ANALYSIS OF FLOW OVER TRIANGULAR (PLANFORM) LABYRINTH WEIR MODELS

A PROJECT REPORT

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE AWARD OF THE DEGREE

OF

MASTER OF TECHNOLOGY

IN

HYDRAULICS AND WATER RESOURCES ENGINEERING

Submitted By:

KAUSHAL

2K17/HFE/09

Under the supervision of

Prof. RAKESH KUMAR

CIVIL ENGINEERING DEPARTMENT

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

June, 2019

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

CANDIDATE'S DECLARATION

I, Kaushal, Roll No. 2K17/HFE/09 student of M.Tech (Hydraulics and Water Resources Engineering), hereby declare that the project dissertation titled "ANALYSIS OF FLOW OVER TRIANGULAR (PLANFORM) LABYRINTH WEIR MODELS" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title of recognition.

Place:

Date: KAUSHAL

DEPARTMENT OF CIVIL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

CERTIFICATE

I hereby certify that the Project Dissertation titled "ANALYSIS OF FLOW OVER TRIANGULAR (PLANFORM) LABYRINTH WEIR MODELS" which is submitted by Kaushal, 2K17/HFE/09, Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place **PROF. RAKESH KUMAR**

Date: (SUPERVISOR)

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my project supervisor, Prof. Rakesh Kumar , for his supervision, invaluable guidance, motivation and support throughout the extent of the project. I have been benefited immensely from his wealth of knowledge. I extend my gratitude to my college, Delhi Technological University (formerly Delhi College of Engineering) for giving me the opportunity to carry out this project.

This opportunity will be a significant milestone in my career development. I will strive to use the gained skills and knowledge in the best possible way, and I will continue to work on their improvement, in order to attain desired career objectives.

KAUSHAL

2K17/HFE/09

M.tech (Hydraulics and Water Resources)

ABSTRACT

In this project, analysis of flow over different models of triangular labyrinth weir is done with the help of ANSYS (Fluent) software. Different weir geometries are designed and analysed under similar condition to determine the optimum geometry among the tested ones. The need for labyrinth weir arises at the places where the width of channel is less and discharge increases. In the case of limited width, a straight weir causes the increase in the reservoir's water level which consequently leads to a greater area of submergence. To avoid this head upstream, which can cause much damage, the labyrinth weir was developed.

The objective here is to reduce the upstream head of triangular labyrinth weir and obtain a relationship between increasing or reducing head with respect to side angle α, effective length L and cycle of weir N. The numerical modelling of a Triangular labyrinth weir is done with the help of ANSYS and the pressure distribution, velocity contour, and depths of flow is studied using contour maps which shows the variable distributions at upstream and downstream of the weir. Total 9 models are designed in ANSYS fluent and all models are simulated under same conditions i.e. same discharge and same channel width and length. Due to different crest lengths, weirs behaved slightly different and H is obtained for each case. The coefficient of discharge is calculated to differentiate in efficiency of different weirs. Also, some non-dimensional parameters are calculated to compare with previous trends.

CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Q – Discharge

Q_n – Discharge through linear weir

C_d – Coefficient of discharge

g – Acceleration due to gravity

L – Total effective crest length

H – Height of water level above crest

w – Width of the channel

α – Angle between flow direction and weir wall (side angle)

ANSYS – Analysis Systems

CFD – Computational Fluid Dynamics

L/w – Length magnification ratio

Q/Q_n – Flow magnification ratio

H/P – Head to weir height ratio

CHAPTER 1

INTRODUCTION

1.1. General

Weir is a hydraulic structure across the width of a river that alters the flow characteristics of water and usually results in a change in the height of the river level. In other words, a weir is a barrier built across a river or channel to provide flow at low heads.

There are many designs of weir, but commonly water flows freely over the top of the weir crest before cascading down to a lower level. Some common type of weirs are:

1. Broad crested
2. Narrow crested weir
3. V-notch
4. Compound
5. Ogee shaped weir
6. Polynomial
7. Labyrinth weir

The need of different types of weir arose to increase the discharge and efficiency of weirs. In this report flow over labyrinth weir is analysed. A weir is an impervious barrier constructed across a river to raise the water level on the upstream side. The water is raised up to the required height and the water then flows over the weir. They are also used to prevent flooding, measure discharge, and help render a river navigable.

A weir is similar to a small dam constructed across river, with the difference that whereas in the case of a dam excess water flows to the downstream side, only through a small portion called spillway, the same in the case of a weir flow over its entire length.

