 3D numerical modeling of sediment transport under current and waves and in the final configuration, he modeled a 3D local scour around a vertical pile under the waves [70]. The numerical result was initially compared to theoretical observations and then reflected upon as opposed to the pier scour experiments of Sumer and Fredsoe. The influence of the variation of the sediment time stepping with the decoupling of the hydrodynamic and the morphodynamic time step was also examined. The numerical model correlated with the experiment and the theoretical erosion and deposition patterns. The de-coupled approach of the simulation of the hydrodynamic and sediment transport process appeared as a valid assumption.

Additionally, Li with the means of numerical simulations and hydraulic optimizations of the lateral oblique forebay, he built a large drainage pumping station by a lateral oblique water way, where he installed five shaft tubular pumps, with a single pump design flow of 34m³/s. His numerical simulation and hydraulic optimization functioned through a three-dimensional simulation software, CFD, on a pumping station pool rectifier. He concluded that within a particular hydraulic losses range, the retaining water weirs' addition and improvement before the forebay match tunnel, are able to improve the flow regime in a significant way, and assist in abating and eliminating the lateral oblique flow drift phenomena via an inertial function. The numerical simulation of the results of the experiment, were proven reliable against the validation of the physical model results. He therefore provided a reference point of research methods of pumping studies using water lateral oblique ways [40].

Similarly, TRS 1311, worked on the applications of river computational fluid dynamics, (CFD), typically using the full Navier-Stokes equations in three dimensions (3D) to provide solutions to fluid flow problems. The work aimed at investigating the following areas:

- Exploring how CFD is being used to model river flows around piers; single and parallel bridges; ice and debris; bend way weirs and other river training structures.
- Defining whether CFD has been used to simulate sediment transport and scour under bridges with and without piers or not.

Establishing who (which state DOTs) uses CFD for the above mentioned purposes, what software is being used, how much this software costs, and the cost to conduct studies of this kind [70-79].

CHAPTER 3

NUMERICAL SIMULATION

3.1 Introduction

Since decades, several trials were focused on how to avoid the scour occurrence behind hydraulic structures. Different weir shapes were suggested, some modifications were carried out on some designs and many solutions were performed to reach good results. However, none of them gives satisfied results. Meanwhile, some other studies were discussing the facilities available for analyzing the flow around and over hydraulic structures saving costs and time. The computational fluid dynamics methods CFD are considered as a magic tool of representing most of complicated phenomena in nature. In this chapter, CFD analyses will be used in order to facilitate the ability of testing numerically many shapes of weir. The FLOW-3D software is a high-powered and highly-accurate multi-physics computational fluid dynamics (CFD) program that enables engineers to gain a valuable insight into many physical flow processes and solutions related to thermal energy transfer, fluid-solid interaction, mechanical and thermal stress analysis. The FLOW-3D program is the most ideal simulation software could be used for research, in the design phase or to improve production processes [80-83].

3.2 Turbulent models

Many turbulent models are designed to solve specific problem. Some of them are analyzing two or more cases in a single numerical model and other are created to present difficult situations of fluids besides simple ones. The flow-3D program is provided with the most important turbulent models that are describing almost all cases related to fluid.

The $k-\epsilon$ model is the simplest model used to describe simple cases related to flow motion. However, the equation constants are found empirically in the standard $k-\epsilon$ model. The RNG model is known to describe low intensity turbulence flows and flows having strong shear regions more accurately. Generally, the RNG model has wider

applicability than the standard $\kappa - \omega$ model. The default values of RMTKE, CDIS1 and CNU are different than are used in the $\kappa - \omega$ model; they are 1.39, 1.42 and 0.085, respectively. CDIS2 is computed from the turbulent kinetic energy ($\mathcal{E}_T$) and turbulent production (P_T) terms.

$$4 \frac{\partial \mathcal{E}_T}{\partial t} + \frac{1}{V_F} \left\{ u A_x \frac{\partial \mathcal{E}_T}{\partial x} + v A_y R \frac{\partial \mathcal{E}_T}{\partial y} + \omega A_z \frac{\partial \mathcal{E}_T}{\partial z} \right\} = \frac{CDIS1 \cdot \mathcal{E}_T}{KT} (P_T + CDIS3 \cdot G_T) + Diff_{\mathcal{E}} - CDIS2 \frac{\mathcal{E}_T^2}{kT} \quad (3.1)$$

In all turbulence transport models, the kinematic turbulent viscosity is computed from

$$\nu_T = CNU \frac{k_T^2}{\mathcal{E}_T} \quad (3.2)$$

where ν_T is the turbulent kinematic viscosity.

One particular numerical challenge of both the two-equation $\kappa - \varepsilon$ and RNG models is the need to limit the value of $\mathcal{E}_T$ from below. Equation (3.1) could produce values of $\mathcal{E}_T$ very near zero, and although physically k_T should approach zero in such instances as well, it may fail to do so for numerical reasons, resulting in unphysically large values of ν_T in Eq. (3.1). To deal with this problem, we limit the value of $\mathcal{E}_T$ such that it cannot fall below

$$\mathcal{E}_{T,min} = CNU^{3/4} \frac{k_T^{3/2}}{TLEN} \quad (3.3)$$

where TLEN is the maximum turbulent length scale. This can be defined by the user or the turbulent length scale can be limited automatically. Further discussion on this is presented in the following section.

Each of the models above offers a set of strengths at varying levels of complexity. The $\kappa - \omega$ two-equation model is no exception. In certain flow conditions, it is superior to the $\kappa - \varepsilon$ or RNG models, in particular, near wall boundaries and in flows with streamwise pressure gradients like jets and wakes. FLOW-3D users often encounter these flow regimes in their applications and therefore, could benefit from the superior properties of this turbulence model [84-89].

The variable $\omega \equiv \kappa - \varepsilon$ has dimensions of 1/time. The $\kappa - \varepsilon$ is formulated as: (266)

$$\frac{\partial \kappa_T}{\partial t} + \frac{1}{v_F} \left\{ u A_x \frac{\partial \kappa_T}{\partial x} + v A_y \frac{\partial \kappa_T}{\partial y} + \omega A_z \frac{\partial \kappa_T}{\partial z} \right\} = P_T + G_T + Diff_{\kappa_T} - \beta^* \kappa_T \quad (3.4)$$

where:

$$\beta^* = \beta_0^* f_{\beta^*}$$

with $\beta_0^* = 0.09$ and

$$f_{\beta^*} = 1 \text{ when } \mathcal{X}_\kappa \leq 0 \text{ and } f_{\beta^*} = \frac{1 + 680 \mathcal{X}_\kappa^2}{1 + 400 \mathcal{X}_\kappa^2} \text{ when } \mathcal{X}_\kappa > 0$$

where:

$$\mathcal{X}_\kappa \equiv \frac{1}{\omega^3} \left(\frac{\partial \kappa_T}{\partial x} \frac{\partial \omega_T}{\partial x} + \frac{\partial \kappa_T}{\partial y} \frac{\partial \omega_T}{\partial y} + \frac{\partial \kappa_T}{\partial z} \frac{\partial \omega_T}{\partial z} \right)$$

RMTKE for the diffusion term is 1/2.

For ω transport we have:

$$\frac{\partial \omega_T}{\partial t} + \frac{1}{v_F} \left\{ u A_x \frac{\partial \omega_T}{\partial x} + v A_y R \frac{\partial \omega_T}{\partial y} + \omega A_z \frac{\partial \omega_T}{\partial z} \right\} = \alpha \frac{\omega_T}{\mathcal{K}_T} (P_T + CDIS3.G_T) + Diff_{\omega} - \beta \omega_T^2 \quad (3.5)$$

where $\alpha = 13/25$, RMDTKE = 1/2 and $\beta = \beta_0 f_\beta$

with $\beta_0 = 9/125$ and

$$f_\beta = \frac{1 + 70 \mathcal{X}_\omega}{1 + 80 \mathcal{X}_\omega}$$

where:

$$\mathcal{X}_\omega \equiv \left| \frac{\Omega_{ij} \Omega_{jk} S_{ki}}{(\beta_0^* \omega)^3} \right|$$

Ω_{ij} and S_{ij} are the mean-rotation and mean-strain-rate tensors respectively. For reference, in the $\kappa - \omega$ model $\varepsilon = \beta^* \omega \kappa$ and $\nu T = \kappa / \omega$. The principal goal of any turbulence model is to provide a mechanism for estimating the influence

of turbulent fluctuations on the mean flow quantities. This influence is usually expressed by additional diffusion terms in the equations for mean mass, momentum, and energy transport. Because turbulence enhances the diffusion of momentum, it effectively enhances the viscosity. Wherever the coefficient of dynamic viscosity appears in the equations, we assume that it is a sum of the molecular and turbulent viscosities,

$$\mu = \rho (\nu + \nu T) \quad (3.6)$$

Strictly speaking, this is not always correct, but it is a good approximation for high levels of turbulence, i.e., when the turbulent viscosity is much larger than the molecular value. At low levels of turbulence, the $\kappa - \varepsilon$ model is not correct without additional modifications.

3.3 CFD Tool Description

The FLOW-3D is a high-powered and highly-accurate multi-physics computational fluid dynamics (CFD) program that enables engineers to gain a valuable insight into many physical flow processes and solutions related to thermal energy transfer, 6-degree of freedom fluid-solid interaction, and mechanical and thermal stress analysis. Its features, combined with advanced algorithms to track free-surface flows, make FLOW-3D the most ideal simulation software to use either for research, in the design phase or to improve production processes such as in figure 3.1 below.

FLOW-3D is an all-inclusive program starting from the setup to simulation to post-processing requiring no additional modules. Meshing in FLOW-3D is very straightforward to perform and it combines the simplicity of a Cartesian structure with complex geometries that can be automatic for localized resolution and computational efficiency. Through the FlowSight feature, its users can visualize and analyze advanced data, also using the Ensign post-processor, to facilitate the communication of their results with other collaborators [90].

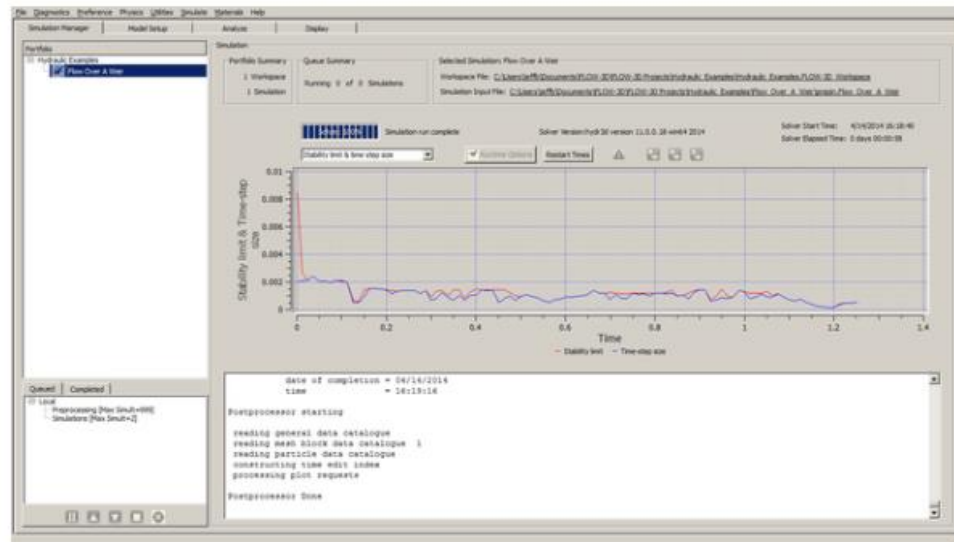


Figure 3.1 The interface of the FLOW-3D program.

3.4 The accuracy of Flow-3D

The program allows its users to optimize their water and environmental designs with minimal costs as its high-powered computational fluid dynamics software offers an extremely accurate modeling, as opposed to the costly physical models used in the design and analysis of hydraulic structures so far. The cost reduction is achieved through the simulation of a full-scale design that also prevents scaling issues from happening. In addition, the program's users are able expand the capacity of existing infrastructure in hydropower plants, develop pioneering methods to fish passages, design intakes that eliminate head loss, develop more advanced forebay designs and tailrace flows, analyze scour more accurately and evaluate air entrainment. Its exceptional unique modeling principles enhance the accuracy of results; 1-D and 2-D codes make flow physics extremely simple to calculate as the program simulates the entire flow process so that significant information about the flow is always taken into consideration (Fig. 3.2) [91].

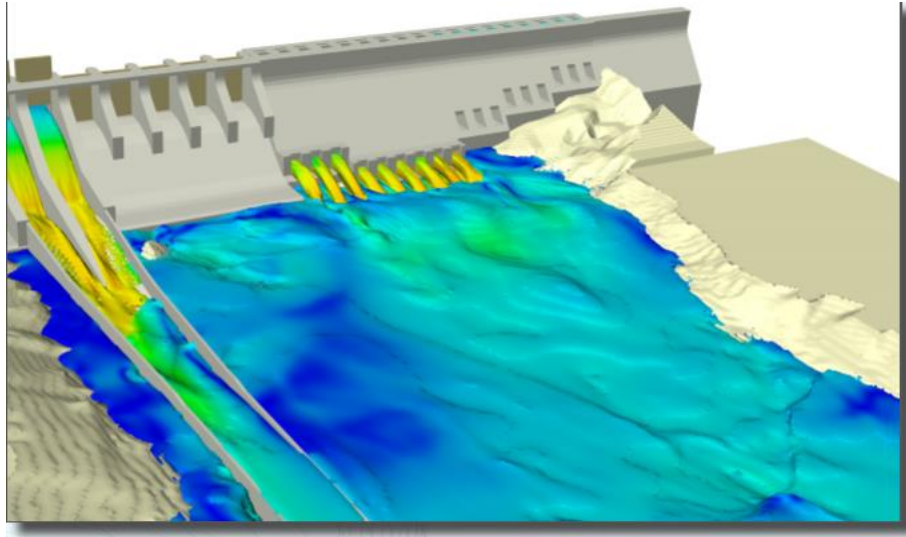


Figure 3.2 FLOW-3D simulation.

3.4.1 Graphical user interface

FLOW-3D includes all the functions from model setup to simulation to detailed results analysis, such as the one in figure 3.3, in one user-friendly application with an intuitive graphical user interface. Users are able to simulate a model, mesh it through its graphical model builder, screen out its incompatibilities and configuration errors, and perform an analysis in a detailed way through extensive post-processing options [91].

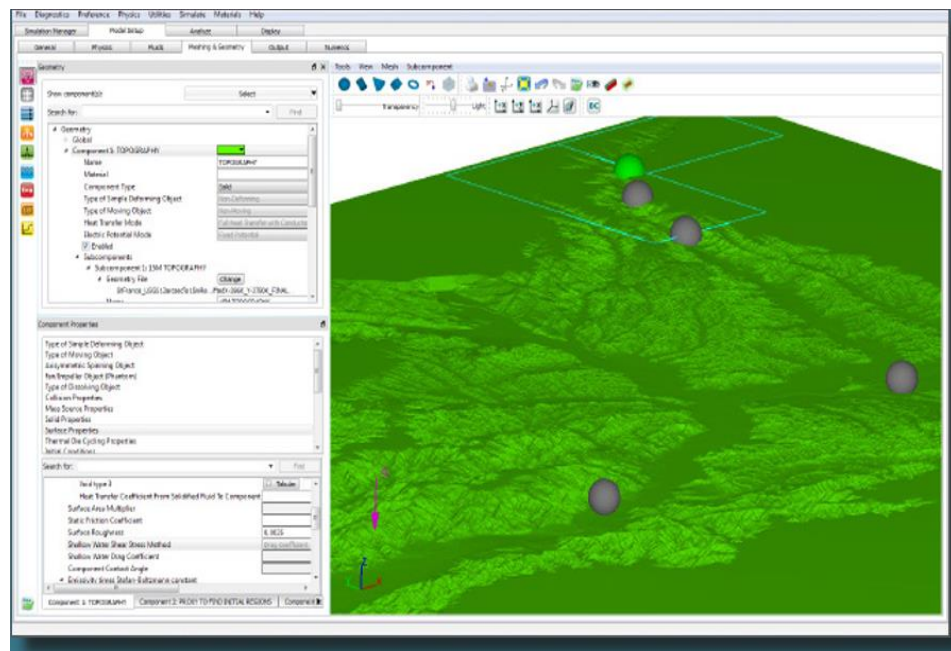


Figure 3.3 Graphical user interface.

3.4.2 Meshing

The program offers an approach to gridding that reflects the advantages of rectangular grids and the flexibility of deformed, body-fitted grids. It provides users with simplicity of generating the fixed grids of rectangular control elements and appealing properties that offer improved accuracy, smaller demands on memory and more simple numerical approximations figure 3.4. Referred to as “free-gridding” thanks to the fact that its grids or geometry can very easily be changed without depending on one another, this feature puts an end to the time-consuming task of generating body-fitted or finite-element grids.

It also offers a range of advanced features such as conforming meshes that enable the users to have highly-refined grids only in relevant regions of the computational domain. The use of this particular feature generates high-accuracy meshes around thin components and flow features while enhances speed and memory with coarser grids in the regions around them [91].

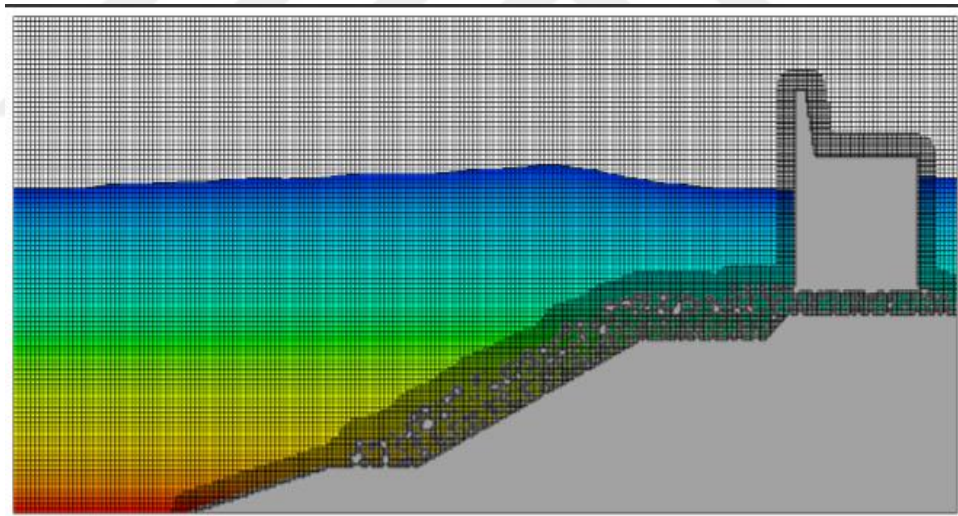


Figure 3.4 Meshing in the FLOW-3D program.

3.4.3 FAVORTM

Amongst others, FLOW-3D offers the very distinctive feature of FAVORTM which stands for Fractional Area/Volume Representation method, and allows a more realistic representation of complicated geometry in a simple Cartesian mesh. As a consequence,

FLOW-3D can be utilized in order to simulate flow in complex hydraulics structures in a more accurate and efficient way. See figure 3.5.

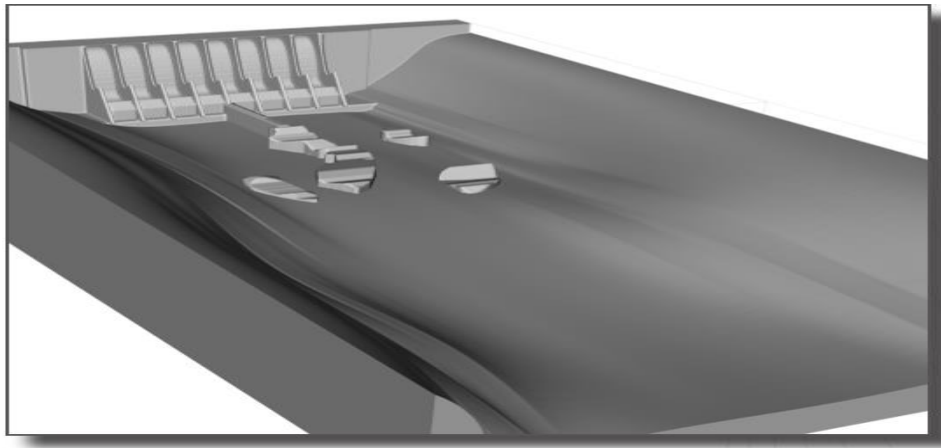


Figure 3.5 Simulation of flow in complex hydraulics structures accurately and efficiently.

3.4.4 TruVOF

TruVOF is a feature offered through FLOW-3D and it constitutes a method for modeling fluids that exceeds the commonly used traditional Volume of Fluid (VOF) techniques and can obtain the most accurate tracking of fluid surfaces in capturing waves and hydraulic jumps figure 3.6.

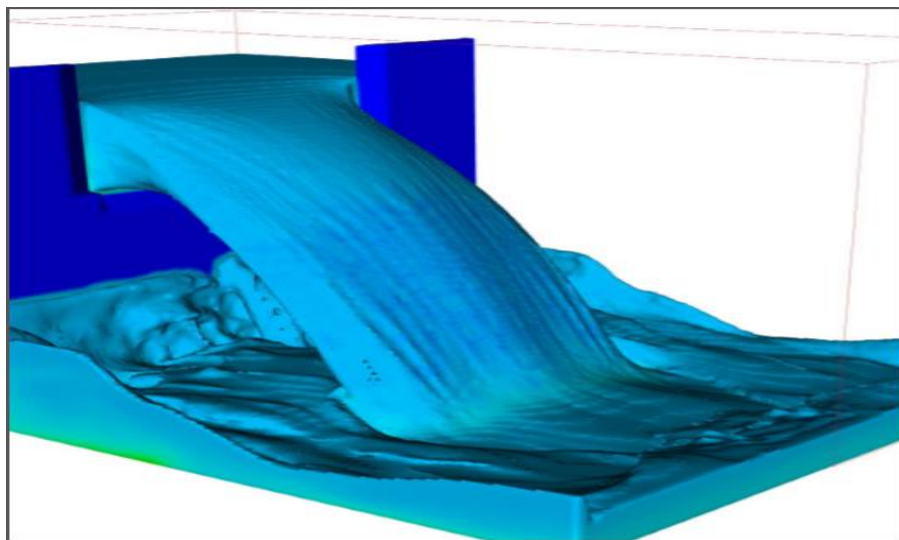


Figure 3.6 Traditional Volume of Fluid.

3.4.5 Post-processing with FlowSight

This cutting-edge tool is based on the Ensignt leading industry, that was modified especially for FLOW-3D. Amongst others, it can process multiple iso-surfaces, create 2D clips with FAVOR™ geometry, process animated streamlines, provide multiple viewpoints of simulation results, process simultaneous view of FSI and fluid flow results, extensively annotate, read and plot data from external sources, process interactive queries, texture mapping, 3D stereo and head tracking, process moving viewpoints and render volume Figure 3.7.

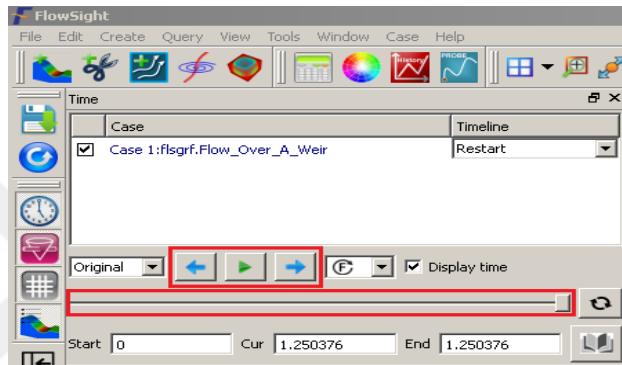


Figure 3.7 post-processing with Flowsight.

3.5 Modeling capabilities

3.5.1 Air Entrainment

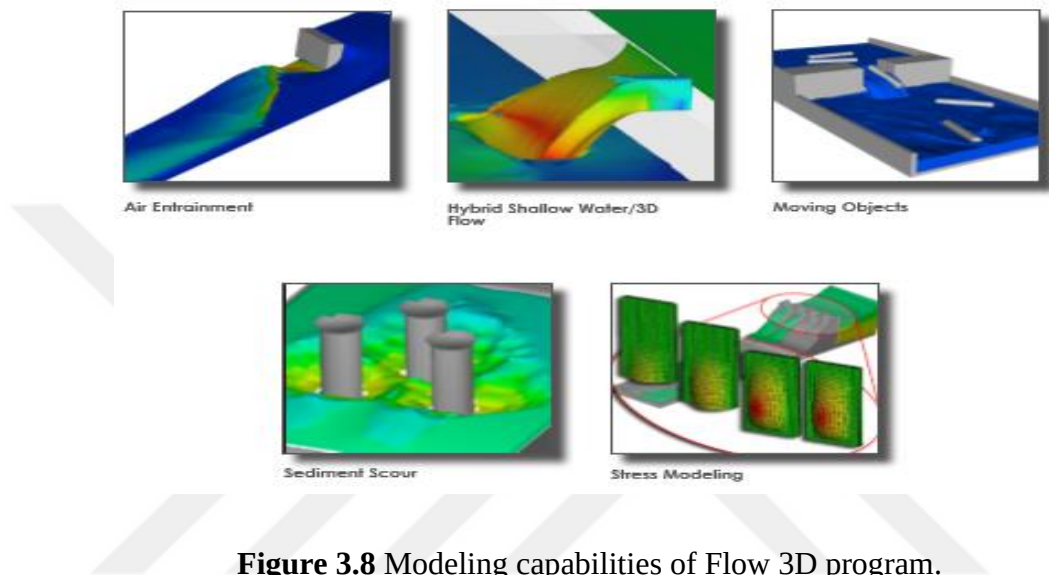
Air Entrainment may contribute to sustain the growth of microorganisms and cause damage to the downstream expanded and overtopping structures. This feature in FLOW-3D defines quantities of entrained air and its volumetric bulking effects. It simulates the flow around 3D structures such as bridges, drilling rigs at sea and dams in large reservoirs in a shallow water environment. This model can incorporate shallow water and full 3D flow models in one simulation, and thus it provides the users with the opportunity to capture the key flow information and model large domains effectively.

3.5.2 Moving Objects

While in engineering it is usually necessary to model flows that include moving solid components, in FLOW-3D the motion of such objects can be completely or partially coupled with constraints in order to optimize a design fast and in a reliable way.

3.5.3 Sediment Scour

When bridges, dams and reservoirs are being designed, an extremely important requirement to bear in mind is scour and deposition. The Sediment Scour model in FLOW-3D provides users with the opportunity to study the erosion and deposition of various sediments including bed load transport generated by complex flow patterns Figure 3.8.



3.5.4 Stress Modeling

The fluid structure interaction model in FLOW-3D gives users an option to speculate and predict stresses and deformations of solids under the load via the use of a coupled solution between fluids and solids. This stress prediction offers important information that regulate the circumstances under which a design corresponds to the correct safety criteria or not and is thus subjected to fail completely.

3.5.5 Catastrophic Events

The FLOW-3D program is capable of simulating various catastrophic events such as dam breaks, avalanches, tsunamis and floods.

3.5.6 Dams and Spillways

Safety in dams and spillways is extremely important when they are still in the designing process. FLOW-3D gives engineers the opportunity and option to predict

the flow rates at probable maximum flood circumstances and define the cavitating regions and pressure loading on the gates figure 3.9.

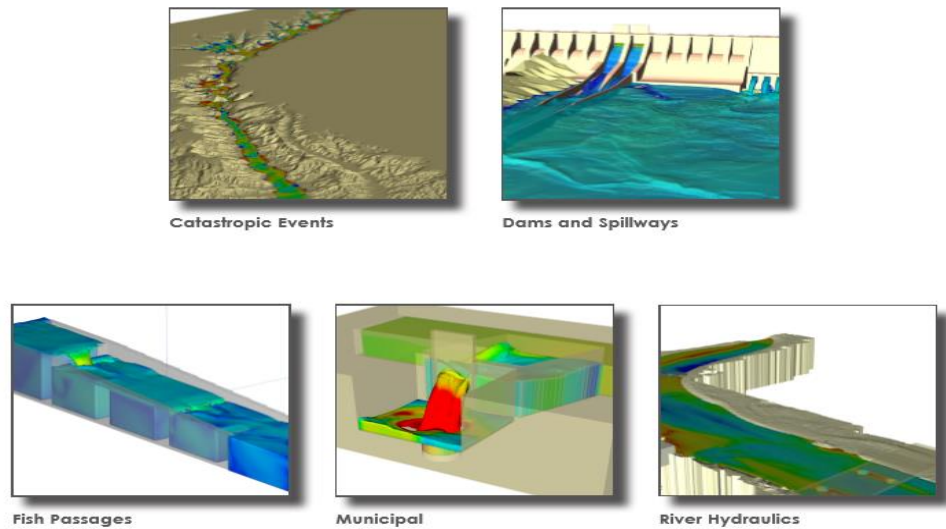


Figure 3.9 Applications of Flow-3D program.

3.5.7 Fish Passages

These are a principal environmental consideration in many hydraulic structures. With FLOW-3D, engineers and designers can accurately inspect and examine current and new designs to define whether a fish species will go through the passage under various flow scenarios and situations.

3.5.8 Municipal

In order to assist in the designing and analysis of contact tanks, control structures, combined sewer and storm water sewer overflow facilities, pump and lift stations, treatment plant headwork's and filtration systems, FLOW-3D can be used in the water and wastewater industry.

3.5.9 River Hydraulics

Aiming at addressing complex river dynamics and predicting fluvial behavior, FLOW-3D is commonly used to also solve free-surface flow patterns and it includes a broad selection of high-powered physics packages that tackle many river management problems [91].

CHAPTER 4

NUMERICAL SETUP

4.1 Overview

In this section, some features of the Flow-3D program will be reviewed and the simulation setup will be clarified as well.

4.2 Channel description and flow conditions

To simulate the flow over weirs it is important to take note of all circumstances expected to be occurred in nature and include them in the numerical simulation in order to decrease the errors in the results. In the present study, a channel of 12 m length, 0.8 m width and 0.9m height with glass sides and steel base is designed numerically, Figure 4.1.

The models are placed at a 0.5 m from the channel inlet. The channel is initially filled with sand to a distance of 2 m from the weir's body with a depth of about 0.21 m. The models will be investigated and evaluated in term of a minimum scour depth under three different flow conditions, 0.015 m³ s⁻¹, 0.02 m³ s⁻¹ and 0.025 m³ s⁻¹. Each side of channel domain, which is a rectangular shape, is given a condition constraining its behavior during the simulation progress.

The channel inlet is given a volume flowrate condition, the outlet is considered as an outflow while the top of channel is given an atmospheric pressure. All other sides are taken as walls besides the weir body (Figure 4.2). In order to do a simulation process, the program should be given an initial water level. Currently, water level is suggested as 0.61 m for the minimum discharge and 0.64 m for the peak flow.

It is planned to do an experimental work after the theoretical one, so a sieve analysis is conducted to get the grain size that will be used in both of the numerical and experimental studies.

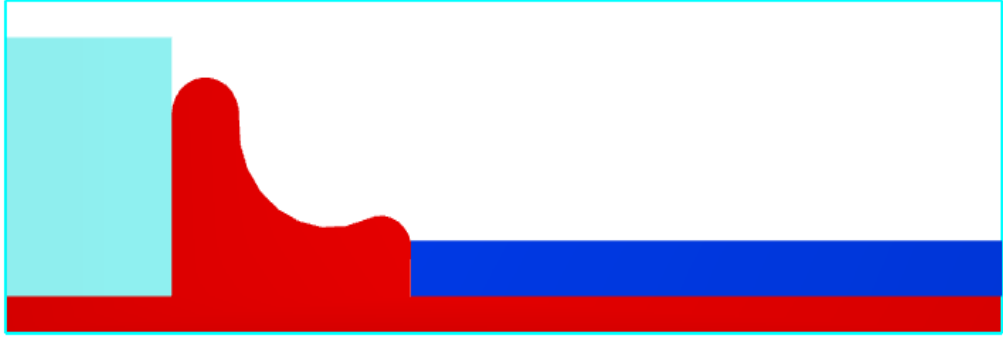


Figure 4.1 Channel domain.

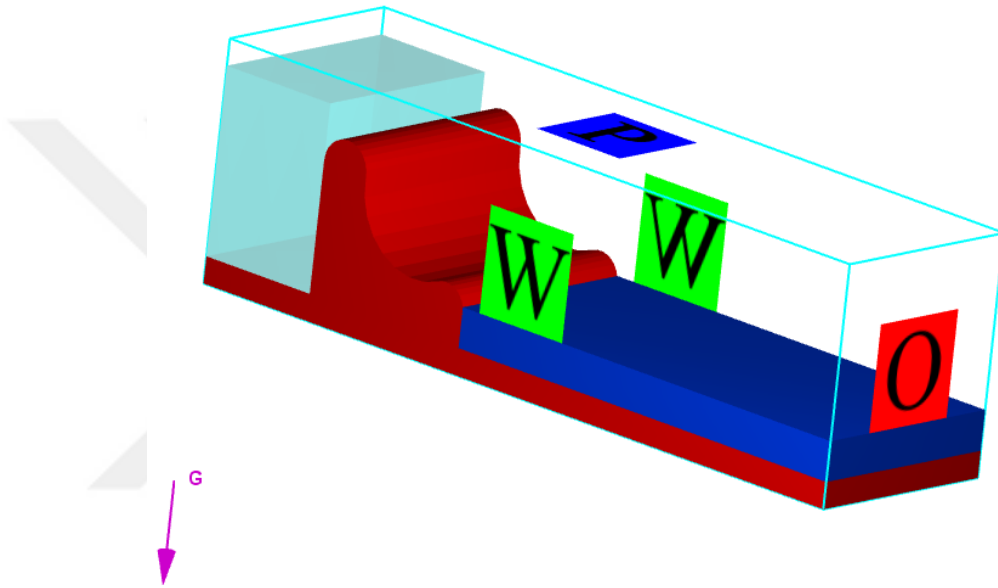


Figure 4.2 Flow boundary.

A uniform sand material is used and sieved to reach the suitable grain size.

$$\sigma_g = \left[\frac{d_{84.1}}{d_{15.9}} \right]^{0.5} = \frac{d_{84}}{d_{50}}$$

The geometric standard deviation (σ_g) is used as a measure of the uniformity of sand. The particles are considered to be uniformly distributed when σ_g is less than 1.3 and non-uniformly distributed when σ_g is larger than 1.3. The sieve analysis performed in the present study (Figure 4.3) is resulted in a high deviation where σ_g was 3.84, which indicates non-uniformity in the particle distribution. The grain size of sand used in all the simulations was 0.0018 m with a density of 2650 kg m⁻³.

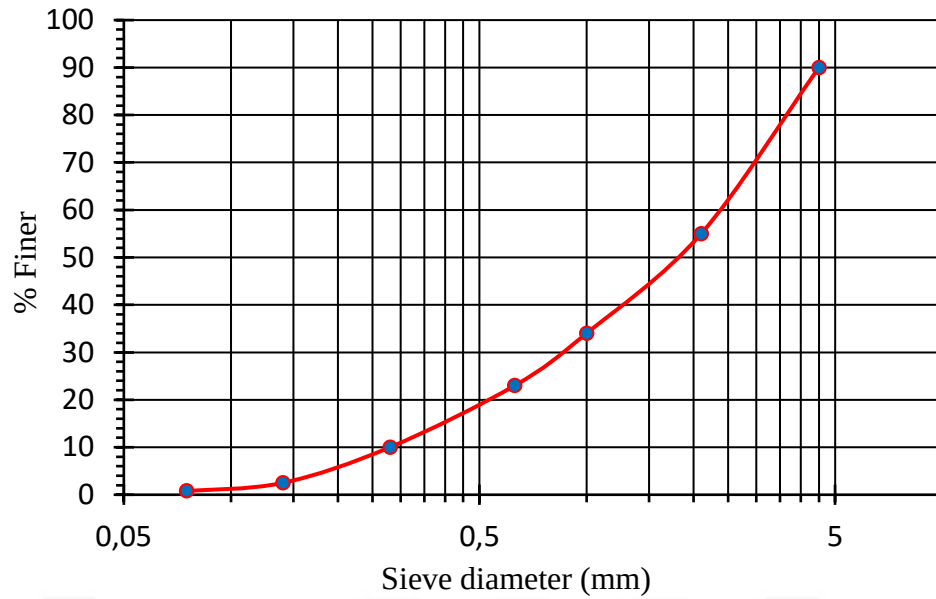


Figure 4.3 Sieve analysis.

