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M. Sc. in Civil Engineering

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**REPUBLIC OF TURKEY
GAZIANTEP UNIVERSITY
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES**

**EXPERIMENTAL STUDY ABOUT THE LOCAL SCOUR
DOWNSTREAM OF OGEE SPILLWAY**

**M. Sc. THESIS
IN
HYDRAULICS**

**BY
LOAY ASAMI
FEBRUARY 2020**

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M. Sc. Thesis

in

Civil Engineering

Gaziantep University

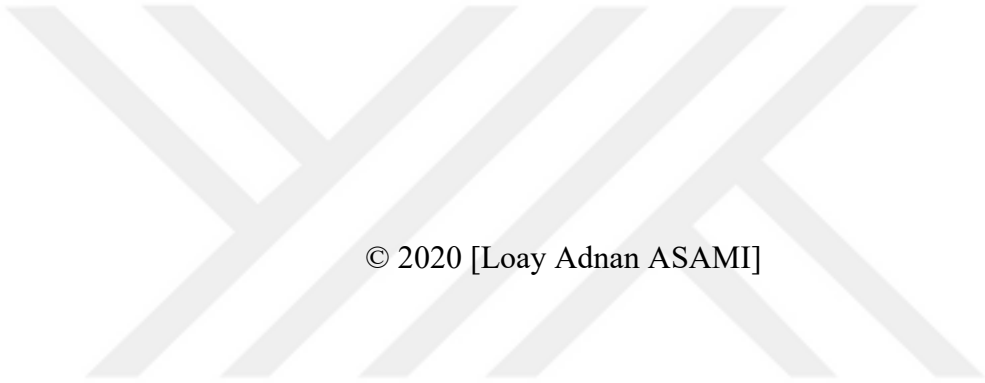
Supervisor

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by

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February 2020



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REPUBLIC OF TURKEY
GAZIANTEP UNIVERSITY
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Loay ASAMI

ABSTRACT

EXPERIMENTAL STUDY ABOUT THE LOCAL SCOUR DOWNSTREAM OF OGEE SPILLWAY

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M. Sc. in Civil Engineering Department

Supervisor: Prof. Dr. Mustafa GÜNAL

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The local scour formed in the bed of rivers because of the water action is a common phenomenon, and by the time became an important topic to study while designing and operating hydraulic structures. Because of the complexity of the topic, no specific methodology was developed to certainly predict the scour development profile, but the majority of the found results were specified by the operating conditions and based on experimental studies.

The purpose of this study is to investigate the local scour depth downstream of the Ogee spillway model. The investigation has been conducted on a physical model at the hydraulic laboratory of Gaziantep University. Mainly, the study discusses the results of using baffle blocks in different conditions on the developing of the local scour downstream of the spillway. The experiments were carried out for different heights and number of blocks to find out their changing in the results under various discharges. Within the study boundaries, the height of blocks, at the first place, followed by the number of blocks lanes have been recognized to be the most effective factors on the results compared to the other variables of this study.

Key Words: Ogee spillway, Spillway, Local scour, Baffle blocks.

ÖZET

DOLUSAVAK SONRASINDA OLUŞAN YEREL OYULMANIN DENEYSEL OLARAK ARAŞTIRILMASI

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Su etkisi nedeniyle nehir yatağında oluşan yerel oyulma yaygın bir olgudur ve zamanla hidrolik yapılar tasarlanırken ve çalıştırılırken önemli bir konu haline gelmiştir. Konunun karmaşıklığından dolayı, taban oyulma profilini kesin olarak tahmin etmek için özel bir metodoloji geliştirilmemiştir, ancak bulunan sonuçların çoğunluğu çalışma koşulları ve deneysel çalışmalara dayanarak belirtilmiştir.

Bu çalışmanın amacı, ogee tipi dolusavak modeli sonrasında oluşan yerel oyulmanın araştırılmasıdır. Araştırma, Gaziantep Üniversitesi hidrolik laboratuvarında fiziksel bir model üzerinde gerçekleştirilmiştir. Esas olarak, çalışma, dolusavak sonrasında oluşan yerel oyulma derinliğinin azaltılması için dolusavak sonrasına yerleştirilen blokların etkisini deneysel olarak araştırmaktır. Farklı debi altında oluşan maksimum yerel oyulma derinliği değişimlerini farklı yükseklik ve blok sayıları için deneysel olarak araştırmaktır. Çalışma sınırları içinde, blokların yüksekliği, ilk etapta, ardından blok şerit sayısı, bu çalışmanın diğer değişkenlerine göre sonuçlar üzerinde en etkili faktörler olarak kabul edilmiştir.

Anahtar Kelimeler: Ogee dolusavak, Dolusavak, Yerel oyulma, Enerji kırıcı blok.



To My Family

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In the name of Allah, peace and blessings be upon our Prophet Muhammad (peace and blessings of Allah be upon him).

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LIST OF SYMBOLS/ABBREVIATIONS

D₅₀	The median size of sediments (%)
D	Size of sediment (Size of sieve opening) (mm)
σ	Standard deviation
γ	Specific Weight (Kg/m ³)
y_{up}	Upstream water depth (m)
y₁	The depth of water in the supercritical conditions (Hydraulic Jump) (m)
y₂	The depth of water in the subcritical conditions (Hydraulic Jump) (m)
y_c	Critical depth (m)
x_r	Modelling Scale
x_m	Dimension/Geometrical variable of the model (m)
x_p	Dimension/Geometrical variable of the prototype (m)
S₀	Channel bottom slope
Q	Discharge (m ³ /s)
C	Spillway discharge coefficient
L	The effective length of the spillway (m)
h	The height of the blocks
d_s	Depth of bed scour (mm)
N	The number of blocks lanes
h_c	The depth of water over the crest of the spillway

CHAPTER 1

INTRODUCTION

1.1 General

The hydraulic constructions in the majority are considered as strategic structures such as reservoirs, spillways, water bridges, seaport constructions, etc. in which any designing, implementing mistakes or even changing in the operating conditions might lead into heavy losses either in human or materials. For this field of study, the laboratory experiments are still one of the most accurate studying ways, if the similarity conditions were appropriately considered. Thus, the experimental studying approach was chosen to conduct this study to the local scour downstream of the spillway taking to the consideration that the results of such studies are tightly related to the certain conditions of the studied case.

One of the widely known issues that majorly affects the stability of the spillway structure is the scour produced locally as a result to the high kinetic energy of the water falling from the crest of the spillway, in other words, the ability of water to scour the bed soil increases with the increasing of its kinetic energy value. To understand the idea well, it is necessary to know that the spillway profile is usually being chosen to provide a chance to control the water flow as it has the same shape of water jumping over a wall if it was placed instead of the spillway. The water ability of scouring could be affected by many factors such as the water flow, the shape and the height of the spillway, the slope of the front face, the type of the bed soil and the water head elevation which are most likely uncontrollable conditions. Generally, the shape of the resulted scour hole is expectable which may be controlled by the design of the spillway and other factors such as the soil type, flow value and the bed slope which are changing the geometry of the hole. (Farhoudi J., Shayan H., 2014)

Some solutions for this phenomenon were proposed by researchers and some of them are already applied nowadays, such as basins, protective apron and the baffle blocks

that might be fixed either on the spillway front face or on the apron. Other suggestions were applied to the design of the structure itself such as the stepped spillway. (Gandhi S., Dhananjay R., 2016)

This experimental study simulates the case of ogee spillway with baffle blocks fixed on a protective apron downstream of the spillway. The blocks have a square cross-section but different heights and arrangements in lanes which were tested under different discharges. In other words, the main variables of the study are the height of blocks, number of blocks lanes and the water discharge.

The initial findings showed as an inverse relationship between the depth of scouring on one side, and the height of blocks, number of lanes and the depth of water, in both conditions, of the hydraulic jump, on the other side. While a proportional relationship was found between the depth of scour development on the first side and the water discharges and the water level over the crest, on the other side.

1.2 Aim of the Study

This study was designed to investigate the effect of changing one of the studied designing variables; the height of blocks, number of blocks lanes and the water discharge on the produced depth of scouring over the time. To cover all cases, 30 experiments proceeded including cases of no blocks fixed on the apron where the protective apron was placed to dissipate the water energy, but to present the reference values to compare results after adding lanes of blocks.

Rather than the designing variables, measurements for some hydraulic variables (depth of water over the crest, depth of water in super and subcritical conditions of the hydraulic jump and the depth of scouring), that are assumed as the most effective variables based on dimensional analysis, have been recorded during the experiments. According to the observations, these variables were tightly linked to the designing variables which significantly changed by changing these variables.

This experimental study is expected to result in the following findings:

- Investigate the scour developing under different conditions of blocks height and number of blocks lanes
- Explain the relationship between the depth of scouring developing and each of the other studied variables, considering the other variables are stable

- Explain the relationship of the scour developing with the effect of all studied variables included
- Express the relationships by regression formulas
- Produce recommendations for future related studies

1.3 Study boundaries

- A modelling scale of 1:345 with a stable height of spillway about 10 cm.
- Water flume with a width of 0.8 m.
- A protective apron is downstream of the spillway with the dimension of 0.8 m width and 0.9392 m length.
- A square cross-section blocks $2.3 \times 2.3 \text{ m}^2$.
- Water pumping system $Q = 0.0973 \text{ m}^3/\text{s}$, $H = 14 \text{ m}$, $P = 18.5 \text{ KW}$, $n = 1450 \text{ rpm}$ and TP: SNT 150 ~ 250
- Sediment pool, where the scour took place, with the dimensions of 0.8 m width, 2.25 m length and 0.4 m depth.
- Sediments median size $D_{50} = 1.45 \text{ mm}$.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The local scour formed in the bed downstream of spillways is effectible by various factors that may increase/decrease the depth of the hole or change the shape of the resulted scour. Specifically, and regarding the ogee type of the spillways, the tailwater depth, the value of discharge, the length of the protective apron (if any) and the characters of the downstream basin are the main known factors that have the direct effects on the shape of the resulted scour.

To handle this serious phenomenon, the researchers conducted many theoretical studies and practical investigations to understand the ability of water to scour the beds of different sediments sizes and how the scouring develops by the time. Also, they developed solutions to safely include the water with high energy downstream of spillway instead of hitting the bed directly causing a hole that may extremely affect the stability of the structure. The protective apron is one of these solutions, it is a concrete surface usually installed directly downstream of the spillway structure, its length should be chosen to include the formed hydraulic jump under different conditions. The different shapes of basins, some designs include blocks of different shapes and sizes, is another widely used solution.

The blocks fixed on different parts from the structure are also known as an effective method to handle the high energy of water passing the spillways. These blocks are usually installed on the front slope side of the spillway or downstream on the aprons.

2.2 Previous Studies

A lecturer in Dams and Water Resources Research Center of Mosul University proceeded an investigation study about the problem of the downstream scouring. He found that the depth and the extent of scour is a proportionally related to the

discharge value, once the flow rate increase by 10% then the depth increases 20% for sediments characteristic ($D_{50}=0.5\text{mm}$, $\sigma = 10.8$, $\gamma= 26 \text{ Kg/m}^3$, rounded particle shape) and 7% for the sediments ($D_{50} = 4.5\text{mm}$, $\sigma = 2.77$, $\gamma= 17 \text{ Kg/m}^3$, angular particle shape). Similarly, he found that the depth of tailwater had a significant effect on the depth of scouring, increasing the depth of tailwater is inversely proportional to the depth of scouring. According to the finding, increase of 25% in the tailwater depth results in a reduction of 40% for the first condition and 22% for the second one. In other words, increasing the depth of tailwater has a more significant effect on the depth of scouring for the fine materials compared with the case of the coarse material, while the extent of the scour is effectible more by the coarse materials in comparing with the finer. At the end of the study, he resulted in mathematical relations among these study variables, depth of tailwater, headwater depth, water discharge and the size of sediments. (Khalil I. Othman, 2007)

Another experimental study was conducted in the water and water Str. Engineering Department of Zagazig University, Egypt, about the effect of using cylinder blocks on the back-sloping surface of the spillway on the energy of water and its ability to scour the bed, the model was implemented as shown in figure 2.1. The study includes a set of experiments for different sizes of blocks, different arrangements and numbers of the baffle blocks under various values of discharges. The study resulted in the best ratio of L/B and D/B , where L is the length of the block, D is the size of block and B is the width of the water channel. According to the study, the best dimensions of cylinder blocks to the width of channel are $L/B = 0.133$, $D/B = 0.1$, which have reduced the depth and the length of scouring by 25% and 27% respectively compared with the smooth case (no blocks). Also, these ratios reduced the deposition parameters, the depth and the length, by 28% and 22.2% respectively. According to the findings, the staggered arrangement of the cylinder blocks is more effective than the diagonal case in terms of the energy dissipation which reduce the depth of scouring by 34.2% and the length by 43% more than the diagonal arrangement. The least was scour produced when submerging the spillway, either for the controlled and uncontrolled cases. (Elnikhely E., 2017)

Another study was conducted also on a model belongs the same structure of this study, using a different model scale, included additional designing variables such

as the length of the apron and the submergence cases of the spillway. It is also an experimental study that investigated a suggested changing on this design of the spillway and its effects on the resulted scour.

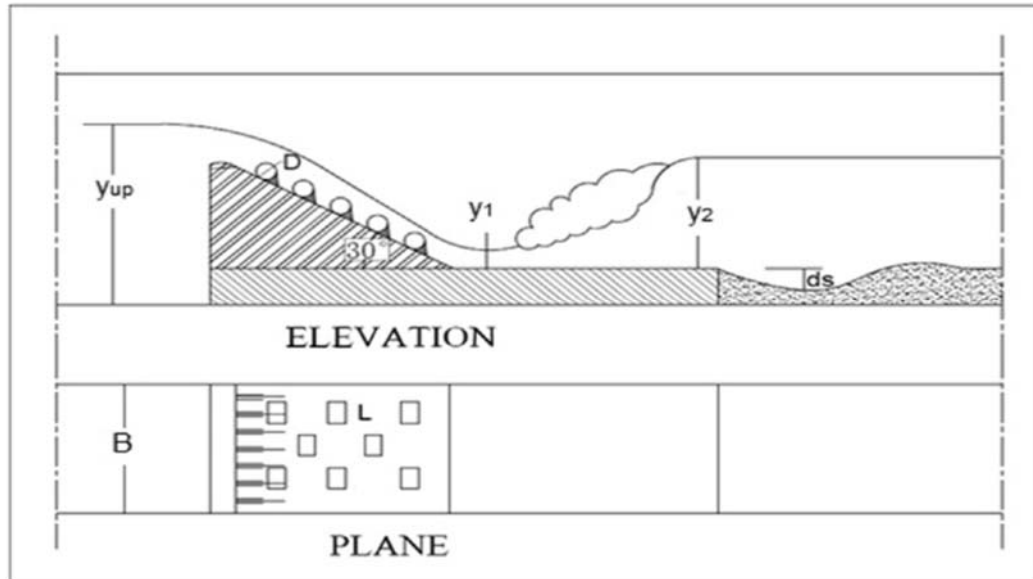


Figure 2.1 Cross-section and top view of the designed model. (Elnikhely E., 2017)

The prototype design included a basin and a short apron downstream of the structure to handle the super-critical flow condition, while the conducted study suggested an apron with two lanes of cubic blocks which end with a triangular sill. Figure 2.2 shows a cross and top section of the studied model.

This apron is followed by a riprap layer, has the same length as the apron, of crashed stones particles before the water reaches the bed of the open channel. Two sets of experiments were conducted, one set for the length of riprap layer equal to the apron of blocks and the second was executed for the double-length, and each set consists of five experiments under five different submergence and gate controlling cases. The study concluded that the maximum scours depths were obtained for free flow with a swept out hydraulic jump at the lowest tailwater elevation, also, increasing tailwater submergence reduced maximum scour as the longer riprap apron did. Comparing to the free flow cases, the controlled and uncontrolled submerged flows produced the least scour. (Hong S., et al., 2015)

The velocity distribution was distinguished to be complex inside the stilling basin for the submerged flows, this dissipated velocity at a relative depth of about 20% gradually in the downstream direction. For the cases of uncontrolled submerged flow, the highest velocity of flow was registered under the water surface at a higher elevation but within a thinner layer than the reverse flow above it. Moreover, the velocity in these cases dissipated more rapidly in the downstream direction. However, the water velocity streamwise was recognized to be almost the same over the mobile sand bed in the scour zone for both cases, the controlled and uncontrolled flows.

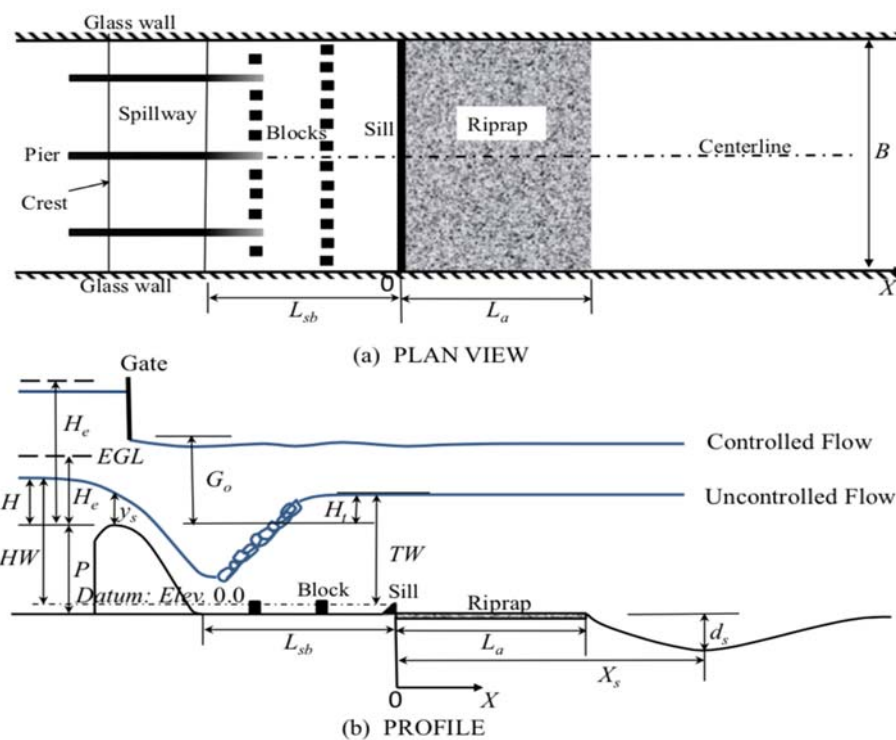


Figure 2.2 Spillway definition sketch. (Hong S., et al., 2015)

Duplicating the length of the apron has a significant influence on the scour depth for the submerged and free flows, but the length of the apron has almost no effects for the cases of the lowest tailwater with the hydraulic jump swept out of the stilling basin.

The velocities just downstream of the spillway and the positions near-bed velocities at horizontal stations were observed to be almost the same when compared with either free or submerged flow cases. (Hong S., et al., 2015)

A similar experimental study was performed on a model of the stepped spillway. (Aminpour Y., et al., 2016).

The study provides the results of 67 experiments under different values hydraulic variables, Froude numbers, basin lengths, tailwater depth, sizes of sediments and two slopes of spillways. According to the results of the study and with consideration to a fixed length of stilling basin, relative tailwater and particle Froude number, the scour hole decrease with the size of the sediment increasing.