4.3 Meshing

The program offers an approach to gridding that reflects the advantages of rectangular grids and the flexibility of deformed, body-fitted grids. It provides users with simplicity of generating the fixed grids of rectangular control elements and appealing properties that offer improved accuracy, smaller demands on memory and more simple numerical approximations. Referred to as “free-gridding” thanks to the fact that its grids or geometry can very easily be changed without depending on one another, this feature puts an end to the time-consuming task of generating body-fitted or finite-element grids.

It also offers a range of advanced features such as conforming meshes that enable the users to have highly-refined grids only in relevant regions of the computational domain. The use of this particular feature generates high-accuracy meshes around thin components and flow features while enhances speed and memory with coarser grids in the regions around them. In the present study, the mesh block covers the channel and weir domains is divided into 300000 cells, figure 4.4.

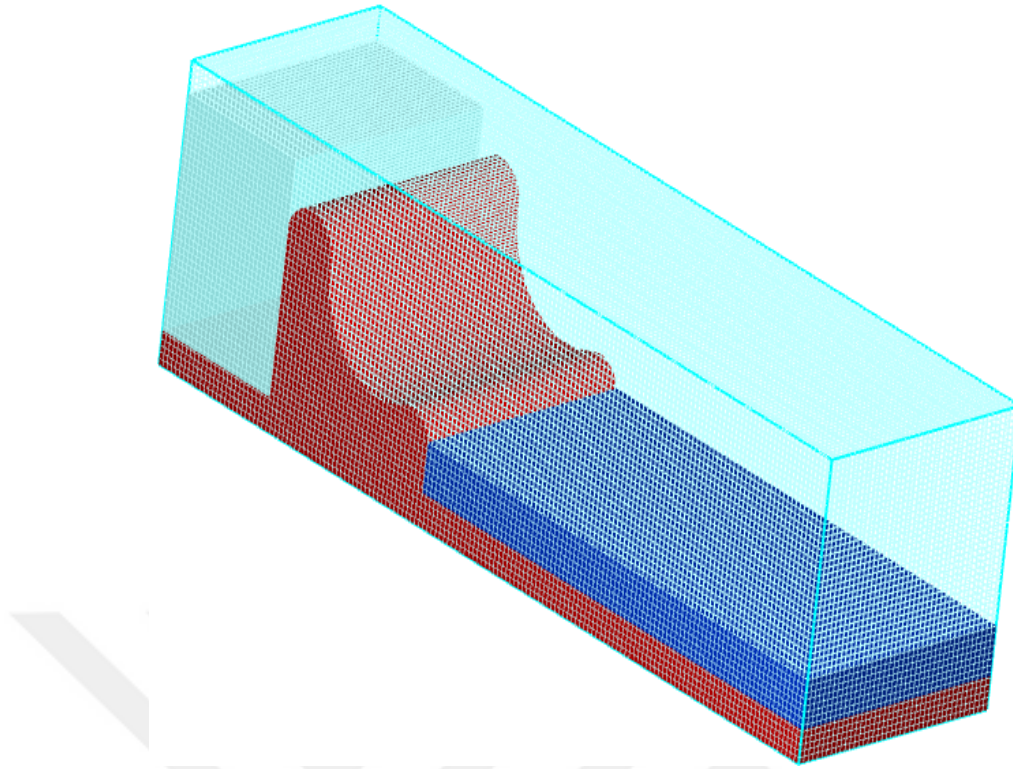


Figure 4.4 Meshing in the FLOW-3D program.

4.4 Evaluation the accuracy of CFD methods

Since decades, human's thought tended to discover easiest ways to achieve the desired goals. The achievement of these goals requires attention to the time and cost trying to reduce them. CFD methods offer the opportunity to solve the complicated engineering problems and carryout ideas in low time and cost.

Many doubts about the possibility of programs to represent engineering problems more closely to reality called for the development of these programs. One of the most important modern software used to describe fluid motion and sedimentation is Flow-3D. Although, it is urgent to evaluate the performance of the program by comparing its outputs against real or experimental data. A single step broad-crested weir model is designed numerically with the same dimensions of the weir examined experimentally by Ahmed (Figure 4.5). All the flow and boundary conditions are taken as in the experiments. The selected model is evaluated in term of minimum scour depth under three different flow conditions as taken experimentally by Ahmed, which are $0.015 \text{ m}^3 \text{ s}^{-1}$, $0.02 \text{ m}^3 \text{ s}^{-1}$, and $0.025 \text{ m}^3 \text{ s}^{-1}$. In addition, each side of the channel domain, which is a rectangular shape, is given a condition constraining its behavior during the simulation progress as in the experimental study [27]. The channel inlet is

given a volume flowrate condition, the outlet is considered as an outflow while the top of channel is given an atmospheric pressure. All other sides are taken as walls besides the weir body. A sand layer is placed just behind the weir and extended 2.0 m downstream the model. The same characteristics of sand taken in the experiment is used and inserted to the Flow-3D program where the particle size was 1.8 mm and the specific gravity was 2.65 gm cm⁻³. The channel domain with the weir model are divided into 100,000 elements by meshing process.

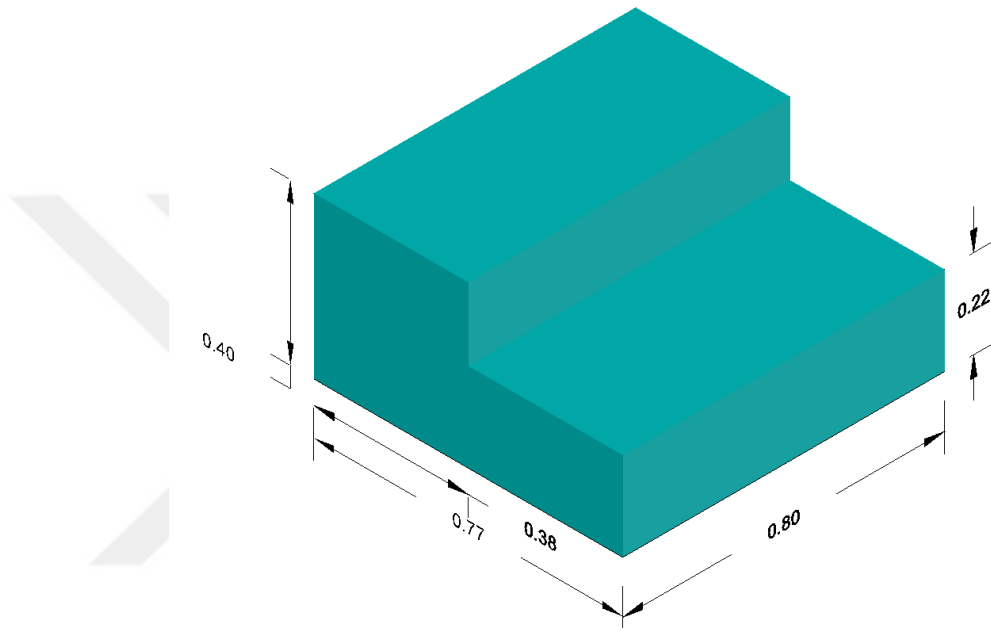


Figure 4.5 Single step broad-crested weir [27].

4.5 Assessment of the Flow-3D Program

To check the ability of the Flow-3D program to present real cases numerically, it is important to choose a simple physical model with almost exact results. Thereby, the single-step broad-crested weir taken by Ahmed is selected as a measure of CFD results adequacy. The results are obtained for three different flow conditions, 0.015 m³ s⁻¹, 0.02 m³ s⁻¹, and 0.025 m³ s⁻¹ (Table 4.1). The maximum scour depth is considered as a comparison tool where the simulation results have shown a deviation of about 0.017 m from the experimental data. Regarding the flow velocity, the numerical methods shows a reduction of about 0.25 m/s. the simulation results good agreed with the experimental work (Figure 4.6). Therefore, it is possible to rely on Flow-3D software in studying many problems numerically before doing field investigations [27].

Table 4.1 CFD results against Experimental records

Q (m ³ s ⁻¹)	Max. depth of scour (m)		Distance of scour from weir (m)		U/S water depth (m)		D/S water depth (m)		Velocity (m/s)	
	Exp.*	CFD	Exp.	CFD	Exp.	CFD	Exp.	CFD	Exp.	CFD
0.015	11	9.93	40	38.5	5.5	5.5	10	0.93	1.563	1.172
0.02	12.8	11.75	50	49	6.3	6.3	13	11.88	1.667	1.443
0.025	12.4	10.98	68	65	7.3	7.3	14	12.52	1.736	1.656

* The experimental data taken from [27].

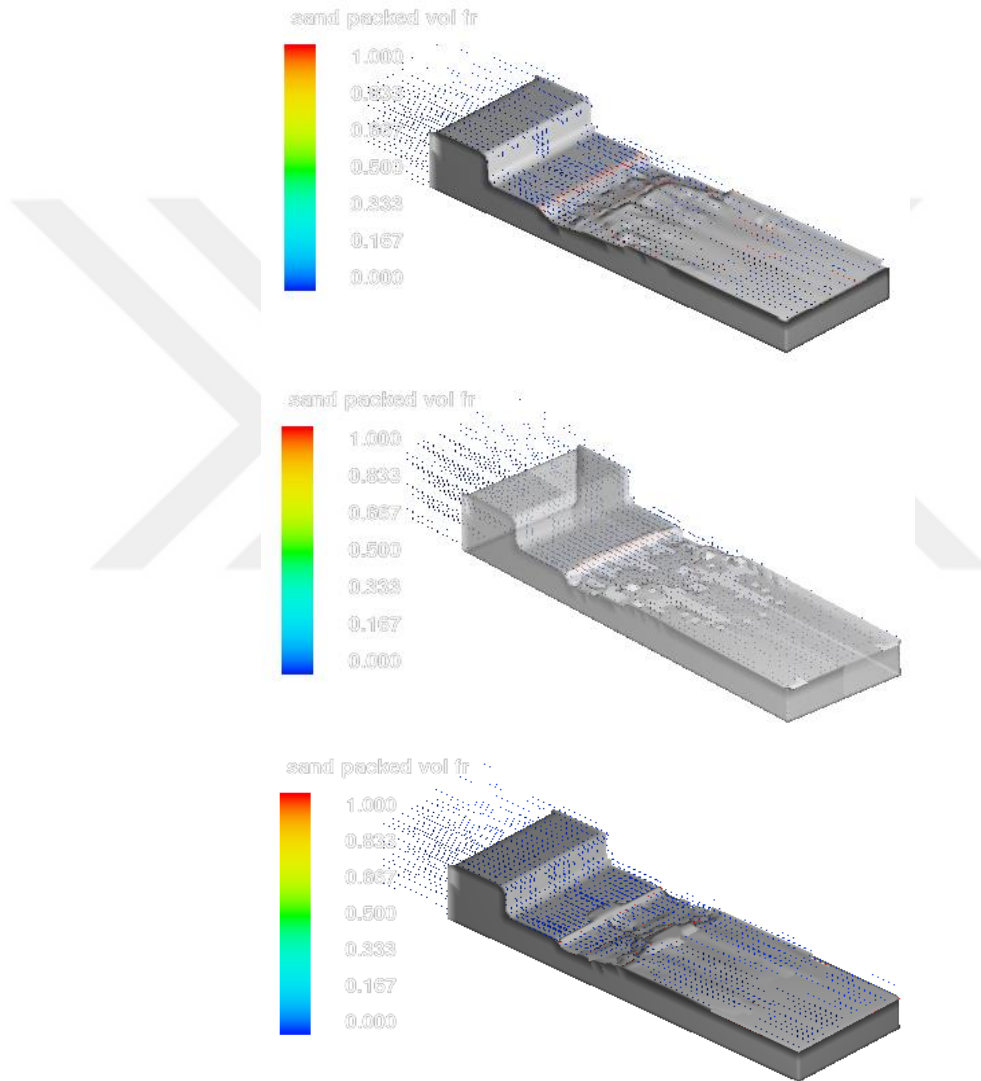


Figure 4.6 Simulation results of the sand packed volume fraction. under different flow conditions.

4.6 Geometrical shape of weirs under study

The flow-3D program is provided with drawing tools of different shapes but still inefficient in drawing arcs. In the present study, AutoCAD software is used as an

efficient tool in drawing the most complicated 3D shapes. The AutoCAD program has the ability of reading Flow-3D files that have (.stl) extension. Nine models were designed in AutoCAD, each file includes a single weir model. Then each file is exported separately into Flow-3D as (.stl) file. (Figure 4.7)

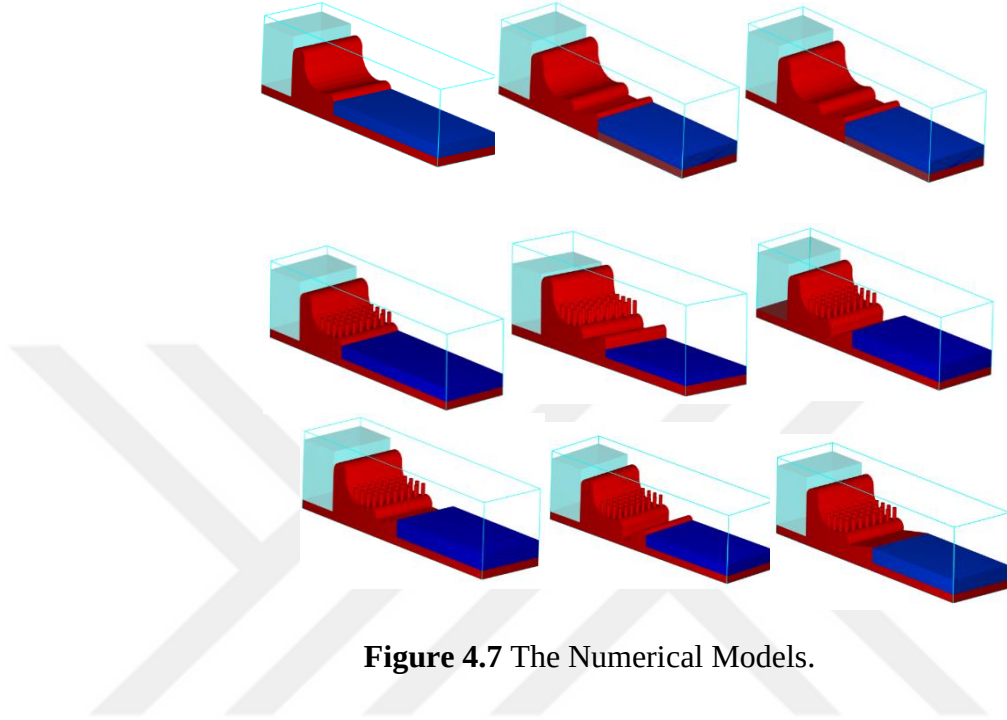


Figure 4.7 The Numerical Models.

4.7 Simulation Constraints

Many features are available in the Flow-3D program help in the insertion of the real parameters expected to be included in the experiments. In the present study, the flow mode is considered as an incompressible flow with free surface (open channel flow mode). Clear water is used as the single fluid in all the simulation work. The Fluid density is considered as 1000 kg m^{-3} , the viscosity is 0.001 N s m^{-2} at 20 C° . The gravity is activated in the physical properties, which is 9.81 m s^{-2} . In the numerical model setup, the renormalized group (RNG) viscous model is used with no-slip wall shear boundary condition. Sandy layer is placed in the channel with a diameter of 0.0018 m and a density of 2650 kg m^{-3} . Three different flow types are used, $0.015 \text{ m}^3 \text{ s}^{-1}$, $0.02 \text{ m}^3 \text{ s}^{-1}$, $0.025 \text{ m}^3 \text{ s}^{-1}$. The initial value of upstream flow depth at the inlet is taken 0.8 m . The water level at the outlet is determined automatically by the program during the simulation progress. Other sides of the channel are considered as walls except the upper one where it is subjected to the atmospheric pressure. Figure 4.8 clarify the symbols used to describe each model. Each weir is distinguished by a single case reviewed as below. R_c , R_i , R_{T1} , R_{T2} are the radii of crest, main body, the weir end and

the end of the additional part, respectively; H is the weir height; L is the total length of weir; W is the width of weir; L_{hs} is the length of the chamber created downstream the main body of the weir; L_R is the length of the inclined side of ramp.

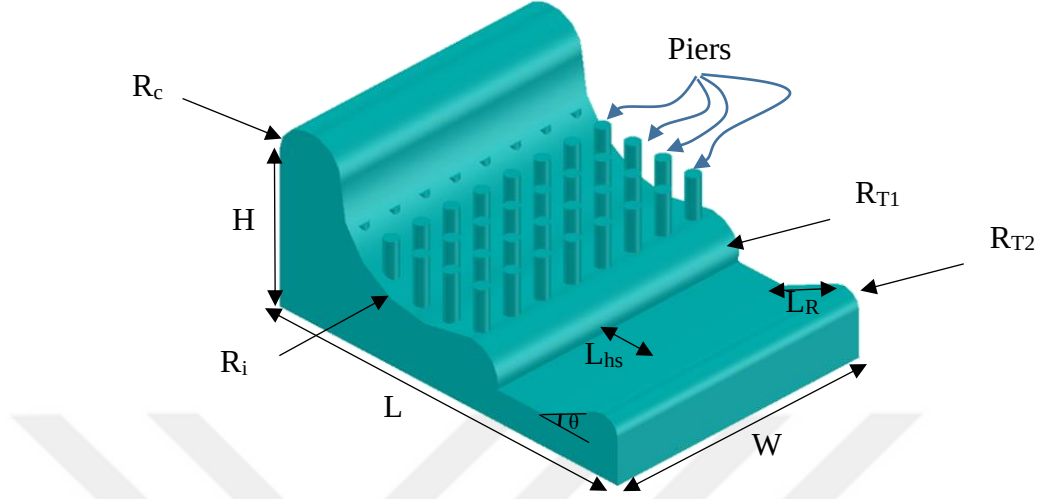


Figure 4.8 Symbols used in defining the dimensions.

Table 4.2 Geometrical characteristics of all models under study

Model	W	L	H	R _c	R _i	R _{T1}	Additional parts				
	(m)	(m)	(m)	(m)	(m)	(m)	L _{hs}	L _R	R _{T2}	θ	Piers
SU ₁	0.8	0.72	0.59	0.1	0.28	0.09	---	---	---	---	No
SU ₂	0.8	1.12	0.59	0.1	0.28	0.09	0.15	0.22	0.05	28	No
SU ₃	0.8	1.07	0.59	0.1	0.28	0.09	---	0.39	---	27	No
SU ₄	0.8	1.07	0.59	0.1	0.28	0.09	---	---	---	27	Yes
SU ₅	0.8	1.12	0.59	0.1	0.28	0.09	0.15	0.22	0.05	28	Yes
SU ₆	0.8	1.07	0.59	0.1	0.28	0.09	---	0.39	---	27	Yes
SU ₇	0.8	1.07	0.59	0.1	0.28	0.09	0.15	0.22	---	27	Yes
SU ₈	0.8	1.12	0.59	0.1	0.28	0.09	0.15	0.22	0.05	28	Yes
SU ₉	0.8	1.12	0.59	0.1	0.28	0.09	---	0.41	---	11	Yes

Case No.1

The energy dissipater, which is a water calming structure, Figure 4.9, had not considered in the first model to represent the base case. A simple shape of sturcture without adding additional parts was used to evaluate the water energy and the downstream scour depth. Accordingly, an appropriate sutable solutions to eliminate the scour were studed.

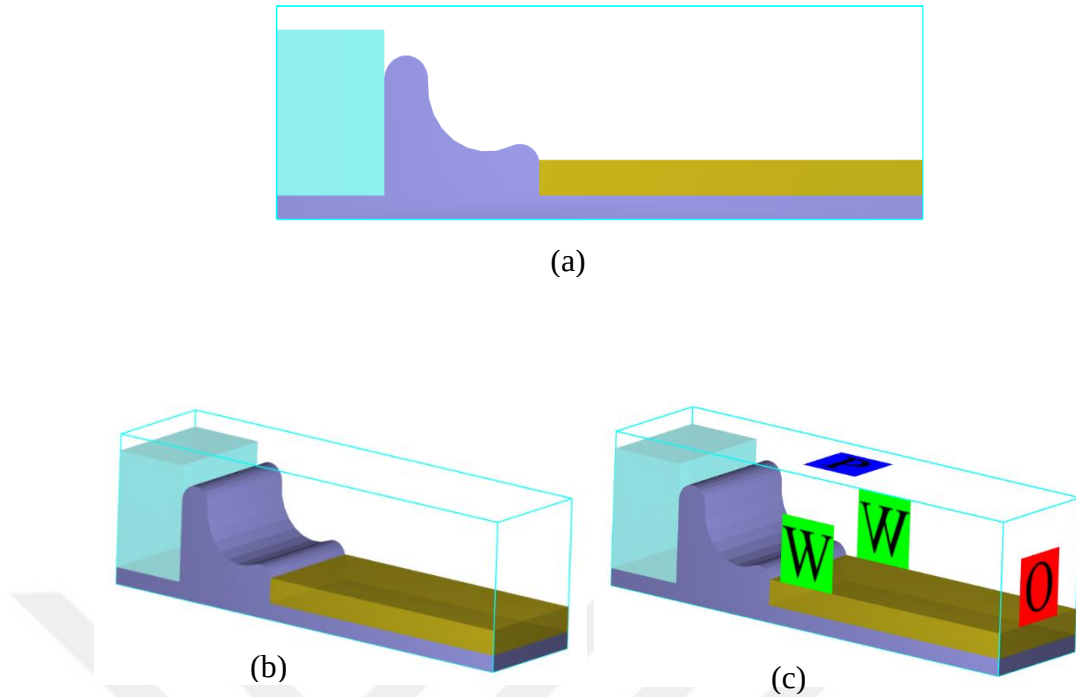


Figure 4.9 The weir model SU1: a. side view, b. isometric view, c. boundary conditions.

Case No.2

An additional part was added in SU₂ model to make a reduction in water energy and scour depth. The new additional part contained a horizontal body with 0.15m thickness above the channel bed. Followed by a ramp of 28°, and ended by a rounded surface of 0.1m diameter.

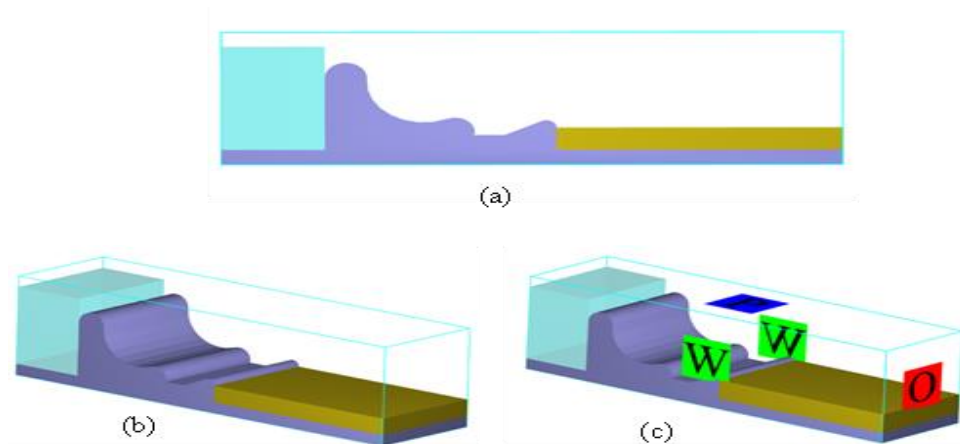


Figure 4.10 The weir model SU2: a. side view, b. isometric view, c. boundary conditions.

Case No.3

The third model SU₃, a ramp with internal angle 27° was followed the main body as shown in Figure 4.11. The dimension of the triangle cross section is (0.2*0.35)m vertical to horizontal respectively, that represent the ratio (1 V: 1.75 H).

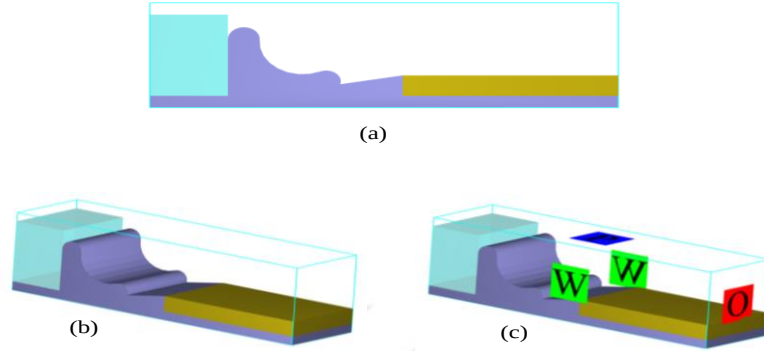


Figure 4.11 The weir model SU3: a. side view, b. isometric view, c. boundary conditions.

Case No.4

In this case, a solution to reduce the turbulent energy is proposed as shown in figure 4.12. Forty piers were added beside the main body that built in the first case. The purpose of this piers is to limit the scour depth downstream the weir. The piers dimension were 0.04m, diameter by 0.25m height, and it placed over an internal plate of 0.1 m high from the downstream bottom of weir with 0.1m space between each to other.

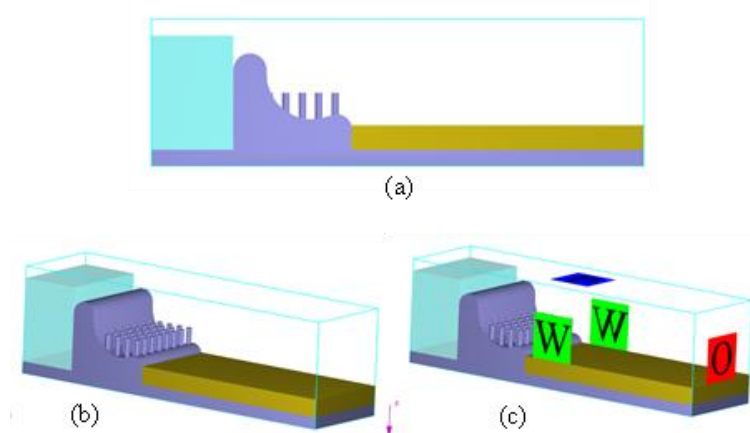


Figure 4.12 The weir model SU4: a. side view, b. isometric view, c. Boundary conditions.

Case No.5

The fifth case SU₅, an additional part were added to the water calming structre as shown in Figure 4.13. Acombination between the main body that was formed as horizontal surface 0.15m above the channel bed and the a ramp with 28°. This ramp was ended by a rounded surface of 0.1m diameter. Morover, a forty piers were added to solve the problem of scoure with the same dimensiones in the case No.4.

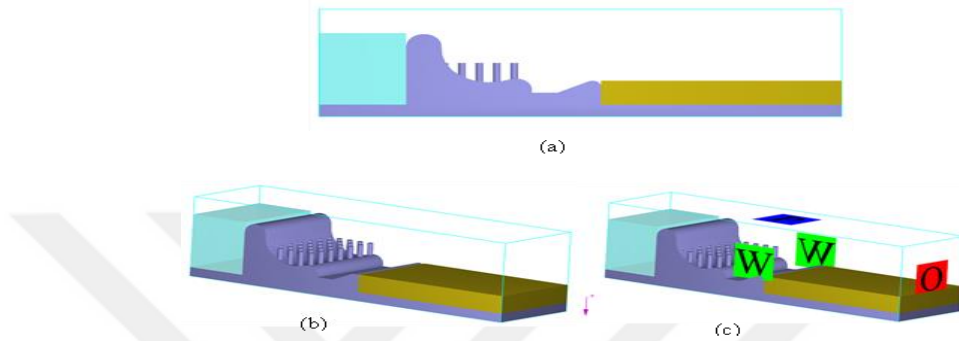


Figure 4.13 The weir model SU₅: a. side view, b. isometric view, c. boundary conditions.

Case No.6

In this case, SU₆ a ramp with 27° was folloed the main body. Figure 4.14 shows a ship of this case. The outer parts's cross section shape is triangle with a 0.35m horizontal distance by 0.2m vertical distance. The scour propble was solved by adding a fort piers downstream the weir. The diametre of the piers was 0.04m and the height was 0.25m. The piers were fixed over an internal plate of 0.1 m height from the downstream bottom of weir with space 0.1m.

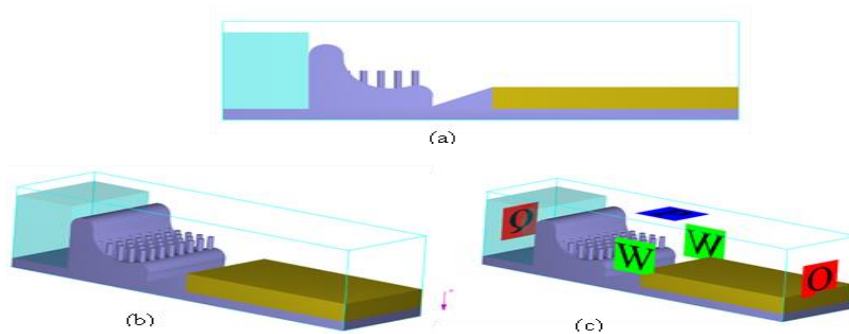


Figure 4.14 The weir model SU₆: a. side view, b. isometric view, c. boundary conditions.

Case No.7

In case 7 the additional part was designed in different way compared with previous cases as shown in Figure 4.15. The energy dissipators that attached with this weir included a plate was connected to the main body, that formed an inner basin 0.2m high and 0.175 m length. A ramp with angle 27° followed the basin, table 4.8 explain with details the information of the geometry of this model.

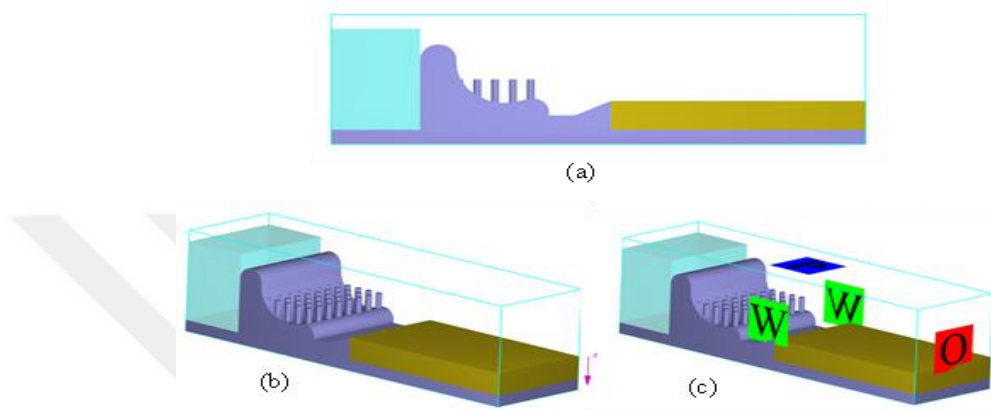


Figure 4.15 The weir model SU7: a. side view, b. isometric view, c. boundary conditions.

Case No.8

In this case SU₈, the energy dissipator part was connected to the main body, formed an inner basin 0.2m high and 0.15m length as shown in Figure 4.16. A ramp of 28° connected to the last part, with round surface ended of 0.05m diameter. Table 4.9 gives the information about the design of this case.

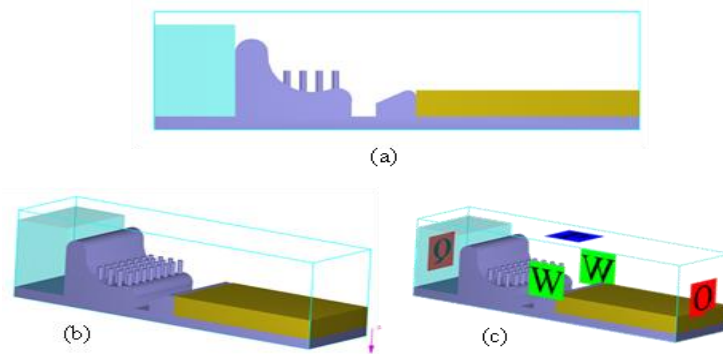


Figure 4.16 The weir model SU8: a. side view, b. isometric view, c. boundary conditions.

Case No.9

The SU₉ model has extra part was connected with the structuer. This additional part is combined to the main body and formed a rampe with 11° over the channel bed, Figure 4.17 shown the shape of this case. The horizontal distance that the ramp occupied has 0.4 m to form with the whole structure 1.12 m length. The dimensions with details of all the cases were presented in table 4.10 to show the difference in design.

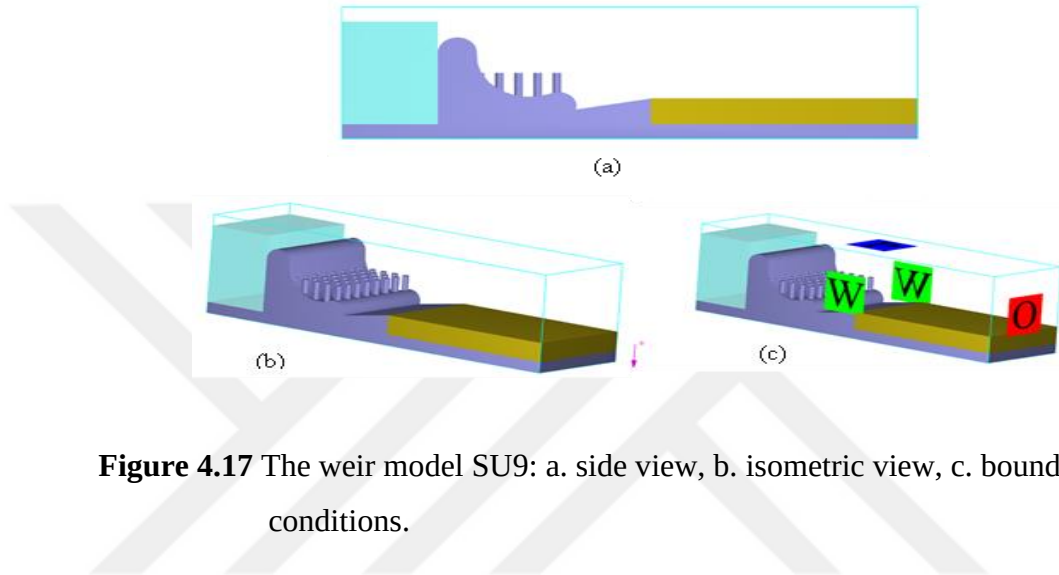


Figure 4.17 The weir model SU9: a. side view, b. isometric view, c. boundary conditions.

4.8 Numerical Simulations

4.8.1 Scour depth at the downstream of the model SU₁

The simulation results shown in figure 4.18 indicate that when a continuous inflow of $0.015 \text{ m}^3 \text{ s}^{-1}$ is applied, a scour region is created behind the weir and extended to the channel sides. Applying a discharge of $0.02 \text{ m}^3 \text{ s}^{-1}$, maximum scour appeared in the middle of the channel downstream the weir at a distance of about 0.15 m from the downstream edge of weir where the scour depth was 0.11 m. A similar behavior was noticed when a discharge of $0.025 \text{ m}^3 \text{ s}^{-1}$ is used.

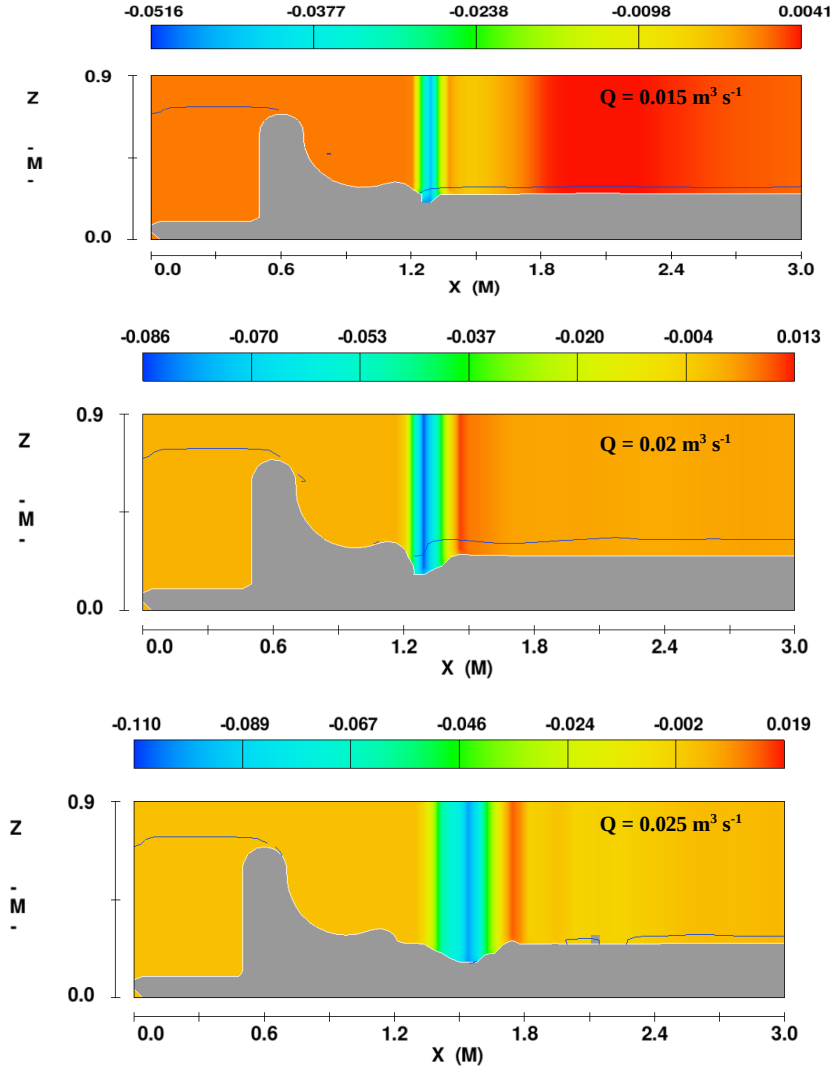


Figure 4.18 Contour map of the packed sediment elevation net change of SU1 model for discharge values of (a) $0.015 \text{ m}^3 \text{ s}^{-1}$, (b) $0.02 \text{ m}^3 \text{ s}^{-1}$, (c) $0.025 \text{ m}^3 \text{ s}^{-1}$.

4.8.2 Scour depth at the downstream of the model SU2

The simulation results show that the severity of scour is concentrated in the middle of the cross-wise direction downstream the weir and decreased significantly in the stream-wise direction. It was noticed that the scour region formed (Figure 4.19) is almost followed the same behavior at the three given discharges. The additional part added to the main body of weir is designed to trap the vortices over there and stop their progressing towards the sand layer. The distance of maximum scour was pointed at 0.07 m from the downstream edge. Regarding the depth of scour, it was slightly changed from 0.02 m to 0.07 m.

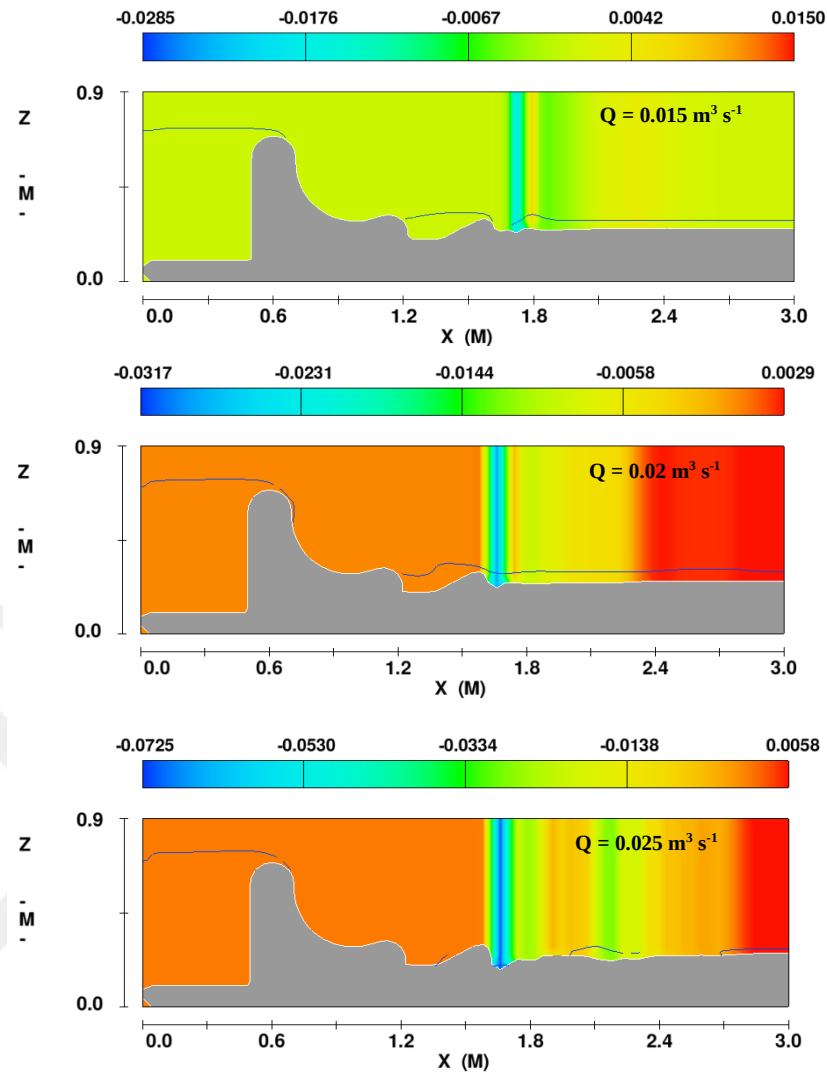


Figure 4.19 Contour map of the packed sediment elevation net change of SU2 model for discharge values of (a) $0.015 \text{ m}^3 \text{ s}^{-1}$, (b) $0.02 \text{ m}^3 \text{ s}^{-1}$, (c) $0.025 \text{ m}^3 \text{ s}^{-1}$.

4.8.3 Scour depth behind the model SU3

In this model, adding the ramp of 11° results in high scour depth which makes the model inefficient in reducing the danger of erosion compared to the second model SU₂ (Figure 4.20). The numerical results show that the severity of scour is concentrated in the middle of the cross-wise direction downstream the weir and decreased significantly in the stream-wise direction. It was noticed that the scour region formed is almost followed the same behavior at the three given discharges. The distance of maximum scour was pointed at 0.075 m from the downstream edge. Regarding the depth of scour, it was changed from 0.02 m to 0.035 m.

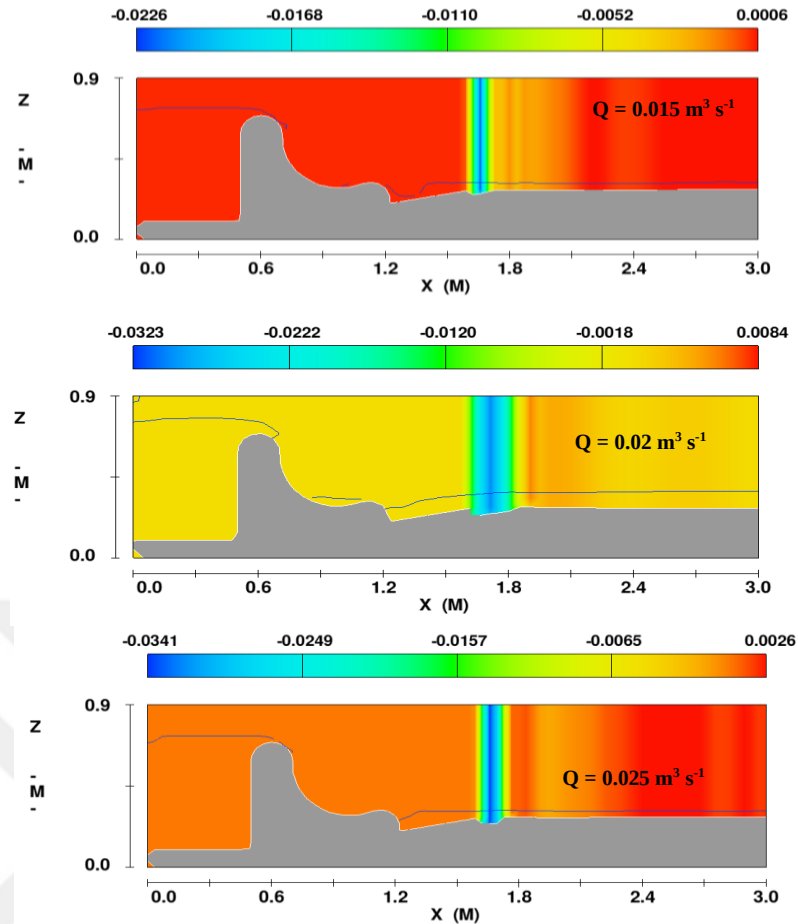


Figure 4.20 Contour map of the packed sediment elevation net change of SU3 model for discharge values of (a) $0.015 \text{ m}^3 \text{ s}^{-1}$, (b) $0.02 \text{ m}^3 \text{ s}^{-1}$, (c) $0.025 \text{ m}^3 \text{ s}^{-1}$.

4.8.4 Scour depth behind the model SU4

The main body of this model is similar to the model SU1. Fourty piers were added in five rows to the weir in a way to dissipate the water energy. The simulation results show that the piers play an important role in dissipating water energy and reducing the scour depth, where the maximum depth of scour was about 0.065 m at a distance of 0.07 m from the downstream edge of the weir (Figure 4.21).

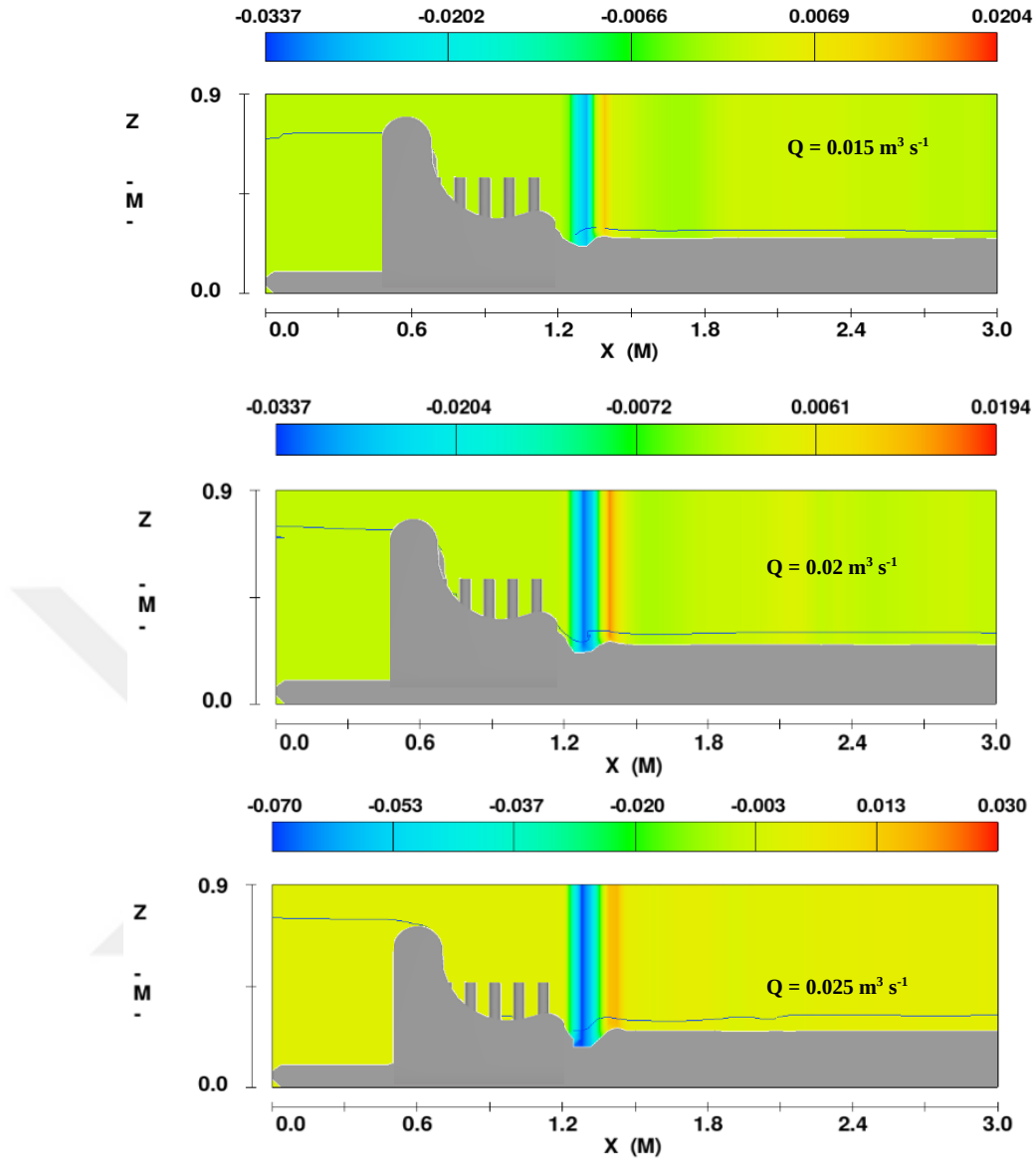


Figure 4.21 Contour map of the packed sediment elevation net change of SU4 model for discharge values of (a) $0.015 \text{ m}^3 \text{ s}^{-1}$, (b) $0.02 \text{ m}^3 \text{ s}^{-1}$, (c) $0.025 \text{ m}^3 \text{ s}^{-1}$.

4.8.5 Scour depth behind the model SU5

The experimental results obtained from this model clarified that the scour depth is reduced significantly. The additional part helped in dissipating much water energy of the outcoming flow throughout the piers (Figure 4.22). The scour region is reduced much more than the model SU₂ where the maximum depth of scour was oscillating between 0.002 m to 0.013 m just after the weir.

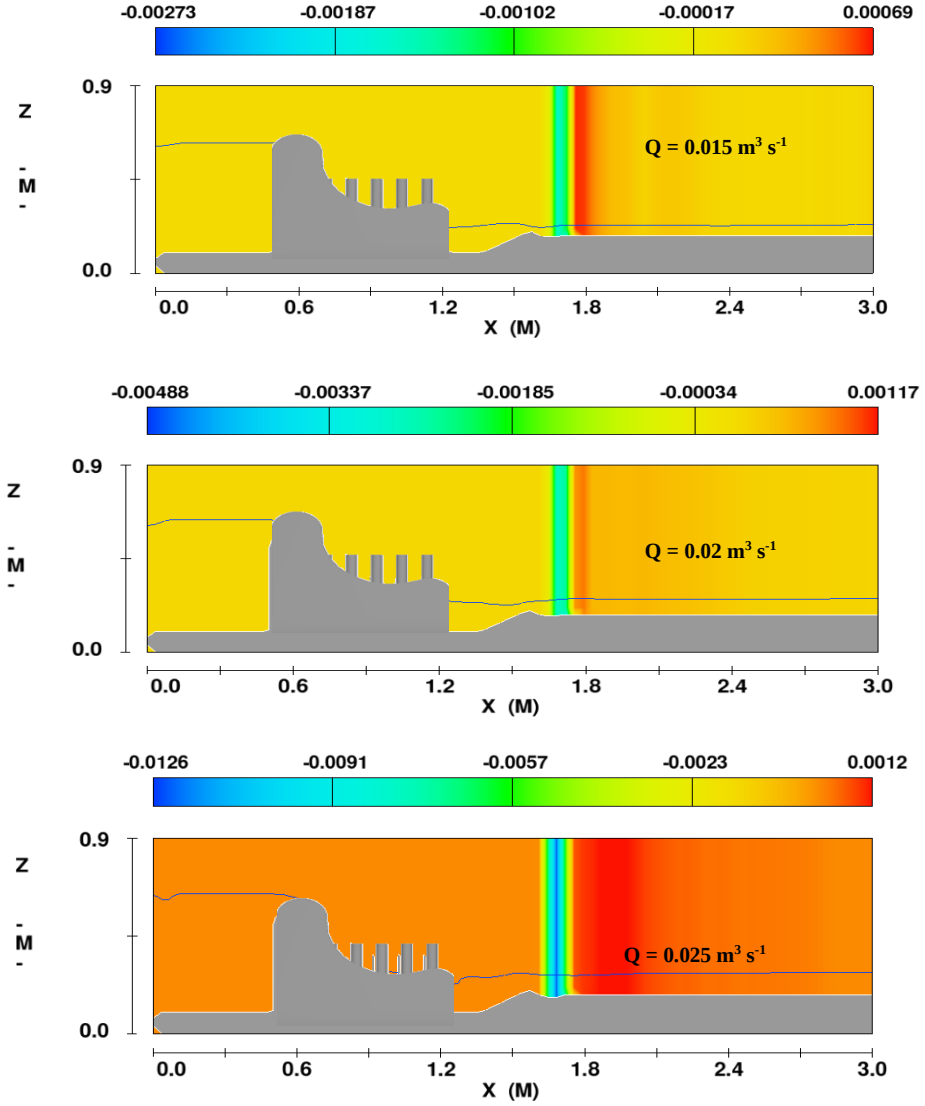


Figure 4.22 Contour map of the packed sediment elevation net change of SU5 model for discharge values of (a) $0.015 \text{ m}^3 \text{ s}^{-1}$, (b) $0.02 \text{ m}^3 \text{ s}^{-1}$, (c) $0.025 \text{ m}^3 \text{ s}^{-1}$.

4.8.6 Scour depth behind the model SU6

In this model, (Figure 4.23.) even that the ramp contributes in dropping the water force, the high inclination angle of the ramp increased the scour depth unlike what happened in model SU₅. The maximum scour depth is ranged between 0.011 m to 0.027 m at a distance of 0.04 m from the weir end.

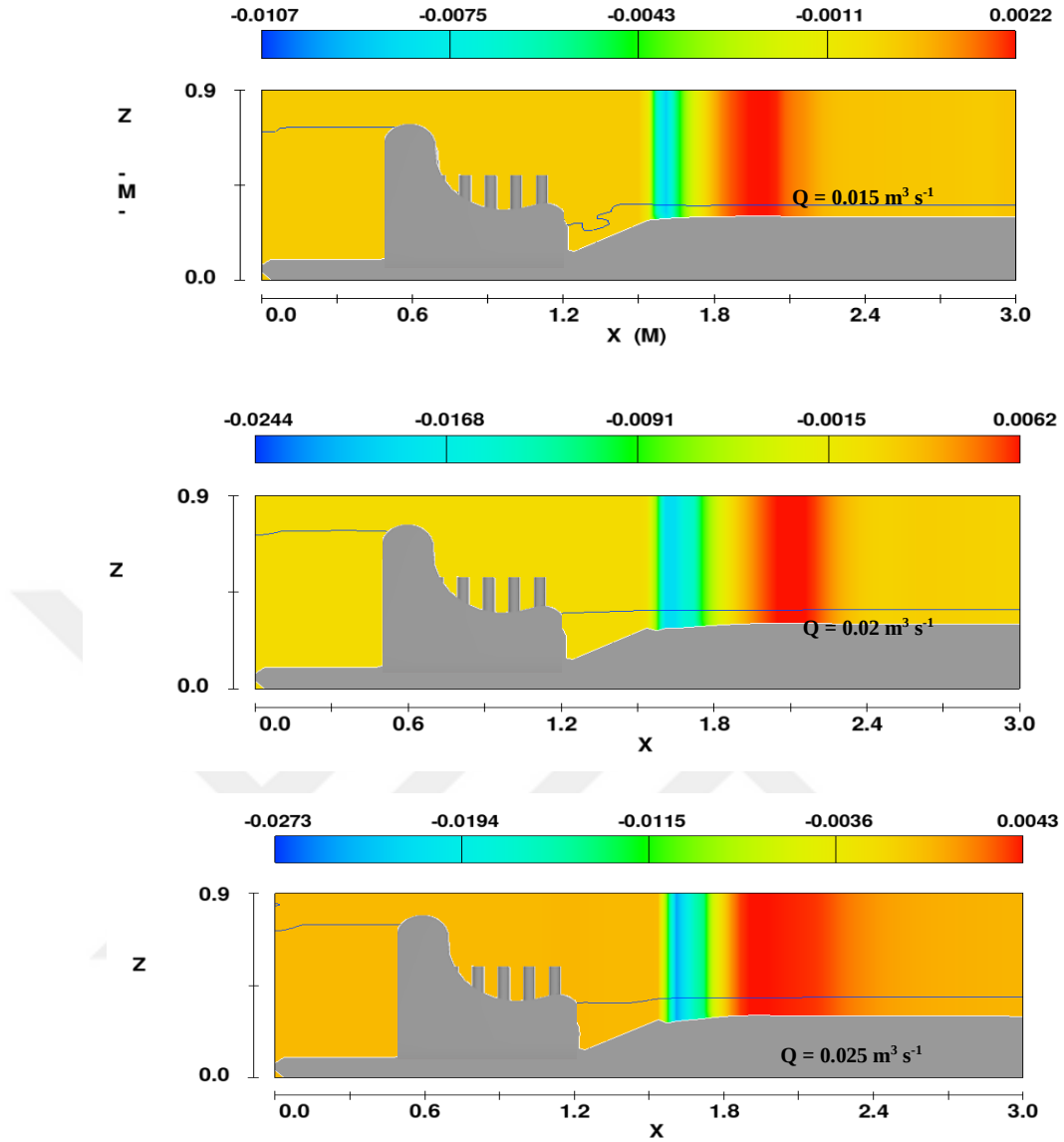


Figure 4.23 Contour map of the packed sediment elevation net change of SU6 model for discharge values of (a) $0.015 \text{ m}^3 \text{ s}^{-1}$, (b) $0.02 \text{ m}^3 \text{ s}^{-1}$, (c) $0.025 \text{ m}^3 \text{ s}^{-1}$.

4.8.7 Scour depth behind the model SU7

In this case, a different shape of the additional part has been suggested to improve the performance where the results were satisfactory. Regarding the numerical model SU7, before starting the simulation, it was expected that the basin designed after the piers helps in reducing the water energy. Unfortunately, what happened is that the water velocity in top of the created basin increased valuably and caused erosion (Figure 4.24). Although that the scour region is not extended too much, less than 0.2 m, especially at the maximum discharge, the erosion is occurred.

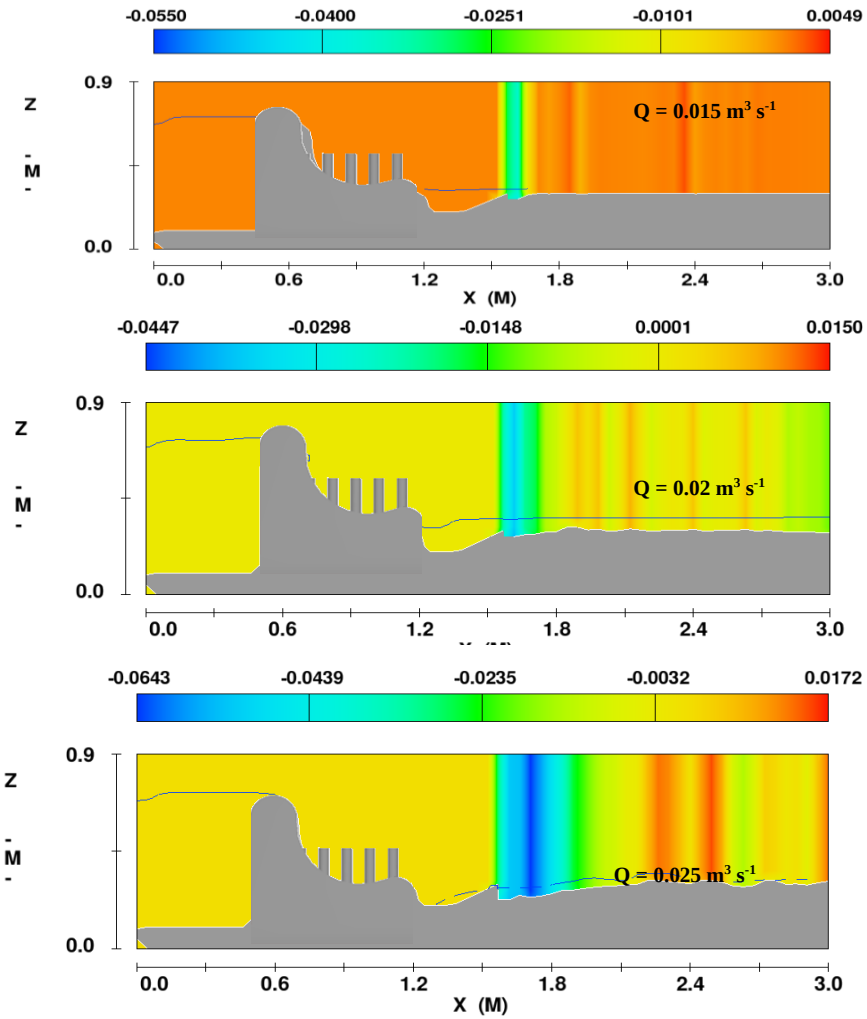


Figure 4.24 Contour map of the packed sediment elevation net change of SU7 model for discharge values of (a) $0.015 \text{ m}^3 \text{ s}^{-1}$, (b) $0.02 \text{ m}^3 \text{ s}^{-1}$, (c) $0.025 \text{ m}^3 \text{ s}^{-1}$.

4.8.8 Scour depth behind the model SU8

As mentioned earlier in this chapter, several attempts were conducted and many efforts were made to reach a free of scour, stable and efficient design. The obtained results show that water currents are quiet over and after the added part where this phenomenon results in a very low scour (Figure 4.25). It is observed that the scour depth, in average, does not exceed 0.015 m over the sand layer under different flow conditions.

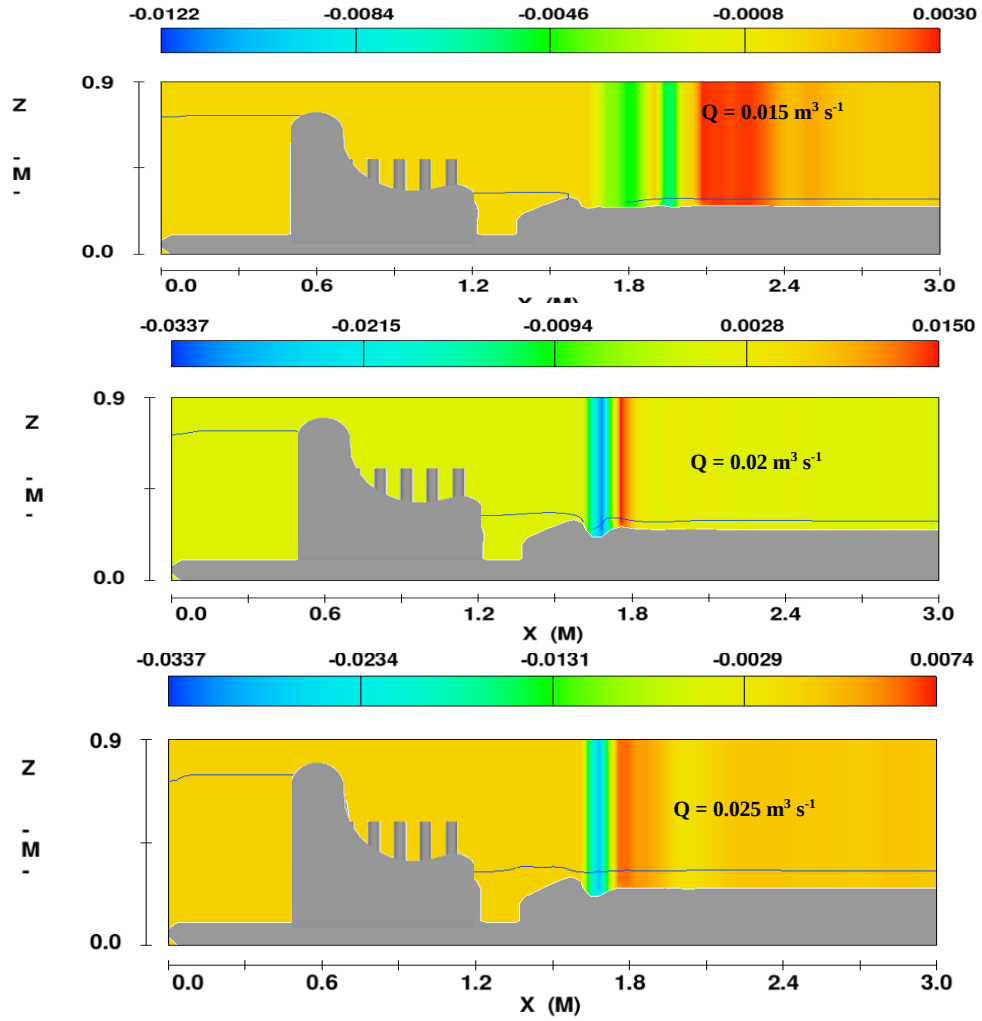


Figure 4.25 Contour map of the packed sediment elevation net change of SU8 model for discharge values of (a) $0.015 \text{ m}^3 \text{ s}^{-1}$, (b) $0.02 \text{ m}^3 \text{ s}^{-1}$, (c) $0.025 \text{ m}^3 \text{ s}^{-1}$.

4.8.9 Scour depth behind the model SU9

The simulation results exceeded all expectations and gave great hope that the hydraulic installations can be built safely without the risk of soil erosion due to obstruction. This weir was the most efficient design among all the weirs under study. Moreover, all the trials efforted by many researchers were focused on reducing the scour depth, not getting a free of scour model. the theoretical results show that the scour depth does not exceed a few millimeters, less than 0.006 m , for the three given discharges (Figure 4.26). The numerical results obtained from all cases should be evaluated experimantally under the same flow conditions and channel constraints in order to validate the performance of each model.

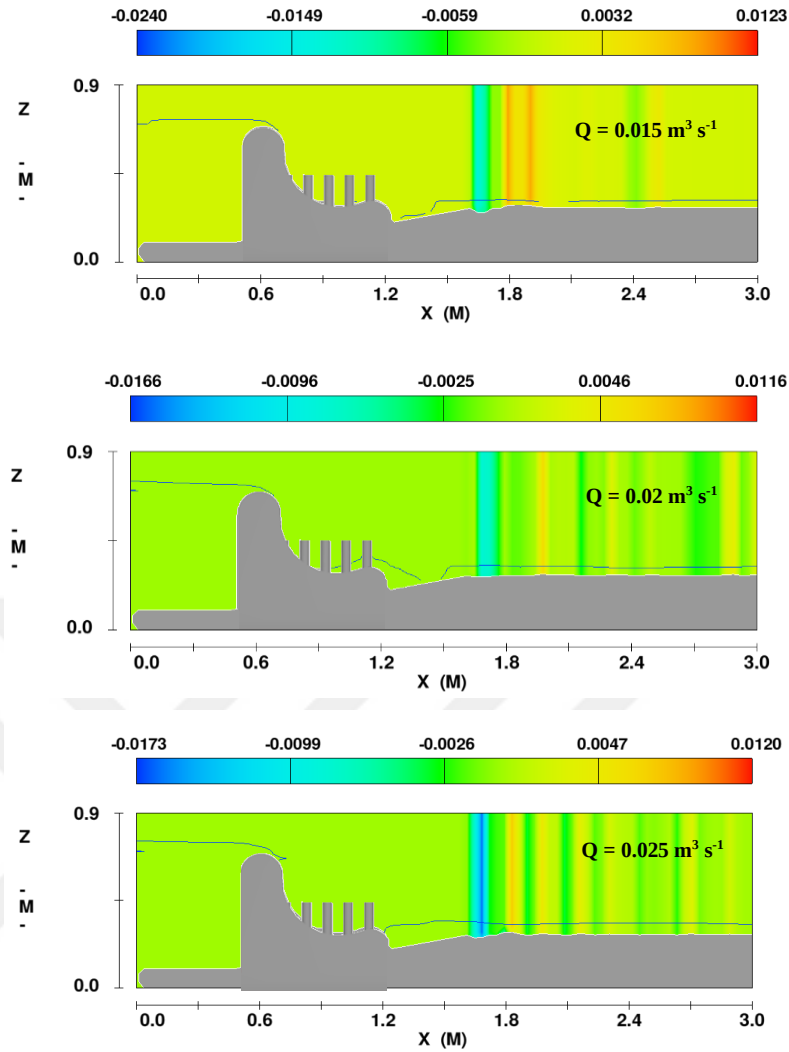


Figure 4.26 Contour map of the packed sediment elevation net change of SU9 model for discharge values of (a) $0.015 \text{ m}^3 \text{ s}^{-1}$, (b) $0.02 \text{ m}^3 \text{ s}^{-1}$, (c) $0.025 \text{ m}^3 \text{ s}^{-1}$.

4.9 Behavior of scour hole in the wake region

In all the simulation processes performed to reduce scour behind the weirs (Table 4.12), it was found that the eighth and ninth models, SU₈ and SU₉, are the best structures compared to the first model SU₁, where they were able to reduce the scour proportion about 89.1 % and 92.6 %, respectively. Then it is followed in preference the fifth SU₅ and sixth SU₆ models (70.26 %, 75.2 %), respectively. While the fourth SU₄ and seventh SU₇ models showed similar scour reduction percentage (40 %). Nevertheless, the second SU₂ demonstrated about 50% reduction in scour. Regarding the third model, SU₃, the scour is decreased about 62.3 % in comparison to the first model, Figure 4.27.

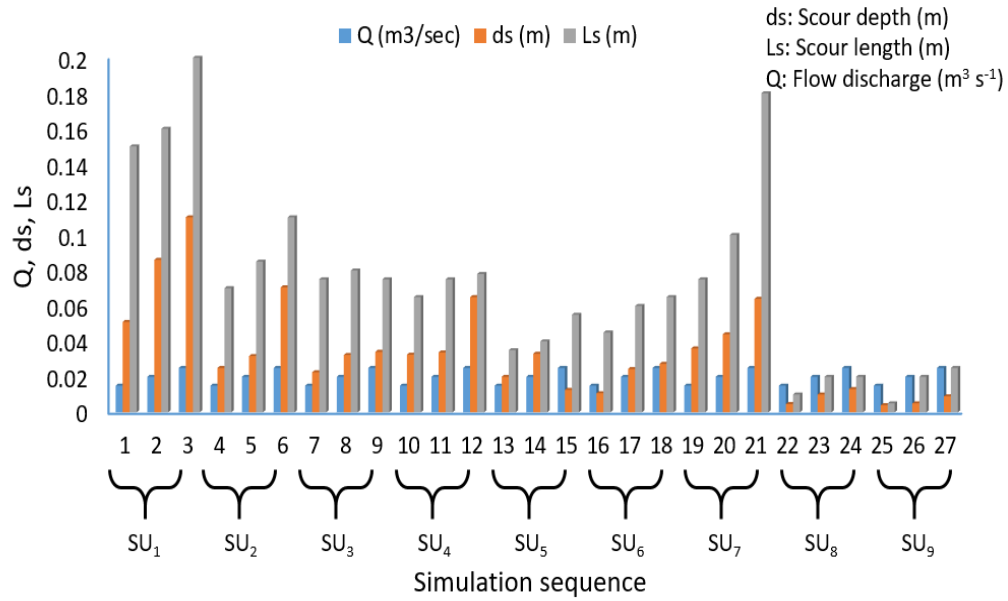


Figure 4.27 Maximum simulated scour depth in the wake region at different flow conditions.

Table 4.3 Simulated scour depth in the wake region at different flow conditions

Model	Q(m³ s⁻¹)	d _{sm} (m)	L _{sm} (m)	Scour reduction %
SU ₁	0.015	0.051	0.15	0
	0.02	0.086	0.16	0
	0.025	0.11	0.2	0
SU ₂	0.015	0.025	0.07	50.9
	0.02	0.0317	0.085	63.1
	0.025	0.0705	0.11	35.9
SU ₃	0.015	0.0226	0.075	55.7
	0.02	0.0323	0.08	62.4
	0.025	0.0341	0.075	69
SU ₄	0.015	0.0325	0.065	36.2
	0.02	0.0337	0.075	60.8
	0.025	0.065	0.078	40.9
SU ₅	0.015	0.02	0.035	60.7
	0.02	0.033	0.04	61.6
	0.025	0.0126	0.055	88.5
SU ₆	0.015	0.0107	0.045	79
	0.02	0.0244	0.06	71.6
	0.025	0.0273	0.065	75.1
SU ₇	0.015	0.036	0.075	29.4
	0.02	0.044	0.1	48.8
	0.025	0.064	0.18	41.8

Table 4.3 Continued

SU ₈	0.015	0.0046	0.15	90.9
	0.02	0.01	0.16	88.3
	0.025	0.0131	0.2	88.1
SU ₉	0.015	0.004	0.07	92.1
	0.02	0.005	0.085	94.1
	0.025	0.0055	0.11	95.2

CHAPTER 5

EXPERIMENTAL SETUP AND FACILITIES

3.1 Introduction

The experimental work of this study was carried out at hydraulic laboratory of Civil Engineering Department of Gaziantep University. The work was planned and carried out to provide detailed information about the reduction of scour downstream the new design of weir named (SU). The experimental work included construction and testing many hydraulic models. The testing program included all the required measurements and tests needed for this study. The details of all equipment, calibration of the measuring devices and other experimental considerations are presented in this chapter.