The length of the basin has an inverse effect when increasing the length of the basin with certain sediments sizes, slope of stepped spillway, relative tailwater and particle Froude numbers, the geometry of the scour hole will decrease. In terms of the Froude number, increasing its value with fixing the other parameters will result in an increase in the hole size. Increasing the slope of the front face of the spillway with the other parameters are constant, will reduce the size of the scour hole. The results show a proportional relation with the tailwater depth, means, increasing the relative depth of tailwater leads into an increase in the size of the hole in both directions, depth and the longitudinal length. Also, the study resulted in an equation expressing the developing of the scour hole geometry by the time.

Comparing the results of the stepped spillway with the ogee type of spillway, the study concluded that the energy dissipation of the stepped type under specific condition is higher than the ogee spillway, in other words, the design of the stepped spillway is more effective in terms of the energy dissipation in compared to the smooth front face of ogee spillway, as using the stepped spillway needed much longer time to reach the semi-equilibrium stage with less depth and longitude of the scour hole.

As for the ability of water to do the action of scouring, the hydraulic jump formed downstream of spillway represents the transmission of flow conditions, supercritical, critical and subcritical conditions. Changing the flow conditions changes the type of flow and usually form the turbulent case of flow, which is an essential reason for the bed scour along with increasing the kinetic energy of the water. Researchers have conducted an experimental study to understand the effect of spaced and staggered semi-circular strip corrugated beds on characteristics of the hydraulic jump downstream of an ogee spillway. (Deshpande M., et al., 2016)

The study also covered the effect of using different corrugation heights and spacing. A set of 70 experiments have proceeded under various values of Froude numbers (2.5-6.2) and relative roughness ranged (0.3-0.8) with different corrugated shapes and discharge values. The study aimed to study the performance of the hydraulic jump with varying the roughness intensity by 50%, 33%, 25% and 20%, respectively, as well as by keeping the same roughness intensity and find out the optimum results. For both cases, the spaced and staggered of semicircular strips, and the depth of hydraulic jump reduced by average values of 29% and 34% respectively, length average values by 21% and 24%, respectively, and an energy loss of average values 34.6% and 36.6%. The shear stress increased 8 times when using the staggered bed in comparison with the smooth bed case. Staggered semicircular corrugated bed showed optimum results compared to the spaced semicircular strip beds. The corrugated bed reduced the geometry of the scour hole, more specifically, it reduces the length of the needed basin and then the cost of its installation.

The study concluded the following results:

- The optimum staggered bed is at the t (The Height) = 1.5 cm, s (spaces) = 6 cm and intensity 25%.
- The optimum spaced strip bed at $t=1.5$ cm, $s=12$ cm and intensity 25% which reduces the sequent depth of hydraulic jump more than the smooth bed by 31% to 22% in comparing with 36.4% to 24% for the staggered bed, at the Froude numbers 2.5 to 6.2, respectively.
- The length of the hydraulic jump at the optimum case of staggered bed reduced more than the smooth bed by 22.5% to 21% at supercritical Froude number 2.5 to 6.2. For the optimum spaced strip bed, the length of the jump reduced more than the smooth case by 21% to 17.9% for the same values of Froude number.
- Relative energy loss increases at the optimum spaced strip bed more than the smooth bed by averagely 34.6%.
- The shear stress in the staggered corrugated bed increases eight time more than the smooth bed due to the corrugations eddy formation.

- The optimum results for the hydraulic jump performance were obtained for the roughness intensity as 25% compared to 50%, 0.33% and 20% intensity values.
- Better performance also obtained for the hydraulic jump by increasing the corrugation height for same roughness intensity.
- The semi-circular strips showed the best results among the other investigated arrangements and even in comparison with the spaced strip bed for the same roughness intensity.

Another consortium of three researchers studied the effect of using a protective apron with different slope degrees downstream of the spillway on the resulted scour hole. The study was conducted to show the results of a set of experiments proceeded on a uniform cohesionless soil as bed material with medium grain size $D_{50}=0.65$ mm. The selected slope angles are 0° , 2.73° , 5.19° and 7.43° . (Alwan H., et al., 2016)

The study proved that the slope of the apron is an important parameter that significantly affects the depth and extent of the scour hole. Changing the slope of apron showed a reduction of 53, 46 and 35% in the maximum scour depth and 33, 49 and 33% in the maximum scour length in comparing with the horizontal apron 0° for the following angles respectively 2.73° , 5.19° and 7.43° .

The study concluded that the tailwater flow system caused two scour regions, the main and the local region of scouring. It was observed in all of the experiments that the scour processes were faster at the first stage of the experiments and the shape of the scour hole keeps changing until the equilibrium case. The maximum depth of scouring occurs at the edge of the channel and the maximum depth and length of scouring observed at the horizontal apron 0° . The depth of scour downstream of the apron is a proportionally related to the slope of the apron, the scour depth increases when increasing the slope of the apron while the extent decreases.

The findings of the study also showed the angle of slope that causes the largest average value of decreasing in the to scour extent, about 49%, which is the degree 5.19° followed by 33% for both angles 2.73° and 7.43° . The study also resulted in a formula to evaluate the scour geometry which was found by using the dimensional analysis techniques and links the Froude number, flow velocity, operating head and

angle of the apron. Mainly, the study investigated the effect of using curved vertical sill downstream of the spillway on the developed local scour depth and extent. The findings of the study led to the following results; using the curved vertical sill reduced both the maximum depth and length of scour in comparing with the no-sill case in different ratios.

According to the study, the best location for the curved sill is within the first third of the floor downstream of the spillway. This location of the sill decreased the relative maximum scour depth from 20% to 43% and reduced the length of the hole by 45% to 66% for different relative diameters of sills.

As an optimum case, the maximum reduction in the depth and length of scour hole occurs for placing the sill at the first third of the floor, and the ratio $D/H=0.122$, the diameter of the sill to the height of spillway.

Moreover, another research was also conducted to investigate how to use the reversed cross-jet flow to alleviate the scour problem downstream of ogee spillway and dissipating energy of the flow. The study handled analytically and experientially the results of the forced formed perfect hydraulic jump compared to the free jump conditions and consequently, shorten the protective apron length. The length of the perfect jump was reduced by 19% as well as the stilling basin length was also reduced by 79% compared to the case without dissipater. (Alghwail A., 2016)

The study ends into the following conclusions; the hydraulic jump formed downstream of the spillway is controllable using the reversed cross-jet dissipater. The cross-jet dissipater is useable to obtain a perfect jump closer to the body of the spillway, hence, to reduce the length of the apron. Moreover, the depth of the tailwater could be reduced by 77% at the same Froude number value found without reversed cross-jet dissipater. The researchers were able to product formulas to find out the possible depth using the depth of water in the supercritical condition of the hydraulic jump and the tailwater ($\psi = \frac{y_2}{y_1}$) along with the loss of energy in the jump controlled by the cross-jet.

Nangare, Patil and Pande are a consortium of researchers designed and investigated study about the methods could be used for the most effective energy dissipation of

water passing an Ogee spillway. According to their study, excess air entrainment causes positive pressure on spillway bed which is a very effective and non-costly way to dissipate energy. The excess air entrainment could be obtained using steps profile of spillway or by using other techniques such as the roller buckets. This issue was verified by an experimental study applied on a developed model of an ogee spillway with consideration to the combined effects of steps and roller buckets etc. The experiments have performed in a range of discharges (0.0052-0.0063 m³/s) and a model head ranged (4-6.5 m). The study resulted into 80.24% more energy dissipation by using ogee spillway with a combination of plain roller bucket, steps and stilling basin in comparing with the normal profile of the ogee spillway, this result was found while remaining only 0.23 m of tailwater depth in the stilling basin and with Froude number 5.53. (Nangare. P, et al., 2018)

The researchers concluded into the following results; this design raises the depth of tailwater in the stilling basin which achieve the best efficiency by retaining flow back with V notch, which also by turn provides the favorable condition for roller bucket.

Also, it was clear from the study that the steps played a key role in energy dissipation. By observing the energy dissipation profile, the rolling buckets and the stilling basin have adequately completed the reducing of energy mission, in other words, the design was recognized to be very harmonious and effective. In addition, the study refers to a relation between the energy dissipation and the number of steps as the dissipation increases with decreasing in steps numbers and discharge value.

In contrast, increasing the length of step has increased the energy dissipation and achieved the best results with the value of $(\frac{y_c}{h})$, the critical depth of water to the spillway head, up to 0.

CHAPTER 3

METHODOLOGY AND EXPERIMENT SET UP

3.1 Introduction

This section explains in detail the steps followed to achieve the full set of experiments supported by the related fundamental concepts used to develop the appropriate implementation. It describes the case of this study in relation to both the prototype and the model. Also, this section includes the calculations were made to result in the crest profile of the spillway using the USBR (1987) and show the final shape was found accordingly. And finally, the techniques were followed to prepare and fix the model adequately.

3.2 Methodology

This study is made to investigate the effect of using a protective apron with different sizes and arrangement of blocks on the ability of water to form the scour hole downstream of an ogee spillway and under different values of flow discharges. The conclusion of this investigation is expected to discover the effect of using the baffle blocks and the relationship among the studied factors, and at the end, to understand the best usage of the blocks.

Usually, researchers suffer finding full sets of historical data, as well as geometrical and hydraulic details for such structures, as their information is not sharable widely. After many attempts to collect these data, this study relied on a conducted study was previously proceeded on an ogee spillway, published by “Open Access Water”. (Hong S., et al., 2015)

Its design was repeated several times on Kissimmee River at central Florida where Okeechobee Lake is formed. The studied spillway is called S65E which is accompanied by many other low-head spillways with vertical gates along the river.

In response to the strategy of the South Florida Water Management District, who are operating the hydraulic system on this river, many of these repeated structure

along the river were removed retaining to the natural case of the river. The reference study was mainly used to result in the dimensions of the model used in this study, however, the researchers of the study used both cubic blocks and riprap apron to protect the bed downstream of the spillway.

Mainly, the variables of the study were the length of the apron, the riprap section, and the depth of the tailwater downstream of the spillway and their impact on the developed scour whole in the bed of the water path.

In terms of this study, the apron length is stable and has the same length of the one of the reference study, with consideration to the model scale, however, the discharges of these set of experiments were selected to include the hydraulic jumps inside the apron and by using tailgate at the end of the water flume to control the depth of tailwater and to pull or push the jump into the apron.

Three different heights of blocks were chosen, the maximum one is the same size of the used blocks in the reference study with consideration to the model scale (2.4 cm), the other two heights are shorter in a fixed ratio compared to the height of the maximum case ($\frac{2}{3}$ and $\frac{1}{3}$), which later will refer to the impacts of changing blocks heights on the scour developing. Regarding the number of blocks, the experiments were processed for the cases of having one, two and three lanes placed on the apron for each of the selected sizes of blocks, and their results are going to be compared to the no blocks cases under different discharges.

3.3 Experiments Setup

3.3.1 Similarity Theory

While designing buildings, machines, transportation roads or highways, and more importantly, strategic constructions such as dams, spillways and ships, there is a high possibility to face some complex required calculations which is impossible to be solved numerically, otherwise, too many additional considerations should be included to simplify the calculations, they could be related to the nature of the liquid flow or other factors belong to the surrounding environment.

In such cases, the experimental solution is the best path to follow in order to test a hypothesis, it is also the only chance to test and predict the future behaviour of such important strategic constructions which will save money and help to avoid disasters

may occur as a result of poor designing. (Al Mourei Y., et al., 2009), (Al Mourei Y., et al., 2017)

Different approaches could be followed to minimize the scale effect and to shape the studied parameters in a way that can reflect the effect on the real-world prototype case. One of the widely used approach is the dimensional analysis, which is used in the study to identify the factors with the considerable effect on the found results and how the best they could be represented in the regression formulas found by this study. (Heller V., 2011)

obtain model–prototype similarity, to quantify scale effects and to define limiting criteria under which they can be neglected. These are inspectional analysis, dimensional analysis, calibration and scale series, which are applied to landslide generated impulse waves.

In principle, it is impossible to make a model for a prototype with the same dimensions and exactly the same surrounding conditions, therefore, the experiments usually perform on smaller models with specific “Model Scale” when similar operating conditions such as velocity, pressure and flow to the prototype conditions are needed to be applied as well, but after being weighted with the Model scales.

The similarity theory determines the needed conditions to consider while performing experimental studies, the accuracy of these conditions will lead to some results that are applicable to the prototype case.

To fully achieve the similarity between the model of experience and the prototype, it is necessary to study and verify the hydraulic similitude in terms of the following three aspects; Hydraulic, Geometric and the Dynamic Similitudes.

3.3.2 The Geometric Similitude

When the model has the same shape as the prototype, the dimensions are usually as smaller as all being weighted with the model ratio, and this is what is called the geometric similitude. (Al Mourei Y., et al., 2009), (White F. M., et al., 2016)

The weighting ratio or the model scale could be identified by the following formula:

$$\frac{L_m}{L_p} = \frac{B_m}{B_p} = \frac{D_m}{D_p} = L_r \quad (3.1)$$

Where;

L_r is a constant named as the model scale or the scale ratio.

L_m , B_m , D_m are the dimensions of the model as m refers to the model.

L_p , B_p , D_p are the dimensions of the prototype as p refers to the prototype.

With the consideration that the model scale is usually being derived using the dimensions of the model and the prototype, but it also could be identified using areas and volumes as per the following:

Where;

$$\frac{A_m}{A_p} = (L_r)^2 \quad (3.2)$$

$$\frac{V_m}{V_p} = (L_r)^3 \quad (3.3)$$

A_m and A_p are the areas of the model and the prototype.

V_m and V_p are the volumes of the model and the prototype.

Briefly, to realized that the geometric similitude is achieved, it is necessary to ensure that the shape and angles are remained as per the prototype case, while the dimensions are changed all in a fixed ratio called the model scale. Figure 3.1 is an example of an illustrative example of a geometric similitude case

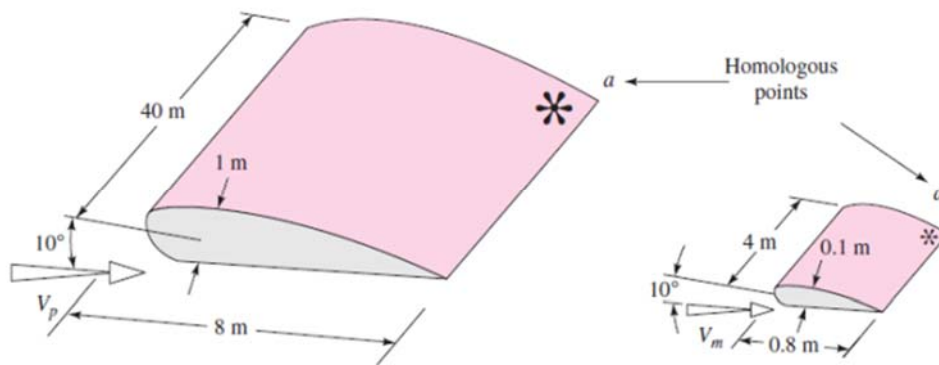


Figure 3.1 Example of a geometrical similitude case, model scale 1:10. (Novak P., et al., 2007)

After all, the geometric similitude could not be completely realized as some conditions are not subjectable to the model scale. For example, the roughness factor of the flow surface is one of the clear conditions which couldn't be weighted with the model scale as it will result in a very smooth surface differently to any natural case. Also, decreasing the vertical dimensions such as the depth of flow using the model scale could sharply increase the viscosity of flow differently to the prototype conditions. The previous two cases and other similar cases fall under the so-called "The Distorted Model". However, and in this study case, the effect of the model scale is likely negligible the water flume where the experiments proceeded is designed to provide a good proportionality between the vertical and horizontal dimensions, and moreover, the study is not covering parameters that are sensitive to a critical factor such as the velocity of flow which could be affected by the roughness of the bed and walls.

Table 3.1 Scale factors of the basic parameter. (Novak P., et al., 2007)

<i>Parameter</i>	<i>Scale factor</i>	<i>Parameter</i>	<i>Scale factor</i>
Velocity	$M_v = M_l^{1/2}$	Area	$M_A = M_l^2$
Volume	$M_V = M_l^3$	Mass	$M_m = (M_\rho) M_l^3 = M_l^3$
Time	$M_t = M_l^{1/2}$	Discharge	$M_Q = M_l^{5/2}$
Force	$M_F = (M_\rho) M_l^3 = M_l^3$	Specific discharge	$M_q = M_l^{3/2}$
Pressure	$M_p = (M_\rho) M_l = M_l$	Energy	$M_E = (M_\rho) M_l^4 = M_l^4$
(intensity)		Momentum	$M_M = (M_\rho) M_l^{7/2} = M_l^{7/2}$

Table 3.1 is a spreadsheet shows the scale factors of the basic physical parameters.

3.3.3 The Kinematic Similitude

The Kinematic similitude is another type of similarity that is needed to be considered and realized to ensure the full hydraulic similitude between the prototype and its model. Mainly, it is realized when the ratios of the model velocity to the prototype velocity at certain points are equaled to each other. (Al Mourei Y., et al., 2009), (White F. M., et al., 2016)

In other words, when homologous particles lie at homologous points at a homologous time:

$$\frac{(V_1)_m}{(V_1)_p} = \frac{(V_2)_m}{(V_2)_p} = \dots = \frac{(V_n)_m}{(V_n)_p} = V_r = \text{Constant} \quad (3.4)$$

$$\text{Then; } \frac{(V)_m}{(V)_p} = V_r$$

Where; $(V_1, V_2, \dots, V_n)_m$ are the values of the flow velocity for the points 1, 2, ..., n of the model.

And $(V_1, V_2, \dots, V_n)_p$ are the values of the flow velocity for the points 1, 2, ..., n in the prototype.

V_r is a constant called the Velocity scale.

Similarly,

$$t_r = \frac{t_m}{t_p} = \frac{L_m/V_m}{L_p/V_p} = \frac{L_m}{L_p} \cdot \frac{V_p}{V_m} = L_r \cdot \frac{1}{V_r} \quad (3.5)$$

Then the time scale is

$$t_r = \frac{L_r}{V_r} \quad (3.6)$$

Also, the acceleration is

$$a_r = \frac{L_r}{t_r^2} \quad (3.7)$$

And the discharge scale is

$$Q_r = \frac{L_r^3}{t_r} \quad (3.8)$$

In this study case, the hydraulic conditions such as water velocity and discharges don't simulate the prototype, as the reference study was only used to provide the dimensions of the prototype, while the hydraulic conditions are the studied factors to investigate the impact of their variance on the resulted scour.

3.3.4 Selection of Model Scale

Finding the model scale is the foundation stone in constructing the model. Therefore, many factors should be considered before finally selecting the scale; The space to build the model in the laboratory, the maximum discharge of water in the laboratory, the type of data that are intended to find and the availability of the appropriate measurement tools, and finally, the budget to construct the model. (Al Mourei Y., et al., 2009), (White F. M., et al., 2016)

As the simulated models have smaller linear dimensions and hydraulic values, then much less area and budget of construction are needed to proceed experiment, which is why the experimental studies are still widely used in this field unless the simulation affected the real operational conditions of the prototype, as clarified before.

For the dams and spillways constructions, the used similitude models could have very small scales that might range in 1:300 – 1:400, while for the pipes and vales 1:5 – 1:25 and for rivers and huge water constructions 1:100 – 1:1000. In the end, the most important point while selecting scales is to make sure that the selected dimensions and hydraulic values, such as the model size and the discharges, could be simulated in the Lab where the study will proceed with consideration to the specifications of the used tools in the experimental study.

Based on this concept, the capacity of the pumping system in the laboratory was considered to assign the water discharges of this study, as well as the dimension of the water flume to select the model scale.

3.3.5 Distorted Models

Since the geometric similitude is not accomplishable, for example, if the same scale was used for the vertical and horizontal dimensions, then, the viscous forces because of the low depth of water compared to the prototype case is very notable. Thus, the distorted models are used when the dimensions in one direction (n) were weighted with a different scale from the other direction (m), in this case, we call the ratio (n/m) as the distortion ratio/coefficient.

Distortion of dimension is usually adopted in the river and open channels models, where a different scale ratio for depth is adopted. These models with vertical scale

greater than horizontal scales are called (Vertically exaggerated models). (Viswanadh G. K., 2017)

The model is usually subjected to one type or more of distortion:

The geometric distortion: which is using different scales for the dimensions in different directions. the distortion may be either of dimension or the configuration (E.g. different bed slope for model)

The shape distortion: such as different bed slope of the model in comparing to the prototype slope of the bed in open channel cases.

The hydraulic distortion: Which is usually related to the hydraulic variables such as velocity, time or discharges.

The physical deformation: which happens because of using materials with somehow different specifications, such as the roughness, from the real case.

It is true that the model of this study is subjected to distorting, more specifically, physical deformation as the materials used to structure the model is different from the real case, such as the banks of the open channel in the real case which were replaced with glass walls in the experiments. However, this changing might be reflected in the shearing stress of the banks, which its effect is not considered in this case study.

In any case, using distorted models may have some advantages, in case the effect of this usage was considered in designing the model and extracting the results.

Merits of distorted models

- Obtaining the needed hydraulic similitude.
- Increasing the depths of flow and slopes of water surface which ease the measurement processes.
- The produced viscous from using the simulation could be overcome by increasing the slope of the open channel bed which increase the velocity to equalize the resistance force of the viscous.
- Easily operated as the distorted models usually have a much smaller size than the prototypes.

Demerits of distorted models

- Distorting turns and slopes of flow.
- As the dimensions were not weighted with the same scale, then the velocity and pressure will be informally distributed in the different sections of the flow.
- As a result of testing depths un-similar to the real case, different waves from the real case might form as a reaction to the flow mobility.
- Using distorted models might produce some doubts about excrement conductor because using models that are not matching the prototypes.

3.3.6 The Scale effect

It is the effect results because of using a different scale from the prototype case. It is known that the values of depths and velocities are much more than the prototype cases, means, the surface tension is almost nonexistent. However, this force couldn't be ignored while proceeding the experiment in the laboratory as it has a notable effect. Also, and because of the viscus, the flow might be turbulent unlike to the real case where the flow is uniform in the natural case of the open channels. In any case, the perfect similitude is not achievable. (Al Mourei Y. et al., 2009)

3.3.7 Spillway Profile

One of the most widely used spillways around the world is the ogee spillway, or in other words, the overflow spillway as it is being designed to allow water flows over its crest. The ogee spillway usually has the shape of "S" letter and its front surface and crest are being designed and curved to have the shape of the water jump in the case of sharp-crested weirs at the maximum design capacity of the spillway, as shown in Figure 3.2. (Akıntuğ B., 2012)

This shape is desirable because of the resulting overflow jet above a sharp-crested weir corresponds to the natural shape and involves atmospheric pressure across the boundary of the nape.

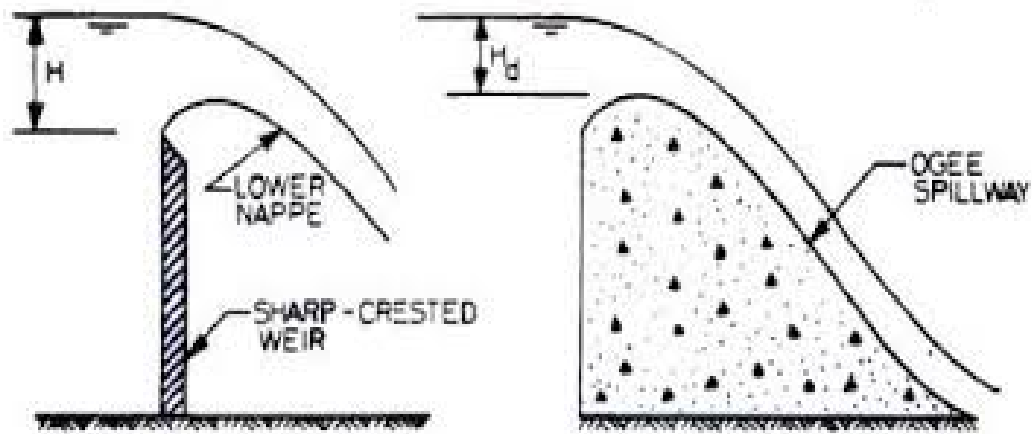


Figure 3.2 Ideal Ogee Spillway profile. (Akıntuğ. B, 2012)

Ogee spillway is the most efficient spillway, which its unique hydraulic characteristics attracted the attention and caused these hydraulic structures to be studied frequently. In the type of spillways, the flow upstream of the spillway is subcritical while it becomes a supercritical almost nearby to the crest then going back to subcritical condition at some point downstream of spillway forming a hydraulic jump. Of course, the condition of flow is tightly related to the flow velocity which justifies the supercritical condition of flow at the crest of the spillway where the flow acceleration and pressure become smaller than hydrostatic pressure because of the strong curvature of streamline. Therefore, the depth of the flow over the crest is slightly smaller than the critical depth. (Daneshkhah A., et al., 2011)

There are two main types of ogee spillway according to the controlling condition of the flow passing over it. The controlled, gated, or guided flow where the flow is being controlled by a gate above the crest of the structure. The second type is the one that has no gate to control the flow, which also called the spillways with ungated or free flow, the same of this study case. It is worth to mention that the majority of the newly structured spillways are being provided with gates to meet the needs of water and to achieve better controlling and avoid the negative effects of sudden events such as floods. (Daneshkhah A., et al., 2011)

Also, it may be classified based on some factors related to the profile shape of the spillway, the most famous shape is the ogee spillway with a vertical upstream face as per this studied case, which also could be sloped. In any case, these changes in

the profile shape are reflected on the computations of design as the used formulas vary by these changes. (Daneshkhah A., et al., 2011)

3.3.8 Spillway Crest Profile

As previously mentioned, there is no certain profile identified as the ideal shape of the ogee spillway. In principle, the design is different from a way to another. The most common are the USBR (1987) and (USACE) for a spillway has a vertical upstream face. According to the USBR (1987) method, the smoothness of the crest profile directly affects the pressure distribution upstream of the spillway, especially at the bottom section. (Akıntuğ B., 2012), (Bulkley–Logston C., 2015)

The crest is usually formed by smooth curves for the purpose of minimizing the separation and inhibit the cavitation of damage. The sloped section at the downstream side has an approximate tendency ratio of 1V:0.6H. In fact, the length and the declination are dictated by the stability requirements. The USBR (1987) method was used to design the model, where the downstream surface tendency and the smoothness of the crest were carefully considered during the designing and the implementation of the model. Figure 3.3 shows the designing criteria of The USBR (1987) method.

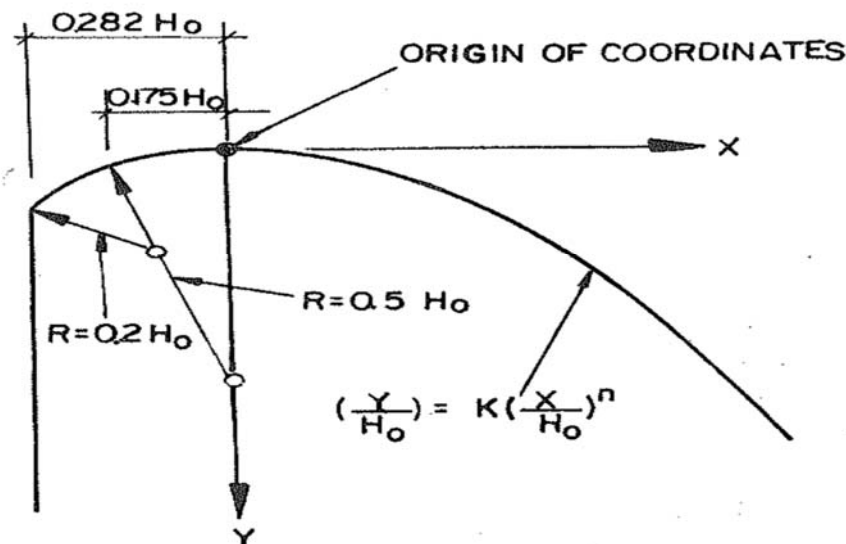


Figure 3.3 Standard crest profile of an overflow spillway (USBR, 1987). (Akıntuğ B., 2012)

K and n constant depend on the upstream inclination and the velocity, and H_0 is the design head. Q (m^3/s) is the discharge over the spillway, C is the discharge coefficient, L (m) is the length of the crest and H (m) is the head over the crest. For the velocities greater than 10 to 15 m/s, chute aeration is required with specific thickness to the relevant boundary layer.

Gates are usually being installed between the piers which in their rule hold transportation bridges above the spillway body. These gates usually control the flow between the piers and abutments. In the prototype case of this study, the spillway carries piers and gates, but these additions to the spillway body were not considered in the model of the experiments.

The model of this experiment is providing simulation to the prototype case of S65E ogee spillway on Kissimmee River south of Orlando, Florida. Different modelling scale from the used reference study was used, either for the geometric or hydraulic parameters, the scale was selected with consideration to the available capabilities in Gaziantep University, especially, the maximum discharge available. In the end, the modelling scale 1:34.5 was selected using. As a result, the model dimensions were found to be as per table 3.2;

Table 3.2 Hydraulic and geometric parameters of the study using the modelling scale

Item	Symbol	Measurement unit	Prototype	Scale 1:34.5
Discharge (Max)	Q	m^3/s	0.1889	0.065
The width of the spillway	B	m	27.3	0.791
Height of crest	P	m	3.44	0.0997
Designed Head	H_d	m	4.42	0.128
Apron Length	L_{sb}	m	32.4	0.939

The design includes a protective apron plate downstream of the spillway, where the blocks were fixed in the shape of lanes.

The design head in this study model is $H_0=0.128$ m. K and n are approximately equal to 0.5 and 1.85, respectively as we have a vertical surface at the upstream of the studied structure. Back to the standard equation representing the upstream face of the spillway. (A. Osman Akan, 2006)

$$\frac{Y}{H_0} = K\left(\frac{X}{H_0}\right)^n \quad (3.9)$$

Then it will have the shape of the following equation:

$$X^{1.85} = \frac{Y}{2.87} \quad (3.10)$$

To find the shape of the profile curve, the value of X has been found for each 0.05 step of Y, as per table 3.3

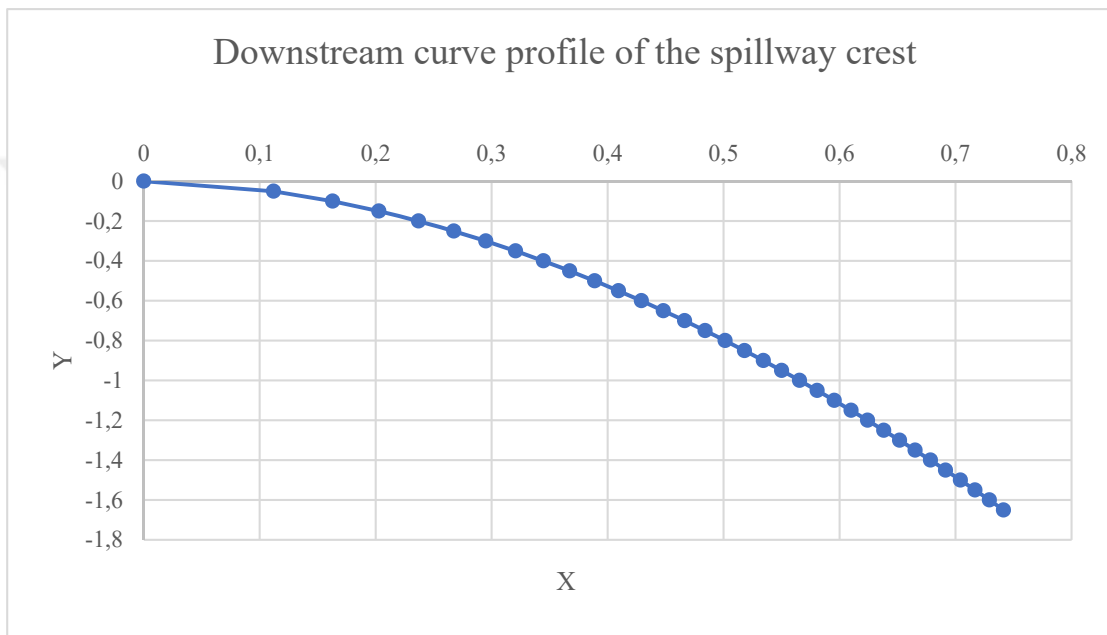


Figure 3.4 The curve of the downstream side from the spillway crest

The crest trend was recognized to be as per figure 3.4, With consideration to the following values:

$$0.282 H_0 = 0.0361 \text{ m}$$

$$0.175 H_0 = 0.0224 \text{ m}$$

$$R_1 = 0.235 H_0 = 0.0256 \text{ m}$$

$$R_2 = 0.53 H_0 = 0.064 \text{ m}$$

Table 3.3 The values from the equation of the spillway upstream face

$X^{1.85}$	$(Y/2.87)^{1/1.85}$	Y	$X^{1.85}$	$(Y/2.87)^{1/1.85}$	Y
$Y/2.87$	X		$Y/2.87$	X	
0	0	0	0.296	0.518	0.850
0.017	0.112	0.050	0.314	0.534	0.900
0.035	0.163	0.100	0.331	0.550	0.950
0.052	0.203	0.150	0.348	0.566	1.000
0.070	0.237	0.200	0.366	0.581	1.050
0.087	0.267	0.250	0.383	0.595	1.100
0.105	0.295	0.300	0.401	0.610	1.150
0.122	0.321	0.350	0.418	0.624	1.200
0.139	0.345	0.400	0.436	0.638	1.250
0.157	0.367	0.450	0.453	0.652	1.300
0.174	0.389	0.500	0.470	0.665	1.350
0.192	0.409	0.550	0.488	0.678	1.400
0.209	0.429	0.600	0.505	0.691	1.450
0.226	0.448	0.650	0.523	0.704	1.500
0.244	0.466	0.700	0.540	0.717	1.550
0.261	0.484	0.750	0.557	0.729	1.600
0.279	0.501	0.800	0.585	0.742	1.650

The model spillway was mainly made by Plexiglas. Using laser-cutting technology, corresponding slices of Plexiglas were made and glued together to shape the body of the ogee spillway model along the width of the channel (80 cm) using more than 170 slices, figure 3.8. The same for the baffle blocks, the cross-section is a square ($2.3 \times 2.3 \text{ cm}^2$) and the maximum height formed of 6 slices with a thickness of 0.4 cm for each, the other cases are 4 slices and 2 slices for the minimum height. The heights of blocks are 2.4, 1.6 and 0.8 cm respectively. Choosing Plexiglas and do the cutting by laser technology ensured the accurate and identical shape of the structure.

The completed shape was also attached to a glass box fixed to the water flume floor using cold Silicone. The glass box has raised the spillway by 40 cm to provide an appropriate depth for the possible local scour in the bed downstream of the spillway.

Below are the details of the full spillway design, figure 3.5, including the adjustments, were reported previously.

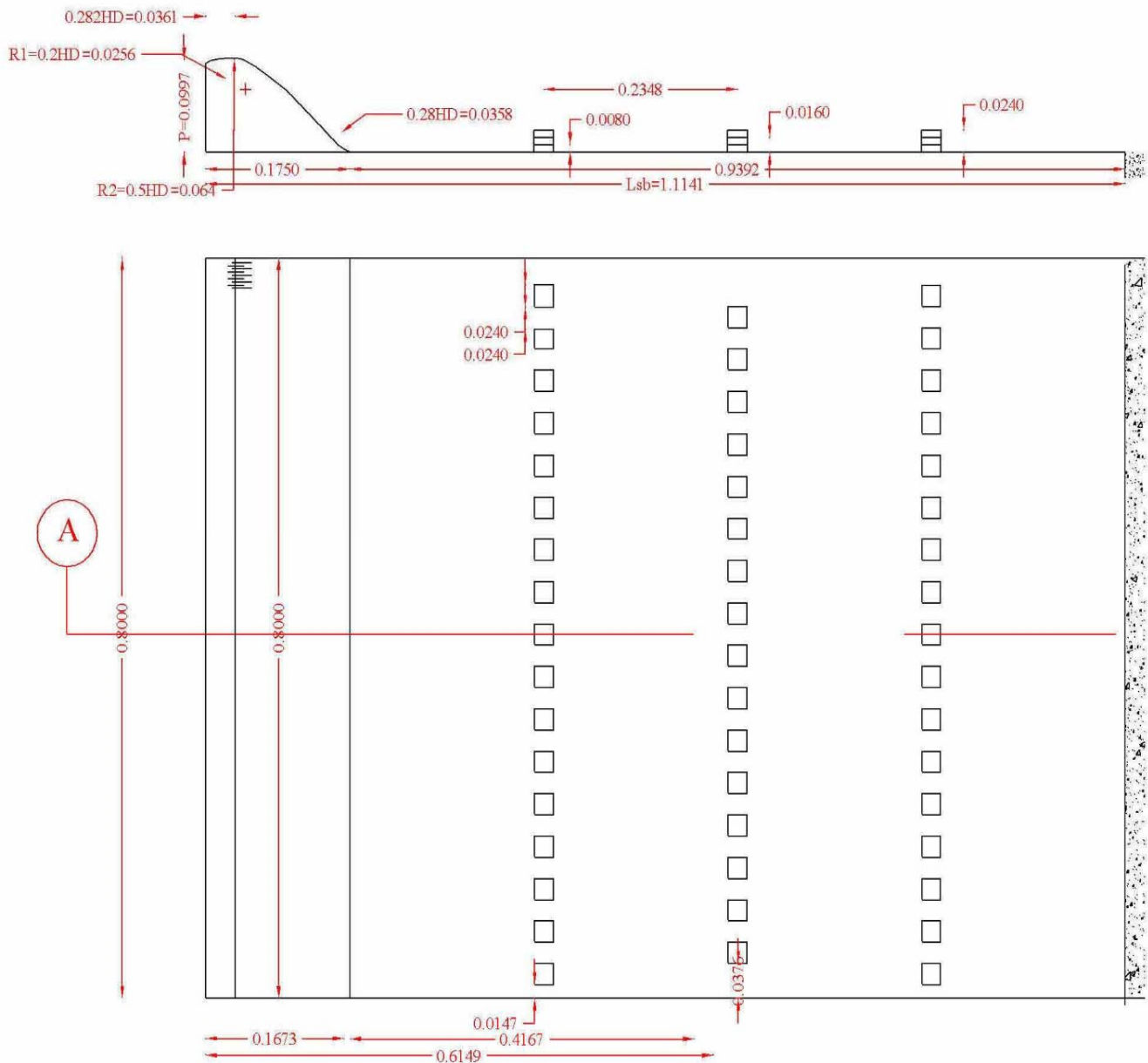


Figure 3.5 Top and side views for the spillway structure with the apron layer downstream of the structure

The box was installed after ensuring the straightness of all surfaces and the surface of the spillway was smoothed using sandpapers to avoid any inconsiderable external effects, figure 3.8.