3.2 Experimental channel and instruments

The experiments are conducted in the hydraulic laboratory of Gaziantep University/ Civil Engineering department/ Turkey. The flume used in the experiments was of zero-slope, 12 m in length, 0.9 m in deep and 0.8 m in width as shown in (Figure 5.1). The channel is designed with a recirculating system of water. The channel is provided with a flow meter for flow measurements. The water diverged from the flow meter is purging in a sump tank, which is combined to the channel inlet and includes in the middle a perforated metal plate for breaking down the velocity of water entered to the channel. The outlet is provided with a trapping basket for collecting the diverged bed materials used in the experiments such as sand. The filtered water passes through underground penstocks to the storage tank. The channel walls are made of glass and the bed is Aluminium. The channel is provided with a sliding point gage for measuring water and bed levels. In addition, a digital point gage and laser meter are provided to investigate water level and scour depth, respectively. (Figure 5.3). At the inlet, a thin layer of punched fiber glass is placed, which calms the entering water. The channel intake is combined to magnetic flow meter (Figure 5.4) where the latter is connected to a pump, which transfer water

from an underground tank to the channel as maximum capacity as 150 l/s. For monitoring the sand layer and flow motion, a digital camera of 12.2-megapixel with 5X optical zoom is used in all the experiments. Figure 5.2

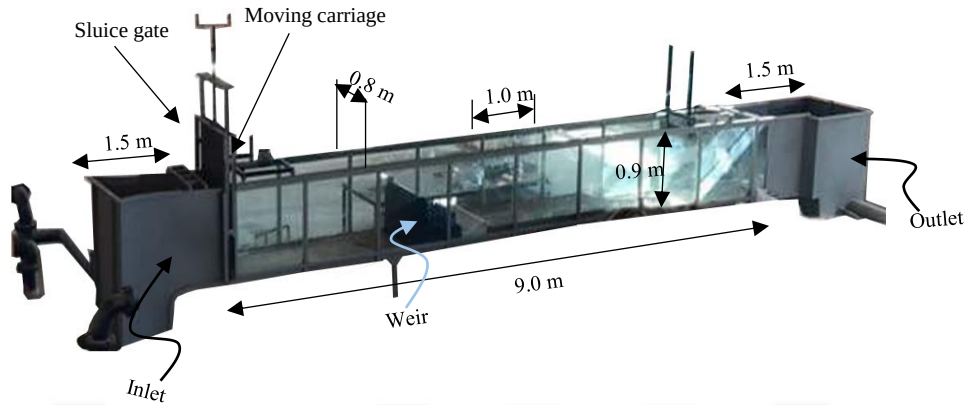


Figure 5.1 Experimental channel.



Figure 5.2 Digital camera.



(a)



(b)

Figure 5.3 (a) Laser meter, (b) Digital point gauge.



Figure 5.4 Flow meter.

3.3 Bed material

A series of experiments were conducted under different flow conditions to investigate the severity of scour downstream of the developed models. A uniform sand material is used and sieved before pouring into the channel. A sand layer of 0.2 m thickness is carpeted behind the weir along 3 m downstream of the channel. The sand layer is adjusted in parallel to the weir surface at the downstream.

$$\sigma_g = \left[\frac{d_{84.1}}{d_{15.9}} \right]^{0.5} = \frac{d_{84}}{d_{50}} \quad (5.1)$$

The geometric standard deviation (σ_g) is used as a measure of the uniformity of sand. The particles are considered to be uniformly distributed when σ_g is less than 1.3 and non-uniformly distributed when σ_g is larger than 1.3. The sieve analysis performed in the present study (Figure 5.5) is resulted in high deviation where σ_g was 3.84, which indicates non-uniformity in the particle distribution.

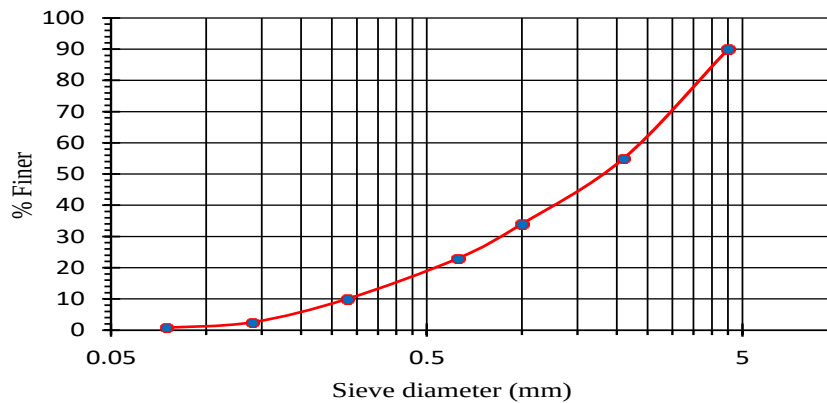


Figure 5.5 Sieve analysis of the soil used in the experiments.

3.4 Model setup

Different nine models were designed (Figure 5.6) The models are made of steel as separated parts and then combined to each other by welding process. Laser machines are used for cutting and form the model parts. The cutting machines are dependent on the design provided by AutoCAD program (version 2010). The models under study are designed and drawn by AutoCAD software (version 2010), then the drawing files are exported to the laser machines as (.dwg) extension. The manufactured weirs are coated with a thin layer of a greasy color. The width of all models was fixed as 0.8 m, which is the width of the experimental channel. Moreover, the height of weirs was constant for all of them as well, which is 0.59 m. Nevertheless, the length of each model is different according to the geometrical characteristics of each weir. All the models are placed at 2.5 m from the channel inlet. These models have been investigated and evaluated in term of minimum scour depth under three different flow conditions, $0.015 \text{ m}^3 \text{ s}^{-1}$, $0.02 \text{ m}^3 \text{ s}^{-1}$ and $0.025 \text{ m}^3 \text{ s}^{-1}$. In the next sections, each model will be reviewed and analyzed, separately, then the overall results will be discussed in order to compare the performance of all models.

3.5 Experimental Models

The experimental program of this study includes nine cases termed as SU models (SU₁ – SU₉) Figure 5.6. The models differ from each other by the design and performance. Each model will be presented separately as below.

The model SU has a single part, “L” shape. The weir is rounded with a radius of 0.1m and 0.09m at the crest and tail end, respectively. The inner surface is rounded with a radius of 0.28 m. The width of the model is 0.8 m and weir height at the upstream is 0.59 m. The models are designed with nine different shapes depending upon the profile of the weir. The designed weirs are based on the variation of downstream energy dissipation. Due to the structural disparities in all the given cases, specific symbols were given in order to describe, separately, the dimensions of each model as shown below (Figure 5.7).

In order to distinguish the difference in dimensions among the models, a summary of the geometrical properties is illustrated in table 5.1.

W: width of weir (m); L: length of weir (m); H: height of weir (m); R_c : crest radius (m); R_i : radius of inner surface (m); R_{T1} : tail radius (m); R_{T2} : tail radius of the added part (m); L_{hs} : distance from the end point of the main body to the lower edge of the ramp (m); L_R : length of ramp (m); θ : inclination angle of ramp (degrees).

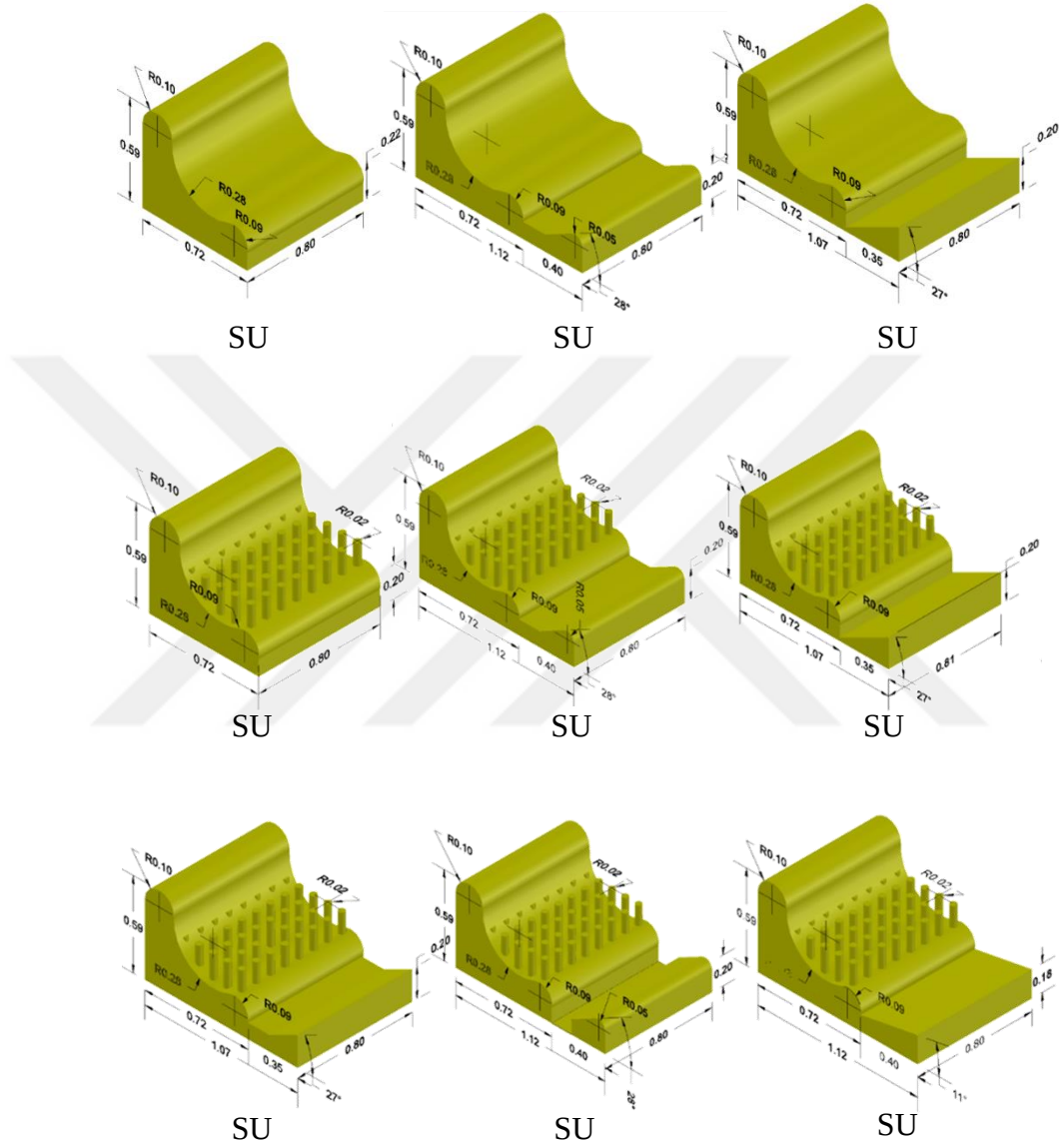


Figure 5.6 The experimental models.

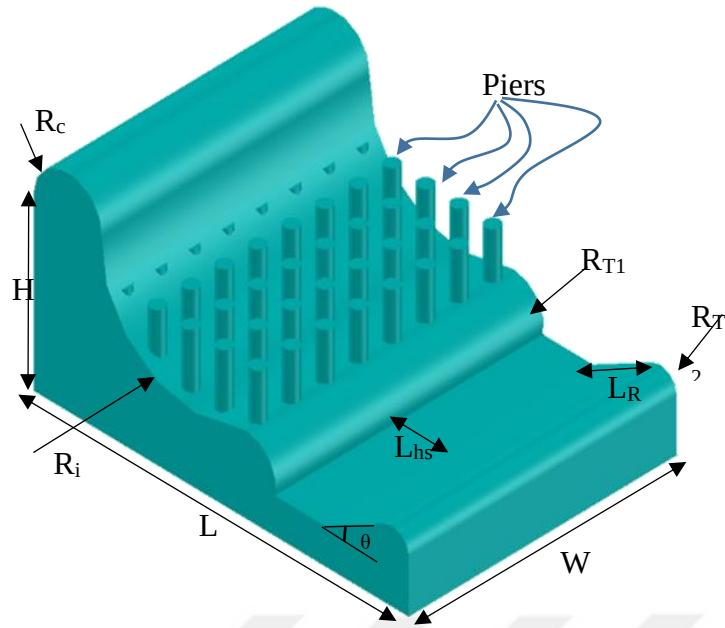


Figure 5.7 Symbols used in defining the dimensions.

Table 5.1 Geometrical characteristics of all models

Model	W (m)	L (m)	H (m)	R _c (m)	R _i (m)	R _{T1} (m)	Additional parts			θ	Piers
							L _{hs}	L _R	R _{T2}		
SU ₁	0.8	0.72	0.49	0.1	0.28	0.09	---	---	---	---	No
SU ₂	0.8	1.12	0.49	0.1	0.28	0.09	0.15	0.22	0.05	28	No
SU ₃	0.8	1.07	0.49	0.1	0.28	0.09	---	0.39	---	27	No
SU ₄	0.8	1.07	0.49	0.1	0.28	0.09	---	---	---	27	Yes
SU ₅	0.8	1.12	0.49	0.1	0.28	0.09	0.15	0.22	0.05	28	Yes
SU ₆	0.8	1.07	0.49	0.1	0.28	0.09	---	0.39	---	27	Yes
SU ₇	0.8	1.07	0.49	0.1	0.28	0.09	0.15	0.22	---	27	Yes
SU ₈	0.8	1.12	0.49	0.1	0.28	0.09	0.15	0.22	0.05	28	Yes
SU ₉	0.8	1.12	0.49	0.1	0.28	0.09	---	0.41	---	11	Yes

Model SU₁

The first model SU₁ is constructed without considering the energy dissipaters, which is the water calming structure, Figure 5.8. It is valuable to analyze the model with its simple shape with no any other parts to get indication how much water energy is, then suggest suitable solutions in order to eliminate the danger of scour occurranc.

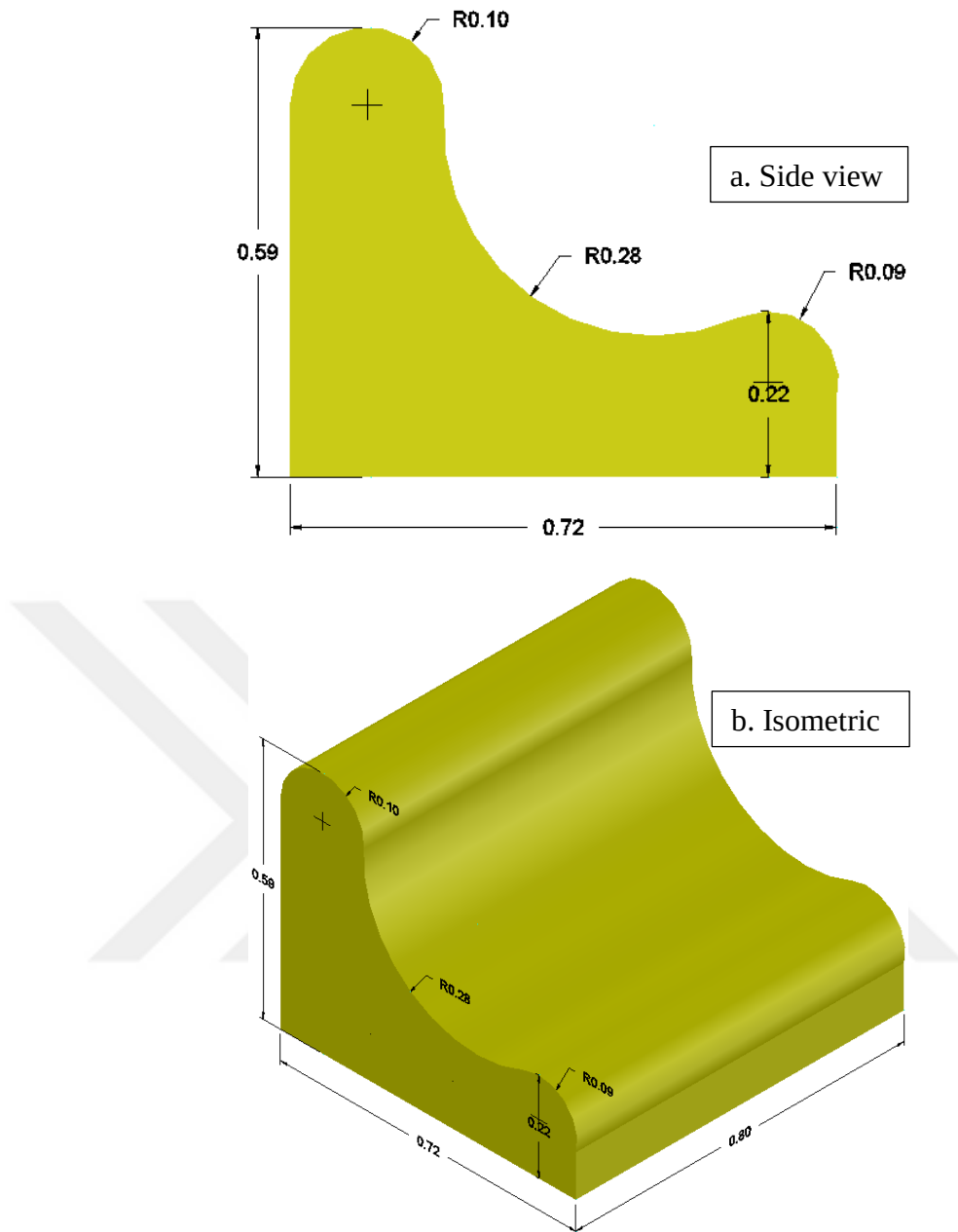


Figure 5.8 Geometrical shape of model SU₁: a. Side view, b. Isometric.

Model SU₂

The second model SU₂ included additional part (Figures 5.9), which is as mentioned before the water calming structure. This part is combined with the main body that is formed a horizontal surface 0.15 m above the channel bed. The latter is followed by a ramp of 28°. The ramp is ended by a rounded surface of 0.1 m diameter .

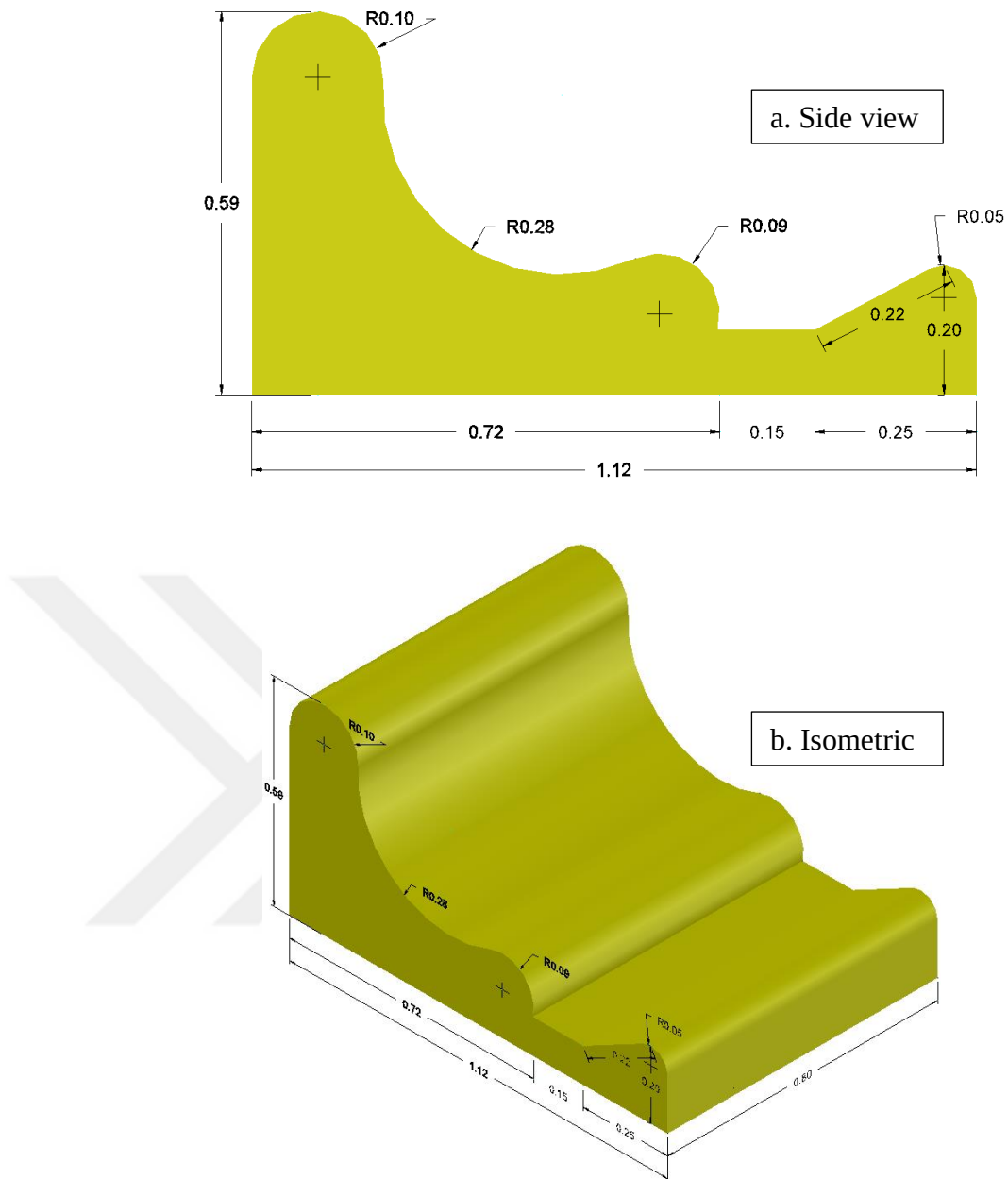


Figure 5.9 Geometrical shape of model SU₂: a. Side view, b. Isometric.

Model SU₃

In the third model SU₃, the main body is followed by a ramp of 27°, which is the energy dissipator, Figure 5.10. The cross-sectional shape of the external part is triangle with a horizontal distance of 0.35 m and vertical distance of 0.2 m .

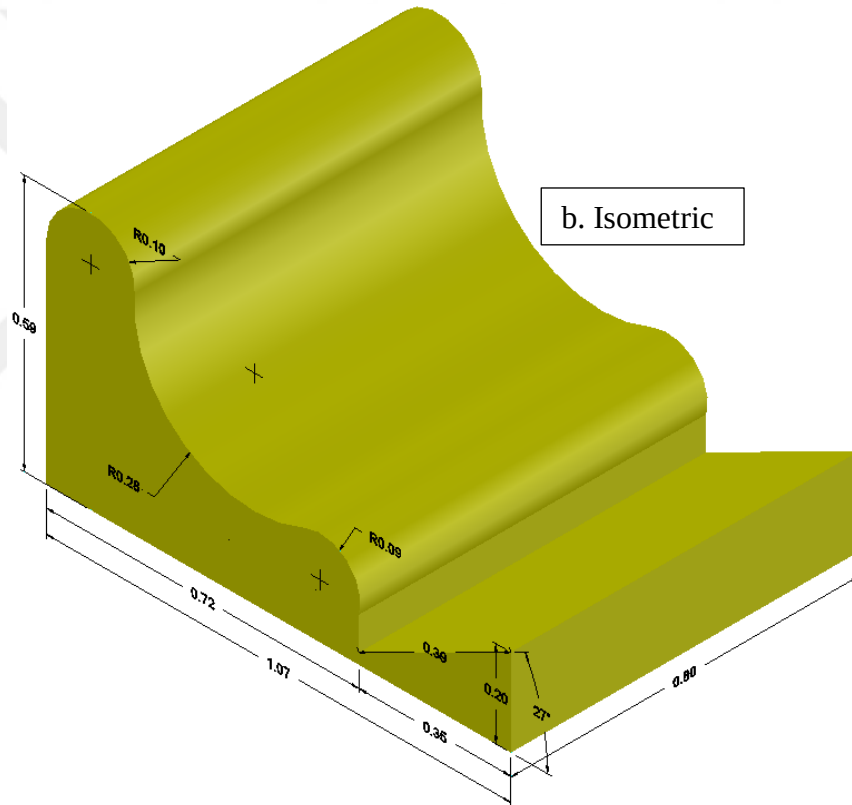
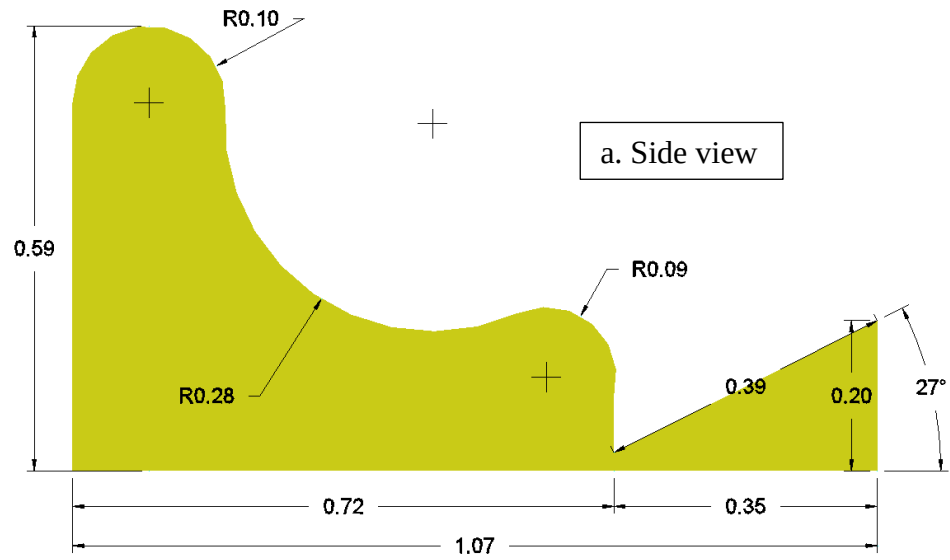


Figure 5.10 Geometrical shape of model SU₃: a. Side view, b. Isometric.

Model SU₄

In this model, a solution for the enormous turbulent energy is suggested (Figure 5.11). Although the main body is similar to the first case, forty piers were added to solve the scour problem downstream the weir. The piers, which are 0.04 m in diameter and 0.25

m in height, were placed over an internal plate of 0.1 m high from the bottom downstream of the weir where the space between the piers is 0.1 m.

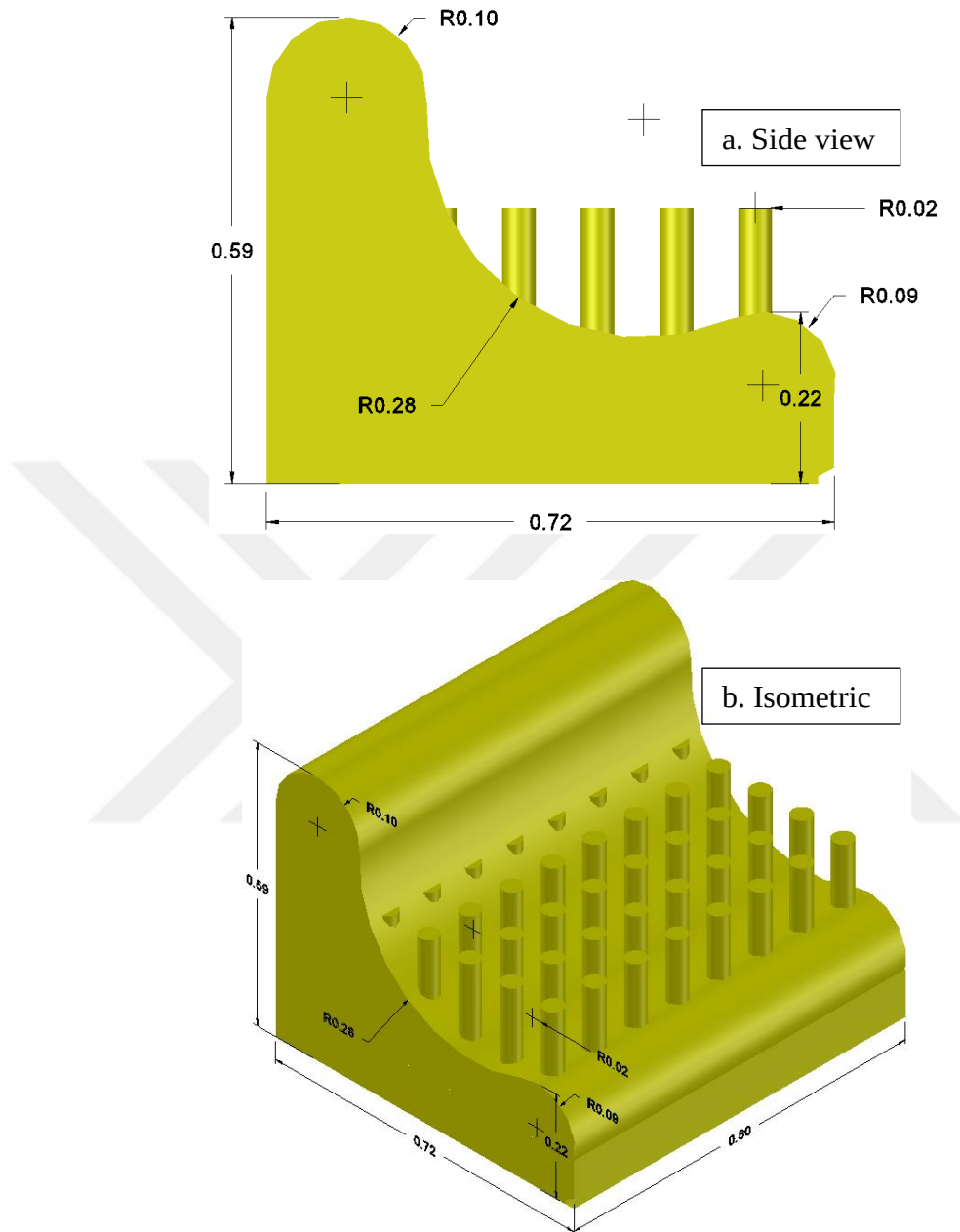


Figure 5.11 Geometrical shape of model SU₄: a. Side view, b. Isometric.

Model SU₅

The Fifth model SU₅ includes additional part, which is as mentioned before the water calming structure (Figure 5.12). This part is combined with the main body that is formed a horizontal surface 0.15 m above the channel bed. The latter is followed by a ramp of 28°. The ramp is ended by a rounded surface of 0.1 m diameter. Forty piers were added to solve the scour problem downstream the weir. The piers, which are 0.04

m in diameter and 0.25 m in height, were placed over an internal plate of 0.1 m high from the bottom downstream of the weir where the space between the piers is 0.1 m.

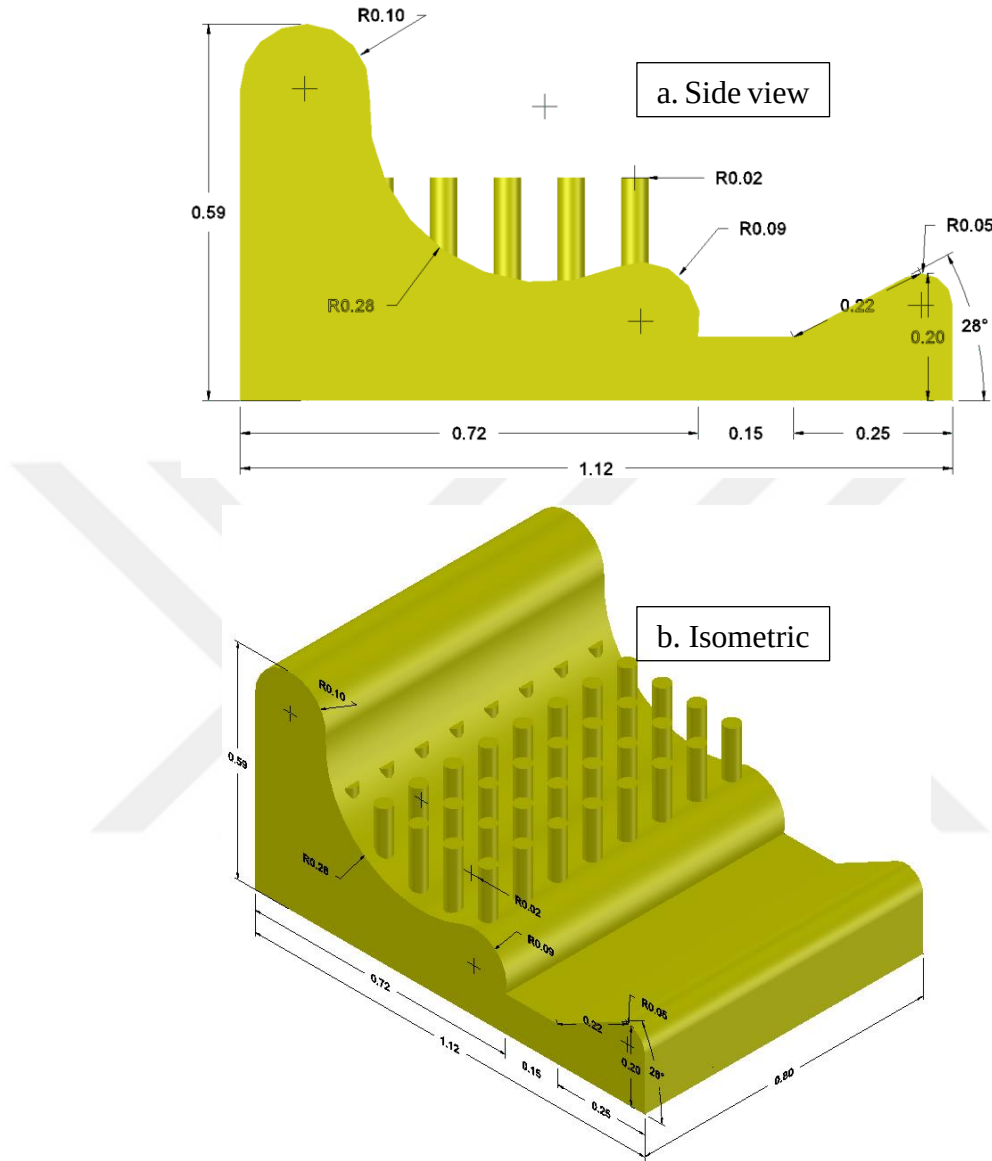


Figure 5.12 Geometrical shape of model SU₅: a. Side view, b. Isometric.

Model SU₆

In this model, SU₆, the main body is followed by a ramp of 27°, which is the energy dissipator (Figure 5.13). The cross-sectional shape of the external part is triangle with a horizontal distance of 0.35 m and vertical distance of 0.2 m. Forty piers were added to solve the scour problem downstream the weir. The piers, which are 0.04 m in diameter and 0.25 m in height, were placed over an internal plate of 0.1 m high from the bottom downstream of the weir where the space between the piers is 0.1 m.