The pieces of the structure were gathered using transparent cold silicon and super glue, as per the figure 3.9, and the whole structure, including the glass box, was glued to the flume using the Adhesive foam.

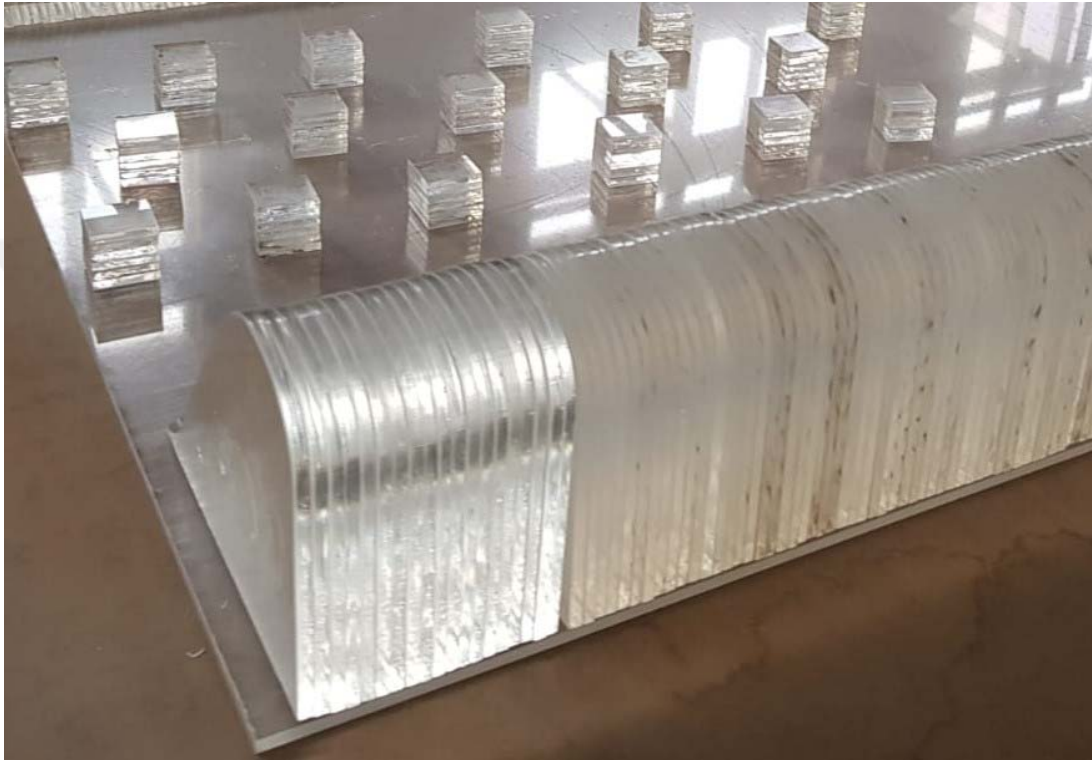


Figure 3.6 The spillway and baffle blocks Plexiglas slices

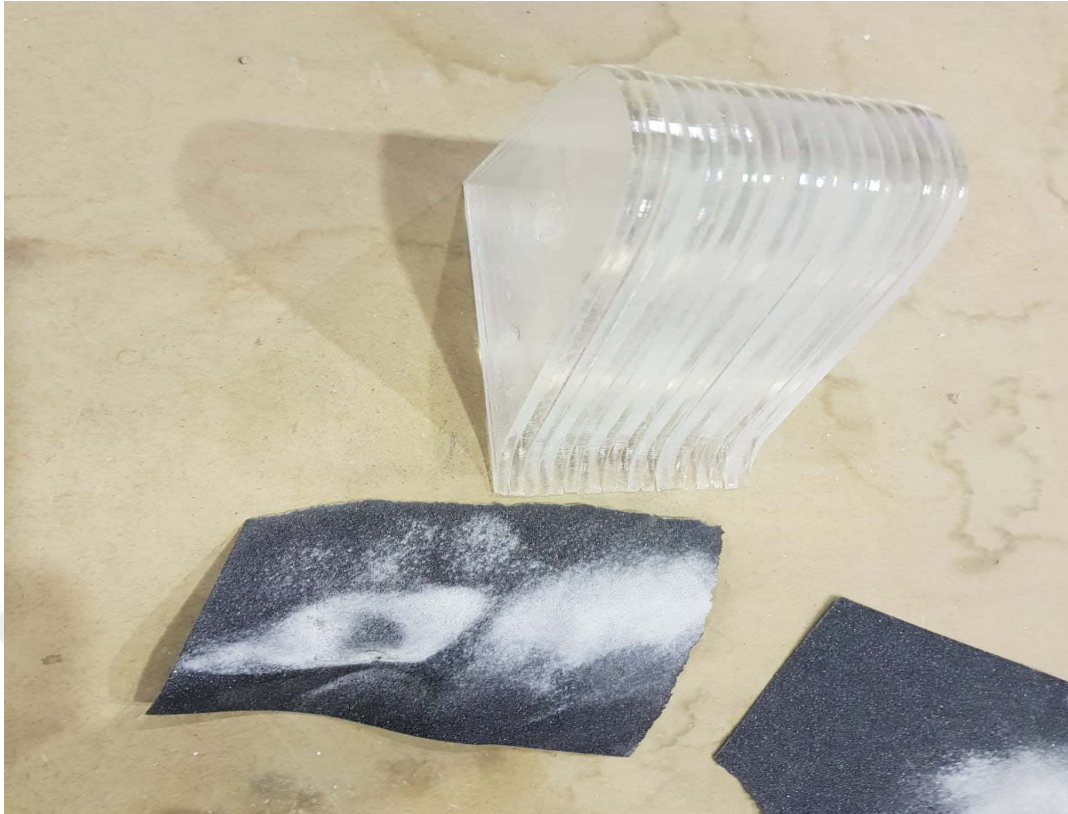


Figure 3.7 Plexiglas slices of the spillway profile, smoothing the crest surface



Figure 3.8 The Plexiglas slices of the spillway profile, gathering slices

3.3.9 Bed Sediments

To choose the ideal type and size of sediments, samples of different size and types of sediments were tested. The conditions of experiments were applied to the different samples for the purpose to observe the resulted scour in terms of the depth, extent and shape. In the end, the selected sediments showed the most reasonable results.

Mechanical sieve analysis and a specific gravity test have been carried out to characterize the sediments sizes distribution in the pool of sediments which is representing the bed sand. The tests showed that the used sand consists of cohesionless sand with a median particle size $D_{50}=1.45$ mm and specific gravity 2.65, the geometric standard deviation of the size was found to be $(D_{84}/D_{16})^{0.5}= 3.16$, referring to using sediments with non-uniform size distribution. Figure 3.10 represent the sediments sizes distribution as per the sieve analysis.

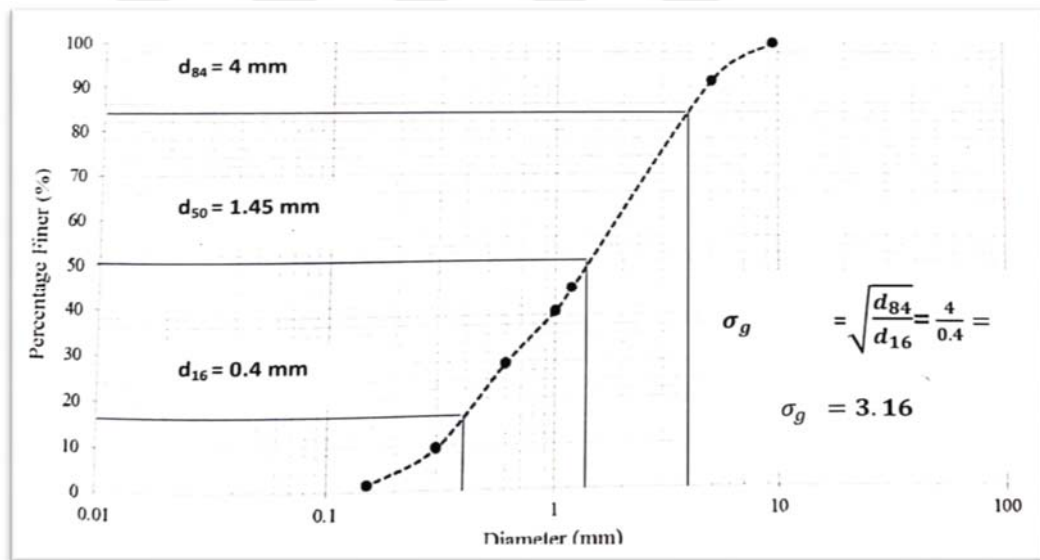


Figure 3.9 Grain size distribution

CHAPTER 4

LABORATORY EQUIPMENT AND WORK

4.1 Introduction

As an experimental study, the experiments were carried out in the hydraulics laboratory of Gaziantep University. It is well equipped with the essential items that are used for different types of experiments; such as closed water system with an underground tank for water, sedimentation reservoir, water pumps and electromagnetic gauge to measure the value of water discharge, and of course, a main water flume equipped with tailgate and two temporary water tanks, inlet and outlet tanks, at the both ends of the flume. The water flow inside the flume passes through the outlet tank into the water outputs to the sedimentation tank, where the water disposes the sediments, then flows through pipes into the underground water tank when it is being pulled up again by pumps into the inlet tank, at the beginning of the flume to back again into the outlet tank through the flume.

4.2 Laboratory Equipment

Each part of this section includes illustrative images along with descriptive details about the used equipment during the laboratory work.

4.2.1 The Water Flume

The channel is roofless and has a rectangular hollow section. It is made from steel at the bottom with glass sidewalls. The headwater is controlled by a gate at the front of the channel and the tailwater depth is also adjustable using a tailgate fixed at the end.



Figure 4.1 Water Flume



Figure 4.2 Water Flume, Control front gate

4.2.2 Water Pumps

The water is being pumped using three electrical pumps with a maximum capacity of $Q = 0.0973 \text{ m}^3/\text{s}$, $H = 14 \text{ m}$, $P = 18.5 \text{ KW}$, $n = 1450 \text{ rpm}$ and TP: SNT 150 ~ 250. They pull water from the main reservoir through 70 cm pipe and pump the water to the flume through another pipe with a length of 53.5 cm.

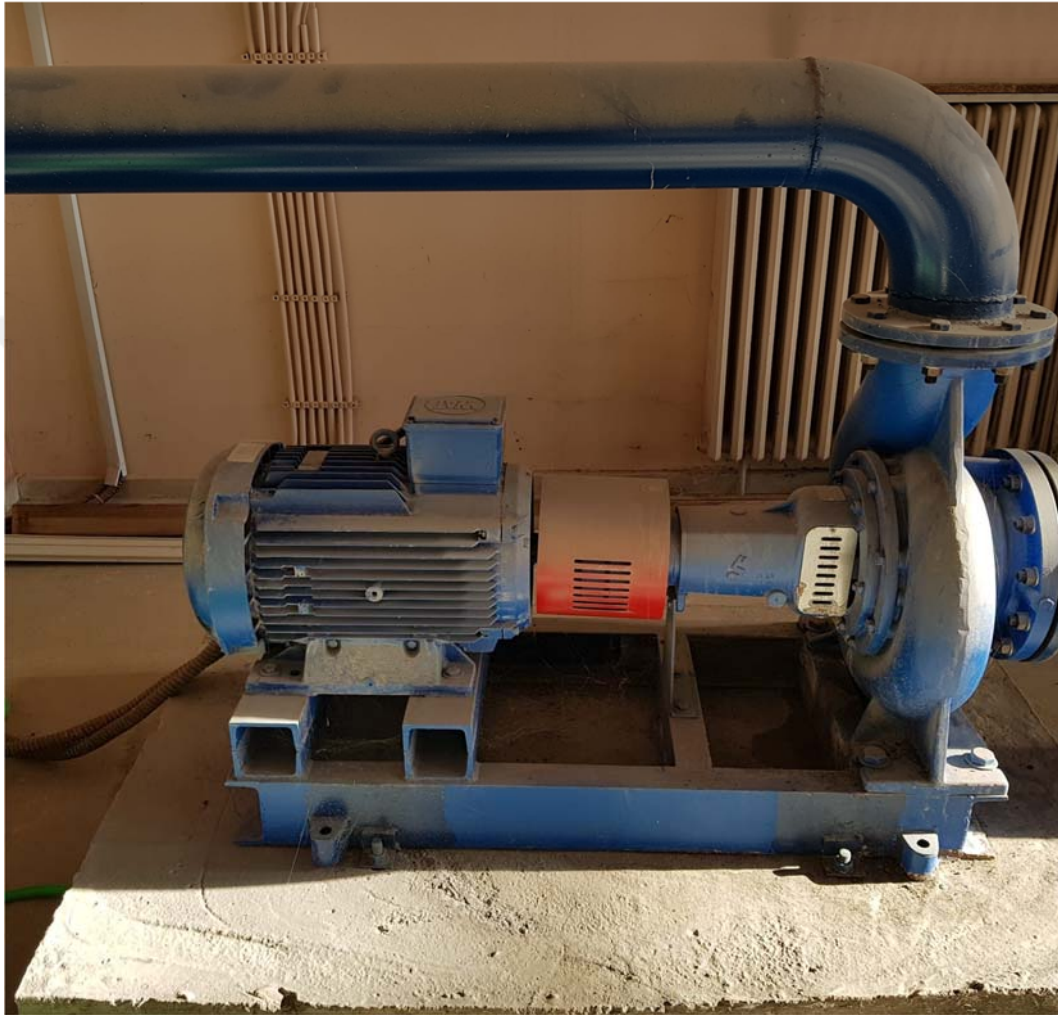


Figure 4.3 Water pumping unit

4.2.3 Inlet Tank

A steel tank has the dimensions (1.3 m of length, 0.8 m of width and 1.5 m depth). It is the tank receives water from the pumps through input pipe that has the length of 53.5 Cm, started with a valve to control the water discharge.



Figure 4.4 Inlet tank of the water flume

4.2.4 Outlet Tank

Another steel tank at the end of the water flume with the dimensions of (length 1.3m, depth 1.5 m and width 0.8 m) collect the water passed the flume and drain the water through two output pipes (2 * 67 cm) into two square holes (0.5 m * 0.5 m * 0.6 m depth) that lead the water into the sedimentation tank.



Figure 4.5 Outlet tank of the water flume

4.2.5 Sedimentation Tank

A concrete underground tank has the dimensions (1.6 m * 1.6 m * 1 m depth), linked with the main reservoir with an underground trench and receive the water passed through the water flume. It is built to allow water to dispose of what it holds of suspended sediments by dissipating water velocity. Its output open has a fine sieve fixed on the open to obstruct sediments passing to the main reservoir.



Figure 4.6 Sedimentation Tank

4.2.6 Main Water Tank (Reservoir)

An underground concrete tanks. The last storage reservoir where the water settles and being pumped again into the flume using the electrical pumps.



Figure 4.7 Main Water Tank (Reservoir)

4.2.7 Electromagnetic Flowmeter

It is a gadget used to measure the value of water discharge passing the pipes to the water flume. It shows the value as digits on a digital screen and refer to the range of error in the shown reads. The water discharge passing to the flume is being controlled by a valve fixed on the pipe just before the electromagnetic gauge.



Figure 4.8 Electromagnetic Gauge

4.2.8 The Point Gauge

A stake tool ends with a needle measures the heights/depths accurately and shows the results either in inches or mms. It is mobile and usually fixed in a sliding base over the flume walls. The values shown usually is comparable to a pre-sat zero point. It could be used to measure the depth of water or bed scour.



Figure 4.9 The Point Gauge

4.2.9 Soil Paving Ruler

A steel plate has the shape of a ruler with a width of about 20 cm hanged by two steel stakes to a movable base that looks like the one used for the point gauge, sliding over the flume on the top of the side walls. The high of the ruler is adjustable by screws. Mainly used to pave the surface of the soil to ensure a homogeneous scour occurs along the width of the channel and downstream of the spillway.



Figure 4.10 Soil Paving Ruler

4.2.10 Tailgate

A gate fixed at the end of the water flume. It's mainly used to control the tailwater level downstream of the spillway which by turn, with other factors, affect the location of the water jump as the jump places closer to the spillway body by decreasing the level of the tailwater.

The opening of the gate is adjustable by a steel rope fixed to the top of the gate from one side and linked to a roller par from the other side which is used to control the angle of the opening.



Figure 4.11 Tailgate

4.3 Laboratory Work

As reported, three values of discharges were selected to proceed with the experiments and to find out the relation of changing flows values and the scour developing with respect to the other designing conditions. The experiments were repeated for the following values of discharges; 0.0408, 0.0337 and 0.0276 m³/s respectively. These values were selected with respect of having the hydraulic jump totally formed inside the apron for the no blocks cases where the jump location pushed inside the apron by increasing/decreasing the tailwater elevation using the tailgate, as shown in the figure 4.12. Later, the same tailwater level used for the other experiments with the same discharges and different conditions regarding the number of blocks lanes and height of blocks, figure 4.13.



Figure 4.12 Hydraulic Jump formation downstream of the spillway – no blocks case



Figure 4.13 Hydraulic Jump formation downstream of the spillway – One blocks lane case

To identify the needed time for each individual experiment, 6 continuous hours proceeded for the experiment of the worst conditions, the maximum discharge without blocks fixed on the apron. The results showed that the scour started to barely develop after two and a half continuous hours of the experiment, as shown in figure 4.14. Therefore, 3 hours were assigned for each of the followed experiments to observe the scour developing by the time.

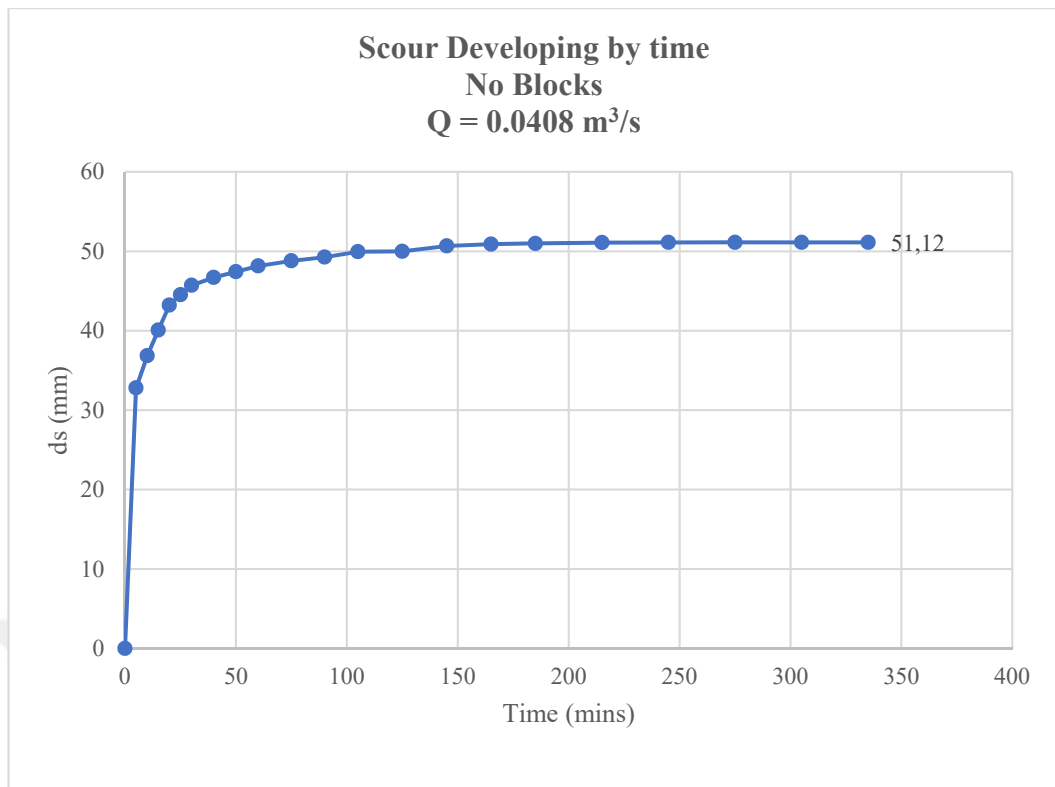


Figure 4.14 The scour developing graph of six hours of the experiment for $Q=0.0408 \text{ m}^3/\text{s}$ and no baffle blocks

Totally, 30 individual experiments were conducted to cover all cases as per the following:

- 3 experiments covering the case of no baffle blocks fixed on the apron for the chosen 3 discharges.
- 3 experiments for one lane of blocks, 6 slices for the height (24 mm) and $Q = 0.0408, 0.0337$ and $0.0276 \text{ m}^3/\text{s}$.
- 3 experiments for two lanes of blocks, 6 slices for the height (24 mm) and $Q = 0.0408, 0.0337$ and $0.0276 \text{ m}^3/\text{s}$.
- 3 experiments for three lanes of blocks, 6 slices for the height (24 mm) $Q = 0.0408, 0.0337$ and $0.0276 \text{ m}^3/\text{s}$.
- 3 experiments for one lane of blocks, 4 slices for the height (16 mm) and $Q = 0.0408, 0.0337$ and $0.0276 \text{ m}^3/\text{s}$.
- 3 experiments for two lanes of blocks, 4 slices for the height (16 mm) and $Q = 0.0408, 0.0337$ and $0.0276 \text{ m}^3/\text{s}$.
- 3 experiments for three lanes of blocks, 4 slices for the height (16 mm) and $Q = 0.0408, 0.0337$ and $0.0276 \text{ m}^3/\text{s}$.

- 3 experiments for one lane of blocks, 2 slices for the height (8 mm), $Q = 0.0408, 0.0337$ and $0.0276 \text{ m}^3/\text{s}$.
- 3 experiments for two lanes of blocks, 2 slices for the height (8 mm), and $Q = 0.0408, 0.0337$ and $0.0276 \text{ m}^3/\text{s}$.
- 3 experiments for three lanes of blocks, 2 slices for the height (8mm), $Q = 0.0408, 0.0337$ and $0.0276 \text{ m}^3/\text{s}$.

The blocks were being fixed on the apron using super adhesive materials, the blocks were fixed as per the particular arrangement of each experiment and their specific locations were recognized by using printed papers to the structure in its original scale 1:1, as per the figure 4.13.

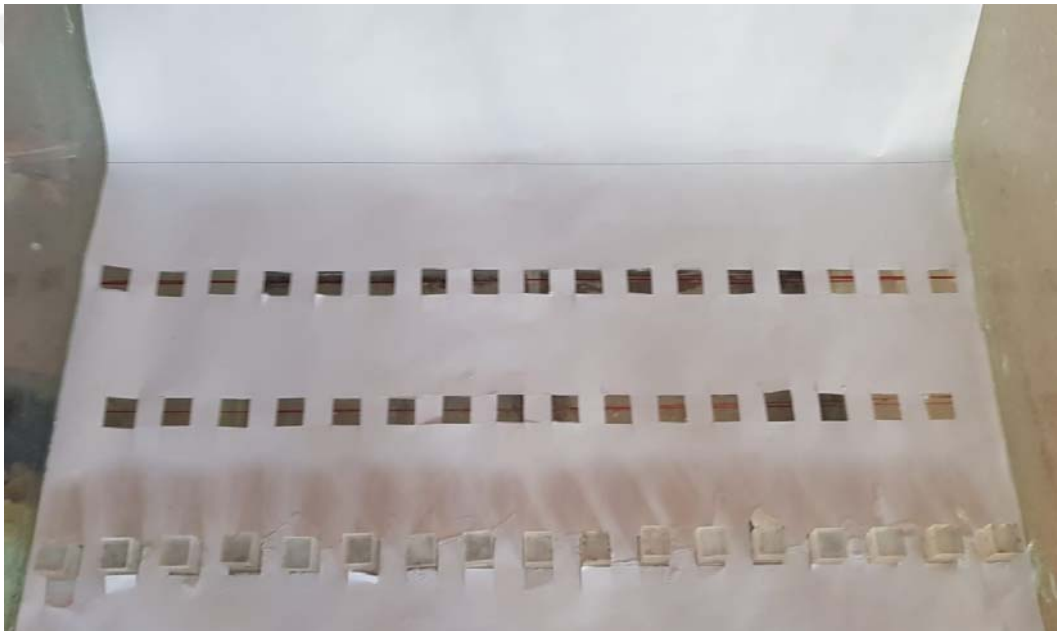


Figure 4.15 Fixing the baffle blocks on the apron

The upper layer of sediments, 7-8 cm, in the sediments pool was being replaced after each individual experiment as it already lost the finest sizes, then, and using the paving ruler, the surface of the replaced layer was being levelled to provide the straight surface which doesn't have any unconsidered effect on the shape of the formed scour before starting the next experiment.

To observe the scour development, the depth of the scour was being recorded every 5 minutes for the first half an hour when the majority of the scour occurs, the frequency of scour measurement decreased gradually then to be one record every 10 minutes for the next half of hour, one record every 15 minutes after the minute

60 till the minute 105 and every 20 minutes starting from the minute 105 till the minute 185 (the end of the experiment).



CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Introduction

This section determines the most effective variables in this case of study, shows the results of the dimensional analysis, and identifies which measurements have been taken during the experiments. Also, it includes the analysis of the collected data; statistical tests, correlations and regressions of the different effective variables, and it concludes with a formula links the majority of the studied variables.

5.2 Results and Discussions

5.2.1 Findings

The maximum scour depth occurred for the cases of having no blocks but only the apron layer to resist the scour phenomena. Figure 5.1 shows the scour developing for the 3 design discharges of these experiments. It is no surprise that the maximum values obtained for the maximum discharge, $Q = 0.0408 \text{ m}^3/\text{s}$, followed for the discharge with the less value, $Q = 0.0337 \text{ m}^3/\text{s}$ and at the last place the values of the minimum discharge, $Q = 0.0276 \text{ m}^3/\text{s}$. For all of the other cases, scour developing behaved similarly with different values, fewer values as per the number and sizes of blocks. However, as for the no block cases, the discharge always had a key role controlling the behaviour of the formed scour along with other major factors such as the tailwater depth and location of the formed hydraulic jump.

It is worth to mention that the hydraulic jump location was controllable during the experiments by the depth of tailwater and affected by the depth of scouring formed at the pool of sediments. It was noted that the jumps were getting closer to the spillway by developing the depth of scouring

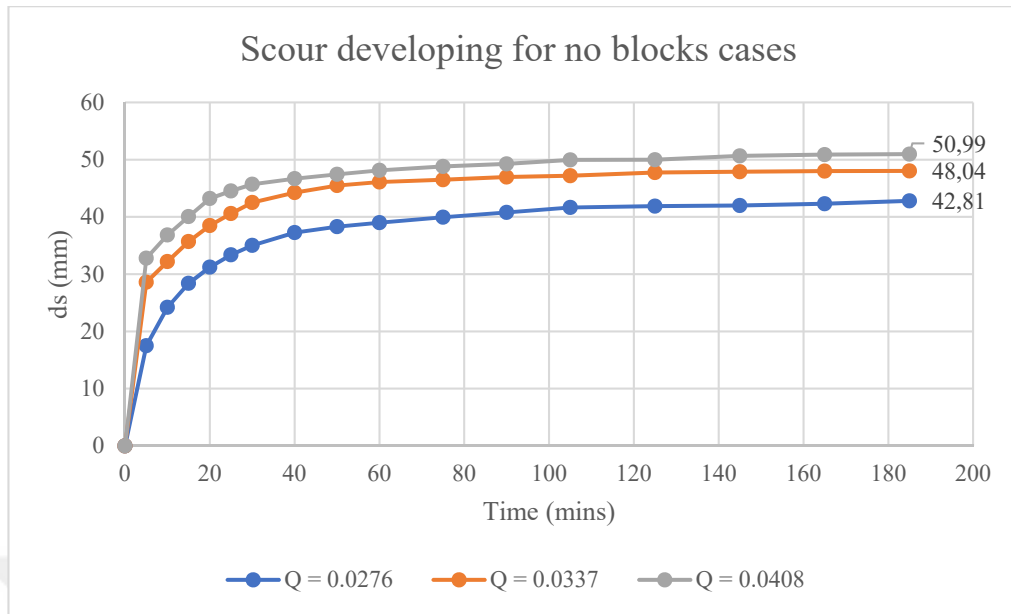


Figure 5.1 The developing of the local scour depth for the three studied values of discharges

As indicated in figure 5.1, the maximum scour values obtained for the maximum discharge. Compared for the results of the other two discharges, the scour produced because of the medium discharge have values closer to the maximum discharge which is most likely because of the location of the jump as it was included within the middle of the 3rd portion, the last third before the bed, of the apron in the maximum discharge case, while it was formed at the last part of the third section for the medium discharge. In other words, the hydraulic jump seemed to have more affection for the scour shaping by getting closer to the end of the apron.

Also, as per Figure 5.1, the water seemed to have a greater ability to scour sediment more rapidly with increasing the water discharge.

The minimum discharge had almost the same behaviour regarding the scour developing but with fewer depths of scouring measured through the experiment period. However, the scour developing has significantly decreased after 2 hours running and almost stopped after running the experiments for the three hours.

The figures 5.2, 5.3, 5.4 below show the depth of maximum scour depths produced for the different discharges, heights and number of blocks lanes.

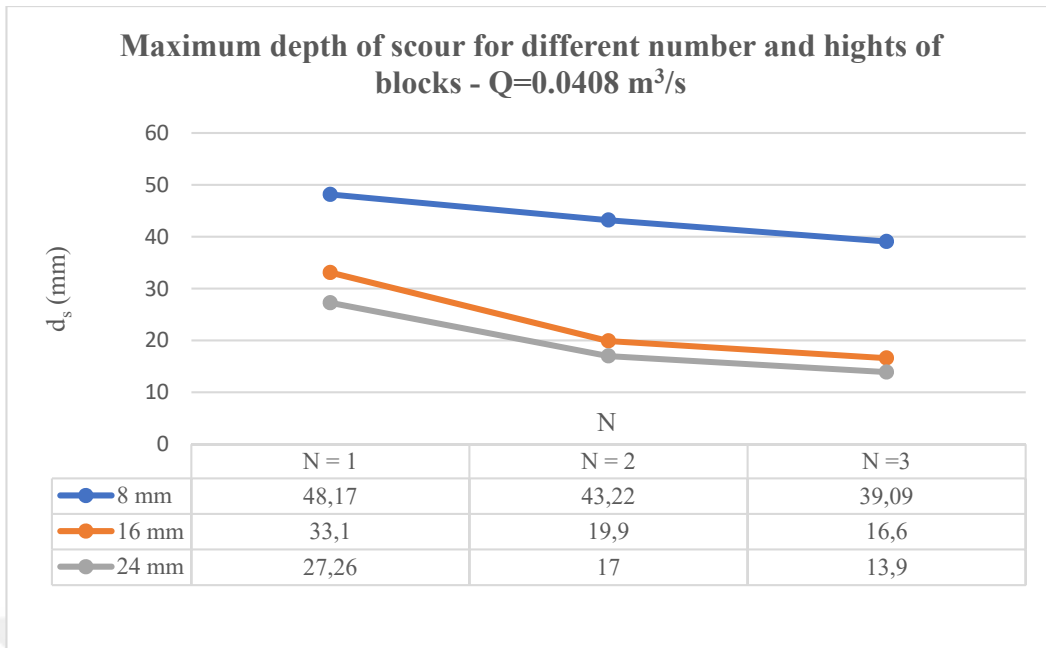


Figure 5.2 The maximum scour depths for the different heights and number of blocks lanes, the maximum discharge

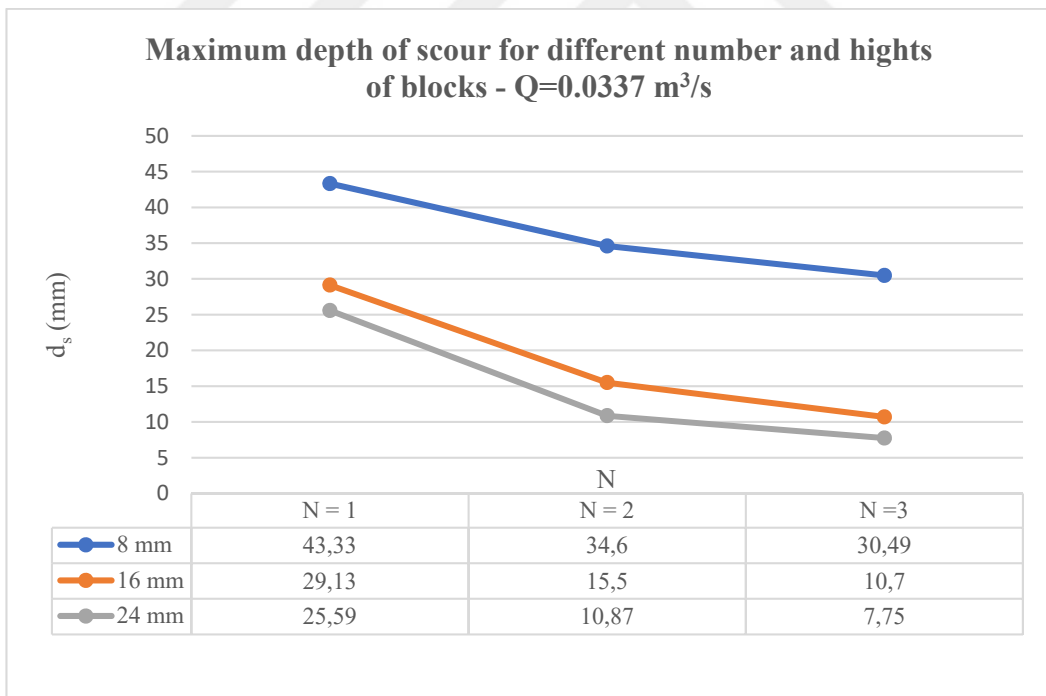


Figure 5.3 The maximum scour depths for the different heights and number of blocks lanes, the medium discharge

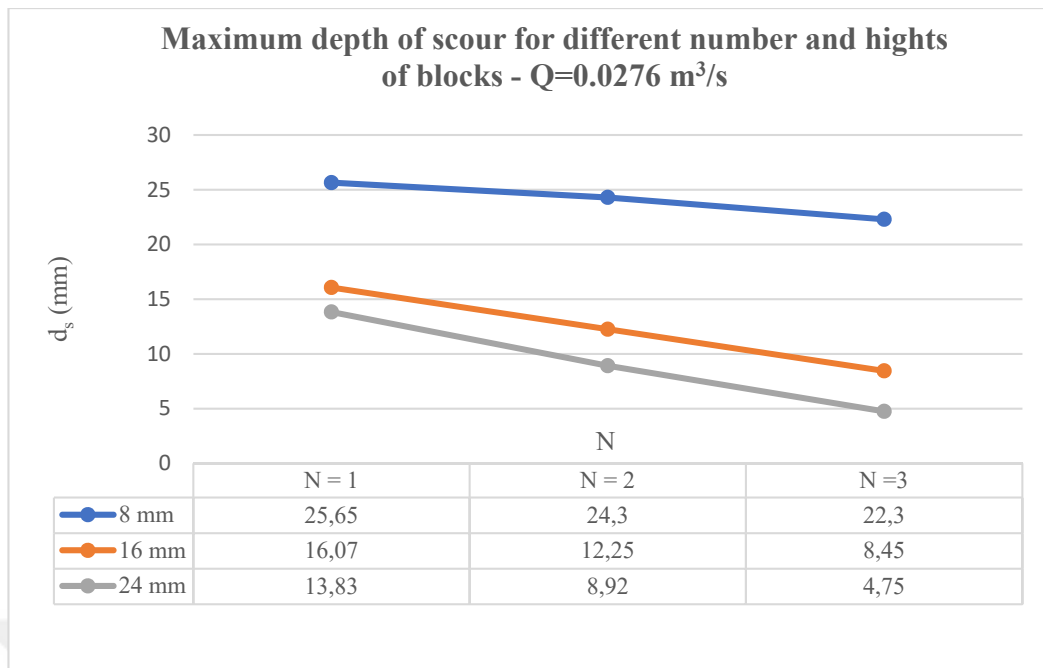


Figure 5.4 The maximum scour depths for the different heights and number of blocks lanes, the minimum discharge

In general, both factors, the size of blocks and the number of blocks lanes seemed to have a significant impact on decreasing the produced scour. The effect of these factors varied from a case to another, for example, the height of blocks had a more significant impact for the minimum discharge as the minimum height of blocks clearly affect the depth of scouring compared to the other two discharges.

For the case of the minimum discharge, the number of blocks lanes didn't have a considerable effect on the scour depth for the minimum height of blocks, compared to the effect because of increasing the height of blocks. Means, in the minimum discharge case, the number of blocks lane became more effective by increasing the height of blocks. In other words, duplicating the height of blocks decreased the scour depth by 62.65% for the case of one lane, by 50.4% for the case of two lanes, and 37.9% for the case of three lanes, compared to the cases of minimum heights of blocks. The maximum height of blocks decreased the depth of scour with additional 8.7%, 13.7%, and 16.6% for the cases of one, two and three lanes respectively, compared to the height of blocks, 16 mm.

Regarding the greater two discharges, having only one lane of blocks regardless of the height had a respectable impact in decreasing the depth of scouring. Increasing the number of lanes to be two had sharply improved the performance of the blocks

system, while the results from using three lanes of blocks seemed to be closer to the case of two lanes. In other words, higher discharges showed better interaction with adding one lane to dissipate energy compared to the minimum discharge, the same regarding the second lane, while the interaction was less in terms of the third lane.

As per the measurements and compared to the cases of minimum heights of blocks, 8 mm, the scour depth has decreased by 67%, 44.8%, and 35% for N=1, 2, and 3 respectively, due to duplicating the height of blocks, 16 mm, for the cases of medium discharge, 0.0337 m³/s. The recorded scour depths have been measured for the maximum height of blocks have indicated into additional 8%, 13%, and 9.6% reduction in the depth compared to the case of blocks height 16 mm.

As for the maximum discharge cases, using the medium height of blocks. 16 mm, declined the scour depth by 68%, 46.04%, and 42.5% for the case of N=1, 2, and 3 respectively, compared to the minimum height of blocks cases, 8 mm, while for using the maximum height of blocks, 24 mm, the scour reduced by additional 11%, 6%, and 7% for N=1, 2, and 3 respectively.