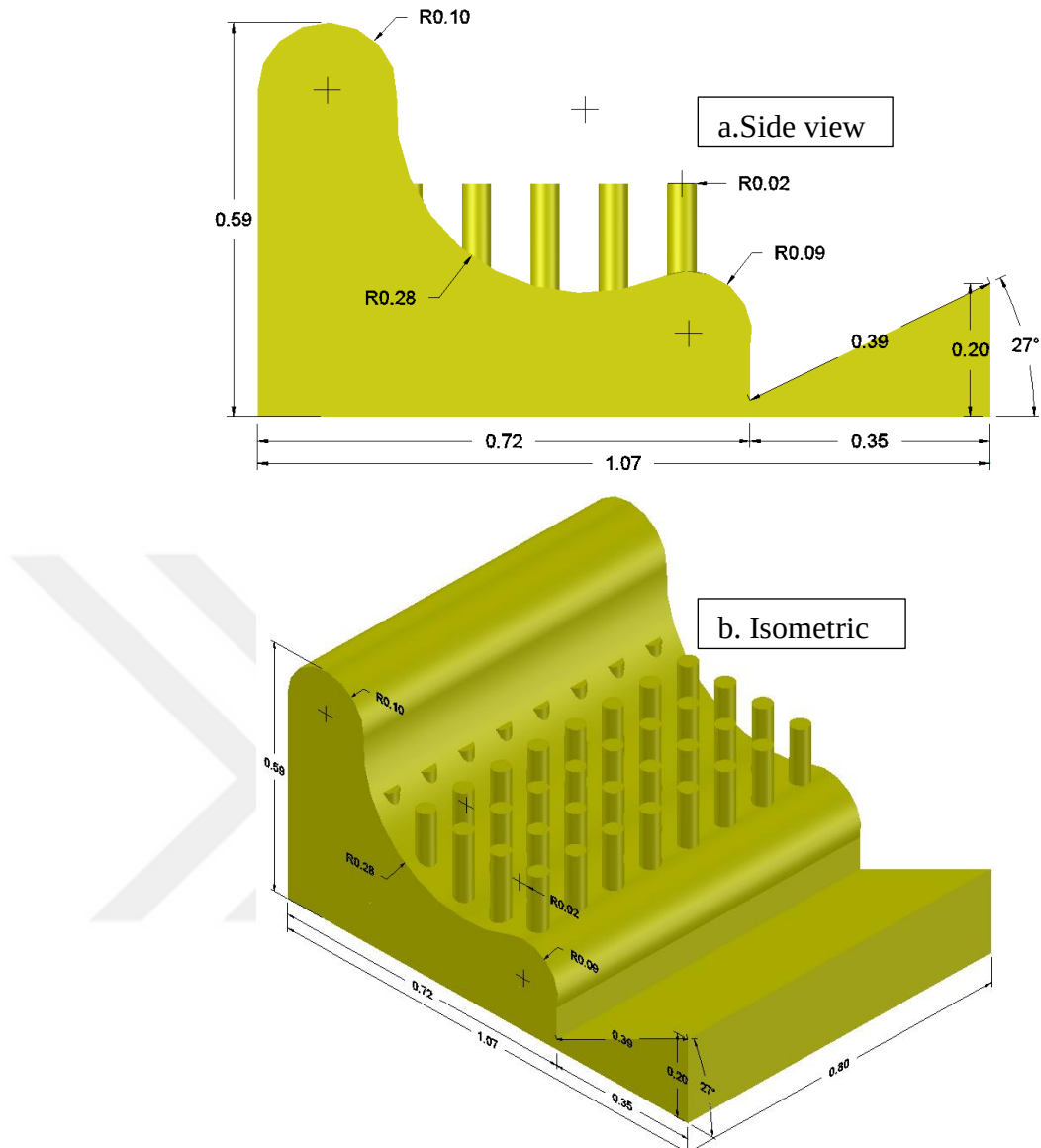


Figure 5.13 Geometrical shape of model SU₆: a. Side view, b. Isometric.

Model SU7

In this model, the design of the additional part differs from the others while the original shape is the same where piers were added to the main body (Figure 5.14). The energy dissipators placed in this weir include a plate connected to the main body which formed an inner basin 0.2 m high and 0.175 m length followed by a ramp of positive angle 27° with the channel bed.

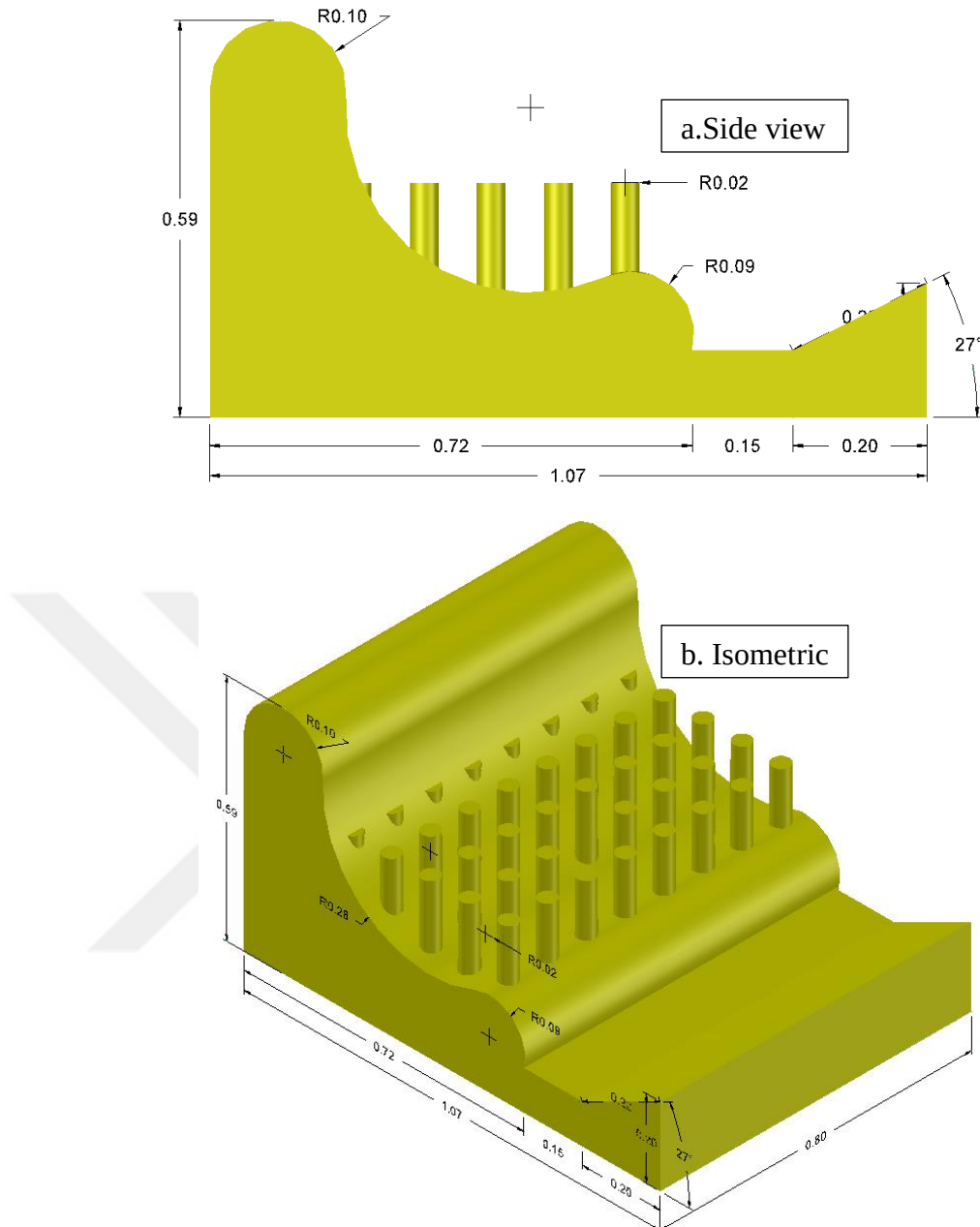


Figure 5.14 Geometrical shape of model SU₇: a. Side view, b. Isometric.

Model SU₈

The energy dissipator part in this case, SU₈, is connected to the main body, formed an inner basin 0.2 m high and 0.15 m length (Figure 5.15) . The latter is followed by a ramp of 28°. The ramp is ended by a rounded surface of 0.05 m diameter.

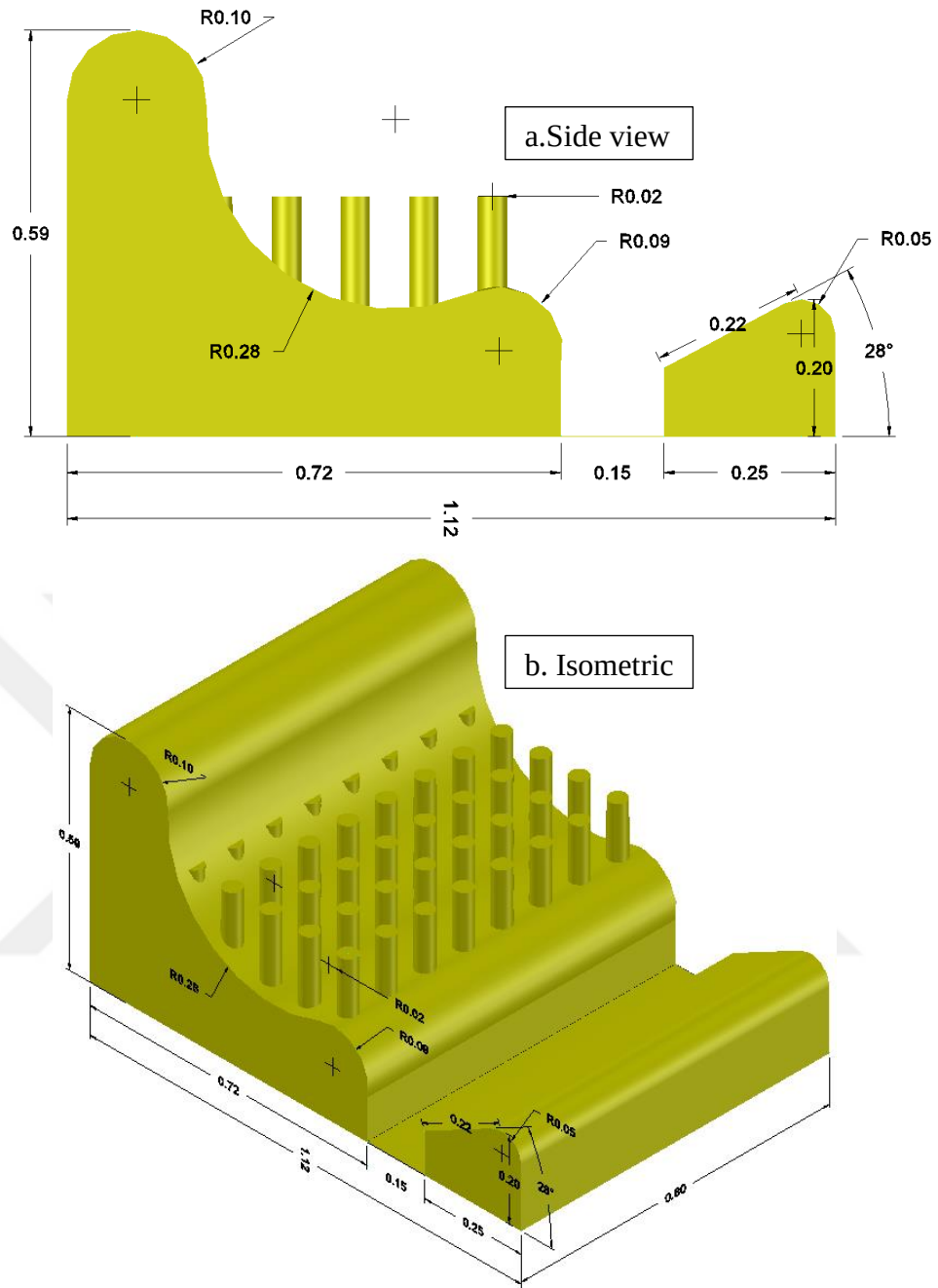


Figure 5.15 Geometrical shape of model SU₈: a. Side view, b. Isometric.

Model SU₉

The ninth model, SU₉, has additional part. This part is combined to the main body and formed a ramp of 11° above the channel bed (Figure 5.16). The horizontal distance the ramp occupied is 0.4 m to form with the whole structure 1.12 m length.

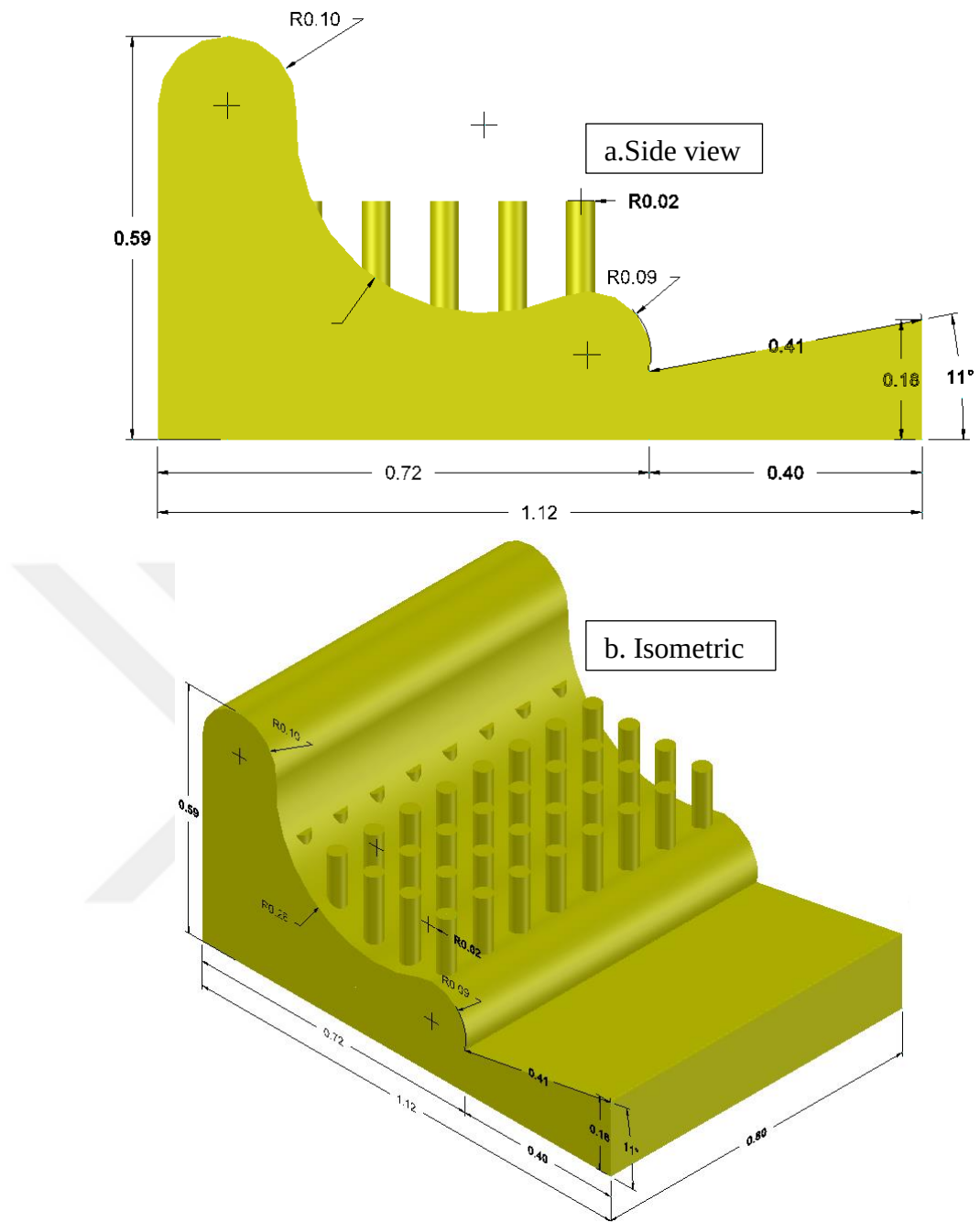


Figure 5.16 Geometrical shape of model SU9: a. Side view, b. Isometric.

CHAPTER 6

EXPERIMENTAL ANALYSES

6.1 Introduction

The analyses conducted for each model include three main aspects; reduction the scour downstream the weirs, energy dissipation and sketching water surface profile. Water surface profiles of all models are plotted and analyzed in order to examining the performance of each model. Moreover, Energy dissipation is considered as a measure of evaluating the efficiency of weirs. The scour reduction comes with the same necessity as the energy dissipation where the two parameters are related to each other.

The local scour created downstream the weir may causes structural failure. Studying the ability of scour reduction is crucial in order to keep the hydraulic structure efficient as long period as possible. The geometry of weir plays an important role in decreasing or increasing the scour by controlling the flow pattern.

6.2 Scour depth analysis

The best method used to figurate the scour values in a simple visualization is the contour map. The contour map consists of several lines; each line defines a single value of scour depth. The contour lines are formed by several points of x,y and z dimensions. The x and y dimensions represent the lateral and longitudinal distances, respectively, while the scour depth is defined by z value. Unlike the scour values, which are measured by a digital point gage moves horizontally and vertically, the other dimensions are measured by rulers fixed to the channel sides. The 3D points obtained after each run are inserted into SURFER software (version 13) in a way to be accepted by the program. Table 6.1 includes all experimental data obtained from each run.

Table 6.1 Experimental data of all models

Model	Q $\text{m}^3 \text{s}^{-1}$	d_s (m)	Ls (m)	Y_u (m)	Y_d (m)	Y_t (m)	P_1 (m)	P_2 (m)	scour reduction%
SU₁	0.015	0.11	0.20	0.64	0.24	0.235	0.59	0.2	0%
	0.02	0.115	0.20	0.65	0.245	0.24	0.59	0.2	0%
	0.025	0.12	0.21	0.66	0.245	0.24	0.59	0.2	0%
SU₂	0.015	0.045	0.08	0.64	0.24	0.23	0.59	0.2	59%
	0.02	0.055	0.08	0.647	0.25	0.245	0.59	0.2	52.2%
	0.025	0.065	0.08	0.66	0.27	0.245	0.59	0.2	45.8%
SU₃	0.015	0.07	0.16	0.64	0.25	0.235	0.59	0.2	36.3%
	0.02	0.075	0.16	0.65	0.24	0.245	0.59	0.2	34.7%
	0.025	0.08	0.16	0.66	0.24	0.245	0.59	0.2	33.3%
SU₄	0.015	0.039	0.08	0.64	0.26	0.235	0.59	0.22	64.5%
	0.02	0.045	0.08	0.65	0.26	0.24	0.59	0.22	60.8%
	0.025	0.05	0.08	0.66	0.26	0.245	0.59	0.22	58.3%
SU₅	0.015	0.018	0	0.66	0.265	0.24	0.59	0.2	83.6%
	0.02	0.02	0	0.65	0.25	0.235	0.59	0.2	82.6%
	0.025	0.031	0.04	0.66	0.265	0.242	0.59	0.2	74.1%
SU₆	0.015	0.026	0.04	0.645	0.245	0.24	0.59	0.2	76.3%
	0.02	0.034	0.04	0.65	0.255	0.245	0.59	0.2	70.4%
	0.025	0.035	0.04	0.66	0.265	0.255	0.59	0.2	70.8%
SU₇	0.015	0.04	0.12	0.645	0.255	0.235	0.59	0.2	63.6%
	0.02	0.045	0.16	0.655	0.265	0.24	0.59	0.2	60.8%
	0.025	0.05	0.16	0.665	0.27	0.245	0.59	0.2	58.3%
SU₈	0.015	0.005	0	0.645	0.245	0.232	0.59	0.2	95.4%
	0.02	0.0065	0	0.65	0.25	0.238	0.59	0.2	94.3%
	0.025	0.009	0.04	0.65	0.26	0.245	0.59	0.2	92.5%
SU₉	0.015	0.0025	0	0.645	0.25	0.235	0.59	0.18	97.7%
	0.02	0.0032	0.04	0.652	0.26	0.24	0.59	0.18	97.2%
	0.025	0.0035	0.04	0.66	0.265	0.245	0.59	0.18	97.1%

Model SU₁

Contour maps of scour depth (Figures 6.3– 6.5) are used as a measure of the weir efficiency in term of scour hole reduction. The experimental results shown in Figure 6.1 indicate that when a continuous inflow of $0.015 \text{ m}^3 \text{ s}^{-1}$ is applied, a scour region is created behind the weir and extended to the channel sides, Figure 6.2. Applying a discharge of $0.02 \text{ m}^3 \text{ s}^{-1}$, maximum scour was noticed in the middle of the channel downstream the weir at a distance of about 0.2 m from the downstream edge of weir where the scour depth was 0.115 m in average. A similar behavior was noticed when a discharge of $0.025 \text{ m}^3 \text{ s}^{-1}$ is used.

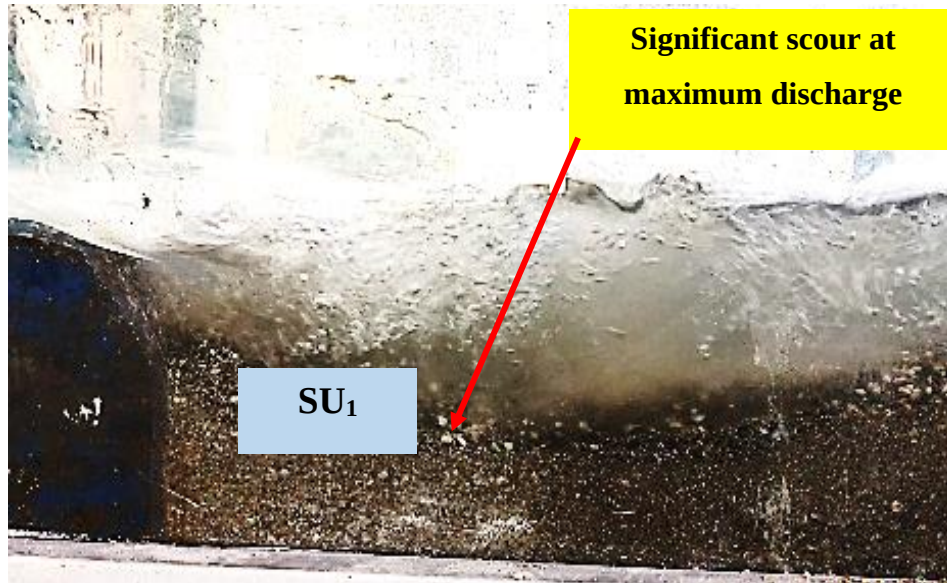


Figure 6.1 Scour region downstream the weir SU1.

Table 6.1 shows the scour depth d_s and the length of scour hole L_s . The scour depths are fluctuated between 0.11 m and 0.12 m for the three discharges $0.015 \text{ m}^3\text{s}^{-1}$, $0.02 \text{ m}^3\text{s}^{-1}$ and $0.025 \text{ m}^3\text{s}^{-1}$, respectively. The average distance of the deepest point of scour hole starting from the downstream edge was 0.205 m. The water level behind the weir is raised to 0.66 m at the maximum flow rate while it was 0.64 m at the minimum flow. The model reflected its ability to elevate the water level at the upstream side and steeply drop it at the weir tail.

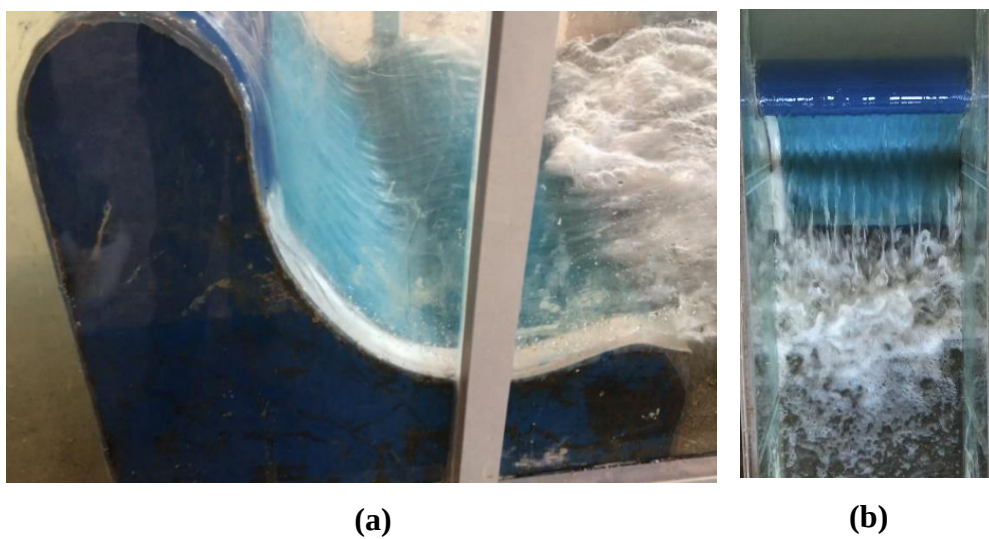


Figure 6.2 Physical Model SU1. a. side view, b. top view.

The flow can be observed from the side and from the top Figure 6.2, where the water flows with the body of the weir until reached its lower edge over which the vortices are formed, causing scour, then returns to settle at a distance estimated at 0.4 m from the edge of weir, so it is necessary to develop the design of the weir to disperse energy, the pictures 6.6 -6.8 showed how the vortices increase with the increase of discharge.

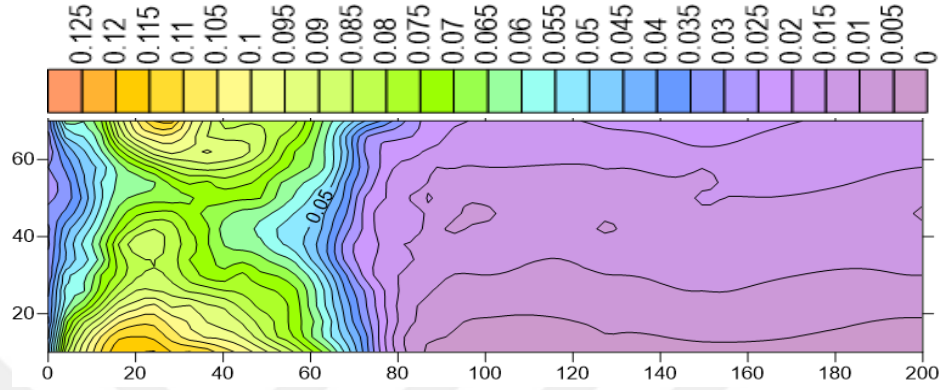


Figure 6.3 Scour contour lines downstream the weir SU1, $Q = 0.015 \text{ m}^3/\text{sec}$.

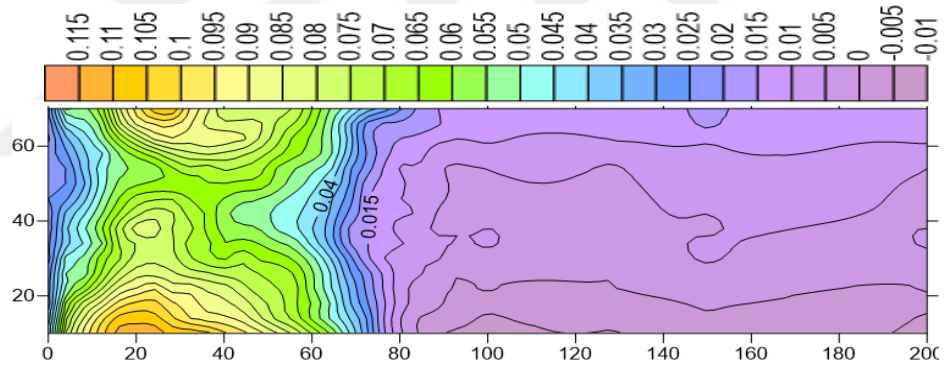


Figure 6.4 Scour contour lines downstream the weir SU1, $Q = 0.02 \text{ m}^3/\text{sec}$.

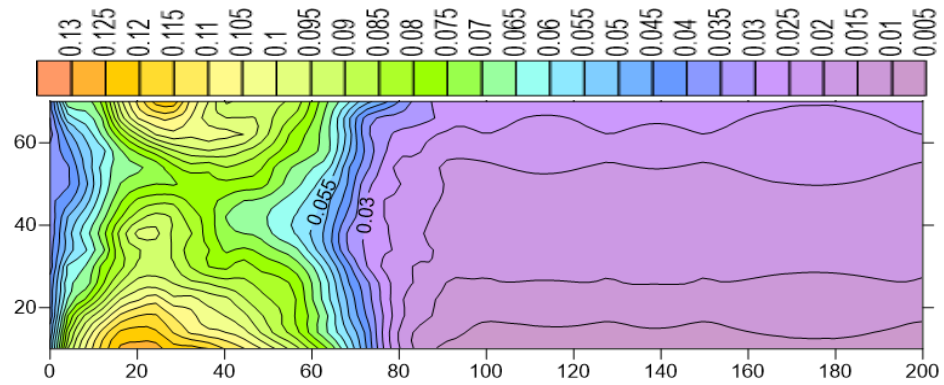


Figure 6.5 Scour contour lines downstream the weir SU1, $Q = 0.025 \text{ m}^3/\text{sec}$.

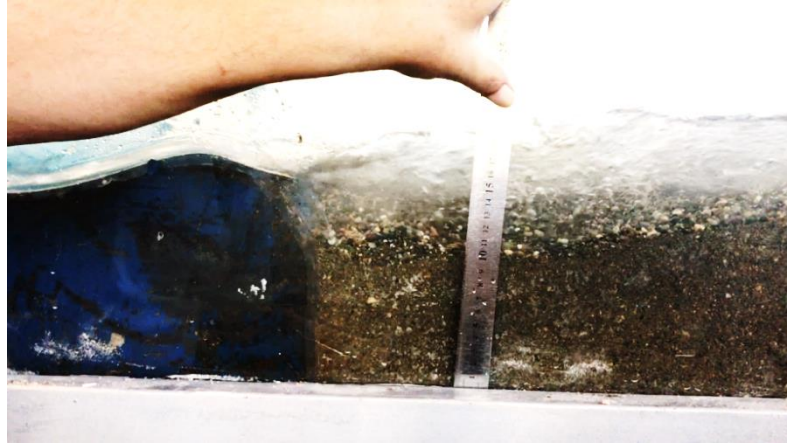


Figure 6.6 Scour depth behind the weir SU1 after 6 hours of experiment, $Q = 0.015$ $\text{m}^3\text{sec}^{-1}$.

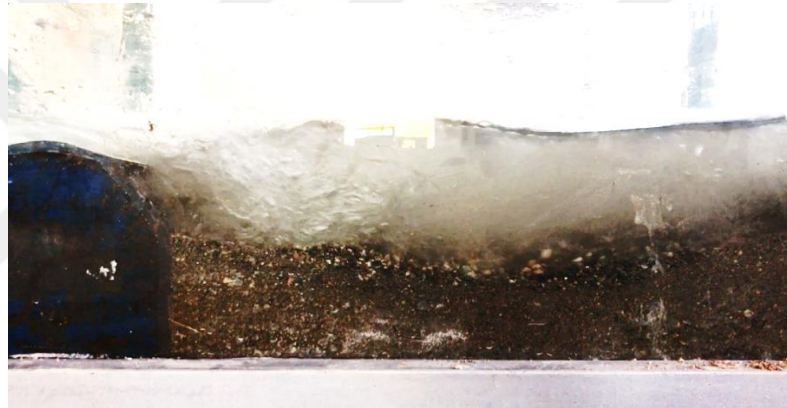


Figure 6.7 Scour depth behind the weir SU1 after 6 hours of experiment, $Q = 0.02$ $\text{m}^3\text{sec}^{-1}$.



Figure 6.8 Scour depth behind the weir SU1 after 6 hours of experiment, $Q = 0.025$ $\text{m}^3\text{sec}^{-1}$.

Model SU₂

The additional part added to the main body of weir is designed to trap the vortices over there and stop their progressing towards the sand layer. The experimental results show that the severity of scour is concentrated in the middle of the cross-wise direction downstream the weir and decreased significantly in the stream-wise direction. It was noticed that the scour region formed (Figure 6.9) is almost followed the same behavior at the three given discharges (Figures 6.11 – 6.13). The distance of maximum scour was pointed at 0.08 m from the downstream edge. Regarding the depth of scour, it was slightly changed from 0.045 m to 0.065 m. Moreover, the vortex intensity is limited just over the additional part and extended a little bit towards the sand layer (Figure 6.10).

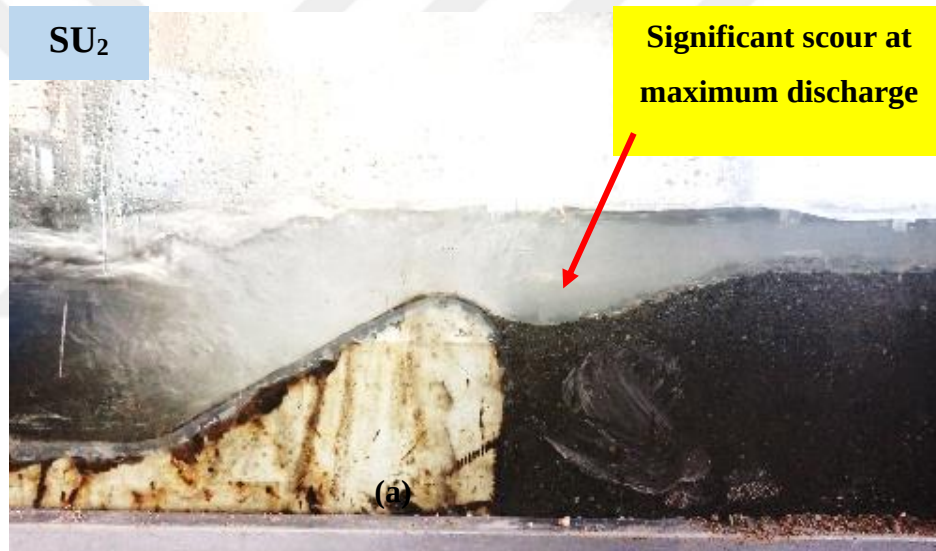


Figure 6.9 Scour region downstream the weir SU₂.

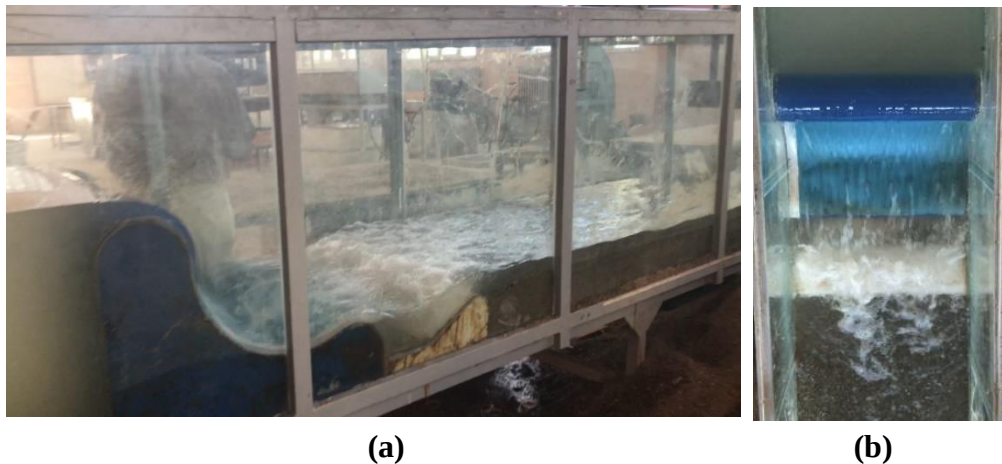


Figure 6.10 Physical Model SU₂. a. side view, b. top view.

This model managed to remove the vortices from the sandy layer by adding the additional part which led to decline vortexes over the added part of the weir, but some of them were able to cross over the sand layer, causing the erosion mentioned in the previous paragraph, so it became necessary to develop this part to prevent the vortexes from leaking to the sand layer and making the flow calmer.

Figures (6.14 – 6.16) show that erosion during the three discharges was similar in shape but it's different in scour depth. Trying to replace the added part to improve the performance of the model may lead to better results or counterproductive. That's what will notice in the following model SU₃.

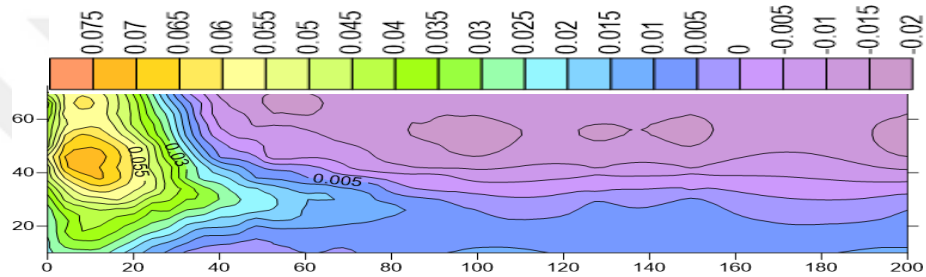


Figure 6.11 Scour contour lines downstream the weir SU2, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.