5.2.2 Dimensional Analysis

Based on the literature review, the following variables and constants were found to directly affect the results of this study experiments. (*Yousef Al Mourei and Wael Muala, 2009*)

h; the height of blocks

Q; Water discharge

N; The number of blocks lanes

g; gravity acceleration

w; The density of water

s; the density of sediments

D₅₀; the median size of sediments

v; water approaching velocity over the crest of the spillway

y_1 ; the depth of water in the critical condition before the hydraulic jump

y_2 ; the depth of water in the subcritical condition after the hydraulic jump

h_c ; the depth of water over the crest of the spillway

d_s ; the scour depth

However, the effects of w , s , and D_{50} were ignored as the same water and sediments were being used for all experiments.

Using Buckingham theorem π of the dimensional analysis, the scour development was found to be functional for the following variables;

$$\frac{d_s}{h_c} = \text{fk}\left(\frac{h}{h_c}, \frac{Q}{v h_c^2}, \frac{h_c g}{v^2}, \frac{y_1}{h_c}, \frac{y_2}{h_c}, N\right) \quad (5.1)$$

Therefore, the variables were being measured by the point gauge and recorded during proceeding the experiments were;

d_s , y_1 and y_2 varied as per the number of lanes, the height of blocks and values of charges

h_c which was only changed by changing discharge

For the purpose of resulting in a comprehensive formula links and shows the relation among the study variables, it was necessary to test the found data statistically.

5.2.3 Dependent variable and independent variables

The graphs below, figure 5.5, 5.6, 5.7, 5.8, and 5.9 express the relationship between the dependent variable on the one side and each of the independent variables on the other hand. The showed results may not accurately reflect the true relations, as statistical analysis is needed to verify the impact of those all variables on each other and by turn on the dependent variable in the regression formula.

Initially, the graphs show a negative trending relationship that governs the relation with each of the independent variables, which could be expressed by minus

marks in the final regression formula. However, some relations showed a much higher variance compared to the others; $\frac{d_s}{h_c}$ vs. $\frac{y_2}{h_c}$ is an example.

The trend lines on the graphs are straight lines link or attempting to link most of the points to express the variance of values and the general trending of the relation.

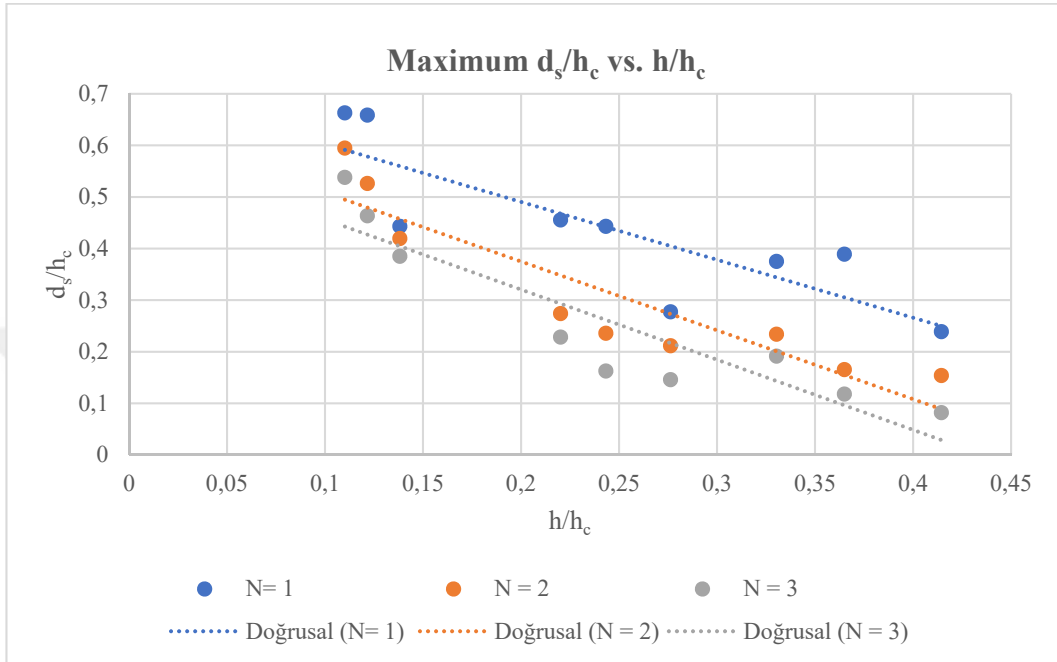


Figure 5.5 Relationship graph - $\frac{d_s}{h_c}$ vs. $\frac{h}{h_c}$

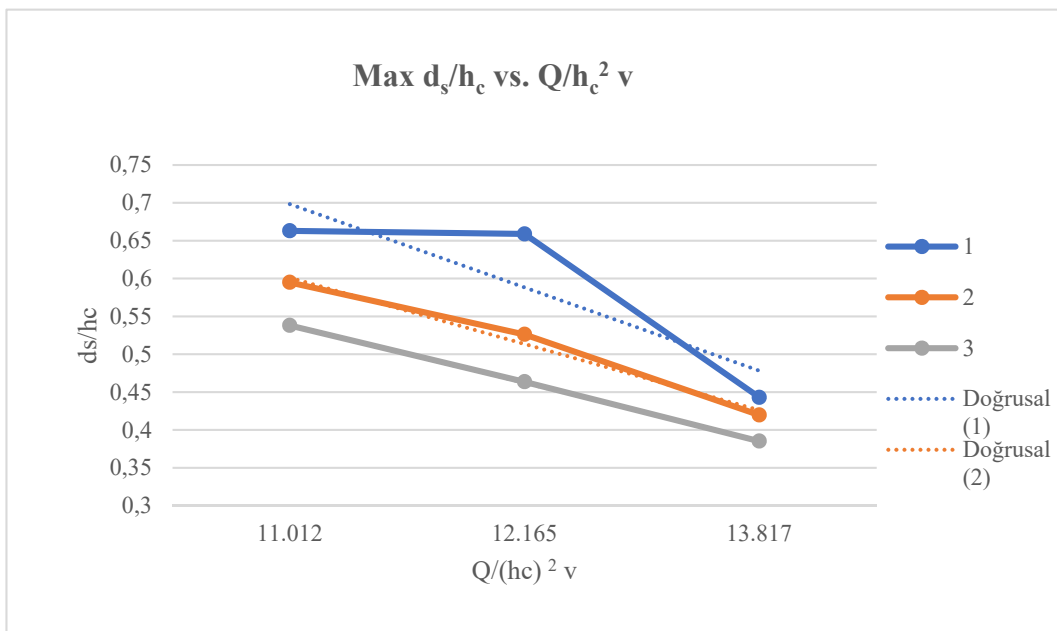


Figure 5.6 Relationship graph - $\frac{d_s}{h_c}$ vs. $\frac{Q}{h_c^2 v}$

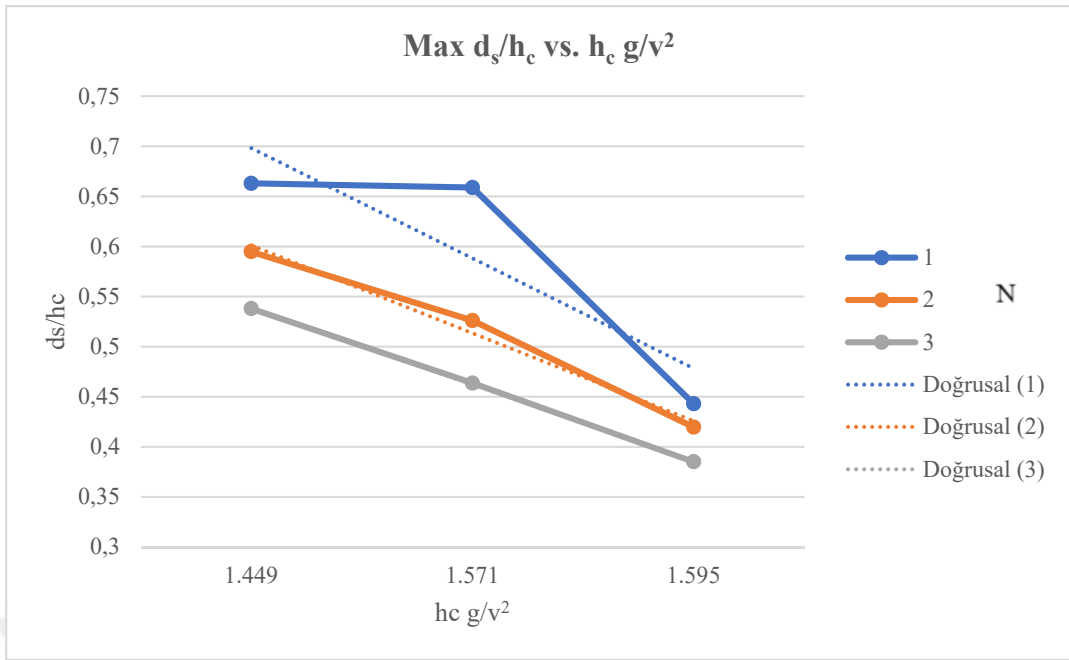


Figure 5.7 Relationship graph - $\frac{d_s}{h_c}$ vs. $\frac{h_c g}{v^2}$

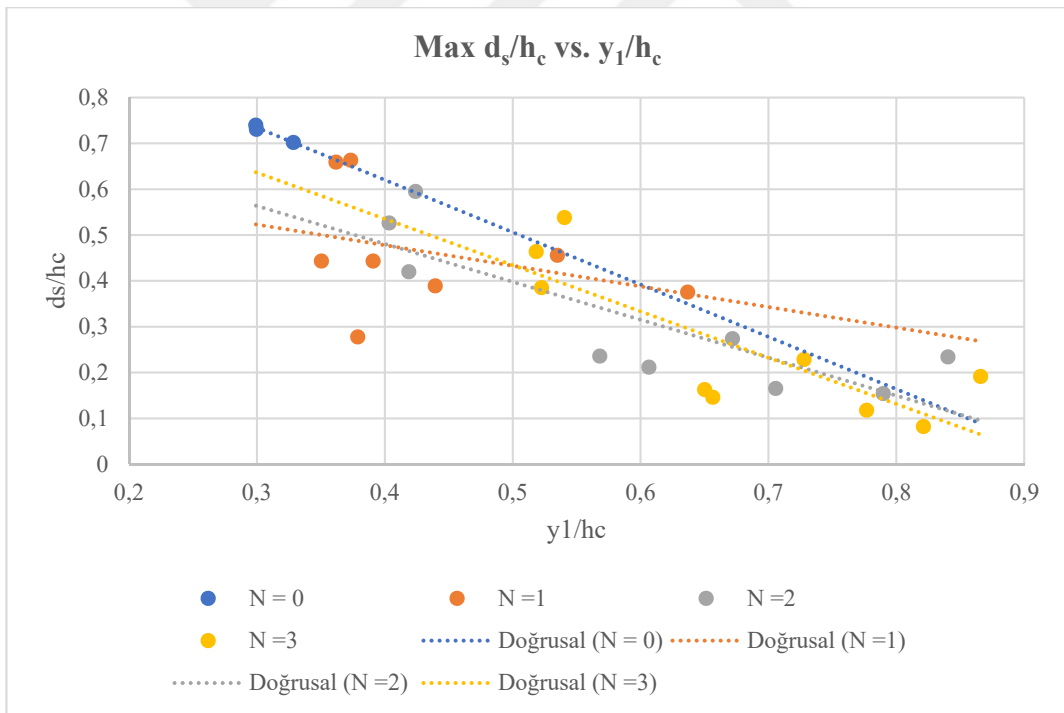


Figure 5.8 Relationship graph - $\frac{d_s}{h_c}$ vs. $\frac{y_1}{h_c}$

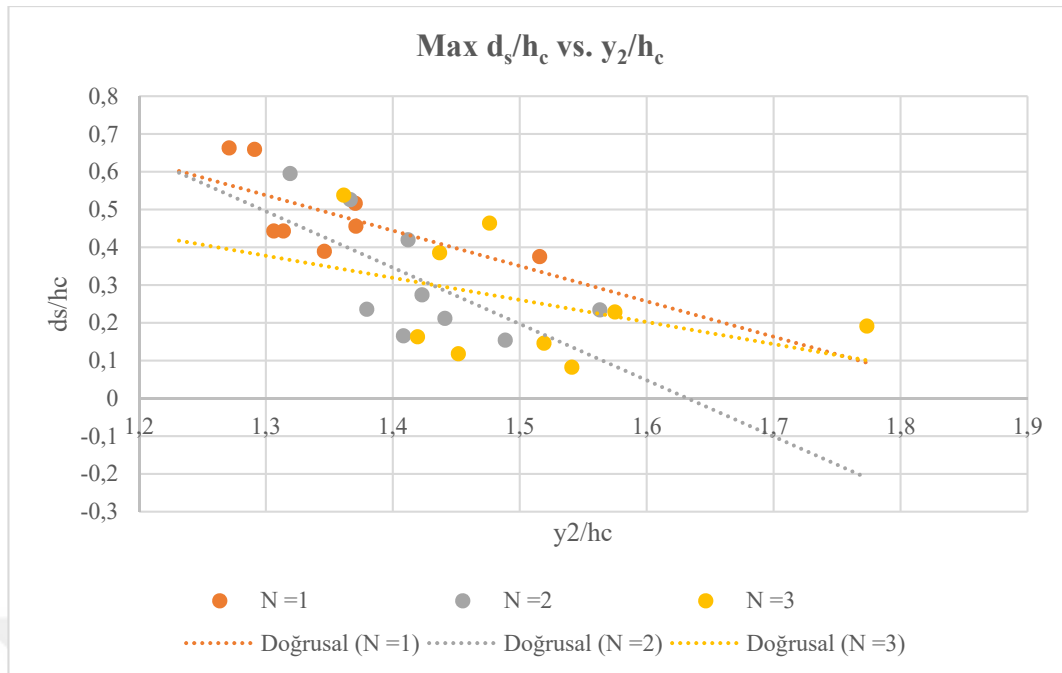


Figure 5.9 Relationship graph - $\frac{d_s}{h_c}$ vs. $\frac{y_2}{h_c}$

5.2.4 Factors Analysis

Starting with the factorial analysis, a test proceeds to find the chance to exclude some variables that can be presented by others. In principle, this analysis finds out the most effective variables and calculates the correlation between these variables and the others. If one of the other variables was highly correlated with more than one variable, it would be deleted. The factor analysis is a procedure used that determines the extent to which there is a shared variance exists between variables or items. (Naomi L. Gerber, et al., 2018)

According to Table 5.2, two of the variables were recognized as the most effective ones as they represent 84.5% of the data, both together. One the other hand, none of the other variables is highly correlated with more than one variable, means, there is no need to do any dimensional reduction (no need to ignore any of the variables).

Table 5.1 Communalities extracted using Principal Component Analysis

Components	Initial	Extraction
$\frac{d_s}{h_c}$	1.000	0.906
$\frac{h}{h_c}$	1.000	0.692
$\frac{Q}{\sqrt{h_c^2}}$	1.000	0.985
$\frac{h_c g}{v^2}$	1.000	0.981
$\frac{y_1}{h_c}$	1.000	0.912
$\frac{y_2}{h_c}$	1.000	0.830
N	1.000	0.613

The table above, table 5.1, shows the correlation of each variable with the whole other variables.

Table 5.2 Total variance of the seven variables

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.749	53.551	53.551	3.749	53.551	53.551
2	2.171	31.017	84.568	2.171	31.017	84.568
3	0.638	9.119	93.686			
4	0.250	3.573	97.260			
5	0.111	1.581	98.840			
6	0.079	1.124	99.965			
7	0.002	0.035	100.000			

Table 5.3 Correlation values with components 1 and 2

Variable	Component	
	1	2
$\frac{y_1}{h_c}$	-0.920	
$\frac{y_2}{h_c}$	0.915	
$\frac{d_s}{h_c}$	0.894	
$\frac{h}{h_c}$	0.808	
N	0.780	
$\frac{Q}{v h_c^2}$		0.992
$\frac{h_c g}{v^2}$		0.990

5.2.5 Statistical Test

A test aims to find out the participation percentages of the studied variable to the found results of experiments, either these variables were the only reasons for these results or other factors that are not included in the study had also affected the results. Also, it answers either if the changes made by the independent factors are significant and can be generalized on all experiments or not. The statistical tests are generally categorized into various types depending upon the type of field. It is carried out extensively in psychology, medicine, nursing and business.

This test will be applied for each of the independent variables compared to the dependent variable and using One Way ANOVA method as it is the best to apply in case of variables with three or more categories, in other words, when differences exist in the means of 3 or more groups, which is true for all of the studied variables. (Kim T. K., 2017)

The Significance value (Sig.) refers to the acceptance/rejection of the null hypothesis as well as its ability to be included in the final formula as an effective part of it. The variables will be included just in case of having their Sig. a value less than 0.05, otherwise, it will be ignored as its change will not be significant on the results of the final formula, in the case was included.

For this analysis case, the hypotheses are stated as follows;

The null hypothesis (H₀): the independent variables (factors) don't have any effect on the dependent variable ($\frac{d_s}{h_c}$).

The alternative hypothesis (H₁): the independent variables (factors) influence the dependent variables ($\frac{d_s}{h_c}$).

In general, the null hypothesis is accepted if (Sig.) is greater than or equal to, in which Sig. = 0.05 is this study case.