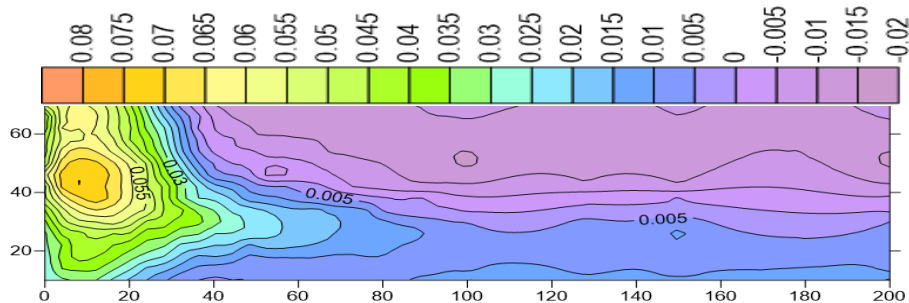


Figure 6.12 Scour contour lines downstream the weir SU2, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

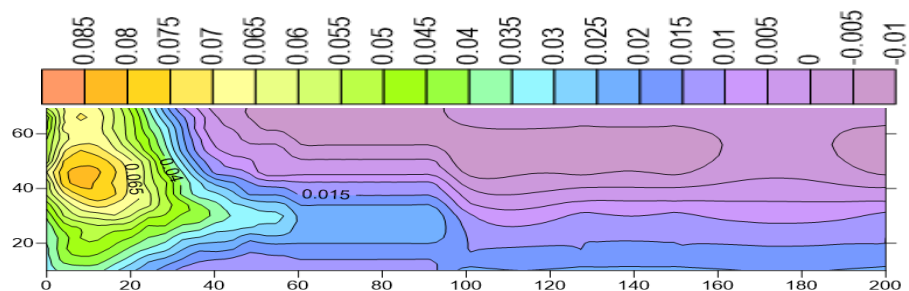


Figure 6.13 Scour contour lines downstream the weir SU2, $Q = 0.025 \text{ m}^3\text{s}^{-1}$.



Figure 6.14 Scour depth behind the weir SU2 after 6 hours of experiment, $Q = 0.015$ m³s⁻¹.



Figure 6.15 Scour depth behind the weir SU2 after 6 hours of experiment, $Q = 0.02$ m³s⁻¹.



Figure 6.16 Scour depth behind the weir SU2 after 6 hours of experiment, $Q = 0.025$ m³s⁻¹.

Model SU₃

In this model, adding the ramp of 27° results in high scour depth which makes the model inefficient in reducing the danger of erosion compared to the second model SU₂ (Figure 6.17). The experimental results show that the severity of scour is concentrated in the middle of the cross-wise direction downstream the weir and decreased significantly in the stream-wise direction. It was noticed that the scour region formed (Figure 6.18) is almost followed the same behavior at the three given discharges (Figures 6.19– 6.21). The distance of maximum scour was pointed at 0.16 m from the downstream edge. Regarding the depth of scour, it was changed from 0.07 m to 0.08 m. In addition, the vortex intensity is extended about 0.3 m from the downstream edge of weir (Figure 6.18).



Figure 6.17 Scour region downstream the weir SU₃.

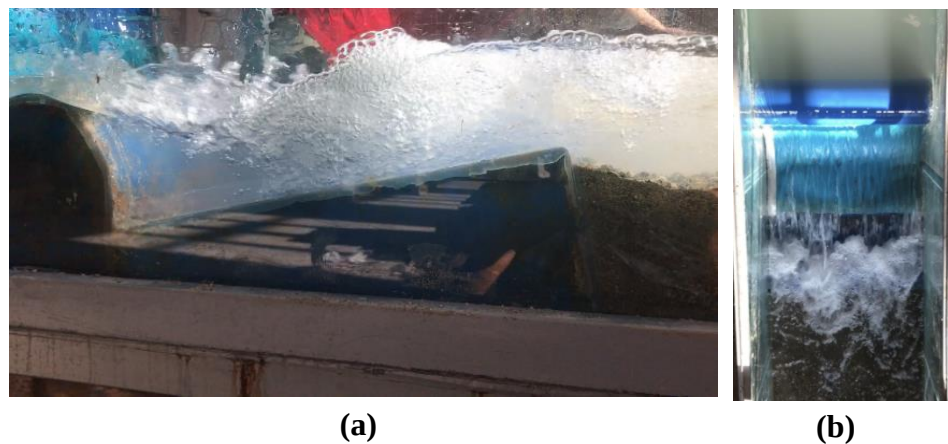


Figure 6.18 Physical Model SU₃. a. side view, b. top view.

Upon observing the figure (6.18), we find that the added part was unsuccessful in preventing the eddies from moving to the sand layer due to the high angle of the rump (27°) and the shortened of the additional part (0.35) m where it is observed in the figures (6.22 – 6.24) that represent what the situation of scour has reached after the passage of six hours after the start of the experiment and the water turbulence extended triangularly if looked at the flow from above.

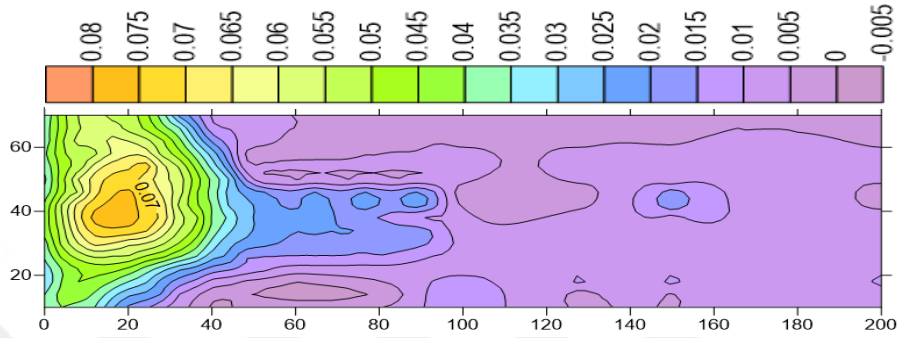


Figure 6.19 Scour contour lines downstream the weir SU3, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.

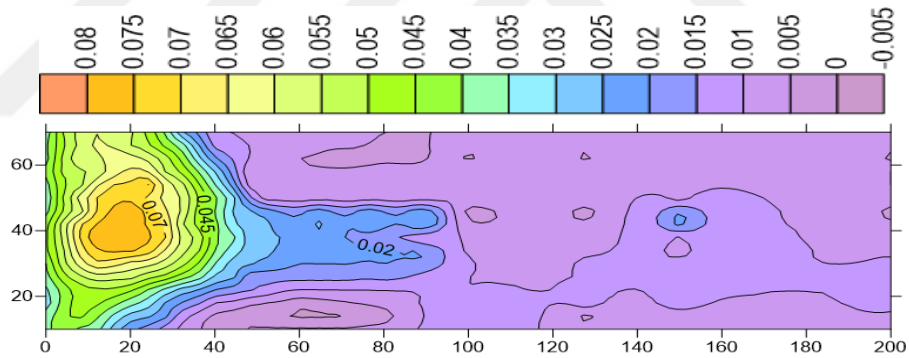


Figure 6.20 Scour contour lines downstream the weir SU3, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

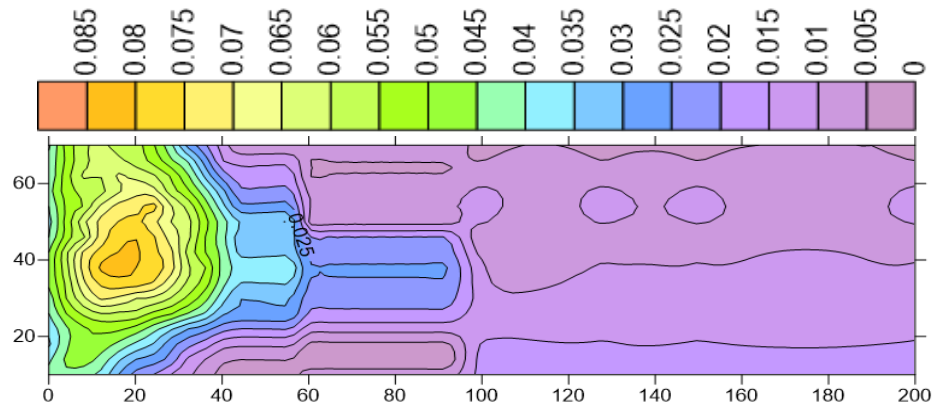


Figure 6.21 Scour contour lines downstream the weir SU3, $Q = 0.025 \text{ m}^3\text{s}^{-1}$.



Figure 6.22 Scour depth behind the weir SU3 after 6 hours of experiment, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.



Figure 6.23 Scour depth behind the weir SU3 after 6 hours of experiment, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.



Figure 6.24 Scour depth behind the weir SU3 after 6 hours of experiment, $Q = 0.025 \text{ m}^3\text{s}^{-1}$.

Model SU₄

The main body of this model is similar to the model SU₁. Fourty piers were added in five rows to the weir in a way to dissipate the water energy. The experimental results show that the piers play an important role in dissipating water energy and reducing the scour depth, where the maximum depth of scour was about 0.05 m at a distance of 0.08 m from the downstream edge of the weir (Figure 6.25). The scour region downstream the weir is retreated to be extended just 0.2 m from the downstream end of the weir (Figures 6.27 – 6.29). It is valuable to compare the performance of the two models, SU₁ and SU₄ where it is noticed that the percentage of scour reduction by using the piers was 64.5%, 61% and 58.3 % for the three given discharges $0.015 \text{ m}^3 \text{ s}^{-1}$, $0.02 \text{ m}^3 \text{ s}^{-1}$ and $0.025 \text{ m}^3 \text{ s}^{-1}$, respectively.



Figure 6.25 Scour region downstream the weir SU₄.



Figure 6.26 Physical Model SU₄. a. side view, b. top view.

In the figures (6.30 – 6.32) that represent the actual images of the runoff six hours after start the experiment, there is a large dissipation of flow energy during the forty pillars that have been placed on the weir, which led to reducing the percentage of scour depth behind the weir approximately two thirds compared to what happened in the model SU₁.

This reduction in the depth of scour indicates that the addition of peirs played a big role in that by collision water on it, and also the intertwining of vortex, dispersed the large water energy that came from its descent from the relatively large rise upstream the weir, which ranged between (0.64 – 0.66)m for three discharges used. escape of some eddies from among the peirs that can be clearly observed in the third discharge used in figure (6.32) calls for the necessity of placing the added part to break the eddies above it before reaches the sand layer.

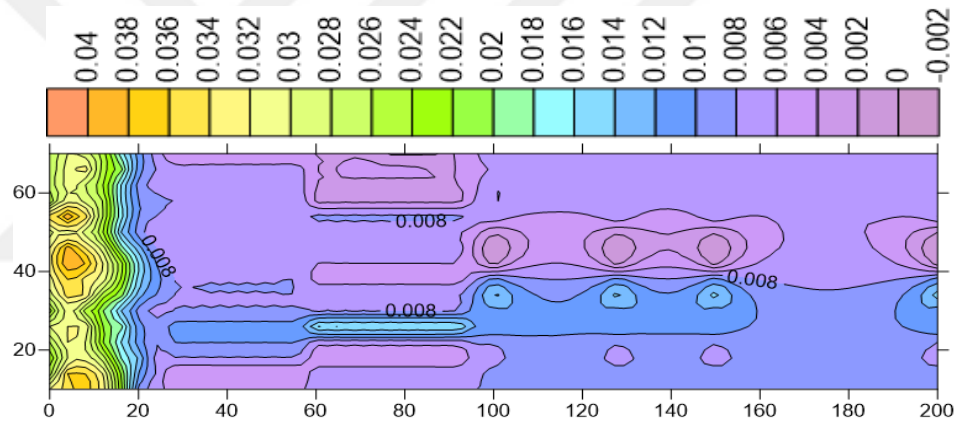


Figure 6.27 Scour contour lines downstream the weir SU4, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.

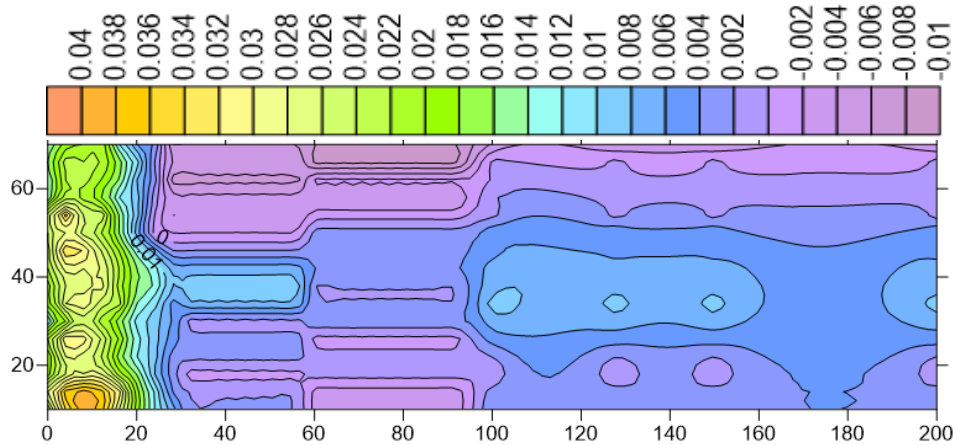


Figure 6.28 Scour contour lines downstream the weir SU4, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

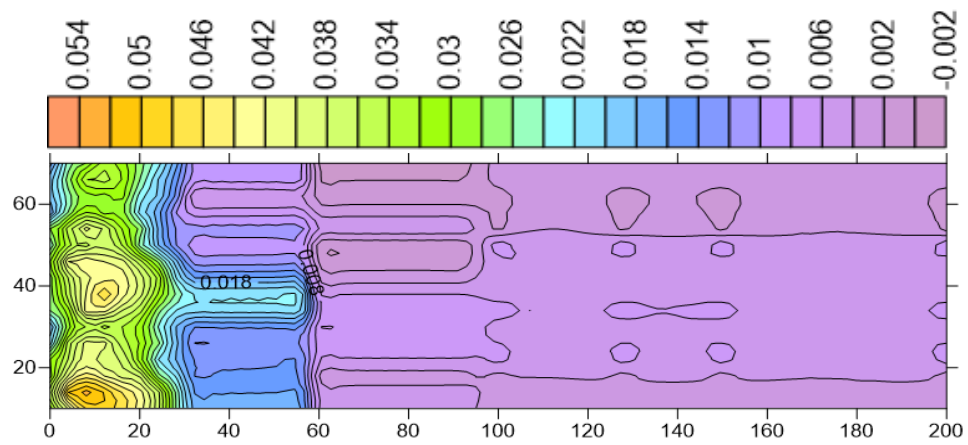


Figure 6.29 Scour contour lines downstream the weir SU4, $Q = 0.025 \text{ m}^3\text{s}^{-1}$.

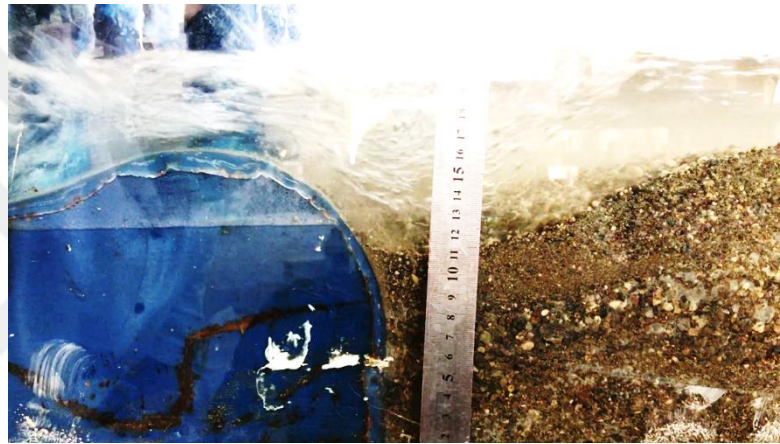


Figure 6.30 Scour depth behind the weir SU4 after 6 hours of experiment, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.



Figure 6.31 Scour depth behind the weir SU4 after 6 hours of experiment, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

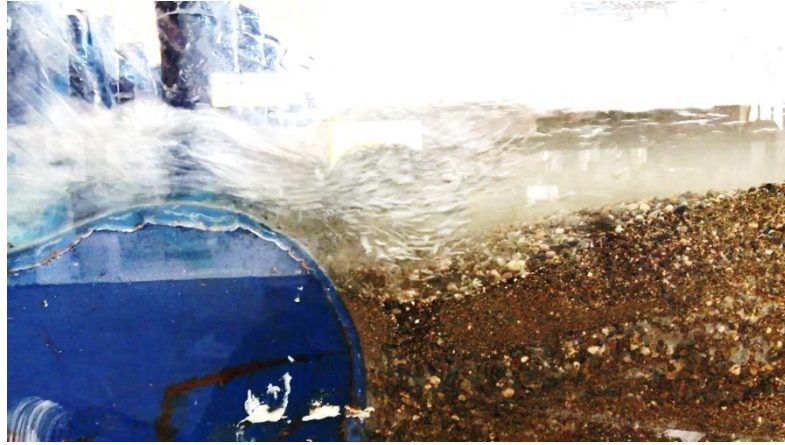


Figure 6.32 Scour depth behind the weir SU4 after 6 hours of experiment, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

Model SU₅

The experimental results obtained from this model clarified that the scour depth is reduced significantly. The additional part helped in dissipating much water energy of the outcoming flow throughout the piers (Figure 6.33). The scour region is reduced much more than the model SU₂ where the maximum depth of scour was oscillating between 0.018 m to 0.031 m just after the weir (Figures 6.35 – 6.37).



Figure 6.33 Scour region downstream the weir SU5.

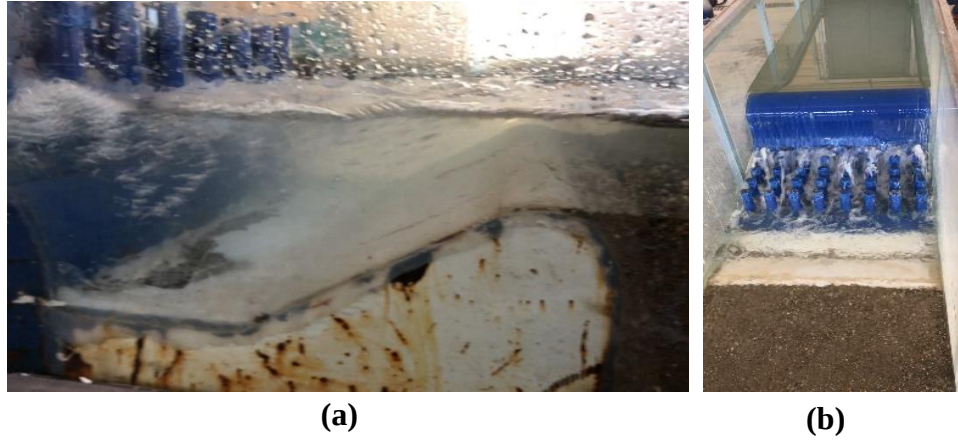


Figure 6.34 Physical Model SU5. a. side view, b. top view.

There is no longer a clear and visible escape of the vortex figure(6.34), exception a few of them that caused erosion in the sandy layer figures(6.38 – 6.40), where the added part had a great role in destroying the vortex and dispersing it energy before reaching the sandy layer, perhaps if a small improvement in the design was made, it would make scour is minimal, the turbulence of water can be seen only on the body of the weir while it appears calm just before and above the sand layer.

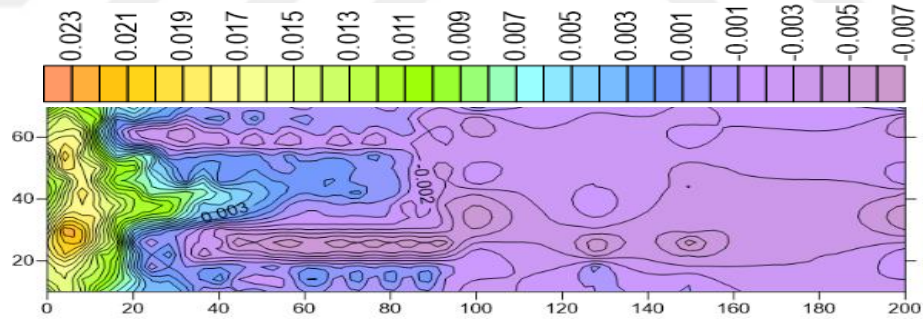


Figure 6.35 Scour contour lines downstream the weir SU5, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.

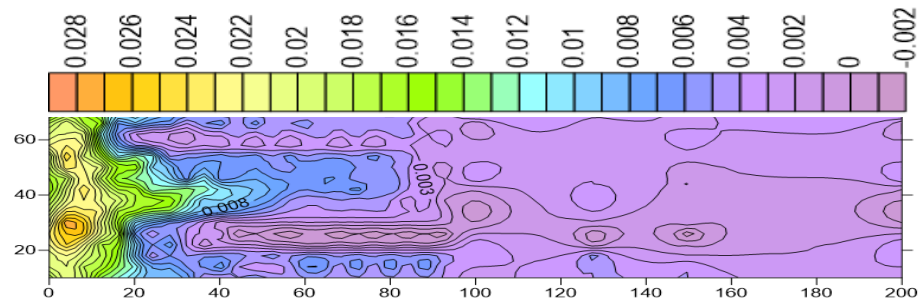


Figure 6.36 Scour contour lines downstream the weir SU5, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

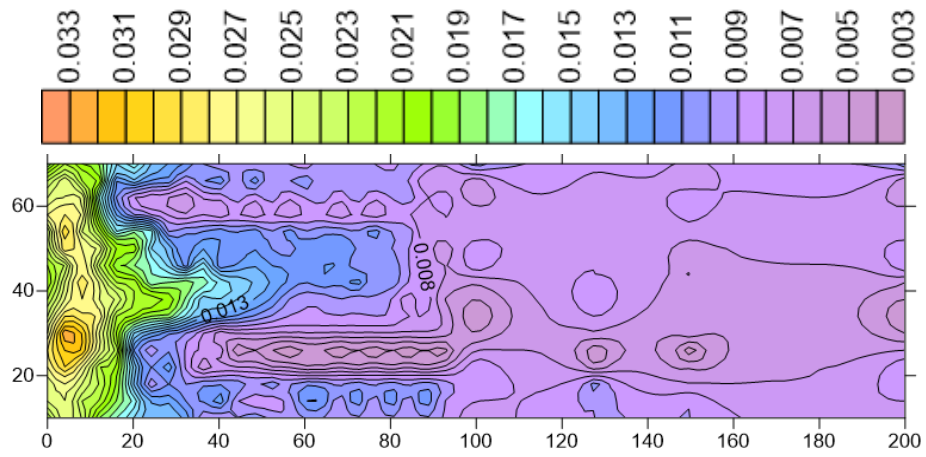


Figure 6.37 Scour contour lines downstream the weir SU5, $Q = 0.025 \text{ m}^3\text{s}^{-1}$.

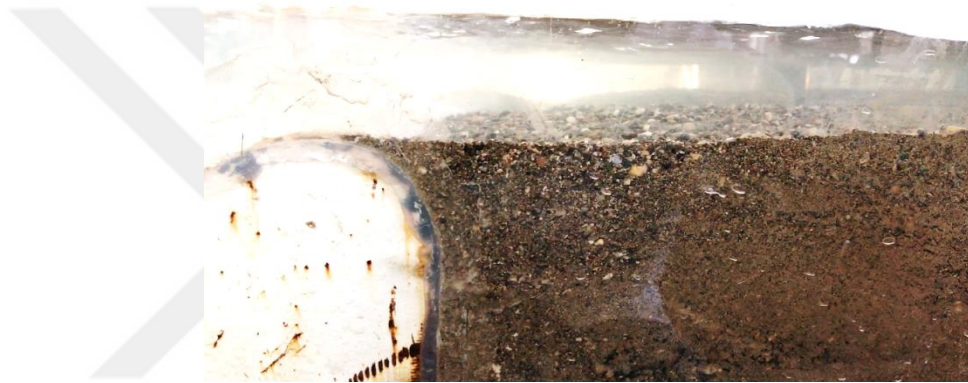


Figure 6.38 Scour depth behind the weir SU5 after 6 hours of experiment, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.



Figure 6.39 Scour depth behind the weir SU5 after 6 hours of experiment, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.



Figure 6.40 Scour depth behind the weir SU5 after 6 hours of experiment, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

Model SU₆

In this model, (Figure 6.41.) even that the ramp contributes in dropping the water force, the high inclination angle of the ramp increased the scour depth unlike what happened in model SU₅. Frequent shallow holes are created on the sand surface and extended about 0.9 m on the longitudinal centerline downstream the weir (Figures 6.43 – 6.45). The maximum scour depth is ranged between 0.026 m to 0.035 m at a distance of 0.04 m from the weir end.



Figure 6.41 Scour region downstream the weir SU6.

In the table (6.6) it is possible to observe the dimensions of the scour hole for each discharge, as well as the height of the water above the weir and its end, in addition height of two crests in the upper and lower parts.



Figure 6.42 Physical Model SU6. a. side view, b. top view.

It has also been explained that the added portion in the form of a triangular ramp did not give better results than the model before SU₅, vortexes formed over the weir and extended to reach the sand layer creating greater erosion than what happened in the previous model, (Figure 6.42.) according to similar models that will be used later, the cause of erosion is due to height value of the rump angle and the short length of the additional part, where the figures (6.46 – 6.48) show what happened to the sand layer using this model(SU₆).

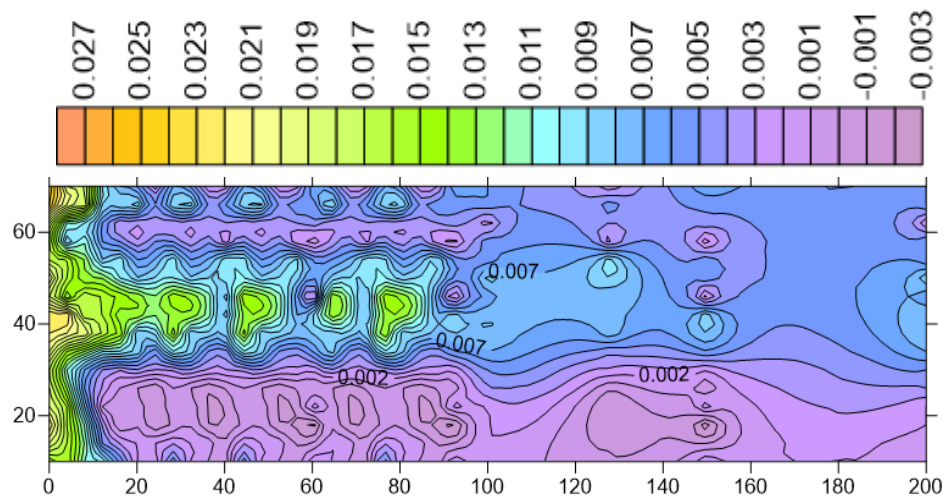


Figure 6.43 Scour contour lines downstream the weir SU6, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.

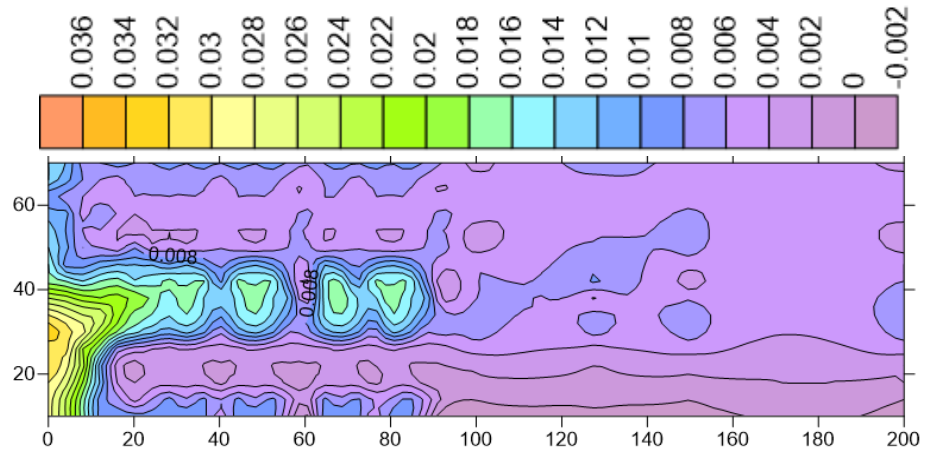


Figure 6.44 Scour contour lines downstream the weir SU6, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

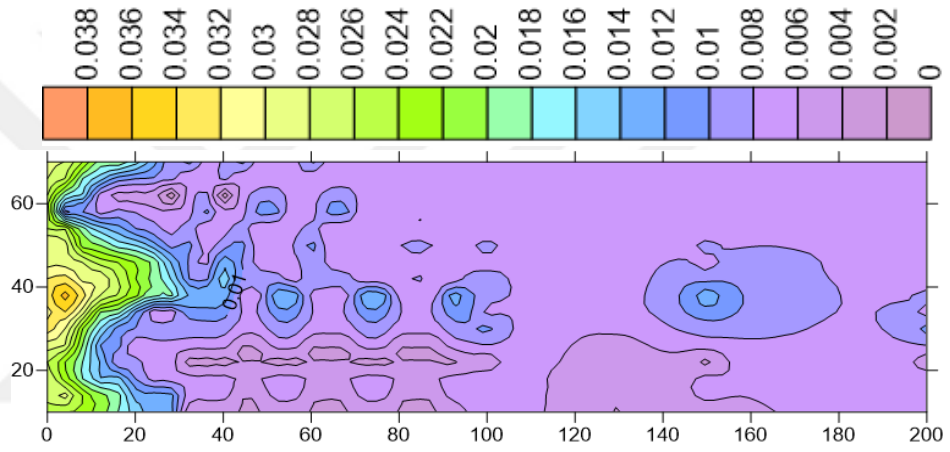


Figure 6.45 Scour contour lines downstream the weir SU6, $Q = 0.025 \text{ m}^3\text{s}^{-1}$.



Figure 6.46 Scour depth behind the weir SU6 after 6 hours of experiment, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.



Figure 6.47 Scour depth behind the weir SU6 after 6 hours of experiment, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

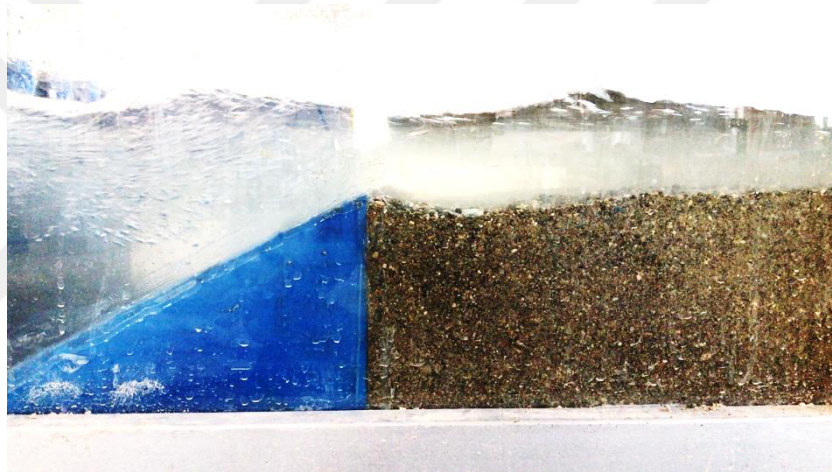


Figure 6.48 Scour depth behind the weir SU6 after 6 hours of experiment, $Q = 0.025 \text{ m}^3\text{s}^{-1}$.

Model SU₇

In this case, a different shape of the additional part has been suggested to improve the performance where the results were satisfactory. Regarding experimental model SU₇, before running the experiment, it was expected that the basin designed after the piers helps in reducing the water energy. Unfortunately, what happened is that the water velocity in top of the created basin increased valuably and caused erosion (Figure 6.49). Although that the scour region is not extended too much, less than 0.2 m, especially at the maximum discharge, an erosion process is occurred (Figures 6.51 – 6.53).

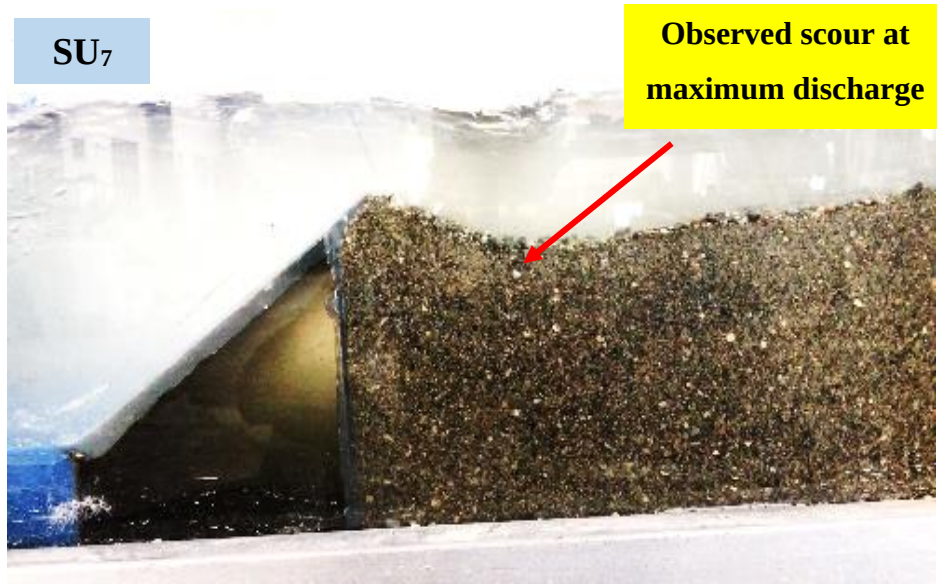


Figure 6.49 Scour region downstream the weir SU7.

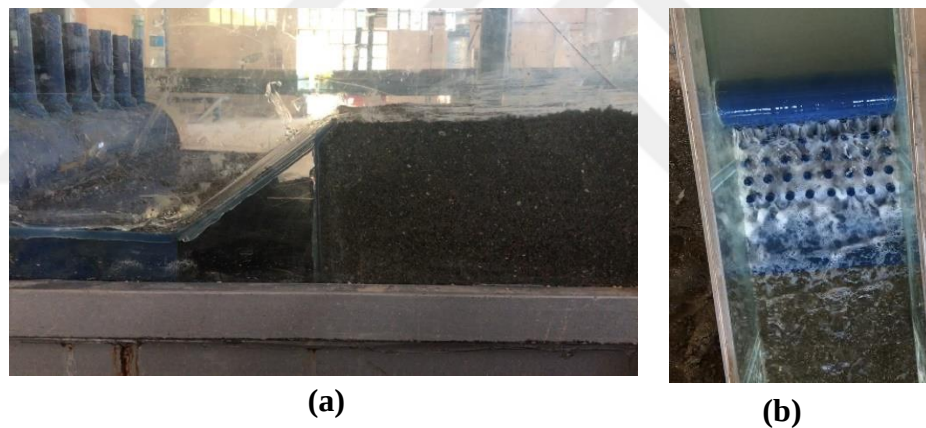


Figure 6.50 Physical Model SU7. a. side view, b. top view.

The results have shown similarities that occurred between the sixth model and the seventh model in performance, as keep the angle of Ramb at 37° , put a horizontal area used to make the water calm, (Figure 6.50.) but it did not add improvement in the performance of this model, found a relative decline compared to the sixth model SU₆.

Noticeable in the figures (6.54 – 6.56) that represent the truth of what happened after the continuation of the run for more than six hours, where the two discharges (0.015 , $0.020 \text{ m}^3\text{s}^{-1}$) performance of the model in them acceptable, as the vortices did not seen significantly across the weir end, while in the third discharge ($0.025 \text{ m}^3\text{s}^{-1}$) the

horizontal area that Designed before the ramp did not prevent the swirls from reaching the sand layer, so it is imperative to reduce the angle of the rump and increase the length of the additonal part so that we can obtain an efficient design

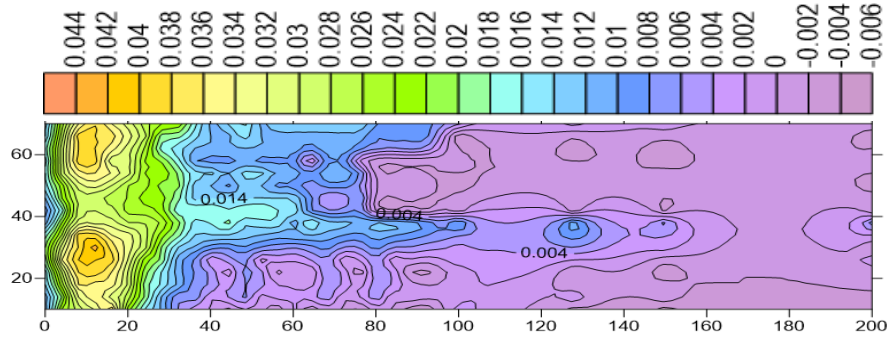


Figure 6.51 Scour contour lines downstream the weir SU7, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.

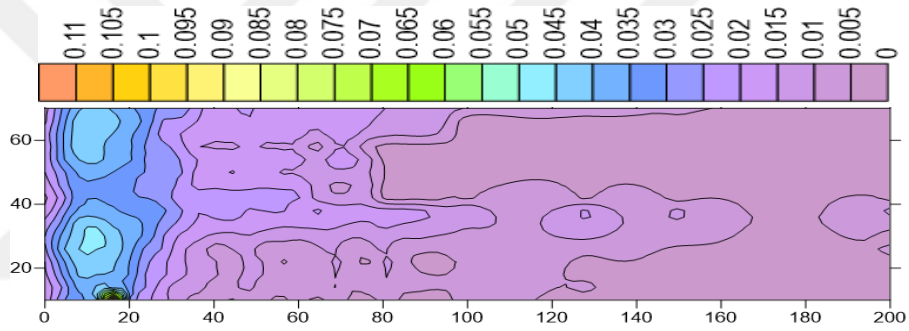


Figure 6.52 Scour contour lines downstream the weir SU7, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

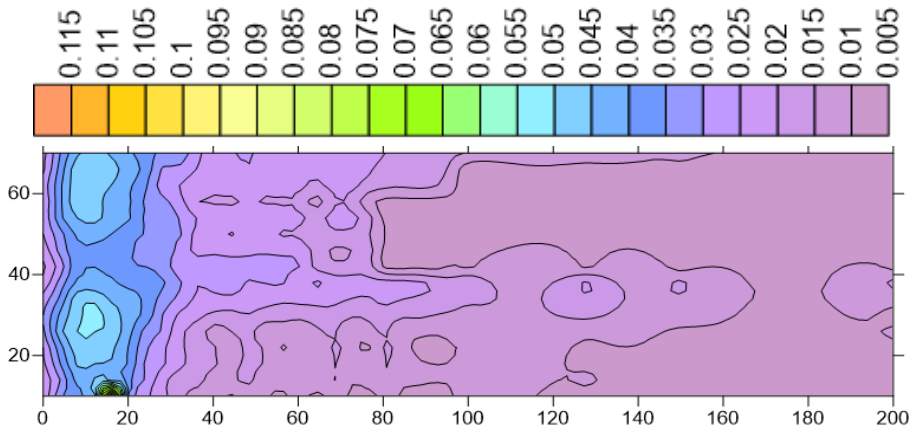


Figure 6.53 Scour contour lines downstream the weir SU7, $Q = 0.025 \text{ m}^3\text{s}^{-1}$.



Figure 6.54 Scour depth behind the weir SU7 after 6 hours of experiment, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.

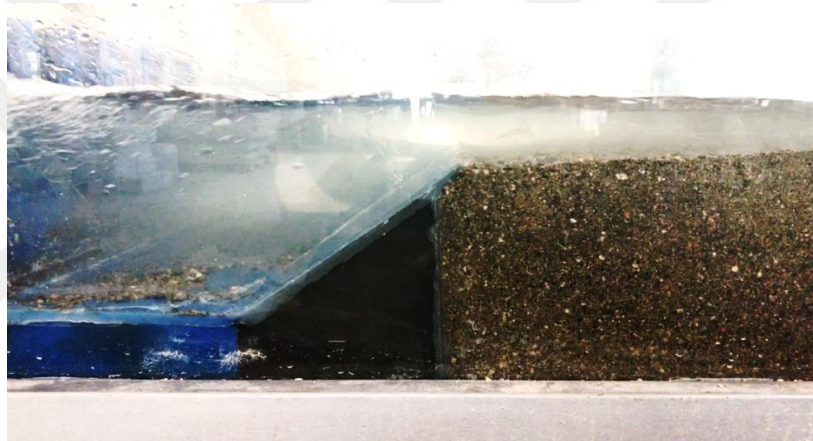


Figure 6.55 Scour depth behind the weir SU7 after 6 hours of experiment, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

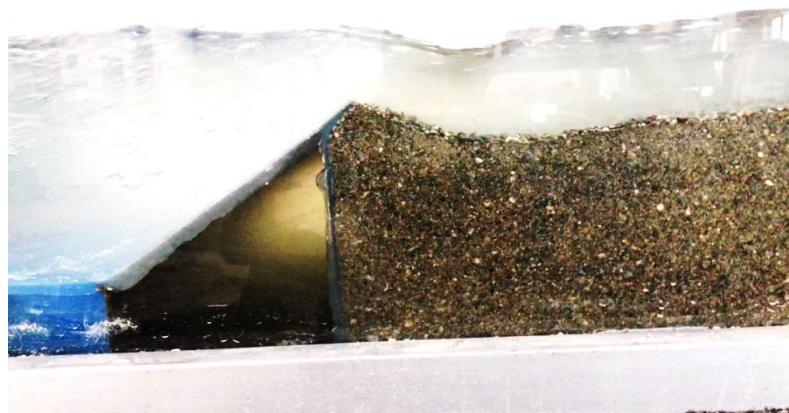


Figure 6.56 Scour depth behind the weir SU7 after 6 hours of experiment, $Q = 0.025 \text{ m}^3\text{s}^{-1}$.

Model SU₈

As mentioned earlier in this chapter, several attempts were conducted and many efforts were made to reach a free of scour, stable and efficient design. The obtained results show that water currents are quiet over and after the added part where this phenomenon results in a very low scour (Figure 6.57). It is observed that the scour depth does not exceed 0.01 m over the sand layer under different flow conditions (Figures 6.59- 6.61).



Figure 6.57 Scour region downstream the weir SU8.

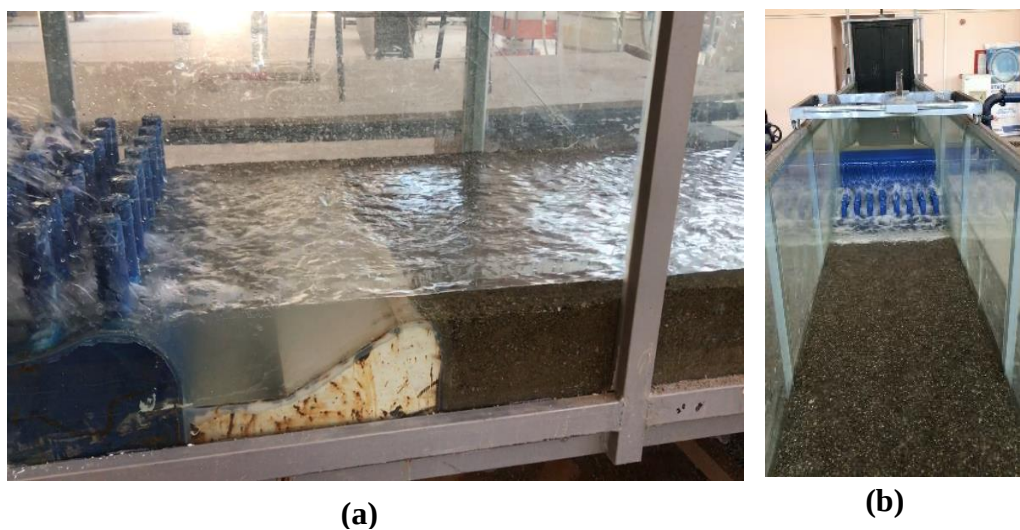


Figure 6.58 Physical Model SU8. a. side view, b. top view.

After the modification procedures in the design of the previous models, especially the second model(SU₂) and the fifth model(SU₅), came to design this model, Figure (6.58), to note that the eddies broke over the body of the weir and the additional part, make the flow quiet, regular, free of eddies, whatever the velocity of the flow changed, but performance the model remains constant in its results, figures (6.62– 6.64).

The model was able to disperse energy greatly, as the difference was large between the water level upstream of the weir and down stream water level, and despite the kinetic energy was completely dispersed to give this model a great distinctive shape and a major coup in the weirs design. All of the contour line graphics should be explained in details. How they were obtained and what they represent.

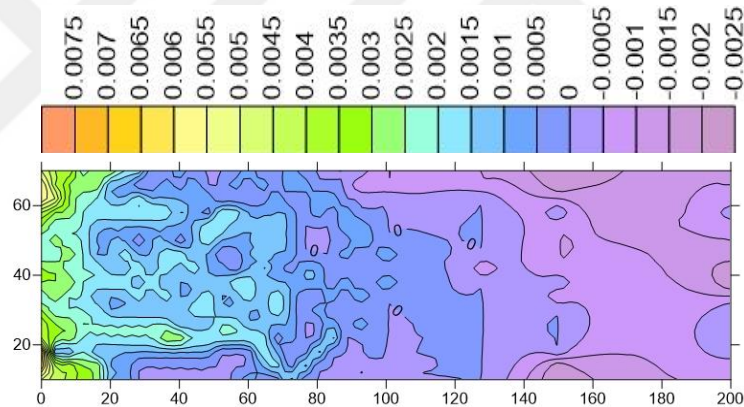


Figure 6.59 Scour contour lines downstream the weir SU8, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.

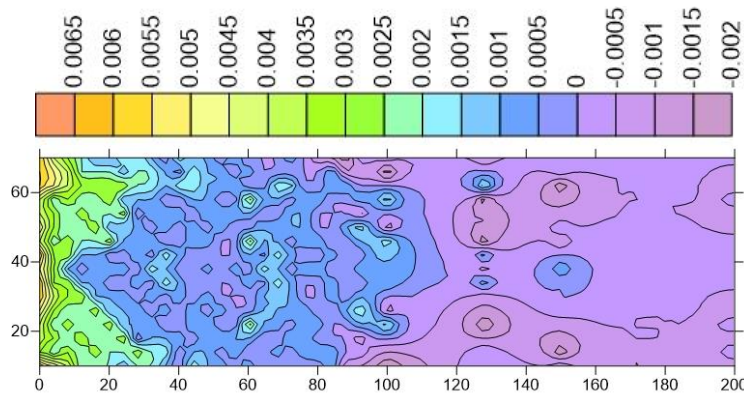


Figure 6.60 Scour contour lines downstream the weir SU8, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

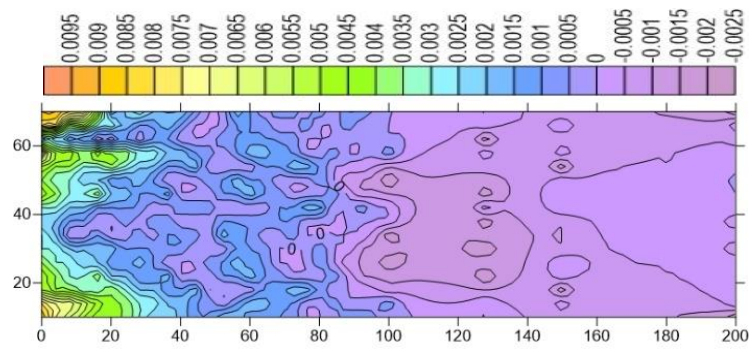


Figure 6.61 Scour contour lines downstream the weir SU8, $Q = 0.025 \text{ m}^3\text{s}^{-1}$.



Figure 6.62 Scour depth behind the weir SU8 after 6 hours of experiment, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.



Figure 6.63 Scour depth behind the weir SU8 after 6 hours of experiment, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.



Figure 6.64 Scour depth behind the weir SU8 after 6 hours of experiment, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

Model SU₉

The results obtained from the experiments conducted on this model exceeded all expectations and gave great hope that the hydraulic installations can be built safely without the risk of soil erosion due to obstruction. This weir was the most efficient design among all the weirs under study. Moreover, all the trials efforted by many researchers were focused on reducing the scour depth, not getting a free of scour model. the experimental results show that the scour depth does not exceed a few millimeters, less than 0.005 m, for the three given discharges.

If no laser point gage is used to read the levels of the sand layer after completing the experiment, it would be difficult to notice any change on the sandy surface behind the weir (Figure 6.65) where the scour was negligible and difficult to be seen (Figures 6.67 – 6.69). This model was distinguished by its unique design, which was distinguished by the fact that the added part was the most easy-to-implement.



Figure 6.65 Scour region downstream the weir SU₉.

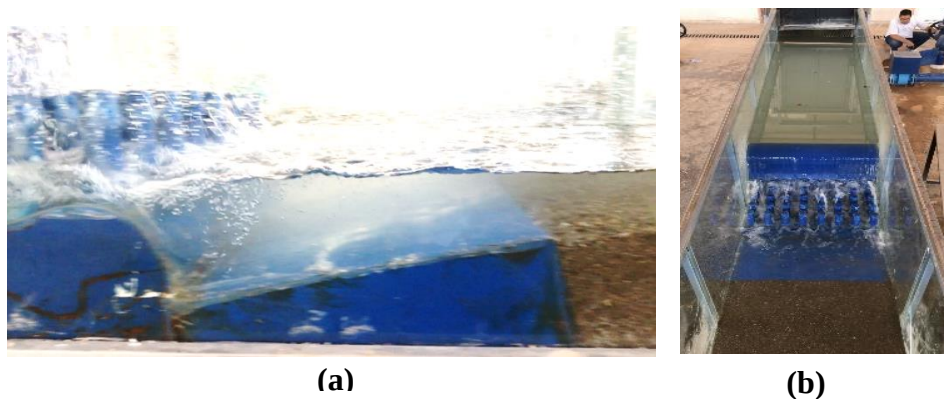


Figure 6.66 Physical Model SU₉. a. side view, b. top view.

Through analyzing all the studied models, SU₉ was the most performal model where it is not seen any disturbance above it, Figure (6.66). Change the rump angle from 37° to 11° and increasing length of additional part gives the model efficiency cannot be compared with any other model, figures (6.70 – 6.72). The flow was very quiet within six hours of experiment with all different discharges approved In this study.

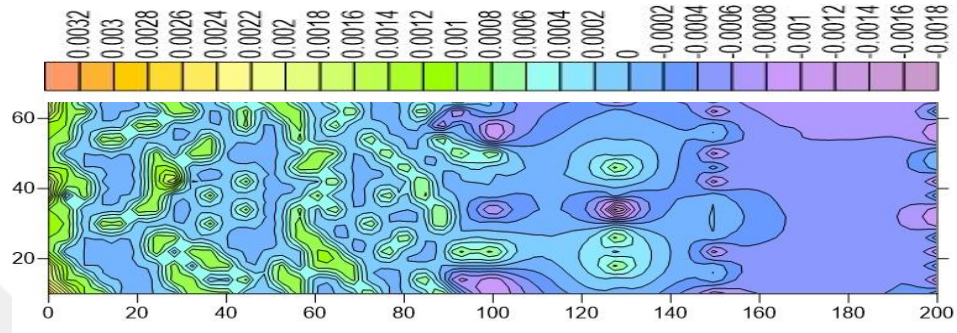


Figure 6.67 Scour contour lines downstream the weir SU9, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.

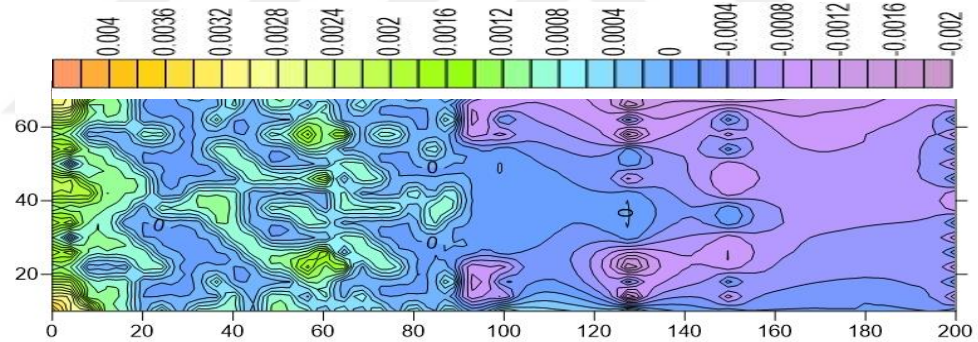


Figure 6.68 Scour contour lines downstream the weir SU9, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.

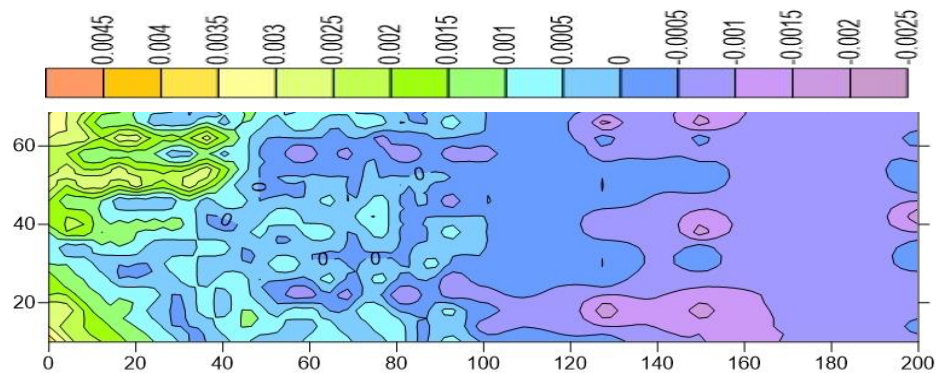


Figure 6.69 Scour contour lines downstream the weir SU9, $Q = 0.025 \text{ m}^3\text{s}^{-1}$.

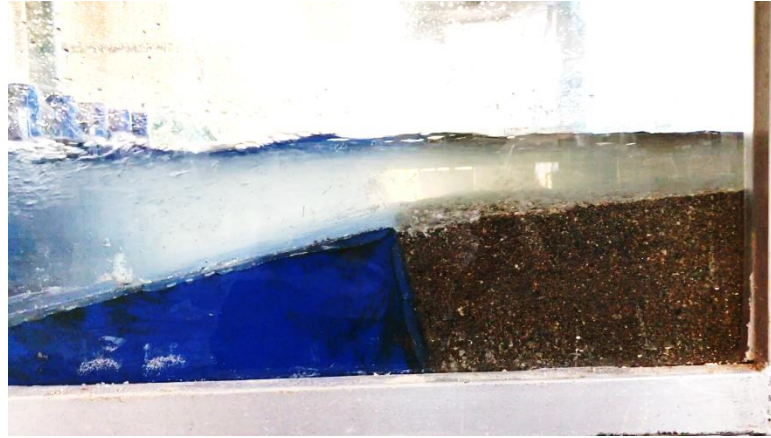


Figure 6.70 Scour depth behind the weir SU9 after 6 hours of experiment, $Q = 0.015 \text{ m}^3\text{s}^{-1}$.

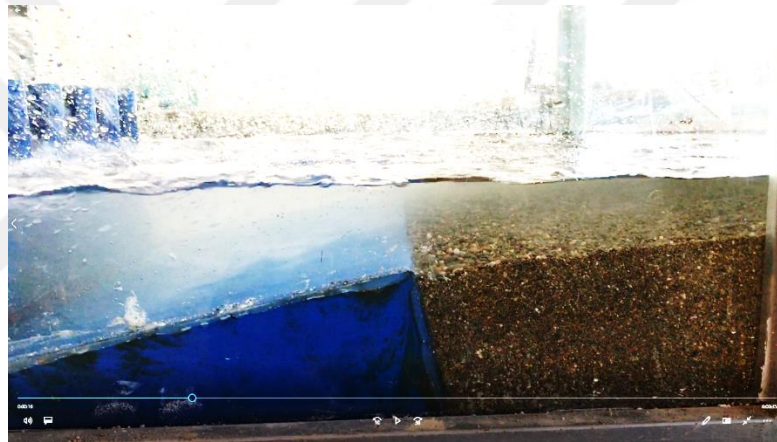


Figure 6.71 Scour depth behind the weir SU9 after 6 hours of experiment, $Q = 0.02 \text{ m}^3\text{s}^{-1}$.



Figure 6.72 Scour depth behind the weir SU9 after 6 hours of experiment, $Q = 0.025 \text{ m}^3\text{s}^{-1}$.

6.3 Percentage of scour reduction

Among all the proposed designs used to reduce scour behind the weirs, it was found that the eighth and ninth models, SU₈ and SU₉, are the best structures compared to the first model SU₁, where they were able to reduce the scour proportion about 94% and 97%, respectively (Table 6.10). Then it is followed in preference the fifth SU₅ and sixth SU₆ models (80%,72%), respectively. While the fourth SU₄ and seventh SU₇ models showed similar scour reduction percentage (60%). Nevertheless, the second SU₂ demonstrated about 50% reduction in scour. Regarding the third model, SU₃, the scour is decreased about 30% in comparison to the first model.

6.4 Water Surface Profile (WSP)

The importance of plotting the experimental water surface profile comes to get indication whether the water flows smoothly over the weir or not and to check the existence of any other phenomenon, such as hydraulic jumps.

- Water surface profile (WSP) of SU₁

Regarding the first model, SU₁, nothing is added to the main body to dissipate the energy, therefore, water jump is created above the downstream part of the weir what pushed the vortices a distance from the weir body. As a result, water depth is increased downstream the weir due to the created scour hole, which is formed due to the severe water fall above the sand layer (Figure 6.73).

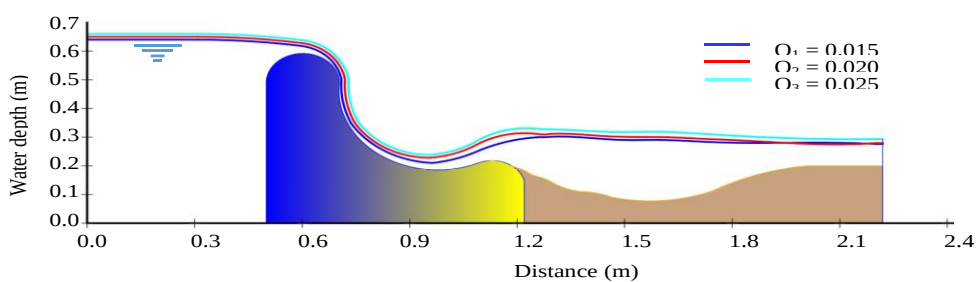


Figure 6.73 Water surface profile (WSP) of SU₁ for the three given discharges.

- Water surface profile (WSP) of SU₂

In the second model, SU₂, the water energy dissipater plays an important role in breaking the progressive velocity of water and reduce the depth of water downstream the weir (Figure 6.74).

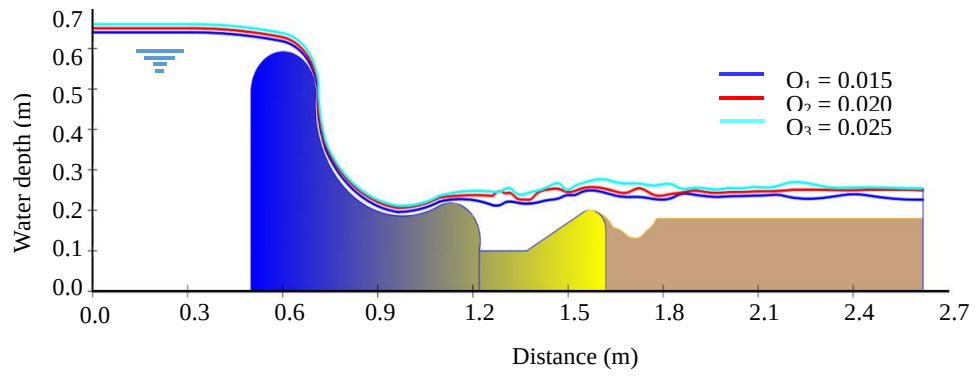


Figure 6.74 Water surface profile (WSP) of SU_2 for the three given discharges.

- Water surface profile (WSP) of SU_3

The third model, SU_3 , comes in performance between the first and the second model (Figure 6.75).

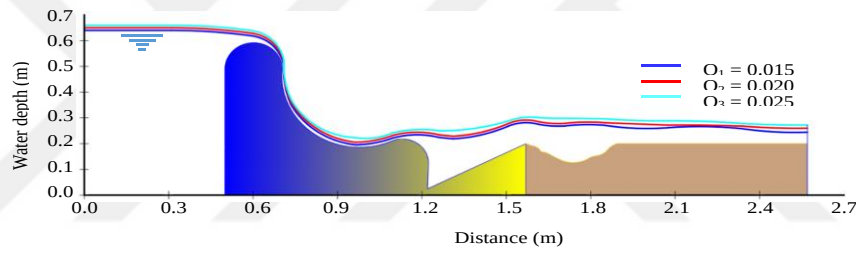


Figure 6.75 Water surface profile (WSP) of SU_3 for the three given discharges.

- Water surface profile (WSP) of SU_4

Regarding the fourth model, SU_4 , the piers are the only part that is added to the weir. The frontal area of the piers works like an obstacle and broke down the velocity of water that decreases the turbulence downstream the weir. (Figure 6.76).

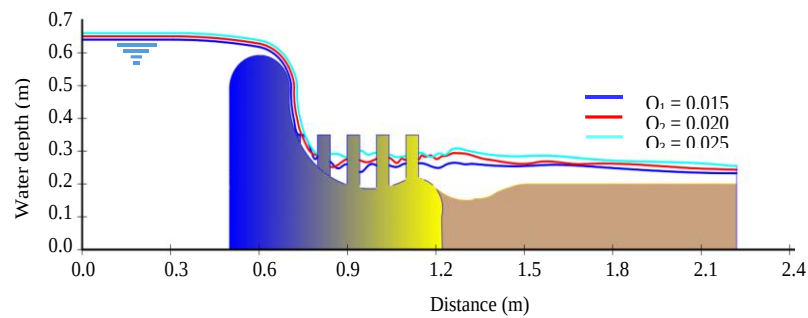


Figure 6.76 Water surface profile (WSP) of SU_4 for the three given discharges.

- Water surface profile (WSP) of SU₅

After adding the second part to the weir, as in the fifth model, SU₅, the water energy is dissipated significantly unlike the fourth model (Figure 6.77).

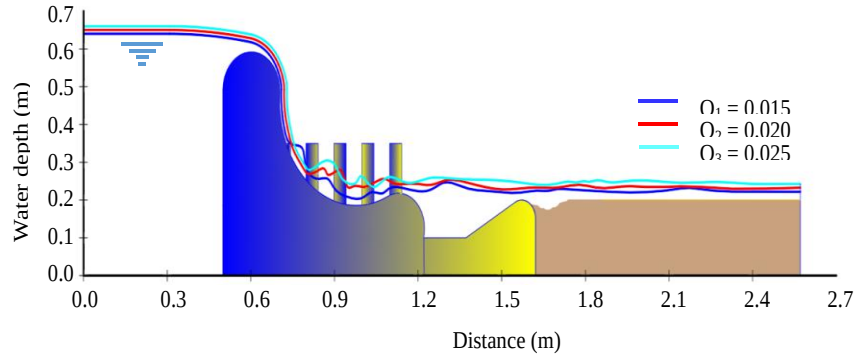


Figure 6.77 Water surface profile (WSP) of SU₅ for the three given discharges.

- Water surface profile (WSP) of SU₆

As in the fifth model, after adding the second part to the weir, the water energy in the sixth model is dissipated significantly as well (Figure 6.78).

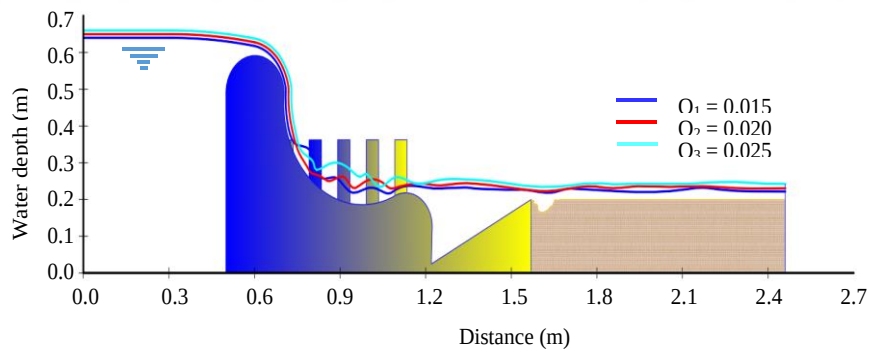


Figure 6.78 Water surface profile (WSP) of SU₆ for the three given discharges.

- Water surface profile (WSP) of SU₇

In this model, two energy dissipaters were added to the main body of weir, the difference was only in designing the second part. The second part affected valuably on the flow pattern where the water currents flows smoothly over the additional section and the sand layer (Figure 6.79).

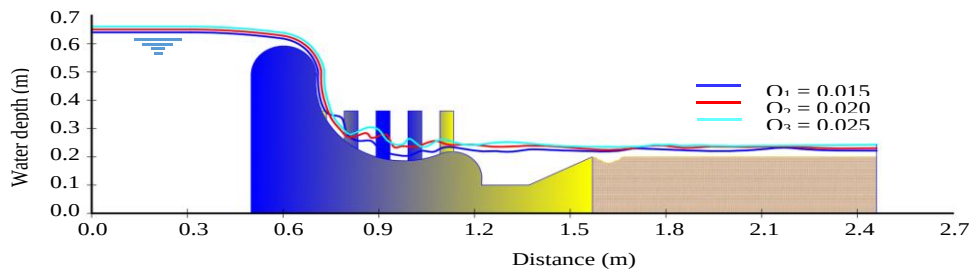


Figure 6.79 Water surface profile (WSP) of SU₇ for the three given discharges.

- Water surface profile (WSP) of SU₈

Due to the basin created between the main body and the additional part, the water surface was almost smooth over the downstream part of weir and continued smoothly with a shallow depth over the sand layer (Figure 6.80).

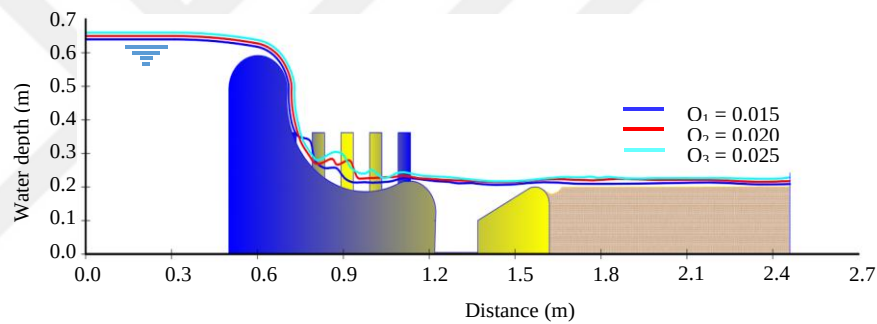


Figure 6.80 Water surface profile (WSP) of SU₈ for the three given discharges.

- Water surface profile (WSP) of SU₉

In this model, the two energy dissipaters added to the main body of weir contribute in absorption water energy and break down scour occurrence (Figure 6.81).

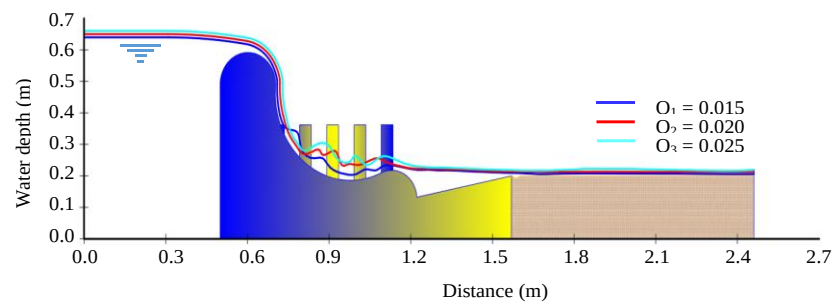


Figure 6.81 Water surface profile (WSP) of SU₉ for the three given discharges.

6.5 Energy Dissipation Could be explained together for all cases

The weir model is designed with a crest height of 0.59 m that increases water level upstream the weir. The water stored in the channel due to the obstacle holds an enormous potential energy which will be converted to kinetic energy over and downstream the weir. If no cautions are taken to avoid the high velocity behind the weir, which is expected to be occurred due to the kinetic water energy, the bed material will be eroded and causes structural failure. All findings are summarized in Table 6.2.

- Evaluating the ability of weirs to dissipate water energy: SU₁

Despite the efficiency of all models, it is noticed that the water diverged away from this weir is flowing with a huge kinetic energy, which increases the scour downstream the weir. The ability of weir to break down water energy was about 56.86 %, in average.

- Evaluating the ability of weirs to dissipate water energy: SU₂

The second model, SU₂, shows a good performance compared to the other. The energy dispersion for the three discharges used in the experiments was about 61.51%, in average.

- Evaluating the ability of weirs to dissipate water energy: SU₃

The energy dissipation ranged in this model was about 59.7%. The performance of this model compared to the first and second models was in between.

- Evaluating the ability of weirs to dissipate water energy: SU₄

As explained before, this model is similar in design to the first model except the piers added to the main body of SU₄ as energy dissipaters. However, the reduction of energy compared to the first model is valuable while it is still insignificant compared to other where the water energy downstream the weir is decreased about 59.71% in comparison to the energy upstream the weir.

- Evaluating the ability of weirs to dissipate water energy: SU₅

The fifth model, SU₅, which is similar to the second model SU₂ except the forty piers added to the inner surface, increased the dispersion of water energy about 61.9%.

- Evaluating the ability of weirs to dissipate water energy: SU₆

The sixth model SU₆ comes in the second stage in performance compared to the model SU₅ where the water energy is reduced about 60.63 %.

- Evaluating the ability of weirs to dissipate water energy: SU₇

Despite of the new design of the external part added to this model, the performance was not good enough compared to the other cases included in this study. The energy dissipation was about 58.47%, which is closed to the first model with an increment just about 1.6%.

- Evaluating the ability of weirs to dissipate water energy: SU₈

In this model, the performance was the best among all the cases discussed previously. The energy of water is decreased enormously about 63.62 %.

- Evaluating the ability of weirs to dissipate water energy: SU₉

The value of energy dispersal in this model reached about 65.36 %. This value is considered as the highest dissipation obtained from the experiments conducted on all the given designs. This weir also presents the best in reducing scour as there was no noticeable scour behind it.

Table 6.2 Energy Dissipation

Model	Q (m ³ s ⁻¹)	Fr	ΔE %
SU ₁	0.015	0.222	57.146
	0.02	0.252	57.012
	0.025	0.273	56.443
SU ₂	0.015	0.407	62.545
	0.02	0.543	61.711
	0.025	0.441	60.266
SU ₃	0.015	0.264	60.418
	0.02	0.295	59.867
	0.025	0.315	58.794
SU ₄	0.015	0.379	60.614
	0.02	0.431	59.71

Table 6.2 Continued

	0.025	0.441	58.831
	0.015	0.627	62.905
SU ₅	0.02	0.759	61.876
	0.025	0.753	60.861
	0.015	0.569	61.389
SU ₆	0.02	0.618	60.383
	0.025	0.678	60.125
	0.015	0.808	59.099
SU ₇	0.02	0.836	58.217
	0.025	0.841	58.096
	0.015	0.876	64.42
SU ₈	0.02	0.895	63.369
	0.025	0.92	63.067
	0.015	0.748	65.935
SU ₉	0.02	0.864	65.608
	0.025	0.979	64.538

6.6 Experimental scour development

The scour is affected by time in addition to other influences mentioned previously, such as the shape of weir and flow characteristics, so all experiments were conducted in the laboratory for a period of six hours to give enough time for observing the variables, as it is noticed that the scour stabilizes in some models for the first two hours, and the other settles in four hours.