Table 5.4 Values, means, and standard deviations of the reads of $\frac{d_s}{h_c}$ under the 4 conditions of the blocks lanes numbers

Number of lanes	# of reads	Mean	Std. Deviation
0	3	0.734	0.030
1	9	0.443	0.155
2	9	0.308	0.168
3	9	0.247	0.179
Total	30	0.373	0.211

Table 5.5 ANOVA test for $\frac{d_s}{h_c}$ reads with respect to the number of blocks lanes

ANOVA (N)					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.615	3	0.205	7.901	0.001
Within Groups	0.675	26	0.026		
Total	1.290	29			

Table 5.6 Values, means, and standard deviations of the reads of $\frac{d_s}{h_c}$ under the 4 height of blocks

Heights of blocks (m)	# of reads	Mean	Std. Deviation
0.000	3	0.734	0.030
0.008	9	0.530	0.106
0.016	9	0.255	0.133
0.024	9	0.213	0.106
Total	30	0.373	0.211

Table 5.7 ANOVA test for $\frac{d_s}{h_c}$ reads with respect to the hight of blocks

ANOVA (h)					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.967	3	0.322	25.977	0.00
Within Groups	0.323	26	0.012		
Total	1.290	29			

Table 5.8 Values, means, and standard deviations of the reads of $\frac{d_s}{h_c}$ for the three water discharges

Discharges (m ³ /s)	# of reads	Mean	Std. Deviation
0.028	10.000	0.300	0.204
0.034	10.000	0.395	0.229
0.041	10.000	0.423	0.200
Total	30.000	0.373	0.211

Table 5.9 ANOVA test for $\frac{d_s}{h_c}$ reads with respect to the water discharges

ANOVA (Q)					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.082	2	0.041	0.922	0.410
Within Groups	1.207	27	0.045		
Total	1.290	29			

Table 5.10 Values, means, and standard deviations of $\frac{d_s}{h_c}$ reads for the three water velocities

Velocities (m/h)	# of reads	Mean	Std. Deviation
2148.100	10.000	0.300	0.204
2307.254	10.000	0.395	0.229
2524.432	10.000	0.423	0.200
Total	30.000	0.373	0.211

Table 5.11 ANOVA test for $\frac{d_s}{h_c}$ reads with respect to the water velocities

ANOVA (v)					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.082	2	0.041	0.922	0.410
Within Groups	1.207	27	0.045		
Total	1.290	29			

Table 5.12 Values, means, and standard deviations of $\frac{d_s}{h_c}$ reads for the water depth over the crest of the spillway

h_c (m)	# of reads	Mean	Std. Deviation
0.05790	10	0.30040	0.203687
0.06576	10	0.39530	0.229132
0.07265	10	0.42280	0.200378
Total	30	0.37283	0.210889

Table 5.13 ANOVA test for $\frac{d_s}{h_c}$ reads with respect to the depth of water of the crest

ANOVA (h_c)					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.082	2	0.041	0.922	0.410
Within Groups	1.207	27	0.045		
Total	1.290	29			

Table 5.14 Values, means, and standard deviations of $\frac{d_s}{h_c}$ reads for the y_1

	Number of reads	Mean	Std. Deviation
0.017	1.000	0.739	.
0.020	2.000	0.602	0.225
0.022	4.000	0.278	0.112
0.024	2.000	0.696	0.009
0.026	1.000	0.473	.
0.027	2.000	0.595	0.097
0.029	1.000	0.389	.
0.030	1.000	0.385	.
0.031	1.000	0.595	.
0.034	1.000	0.464	.
0.037	1.000	0.236	.
0.038	1.000	0.088	.
0.039	2.000	0.511	0.078
0.043	1.000	0.132	.
0.046	3.000	0.231	0.124
0.048	1.000	0.082	.
0.049	1.000	0.274	.
0.051	1.000	0.118	.
0.053	1.000	0.201	.
0.061	1.000	0.206	.
0.063	1.000	0.191	.
Total	30.000	0.373	0.211

Table 5.15 ANOVA test for $\frac{d_s}{h_c}$ reads with respect to the depth of water downstream of spillway before the hydraulic jump

ANOVA (y_1)					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.156	20	0.058	3.877	0.021
Within Groups	0.134	9	0.015		
Total	1.290	29			

Table 5.16 Values, means, and standard deviations of $\frac{d_s}{h_c}$ reads for y_2

	Number of reads	Mean	Std. Deviation
0.074	1.000	0.739	.
0.076	1.000	0.443	.
0.079	4.000	0.278	0.112
0.081	1.000	0.761	.
0.083	1.000	0.385	.
0.085	1.000	0.689	.
0.086	2.000	0.314	0.226
0.088	1.000	0.088	.
0.089	2.000	0.236	0.217
0.090	2.000	0.614	0.124
0.091	1.000	0.236	.
0.092	1.000	0.663	.
0.093	2.000	0.149	0.023
0.095	1.000	0.118	.
0.096	1.000	0.595	.
0.097	1.000	0.464	.
0.099	1.000	0.566	.
0.100	1.000	0.456	.
0.103	1.000	0.274	.
0.110	1.000	0.374	.
0.114	2.000	0.204	0.004
0.129	1.000	0.191	.
Total	30.000	0.373	0.211

Table 5.17 ANOVA test for $\frac{d_s}{h_c}$ reads with respect to the depth of water downstream of spillway after the hydraulic jump

ANOVA (y ₂)					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.138	21	0.054	2.865	0.064
Within Groups	0.151	8	0.019		
Total	1.290	29			

5.2.6 Correlation

The correlation represents the likelihood of a variable to affect or to be affected by other variables, in other words, it expresses the relationship between two variables in a shape of number ranged between [-1. 1].

The number +1 is a high proportional correlation, the increase in a variable means increase in the other one and vice versa.

The number -1 is a high inverse correlation, the increase in a variable means a decrease in the other one and vice versa.

0 stands for that there is no relation between the two studied variables, the change in one variable doesn't mean that the other variable should be changed. (Schober P., et al., 2018)

Therefore, this likelihood is expressed as a percentage of probability. However, it only refers to the probability of effecting results for this variable individually, with no consideration to other variables or considering the other variables. In other words, the variable with high correlation probability in the individual analysis case could be ignored for its inconsiderable effect in the case of all variable correlation.

The regression of all variables together, at the end of the analysis, will finally lead into the relation formula representing the most dominating variables.

Regardless of the correlation values, they couldn't be considered unless its significance was accepted through the statistical test as it represents the significance of the correlation.

Pearson correlation was selected as the studied variables are numeric.

Table 5.18 The correlation between $\frac{d_s}{h_c}$ and $\frac{h}{h_c}$

Correlation		$\frac{d_s}{h_c}$	$\frac{h}{h_c}$
$\frac{d_s}{h_c}$	Pearson Correlation	1	-0.850
	Sig. (2-tailed)		0.000
	Number of reads	30	30
$\frac{h}{h_c}$	Pearson Correlation	-0.850	1
	Sig. (2-tailed)	0.000	
	Number of reads	30	30

The correlation is negative and strong, means there is an 85% likelihood of decreasing in $\frac{d_s}{h_c}$ by increasing $\frac{h}{h_c}$ and vice versa.

Table 5.19 The correlation between $\frac{d_s}{h_c}$ and $\frac{Q}{v h_c^2}$

Correlation		$\frac{d_s}{h_c}$	$\frac{Q}{v h_c^2}$
$\frac{d_s}{h_c}$	Pearson Correlation	1	0.244
	Sig. (2-tailed)		0.193
	Number of reads	30	30
$\frac{Q}{v h_c^2}$	Pearson Correlation	0.244	1
	Sig. (2-tailed)	0.193	
	Number of reads	30	30

The correlation is weak and positive. The likelihood of increasing $\frac{d_s}{h_c}$ by increasing $\frac{Q}{v h_c^2}$ is about 22% and vice versa.

Table 5.20 The correlation between $\frac{h_c g}{v^2}$ and $\frac{d_s}{h_c}$

Correlations		$\frac{d_s}{h_c}$	$\frac{h_c g}{v^2}$
$\frac{d_s}{h_c}$	Pearson Correlation	1	0.249
	Sig. (2-tailed)		0.185
	Number of reads	30	30
$\frac{h_c g}{v^2}$	Pearson Correlation	0.249	1
	Sig. (2-tailed)	0.185	
	Number of reads	30	30

Again, the correlation is positive and weak with a likelihood of 25% to increase $\frac{d_s}{h_c}$ by increasing $\frac{h_c g}{v^2}$.

Table 5.21 The correlation between $\frac{y_1}{h_c}$ and $\frac{d_s}{h_c}$

Correlations		$\frac{d_s}{h_c}$	$\frac{y_1}{h_c}$
$\frac{d_s}{h_c}$	Pearson Correlation	1	-0.750
	Sig. (2-tailed)		0.000
	Number of reads	30	30
$\frac{y_1}{h_c}$	Pearson Correlation	-0.750	1
	Sig. (2-tailed)	0.000	
	Number of reads	30	30

A negative strong correlation between $\frac{y_1}{h_c}$ and $\frac{d_s}{h_c}$. The likelihood of decreasing $\frac{d_s}{h_c}$ by increasing $\frac{y_1}{h_c}$ is around 75% and vice versa.

Table 5.22 The correlation between $\frac{y_2}{h_c}$ and $\frac{d_s}{h_c}$

Correlations		$\frac{d_s}{h_c}$	$\frac{y_2}{h_c}$
$\frac{d_s}{h_c}$	Pearson Correlation	1	-0.710
	Sig. (2-tailed)		0.000
	Number of reads	30	30
$\frac{y_2}{h_c}$	Pearson Correlation	-0.710	1
	Sig. (2-tailed)	0.000	
	Number of reads	30	30

Similarly, the correlation between $\frac{y_2}{h_c}$ and $\frac{d_s}{h_c}$ is negative and moderate with a likelihood of decreasing $\frac{d_s}{h_c}$ of 71% by increasing $\frac{y_2}{h_c}$ and vice versa.

Table 5.23 The correlation of N and $\frac{d_s}{h_c}$

Correlations		$\frac{d_s}{h_c}$	N
$\frac{d_s}{h_c}$	Pearson Correlation	1	-0.644
	Sig. (2-tailed)		0.000
	Number of reads	30	30
N	Pearson Correlation	-0.644	1
	Sig. (2-tailed)	0.000	
	Number of reads	30	30

And finally, increasing the number of blocks lanes is a factor could decrease with a likelihood of 64.4% and vice versa.

5.2.7 Regression

This step is to find out the relationship, in numbers, among each of the independent variables with the dependent variable including the intercept (constant), the value

of $\frac{d_s}{h_c}$ in case of the independent variables are equal to 0. R square represents the amount of change in the dependent variable explained by the independent variable. (Sarstedt M., et al., 2014)

The analysis starts with finding out the regression of the dependent variable on each of the independent variables separately, without considering the other independent variables on the final results, and ends with studying the regression of the all independent variables on the dependent variable to result into the final formula includes the most dominating variables.

In this study case, it was found that the linear regression is suitable and can well represent the relations among the independent and dependent variables, which also have been tested using the ANOVA method to ensure the significance of the linear regression.

The following tables show the overall model fit analysis for each of the independent variables with the dependent variable; where R^2 is the proportion of variance in the dependent variable which can be predicted from the independent variables, and the adjusted R^2 represents predictors are added to the model, each predictor will explain some of the variance in the dependent variable simply due to chance. (Bruin, J. 2006)

According to table 5.24, the regression of $\frac{d_s}{h_c}$ on $\frac{h}{h_c}$ is significant as Sig is less than 0.05. This regression can explain 72.2% of the changes in $\frac{d_s}{h_c}$ as R Square equals to 0.722.

Table 5.24 The regression between $\frac{h}{h_c}$ and $\frac{d_s}{h_c}$

Model Summary						
Model	R	R ²	Adjusted R ²	Std. Error of the Estimate		
1	0.850 ^a	0.722	0.713	0.113		
ANOVA ^a						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	0.932	1	0.932	72.876	0.000 ^b
	Residual	0.358	28	0.013		
	Total	1.290	29			
Coefficients ^a						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	0.690	0.043		16.227	0.000
	$\frac{h}{h_c}$	-1.431	0.168	-0.850	-8.537	0.000

a. Dependent Variable: $\frac{d_s}{h_c}$

b. Predictors: (Constant), $\frac{h}{h_c}$

The constant (the intercept value) equal to 0.69 and the parameter of the variable $\frac{h}{h_c}$ equals to (- 1.431), this says that the regression equation can be written as:

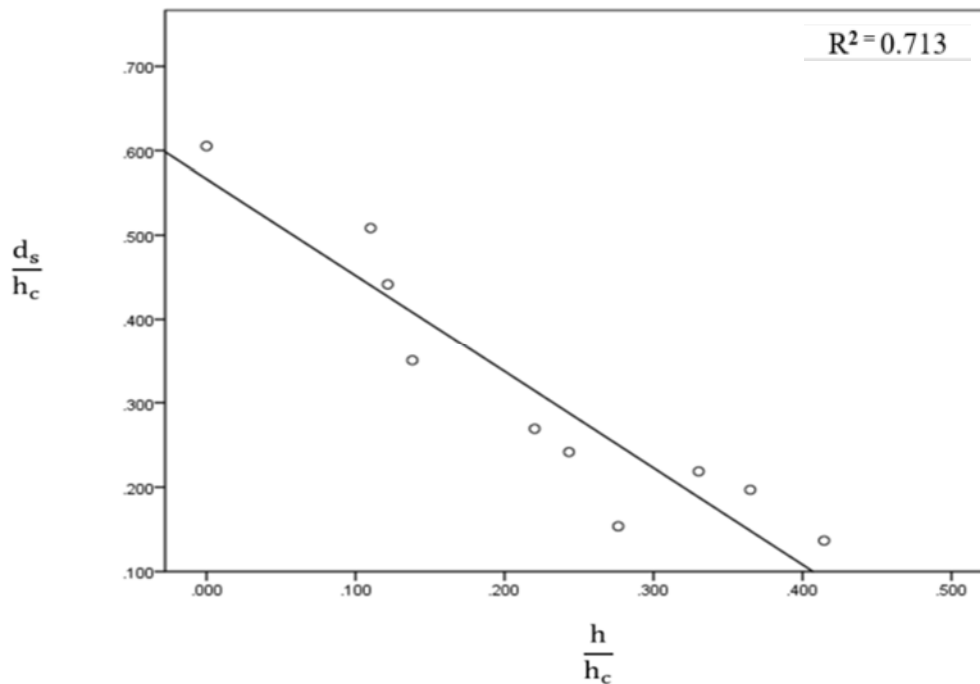


Figure 5.10 Fit line of $\frac{d_s}{h_c}$ and $\frac{h}{h_c}$

$$\frac{d_s}{h_c} = 0.69 - 1.431\left(\frac{h}{h_c}\right) \quad (5.2)$$

Similarly, and as per table 5.25, the regression is significant as Sig. is less than 0.05 and the regression explains 24.4% of $\frac{d_s}{h_c}$ changing. The constant is -0.683 and the variable parameter is 5.166. Thus, the regression equation is:

$$\frac{d_s}{h_c} = -0.683 + 5.166\left(\frac{Q}{v h_c^2}\right) \quad (5.3)$$

Table 5.25 The regression between $\frac{Q}{v h_c^2}$ and $\frac{d_s}{h_c}$

Model Summary						
Model	R	R ²	Adjusted R ²		Std. Error of the Estimate	
1	0.244 ^a	0.060	0.026		0.208	
ANOVA ^a						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	0.077	1	0.077	1.779	0.193 _b
	Residual	1.213	28	0.043		
	Total	1.290	29			
Coefficients ^a						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-0.683	0.792		-0.862	0.396
	$\frac{Q}{v h_c^2}$	5.166	3.873	0.244	1.334	0.193
a. Dependent Variable: $\frac{d_s}{h_c}$						
b. Predictors: (Constant), $\frac{Q}{v h_c^2}$						

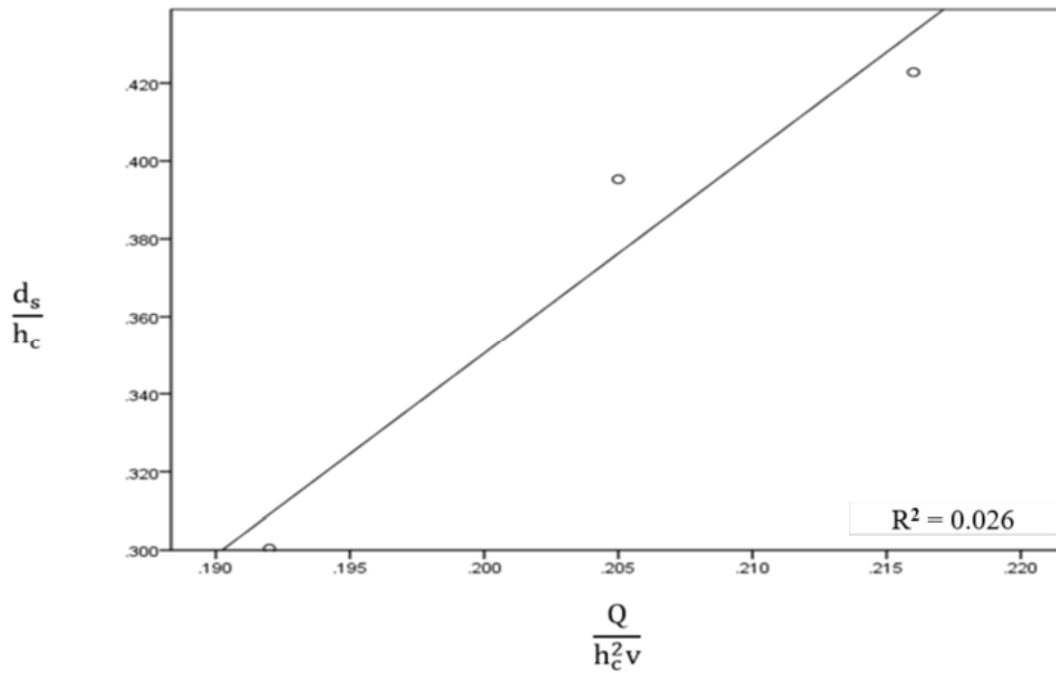


Figure 5.11 Fit line of $\frac{Q}{v h_c^2}$ and $\frac{d_s}{h_c}$

Table 5.26 Regression between $\frac{h_c g}{v^2}$ and $\frac{d_s}{h_c}$

Model Summary						
Model	R	R ²	Adjusted R ²	Std. Error of the Estimate		
1	0.249 ^a	0.062	0.028	0.208		
ANOVA ^a						
	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	0.080	1	0.080	1.846	0.185 _b
	Residual	1.210	28	0.043		
	Total	1.290	29			
Coefficients ^a						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-0.490	0.636		-0.770	0.448
	$\frac{h_c g}{v^2}$	5.011E-6	0.000	0.249	1.359	0.185
a. Dependent Variable: $\frac{d_s}{h_c}$						
b. Predictors: (Constant), $\frac{h_c g}{v^2}$						

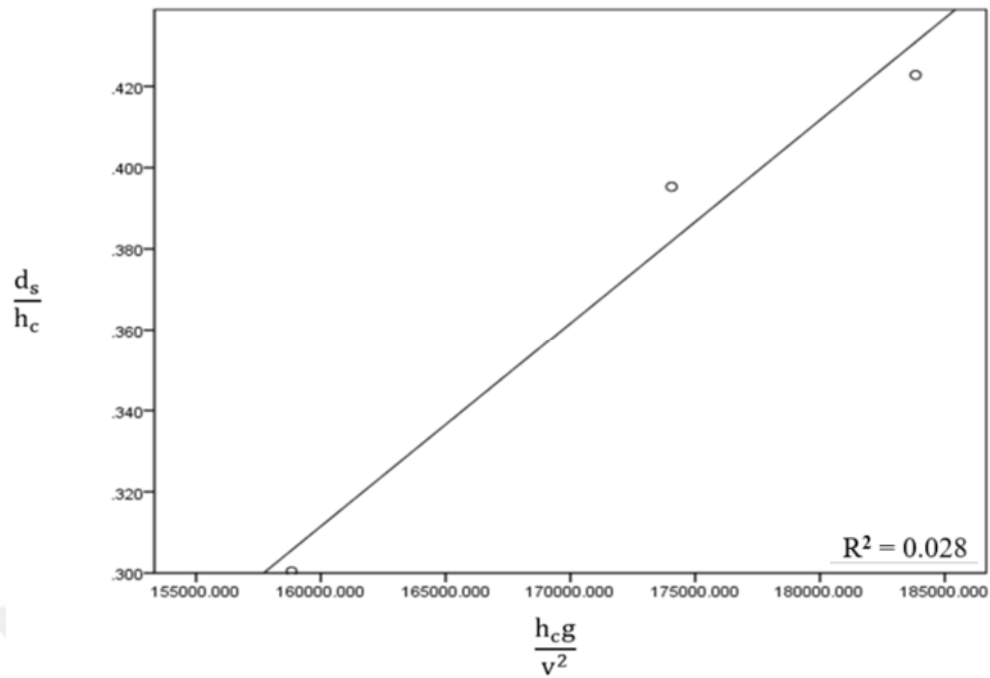


Figure 5.12 Fit line $\frac{h_c g}{v^2}$ and $\frac{d_s}{h_c}$

Again, the regression is significant as Sig. is less than 0.05. It can explain 25% of the dependent variable changing. The constant is -0.490 and the independent variable parameter is $5.011 \cdot 10^{-6}$, as shown in table 5.26. The regression equation could be expressed as:

$$\frac{d_s}{h_c} = -0.490 + 5.011 \cdot 10^{-6} \left(\frac{h_c g}{v^2} \right) \quad (5.4)$$

Table 5.27 shows a significant regression with a probability to explain the changing of $\frac{d_s}{h_c}$ much greater this time, as R square equals to 75%. The constant is 0.843 and the dependent variable parameter is -0.881.

$$\frac{d_s}{h_c} = 0.843 - 0.881 \left(\frac{y_1}{h_c} \right) \quad (5.6)$$

Table 5.27 The regression between $\frac{y_1}{h_c}$ and $\frac{d_s}{h_c}$

Model Summary						
Model	R	R ²	Adjusted R ²		Std. Error of the Estimate	
1	0.750 ^a	0.562	0.547		0.142	
ANOVA ^a						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	0.725	1	0.725	35.988	0.000 ^b
	Residual	0.564	28	0.020		
	Total	1.290	29			
Coefficients ^a						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	0.843	0.083		10.210	0.000
	$\frac{y_1}{h_c}$	-0.881	0.147	-0.750	-5.999	0.000
a. Dependent Variable: $\frac{d_s}{h_c}$						
b. Predictors: (Constant), $\frac{y_1}{h_c}$						

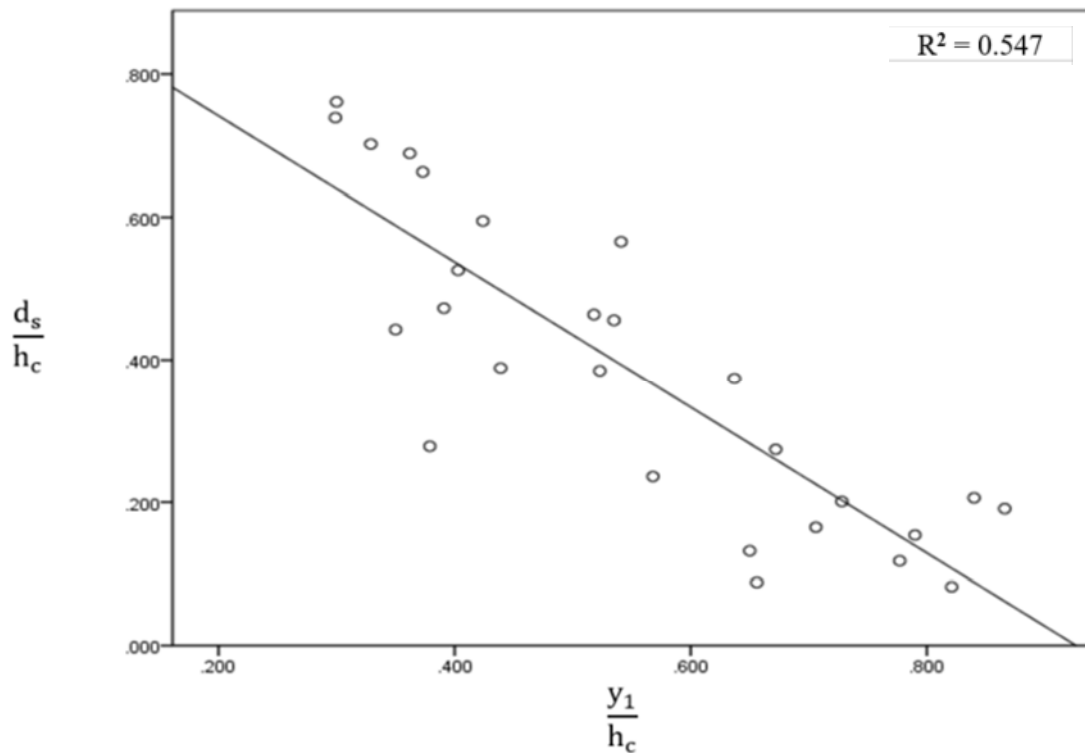


Figure 5.13 The fit line of $\frac{y_1}{h_c}$ and $\frac{d_s}{h_c}$

Table 5.28 The regression between $\frac{y_2}{h_c}$ and $\frac{d_s}{h_c}$

Model Summary						
Model	R	R ²	Adjusted R ²	Std. Error of the Estimate		
1	0.710 ^a	0.504	0.486	0.151		
ANOVA ^a						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	0.650	1	0.650	28.420	0.000 ^b
	Residual	0.640	28	0.023		
	Total	1.290	29			
Coefficients ^a						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	2.174	0.339		6.413	0.000
	$\frac{y_2}{h_c}$	-1.283	0.241	-0.710	-5.331	0.000

a. Dependent Variable: $\frac{d_s}{h_c}$

b. Predictors: (Constant), $\frac{y_2}{h_c}$

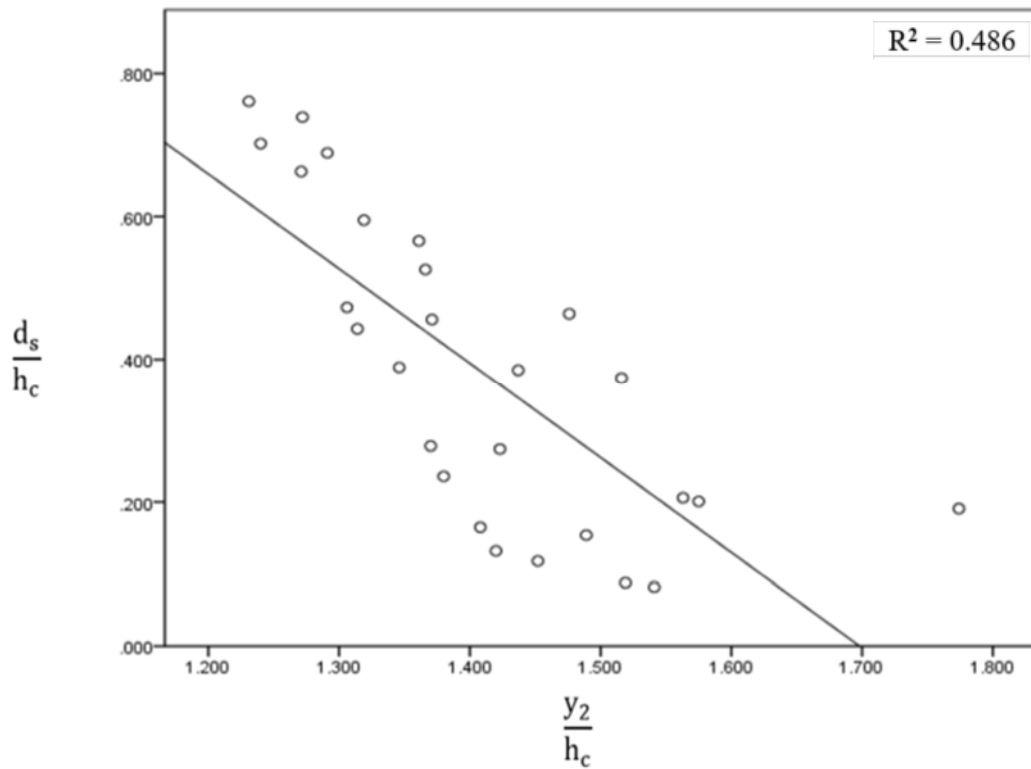


Figure 5.14 The fit line of $\frac{y_2}{h_c}$ and $\frac{d_s}{h_c}$

The regression is significant and can explain 71% of $\frac{d_s}{h_c}$ changing. The constant is 2.174 and the independent parameter is -1.283, as per the table 5.28.

$$\frac{d_s}{h_c} = 2.174 - 1.283 \left(\frac{y_2}{h_c}\right) \quad (5.6)$$

Table 5.29 proves another significant regression with an explanation ratio to $\frac{d_s}{h_c}$ of 64.4%. The constant is 0.618 and the independent parameter is -0.136.

$$\frac{d_s}{h_c} = 0.618 - 0.136 N \quad (5.7)$$

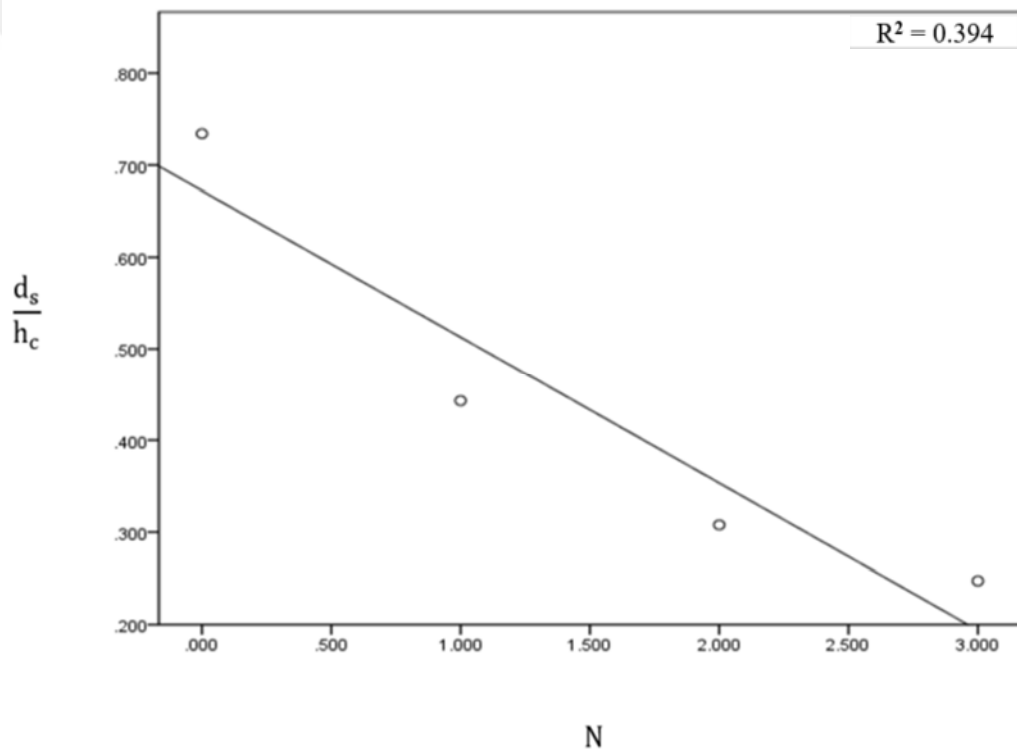


Figure 5.15 The fit line of N and $\frac{d_s}{h_c}$

Table 5. 29 The regression between N and $\frac{d_s}{h_c}$

Model Summary						
Model	R	R ²	Adjusted R ²		Std. Error of the Estimate	
1	0.644 ^a	0.415	0.394		0.164	
ANOVA ^a						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	0.535	1	0.535	19.860	0.000 ^b
	Residual	0.755	28	0.027		
	Total	1.290	29			
Coefficients ^a						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	0.618	0.063		9.861	0.000
	N	-0.136	0.031	-0.644	-4.456	0.000
a. Dependent Variable: $\frac{d_s}{h_c}$						
b. Predictors: (Constant), N						

Table 5.30 All independent variable regression on the dependent variable

Model Summary						
Model	R	R ²	Adjusted R ²	Std. Error of the Estimate		
1	0.938 ^a	0.880	0.849	0.082		
ANOVA ^a						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1.135	6	0.189	28.192	0.000 _b
	Residual	0.154	23	0.007		
	Total	1.290	29			
Coefficients ^a						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	0.381	0.907		0.420	0.678
	$\frac{h}{h_c}$	-0.954	0.192	-0.566-	-4.978	0.000
	$\frac{Q}{v h_c^2}$	-6.498	21.733	-0.307	-0.299	0.768
	$\frac{h_c g}{v^2}$	1.023E-5	0.000	0.508	0.498	0.623
	$\frac{y_1}{h_c}$	-0.266	0.212	-0.226	-1.256	0.222
	$\frac{y_2}{h_c}$	0.014	0.287	0.008	0.048	0.962
	N	-0.060	0.024	-0.285	-2.497	0.020
a. Dependent Variable: $\frac{d_s}{h_c}$						
b. Predictors: (Constant), $\frac{h}{h_c}$, $\frac{Q}{v h_c^2}$, $\frac{h_c g}{v^2}$, $\frac{y_1}{h_c}$, $\frac{y_2}{h_c}$, N						

According to the regression analysis shown in table 5.30, the comprehensive regression formula that expresses the relationships among all variables is;

$$\frac{d_s}{h_c} = 0.381 - 0.954 \left(\frac{h}{h_c} \right) - 6.498 \left(\frac{Q}{v h_c^2} \right) + 1.023E - 5 \left(\frac{h_c g}{v^2} \right) - 0.226 \left(\frac{y_1}{h_c} \right) + 0.14 \left(\frac{y_2}{h_c} \right) - 0.060 N \quad (5.8)$$

Statistically, only variables with Sig. values less than 0.05 could be considered to have an affection on the final results on the regression formula. Therefore, the two variables ($\frac{h}{h_c}$, N) seemed to have the most effective significance on the dependent

variable $\frac{d_s}{h_c}$ as per the values of Sig. for all variables regression case. It worth to mention that the accuracy of the regression formula is tightly related to the number of experiments proceeded, which mean more variables could have a considerable value of Sig. and by turn would be included in the final regression formula.

In general, and with consideration to the conditions and number of experiments, the model explained 93.8% of dependent variable changes and the remaining 6.2% attributable to an unknown number of external factors.

The comprehensive representative formula could be represented as per the following:

$$\frac{d_s}{h_c} = -0.954 \left(\frac{h}{h_c} \right) - 0.060 N \quad (5.9)$$

5.3 The comparison of the dependent variable values found by measurement and calculations

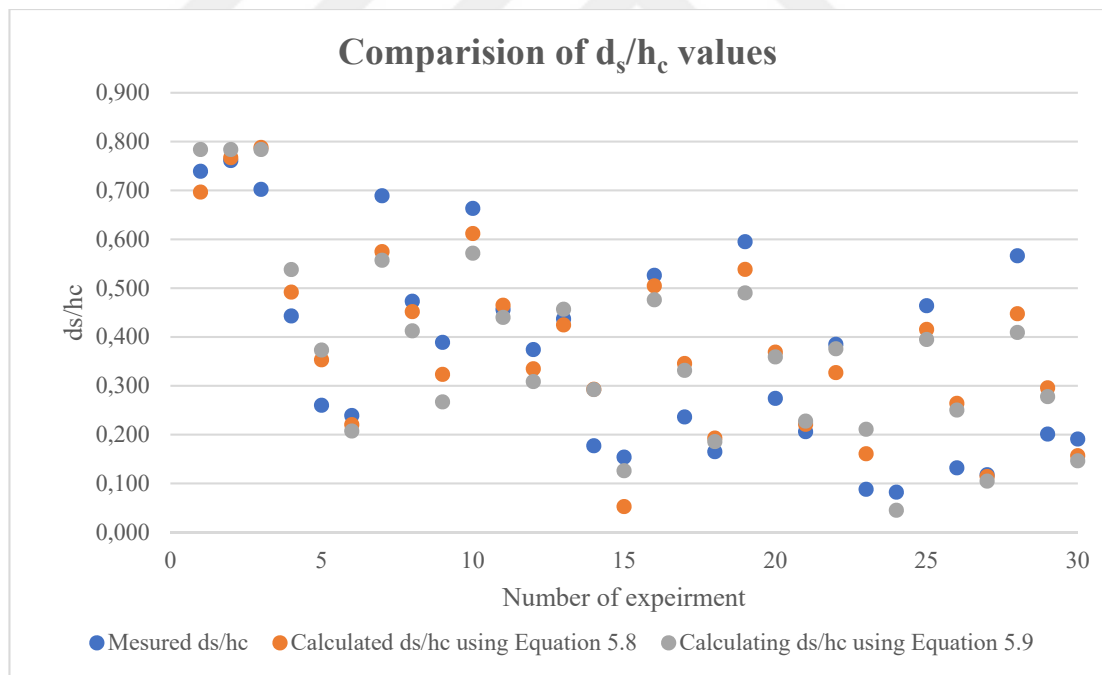


Figure 5.16 The comparison of $\frac{d_s}{h_c}$ values

In order to verify the extent to how much do the found formulas are indeed representing the values of the dependent variable $\frac{d_s}{h_c}$. Figure 5.16 was found to compare the

measured values of the dependent variable during proceeding the laboratory experiments with the values calculated by the two found representative formulas.

According to the statistical analysis, the equation 5.9 was recognized to be the best represented to the study variables like the effects of the other variables, those were not included in the Equation 5.9, were negligible compared with the most effective independent variables $\frac{h}{h_c}$ and N. As shown in Figure 5.16, the dots which represent the values calculated by both found formulas are placed very close to each other along the entire X-axis, the number of variables, means that considering the equation 5.9 to represent the results was sufficient, and it is true to consider the effect of other variables as negligible.

And for the purpose of comparing the calculated results by the formulas concluded by this study with reality, the values of $\frac{d_s}{h_c}$ measured during the experimental study have been added to Figure 5.16, which also seem to place close to the calculated values from both formulas.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

- The data analysis proved that all of the studied variables have roles in shaping the final results of this study, with different effectiveness.
- The height of blocks and the number of blocks lanes were recognized as the most effective factors on the scour developing downstream of the spillway.
- The height of blocks seemed to have the greatest effect compared to the other factors, followed by the number of blocks lanes, as the regression relation of these variables is 0.954, and 0.06 respectively.
- Some variables might don't have a direct effect on the results. But were represented by other variables, such as the water discharge and velocity, which directly changed the depth of water over the structure crest (h_c) as well as the variables (y_1 and y_2) which are the depth of water in the supercritical and subcritical conditions.
- Increasing the height of blocks is more effective with the less value of the discharges, means, the effect of increasing blocks height was more significant with the minimum discharges compared to the other values of discharges.
- For the case of the minimum height of blocks, the scour depth reduced by around 43% compared to the no blocks apron case in the case of the minimum discharge, 27% for the medium value of discharge and only 13% for the maximum discharge case.
- Duplication the height of blocks reduced the scour 76% for the case of minimum discharge, 63% for the medium discharge and 56% for the maximum discharge

- For the number of blocks lanes and similarly to the height of blocks, this factor performed better with the fewer discharges in general, despite the higher discharges showed better sensitivity to adding a second lane.
- Regarding the minimum discharge case, adding one lane reduced the scour occurred in the no blocks case by 58% in average, the ratio increased by about 10% by adding a second lane and addition 7% approximately for adding the third lane.
- While for the maximum discharge, the scour depth reduced around 29% by adding one lane of blocks compared with the no blocks case, additional 26% in average for the second lane, and almost no change for adding the third lane.

6.2 Recommendations

- In case of one of blocks lane fixed on the apron, to study the effect of changing the lane location along the apron.
- In case of multiple lanes of blocks fixed to the apron, to study the effect of changing distances among blocks lanes.
- Analyze the effect of using more different shapes of blocks, for example, different heights and other cross-sections
- Study the relation between the height and cross-section of blocks.
- Find out the relation between the height of blocks and the extent of the apron.
- Investigate the effect of different blocks arrangement
- Increase the number of experiments either in case of repeating the same study or holding similar studies to investigate whether more variables would have considerable effects or not.

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