6.6.1 Scour development with time: SU₁

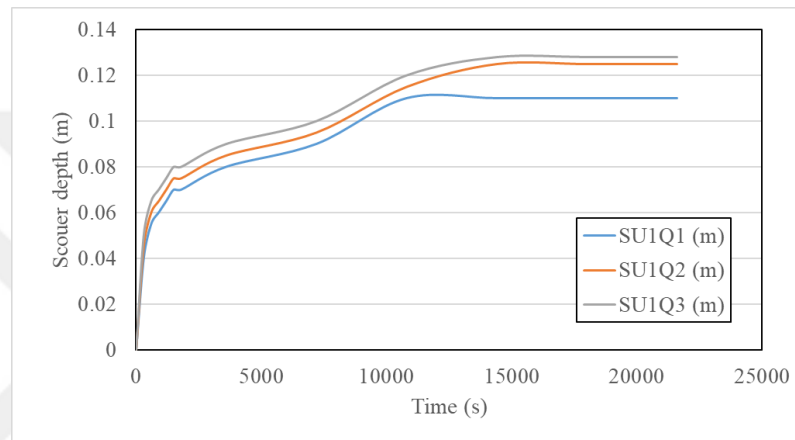
This model SU₁ has disturbances flow and vortices that continued during the first and a half hour, the scour value reached (0.08 m, 0.085 m, 0.09 m) for the three given discharges $0.015 \text{ m}^3\text{s}^{-1}$, $0.02 \text{ m}^3 \text{ s}^{-1}$ and $0.025 \text{ m}^3\text{s}^{-1}$, respectively (Table 6.20). The scour continues increasing to (0.11m, 0.115 m, 0.12 m) after four hours, then it remained stable to the end of 6 hours of experiment, Figure (6.82).

Table 6.3 Scour development with time at different flow conditions: SU1

Time (sec)	Q ₁ (m)	Q ₂ (m)	Q ₃ (m)
0	0	0	0
300	0.04	0.045	0.05
600	0.055	0.06	0.065
900	0.06	0.065	0.07
1200	0.065	0.07	0.075
1500	0.07	0.075	0.08

Table 6.3 Continued

1800	0.07	0.075	0.08
3600	0.08	0.085	0.09
7200	0.09	0.095	0.1
10800	0.11	0.115	0.12
14400	0.11	0.125	0.128
18000	0.11	0.125	0.128
21600	0.11	0.125	0.128

**Figure 6.82** Scour development with time at different flow conditions: SU1.

6.6.2 Scour development with time: SU2

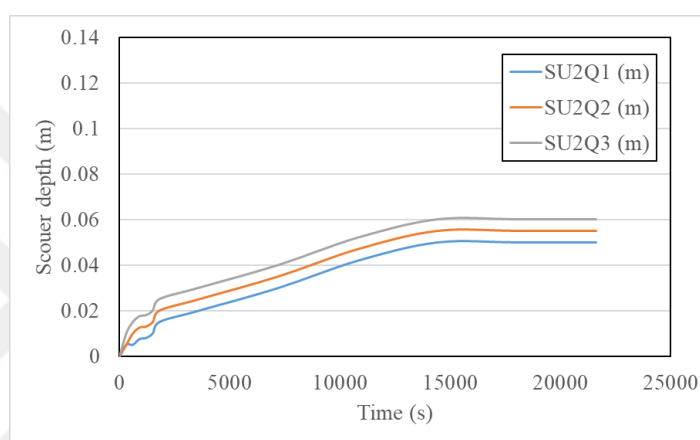
As for the second model SU_2 during the first half hour, scour reached (0.015, 0.02, 0.025) m for the three given discharges respectively then started to increase slightly until reached (0.045, 0.055, 0.065) m after four hours (Table 6.21.), then it continued with the same value until end of experiment at six hours and the value of scour in this model was better than the previous model SU_1 . Figure (6.83).

Table 6.4 Scour development with time at different flow conditions: SU2

Time (sec)	Q ₁ (m)	Q ₂ (m)	Q ₃ (m)
0	0	0	0
300	0.005	0.005	0.01
600	0.005	0.01	0.015
900	0.0075	0.0125	0.0175
1200	0.008	0.013	0.018

Table 6.4 Continued

1500	0.01	0.015	0.02
1800	0.015	0.02	0.025
3600	0.02	0.025	0.03
7200	0.03	0.035	0.04
10800	0.042	0.047	0.052
14400	0.05	0.055	0.06
18000	0.05	0.055	0.06
21600	0.05	0.055	0.06

**Figure 6.83** Scour development with time at different flow conditions: SU2.

6.6.3 Scour development with time: SU₃

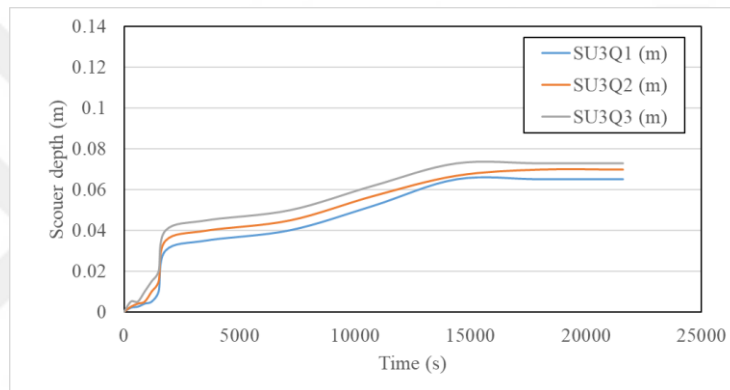
In the third model SU₃, the scour jumped during the first half hour to (0.025, 0.035, 0.04) m for the three given discharges, respectively (Table 6.22), and continued increasing gradually until reached after four and a half hours to (0.07, 0.075, 0.08) m to continue stable after that on the same value until the end of experiment, Figure (6.84).

Table 6.5 Scour development with time at different flow conditions: SU3

Time (sec)	Q ₁ (m)	Q ₂ (m)	Q ₃ (m)
0	0	0	0
300	0.002	0.0025	0.005
600	0.0025	0.004	0.005
900	0.004	0.005	0.01

Table 6.5 Continued

1200	0.005	0.01	0.015
1500	0.01	0.015	0.02
1800	0.03	0.035	0.04
3600	0.035	0.04	0.045
7200	0.04	0.045	0.05
10800	0.052	0.057	0.062
14400	0.065	0.067	0.073
18000	0.065	0.07	0.073
21600	0.065	0.07	0.073

**Figure 6.84** Scour development with time at different flow conditions: SU3.

6.6.4 Scour development with time: SU₄

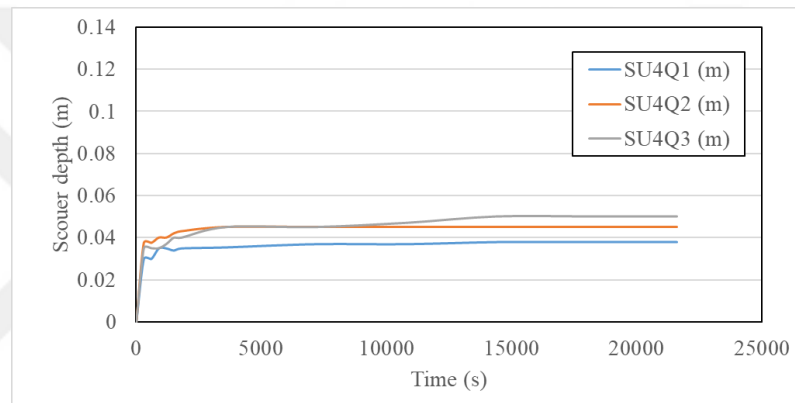
In the fourth model, SU₄, the scour depth was (0.03, 0.38, 0.04) m during the first five minutes. After that it increased slightly to settle after half an hour for the two discharges (0.015, 0.020 m³ s⁻¹) (0.039, 0.045 m), respectively (Table 6.23). As for the third discharge (0.025 m³ s⁻¹), the scour settled after four hours of experiment, Figure (6.85).

Table 6.6 Scour development with time at different flow conditions: SU₄

Time (sec)	Q ₁ (m)	Q ₂ (m)	Q ₃ (m)
0	0	0	0
300	0.03	0.0375	0.035
600	0.03	0.0375	0.035
900	0.035	0.04	0.035

Table 6.6 Continued

1200	0.035	0.04	0.037
1500	0.034	0.042	0.04
1800	0.035	0.043	0.04
3600	0.0355	0.045	0.045
7200	0.037	0.045	0.045
10800	0.037	0.045	0.047
14400	0.038	0.045	0.05
18000	0.038	0.045	0.05
21600	0.038	0.045	0.05

**Figure 6.85** Scour development with time at different flow conditions: SU4.

6.6.5 Scour development with time: SU₅

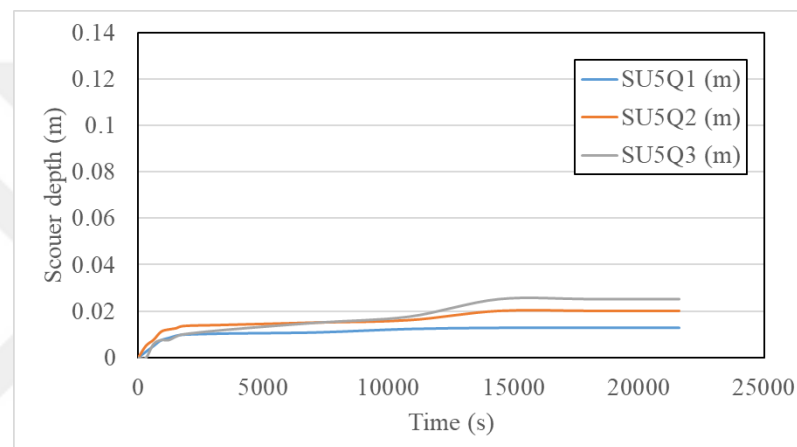
In this model, the scour has settled during the first (15) minutes of experiment for the first and second discharges ($0.015, 0.020 \text{ m}^3\text{s}^{-1}$) to be (0.018, 0.02 m) (Table 6.24) while the scour has settled for the third discharge ($0.025 \text{ m}^3\text{s}^{-1}$) after four hours to reach (0.03 m), Figure (6.86).

Table 6.7 Scour development with time at different flow conditions: SU5

Time (sec)	Q ₁ (m)	Q ₂ (m)	Q ₃ (m)
0	0	0	0
300	0.0025	0.005	0
600	0.005	0.0075	0.0058
900	0.0075	0.011	0.0075
1200	0.0085	0.012	0.0075

Table 6.7 Continued

1500	0.0095	0.0125	0.009
1800	0.01	0.0135	0.01
3600	0.0105	0.014	0.012
7200	0.011	0.015	0.015
10800	0.0125	0.016	0.0175
14400	0.013	0.02	0.025
18000	0.013	0.02	0.025
21600	0.013	0.02	0.025

**Figure 6.86** Scour development with time at different flow conditions: SU5.

6.6.6 Scour development with time: SU₆

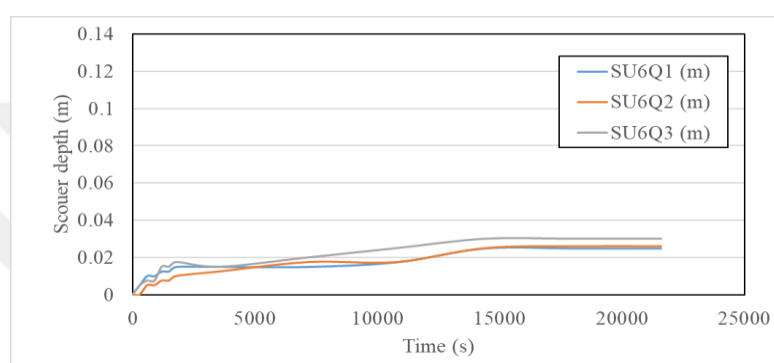
The model SU₆ occupied the second level after the fifth model SU₅ in reducing the scour value at downstream of weir. The scour is fluctuated during the first half hour of the experiment, so it became stable after four hours to be (0.026, 0.034, 0.035) m for the three given discharges (Table 6.25), Figure (6.87).

Table 6.8 Scour development with time at different flow conditions: SU6

Time (sec)	Q ₁ (m)	Q ₂ (m)	Q ₃ (m)
0	0	0	0
300	0.005	0	0.005
600	0.01	0.005	0.0075
900	0.01	0.005	0.0075
1200	0.0125	0.0075	0.015

Table 6.8 Continued

1500	0.0125	0.0075	0.015
1800	0.015	0.01	0.0175
3600	0.015	0.0125	0.015
7200	0.015	0.0175	0.02
10800	0.0175	0.0175	0.025
14400	0.025	0.025	0.03
18000	0.025	0.026	0.03
21600	0.025	0.026	0.03

**Figure 6.87** Scour development with time at different flow conditions: SU6.

6.6.7 Scour development with time: SU7

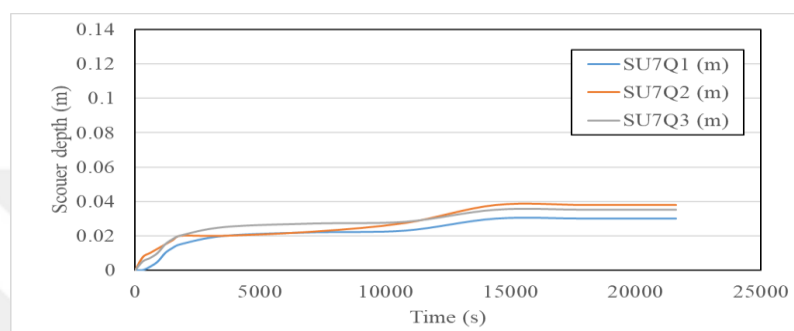
The efficiency of this model SU7 did not differ from the others shown previously in reducing scour. The value of scour during the first half hour of the experiment (0.011, 0.02, 0.02) m for the three given discharges (0.015, 0.020, 0.025 m^3s^{-1}) maintain its values through four hours (Table 6.26), and then reach (0.04, 0.045, 0.05) m until the end of experiment, Figure (6.88).

Table 6.9 Scour development with time at different flow conditions: SU7

Time (sec)	Q ₁ (m)	Q ₂ (m)	Q ₃ (m)
0	0	0	0
300	0	0.0075	0.005
600	0.002	0.01	0.007
900	0.005	0.0125	0.01
1200	0.01	0.015	0.015
1500	0.013	0.0175	0.018
1800	0.015	0.02	0.02

Table 6.9 Continued

3600	0.02	0.02	0.025
7200	0.022	0.0225	0.027
10800	0.023	0.0275	0.028
14400	0.03	0.038	0.035
18000	0.03	0.038	0.035
21600	0.03	0.038	0.035

**Figure 6.88** Scour development with time at different flow conditions: SU7.

6.6.8 Scour development with time: SU₈

The eighth model SU₈ was the best model in reducing scour and improving flow pattern unlike all the previous models (Table 6.27) Where the depth of scour hole settled within 20 minutes (0.005, 0.0065, 0.009) m and remained unchanged until the end of the experiment, Figure (6.89).

Table 6.10 Scour development with time at different flow conditions: SU8

Time (sec)	Q ₁ (m)	Q ₂ (m)	Q ₃ (m)
0	0	0	0
300	0	0	0
600	0	0	0
900	0.002	0.0025	0.0025
1200	0.002	0.0025	0.0025
1500	0.0025	0.003	0.003
1800	0.0028	0.004	0.005
3600	0.003	0.005	0.0075
7200	0.005	0.006	0.0095
10800	0.005	0.007	0.0095
14400	0.005	0.007	0.0095
18000	0.005	0.007	0.0095
21600	0.005	0.007	0.0095

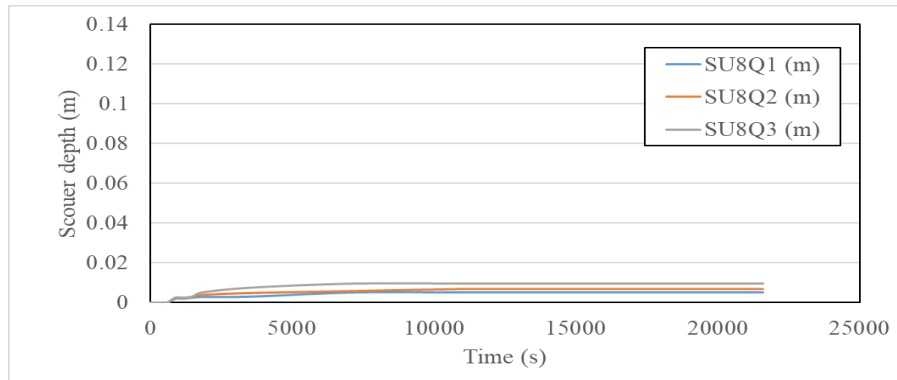


Figure 6.89 Scour development with time at different flow conditions: SU8.

6.6.9 Scour development with time: SU₉

The last model examined in the present study, SU₉, was the best and the most efficient weir as no noticeable scour was observed from the beginning of experiment until the end (Table 6.28), Figure (6.90).

Table 6.11 Scour development with time at different flow conditions: SU9

Time (sec)	Q ₁ (m)	Q ₂ (m)	Q ₃ (m)
0	0	0	0
300	0	0	0.001
600	0	0	0.001
900	0	0	0.002
1200	0	0.001	0.002
1500	0	0.001	0.0025
1800	0.001	0.001	0.003
3600	0.002	0.002	0.003
7200	0.002	0.0025	0.0035
10800	0.0025	0.0025	0.0035
14400	0.0025	0.003	0.0035
18000	0.0025	0.003	0.0035
21600	0.0025	0.003	0.0035

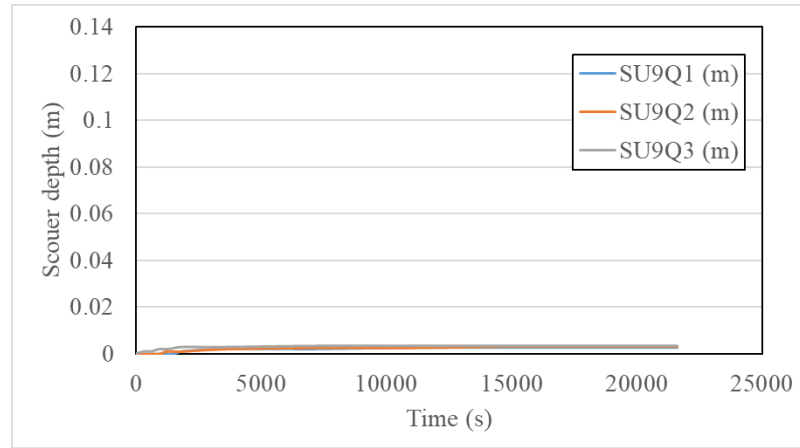


Figure 6.90 Scour development with time at different flow conditions: SU9.

Table 6.12 Flow 3D program results against Experimental records

Model	Q ($\text{m}^3 \text{s}^{-1}$)	Max. depth of scour (m)		Distance of scour from weir (m)		Scour reduction %	
		CFD	Exp.	CFD	Exp.	CFD	Exp.
SU ₁	0.015	0.051	0.11	0.15	0.20	0	0%
	0.020	0.086	0.115	0.16	0.20	0	0%
	0.025	0.110	0.12	0.20	0.21	0	0%
SU ₂	0.015	0.025	0.045	0.07	0.08	50.9%	59%
	0.020	0.0317	0.055	0.085	0.08	63.1%	52.2%
	0.025	0.0705	0.065	0.11	0.08	35.9%	45.8%
SU ₃	0.015	0.0226	0.07	0.075	0.16	55.7%	36.3%
	0.020	0.0323	0.075	0.08	0.16	62.4%	34.7%
	0.025	0.0341	0.08	0.075	0.16	69%	33.3%
SU ₄	0.015	0.0325	0.039	0.065	0.08	36.2%	64.5%
	0.020	0.0337	0.045	0.075	0.08	60.8%	60.8%
	0.025	0.065	0.05	0.078	0.08	40.9%	58.3%
SU ₅	0.015	0.020	0.018	0.035	0	60.7%	83.6%
	0.020	0.033	0.02	0.04	0	61.6%	82.6%
	0.025	0.0126	0.031	0.055	0.04	88.5%	74.1%
SU ₆	0.015	0.0107	0.026	0.045	0.04	79%	76.3%
	0.020	0.0244	0.034	0.06	0.04	71.6%	70.4%
	0.025	0.0273	0.035	0.065	0.04	75.1%	70.8%
SU ₇	0.015	0.036	0.04	0.075	0.12	29.4%	63.6%

Table 6.12 Continued

	0.020	0.044	0.045	0.10	0.16	48.8%	60.8%
	0.025	0.064	0.05	0.18	0.16	41.8%	58.3%
	0.015	0.0046	0.005	0.15	0	90.9%	95.4%
SU ₈	0.020	0.010	0.0065	0.16	0	88.3%	94.3%
	0.025	0.0131	0.009	0.20	0.04	88.1%	92.5%
	0.015	0.004	0.0025	0.07	0	92.1%	97.7%
SU ₉	0.020	0.005	0.0032	0.085	0.04	94.1%	97.2%
	0.025	0.0055	0.0035	0.11	0.04	95.2%	97.1%

We note above that most of the results obtained in laboratory are very close to the results obtained from Flow 3D program (Table 6.12) as is the case with models SU2, SU5, SU7, SU8 and SU9, due to the high dispersion of energy on the main body of the weir and the part added to its end, and the stability of the flow downstream the weir, their results are closer to the theoretical results, while the results in the models that do not contain supports or added parts differ from the laboratory results, sometimes they are identical and sometimes they are somewhat close due to the fluctuation of the flow under the weir and its instability, such as SU1, SU3, SU4 and SU6.

6.7 Dimensional Analysis

The depth and length of scour located at downstream the weir W_c , is considered as function of the discharge, length of ramp, height of ramp, channel width, tail water depth, number of pier, and flow characteristics. The Buckingham Pi-theorem is used to generate a non-dimensional relationship between the depth and length of scour individually and the independent variables in this study. The functional relationship among the dependent and the independent variables is:

$$D_s = f(Q, L_r, W_c, T_w, P_2, B_p, \rho, g, \theta) \quad (6.1)$$

And

$$L_s = f(Q, L_r, W_c, T_w, P_2, B_p, \rho, g, \theta) \quad (6.2)$$

Where, D_s = Depth of scour, L_s = Length of scour hole, dependent variable (L), Q = discharge (L^3T^{-1}). L_r = length of ramp (L), W_c = Width of the channel (L), T_w = Tail water depth (L), P_2 = length of the ramp (L), B_p = number of piers multiply by

circumference of pier (L), ρ = Density of water ($M L^{-3}$), g = Gravity ($L T^{-2}$), θ = the ramp angle in additional part. The non-dimensional forms of the above equations are:

$$\frac{D_s}{W_c} = f \left(\frac{g W_c^5}{Q^2}, \frac{L_r}{W_c}, \frac{T_w}{W_c}, \frac{P_2}{W_c}, \frac{B_p}{W_c}, \theta \right) \quad (6.3)$$

And

$$\frac{L_s}{W_c} = f \left(\frac{g W_c^5}{Q^2}, \frac{L_r}{W_c}, \frac{T_w}{W_c}, \frac{P_2}{W_c}, \frac{B_p}{W_c}, \theta \right) \quad (6.4)$$

Multiple regression analysis of the depth of scour and length of scour previous cases for dependent variable in Equation (6.4), $\frac{D_s}{W_c}$, and $\frac{L_s}{W_c}$ versus independent variables in the same equation led to the following forms of equations, all the data for dependent and independent variables is used to analyse in this case.

$$\begin{aligned} \frac{D_s}{W_c} = & 0.269 \frac{Y_t}{W_c} - 9.358 * \frac{g W_c^5}{Q^2} - 0.0847 * \frac{L_r}{W_c} - 0.00122 * \frac{N_p}{W_c} - 0.25 * \frac{P_2}{W_c} \\ & - 0.00034 \theta \end{aligned} \quad (6.5)$$

The analysis gives R^2 of 0.95, which tells us the percent of the variation in explained by the regression. In this case 95% of the variation in independent variable is explained by dependent variables and 5 % is unexplained. The standard error in this case is 0.01717, which is measure of how far the actual points are from the regression line. In addition to that, the significant F is 2.34 E-12 which is less than 0.05. Therefore, the overall regression model is significant. Linear relationship between $\frac{D_s}{W_c}$ that measured from experiment and predicted from the equation (6.5) is drawn as shown in figure (6.91). The equation of the length of scour by channel width in this case is;

$$\begin{aligned} \frac{L_s}{W_c} = & -0.426 \frac{Y_t}{W_c} - 4.5E - 6 * \frac{g W_c^5}{Q^2} - 0.051 * \frac{L_r}{W_c} - 0.0011 * \frac{N_p}{W_c} - 1.45 * \\ & \frac{P_2}{W_c} - 0.002 \theta \end{aligned} \quad (6.6)$$

The analysis gives R^2 of 0.87, which tells us the percent of the variation in explained by the regression. In this case 87% of the variation in independent variable is explained by dependent variables and 13 % is unexplained. The standard error in case of length of scour is 0.045. In addition to that, the significant F is 4.82E-08 which is less than

0.05. Therefore, the overall regression model is significant. Linear relationship between $\frac{L_s}{W_c}$ that measured from experiment and predicted from the equation (6.6) is drawn as shown in figure (6.92).

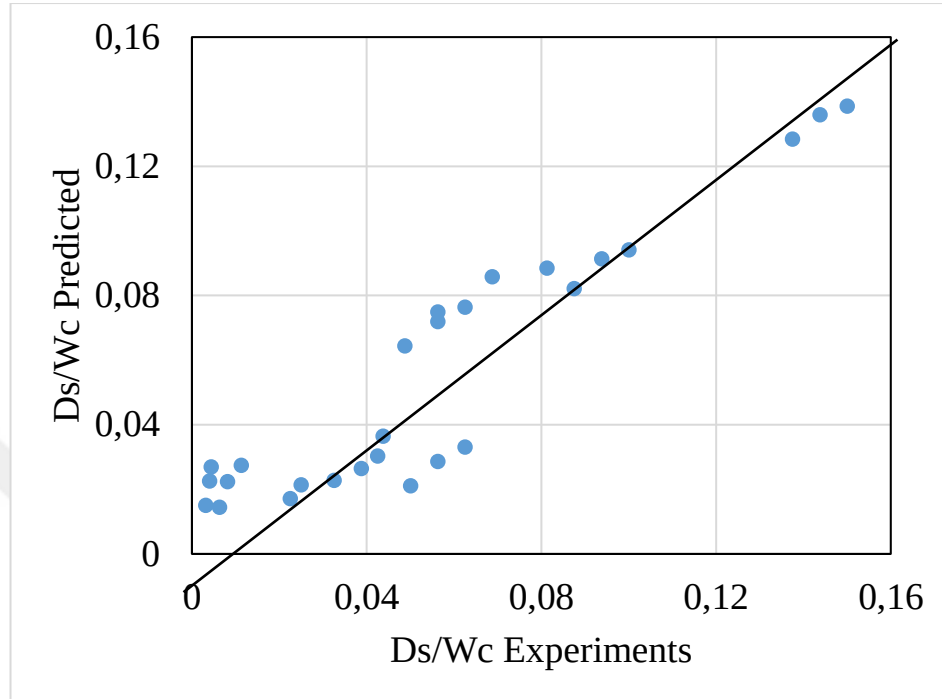


Figure 6.91 Linear relationship between predicted and measured $\frac{D_s}{W_c}$.

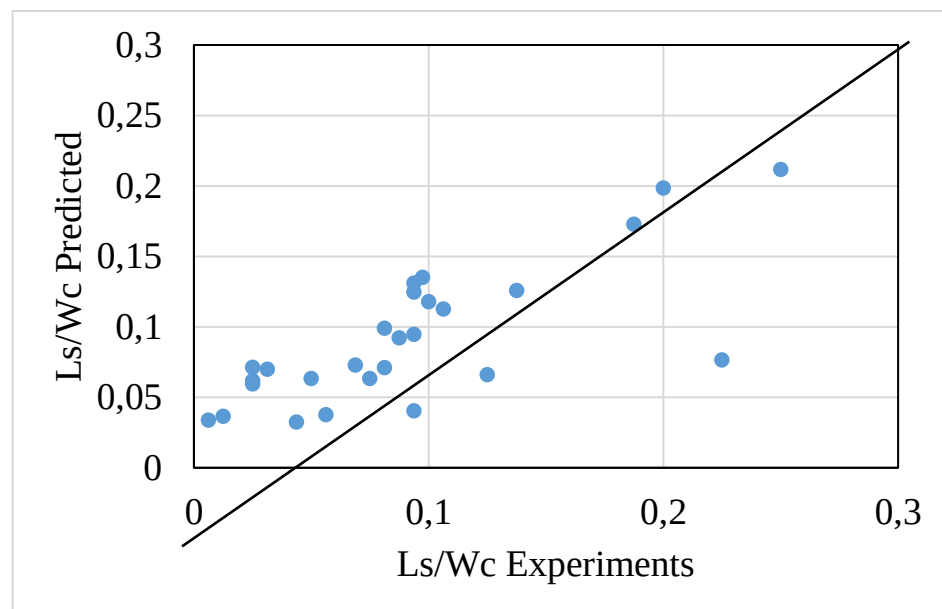


Figure 6.92 Linear relationship between predicted and measured $\frac{L_s}{W_c}$.

CHAPTER 7

CONCLUSION AND RECOMMENDATION

7.1 Conclusion:

Previous studies reviewed were progressing slowly in finding solutions to reduce the depth and length of the erosion pit. The current study found a different approach from the previous ones by designing nine new models of sheds that may have an influential role in preventing erosion behind hydraulic installations. The new method can raise the water level at the weir top, dispersing the energy of the runoff and ultimately decreasing the erosion at the weir bottom. The results obtained were consistent with or without the presence of struts at the bottom of the weir or not, and despite the shape and angle of the added part.

The current study used the Flow 3D program as a simulation platform tool. In comparison with previous studies, the Flow 3D program results showed high efficiency and closeness to reality. Most of the proposed rumbles models showed impressive results in reducing the depth and length of the erosion pit below the weir, especially SU₈, SU₉ models. It was almost non-existent in the ninth model SU₉, which prompted us to verify these results by implementing them in the laboratory.

The laboratory contains state of the art laser devices. The experiments were conducted under conditions similar to the parameters of the modelling in terms of the dimensions of the model, the dimensions of the channel used and the type of sand layer used. The results showed that they matched with the results obtained from the Flow 3D program. Most of the models that contain stents are superior in performance to their counterparts without stents, and the eighth and ninth models were unique in their performance in terms of preventing the occurrence of erosion behind them, as can be drawn from the following results:

1. Flow3D program showed high efficiency in representing the flow in reality. The program was tested on previous laboratory results, and the program data was

2. similar to the laboratory data in terms of flow speed, water flow shape, and the depth of the erosion pit, in addition to its length and table (4.1). There is a significant convergence between program results and laboratory results.
3. The Flow3D program had the opportunity to select the most efficient models from out of many. The first model SU1 was designed in the Auto CAD program with three variables, namely, the radius of the top, the bottom and the tail, which allowed for the creation of a variety of models. These variables were adjusted until the best performing measurements were determined, 0.1, 0.28, and 0.09 m.
4. The first model SU1 gave the flow a streamlined shape above the weir and on its side for the three drains used (0.015, 0.020, 0.025) m³ per second, while the flow was disturbed at the bottom of the weir to form vortices that led to erosion behind it. anyway that the initial design of the weir was superior On the other forms of weirs that previous researchers studied, but in our current study it was not satisfactory, as the depth and length of the erosion pit reached (0.11, 0.2) m for the highest discharge (0.025) m³ s⁻¹.
5. The first SU1 model did not give satisfactory results until the loom part was added to increase the calming of the water, dissipate its energy and reduce erosion behind the weir. The results were somewhat satisfactory, as the value of erosion in the two new models SU2, SU3 were 0.0317 m. and 0.0323 m., respectively, while the lengths of the erosion pit ranged between 0.085 m. and 0.080 m. This means that the percentage of erosion reduction increased from (0% to 63%). The results prompted the pursuit of developing improved models.
6. Forty piles comprised of five rows and eight columns were placed at the bottom of the weir to increase the dissipation of energy. A significant change was observed in the flow pattern, as the energy of the water descending from the top of the weir was dispersed by the columns placed at the bottom of the weir. This significantly prevented the occurrence of high eddies at the bottom of the weir thus further reducing the percentage of erosion. The significant level of erosion reduction reached to percentages which have not previously been achieved in other studies. Models SU5, SU6 and SU4 achieved a 60%, 70.3% and 70.1% reduction of erosion.

7. To make further improvements and try to reach perfection in the performance of the models, some improvements were made in the design of the supplemental part which was added to the weirs to kill the vortices on it. The lengths of the added part were modified to 0.35 m. and 0.40 m. Additionally, the angles of the ram were configured as 11o, 27o, 28o. It was these adaptations that drastically improved the performance of the model, increasing the percentage of erosion reduction to 93%.
8. One of the most prominent influences on improving the models was the added columns and the slope of the ram, where it was noted that the best angle for the ram was 11o, represented by the part added in the ninth model SU9, which was characterized by the least smear behind it and that the value of slough was negligible as it reached 0.009 m., 0.005 m., and 0.004 m. for expenses.
9. The height of the water at the top of the weir reaches 0.65 m. at the top of the discharge. Retaining water at this level without the occurrence of engineering problems due to erosion at the bottom of the weir is an achievement. The shape of the designed weir disperses the energy well, and there was no noticeable erosion that threatens the hydraulic installations. It is noticeable that the rise of the water downstream the weir was minimal, and it was free of eddies.
10. When the results obtained during the modeling of the nine designs in the Flow-3D program were successful, the following step was to verify their success in the laboratory. This was done to make sure that the program results were accurate and realistic. Secondly, this was done so that the data of the Flow-3D program is rare and unique. Finally, the proposed models in the Flow-3D program needed to be converted from the theoretical field to the practical field.
11. Using steel and laser cutting devices, the nine models (SU1 - SU9) were formed in the laboratory with high accuracy and under the same conditions that were used in the theoretical models, to monitor the performance of each model separately and compare their performances as simulated in the Flow 3D program.
12. Contour maps were used to show the depth of erosion as a measure of the efficiency of the weir. The experimental results indicate that when the three discharges are applied continuously for a period of six hours, erosion areas arise

behind the weirs, extend to both sides of the canal, and their shapes differ according to the model utilized. The deepest erosion pit was formed behind the first model (SU1) It reached 0.12 m. and a length of 0.21 m. using the highest drainage of the three used discharges 0.015 m³/sec. , 0.020 m³/sec. , and 0.025 m³/second. The lowest pit was 0.0035 m. and the shortest length 0.04 m. for the highest drainage used in the ninth model (SU9).

13. Among all the proposed designs used to reduce erosion behind weirs, it was found that the eighth and ninth models (SU8, SU9) are the best models compared to the first model SU1 because their percentage of erosion reduction was 94% and 97%. The fifth and sixth models (SU5, SU6) achieved 80% and 72% reduction in erosion, while the fourth and seventh models (SU4, SU7) showed a similar reduction rate of 60%. However, the second SU2 showed about a 50% reduction in erosion. Regarding the third model, SU3, the scour decreased about 30% compared to the first model.
14. It was found that the Flow 3D program represented the flow in a real way, as most of the theoretical results matched the laboratory results in most of the models.
15. The dimensional analysis showed that the depth and length of the erosion pit divided by the width of the channel (L_s/W_c , D_s/W_c) depends on the length of the added part, the number of columns placed at the bottom of the weir, and the angle of the ramps at the back of the part added to the weir.

7.2 Recommendations

- a) Using the Flow 3D program saves time and cost. It is recommended to use it before representing any laboratory models.
- b) It is very useful to study the radii (the top of the weir, the foot of the weir and the end of the weir extensively) to select the optimal values that contribute to giving the designed model a better performance.
- c) Since the number of columns in the weir has greatly affected its performance, it is necessary to study their numbers and the way they are distributed on the surface in addition to their formation, as it is possible to use oval, rhombus, rectangular or triangular supports.

- d) The laboratory model can be made of water-resistant wood to facilitate the above possibilities in a more flexible way than using steel.
- e) The added part can study its optimum length as well as the length of the main weir body to obtain the least lengths that reduce its construction cost.
- f) The effect of the angle of inclination of the layered part had an important effect on the depth and length of the erosion pit. It has become very important to study the angle of each added part until reaching the best angle that reduces erosion under the weir.



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CURRICULUM VITAE

Personal Information

Name: Sulaiman Dawood JASIM

Language: Arabic – English – Turkish

Education

1. 1985/ B.Sc. Degree in Department of Water Resources Engineering/ College of Engineering / University of Mosul/ Iraq.
2. 2005/ M.Sc. Degree in Department of Water Resources Engineering/ College of Engineering / University of Mosul/ Iraq.

Publications

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