The linear weir when folded in plan view in different geometries such as rectangle, trapezoid, semi-circle or triangle forms a labyrinth weir. Here, a triangular labyrinth weir is used and its different models are designed to compare the effect of slight change in geometry on the flow parameters. Optimising the many geometric variables in the hydraulic design of a labyrinth weir can be challenging, like sidewall angle, effective length, crest shape, number of cycles, the configuration of labyrinth cycles and orientation and placement of labyrinth weir must all be determined, to eliminate such problems some of the parameters are fixed by studying the previous researches and one or two parameters are changed to get the hydraulic efficient model geometry. The side angle of labyrinth weir α is changed and the total effective length of weir is also changed accordingly, which brings the overall change in the geometry of triangular and thus the flow is modified. The outcome changes are noted and analysed. Model with minimum height of water over crest is the efficient of all models. Also, H/P ratio plays an important role in these, the H/P ratio should vary from 0.1 to 0.9. The efficient model should have H/P ratio as minimum as possible.

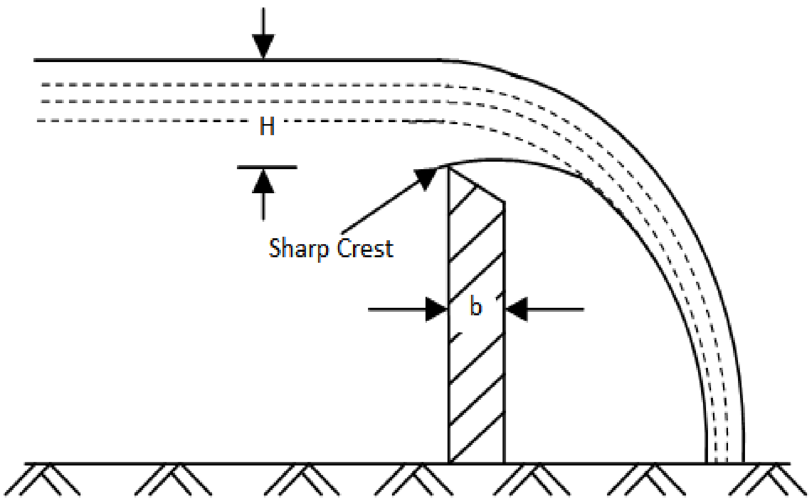

Figure 1: Discharge at weir

The discharge for weir is given as:

$$Q = \frac{2}{3} C_d L \sqrt{2g} H^{\frac{3}{2}}$$

Where,

Q - Discharge

C_d – Coefficient of discharge

L – Length of crest (effective length of weir)

H – Height of water above crest level

g – acceleration due to gravity

The H measured at a point some distance upstream of the weir to eliminate effect of streamline curvature of flowing water, this distance is not fixed and purely based on how far is the water height becomes stable.

The crest length is measured as mid line of crest in case of broad crested weir and this is neglected when the weir is sharp crested.

1.2. Classification of weirs

1.2.1 Based on geometry of flow section

1.2.1.1 rectangular

1.2.1.2 Triangular

1.2.1.3 Trapezoidal

1.2.2 Based on Crest sharpness

1.2.2.1. Sharp crested

1.2.2.2. Broad crested

1.3. Labyrinth Weirs

These types of weirs are simple rectangular type weir but have their geometry different in planform. There are many kinds of labyrinth weir being used worldwide for different need and applications, some of which are:

1.3.1. Triangular labyrinth weir
1.3.2. Trapezoidal labyrinth weir
1.3.3. Semi-circular labyrinth weir
1.3.4. Piano key labyrinth weir
1.3.5. Horse shoe labyrinth weir
1.3.6. Rectangular labyrinth weir

1.4. Characteristics of labyrinth weir

The defining characteristic of the labyrinth weir is its ability to supply increased discharge when compared to conventional weirs for a given head or it can be said that it lowers the upstream head at given discharge when compared to normal rectangular weir. For any existing weir, the discharge capacity can be increased by either lengthening the weir crest, or increasing the discharge coefficient or operating head. Labyrinths are well suited to sites where increasing the weir width and maximum reservoir water surface elevation would be difficult, yet larger discharge capacities are needed. As they are able to do all of this effectively due to the increase in capacity and the decrease in flood attenuation under low flow conditions, they are particularly well suited to the rehabilitation of existing spillway structures. There are infinitely many shapes available for geometrical considerations of labyrinth weirs, although the most popularly used ones are rectangular, triangular and trapezoidal. It has been found through tests based on the discharge across a unit length that rectangular labyrinths are the least efficient of these shapes.

The use of labyrinth weirs has become an established option for design engineers, however, because of the hydraulic complexity of these spillways resulting from the range of available geometries, headwater, tail water, approach conditions and other performance factors, there is room for further research to be conducted and uncertainties still exist. The discharge a labyrinth is capable of passing is a function of the total head, effective crest length and crest coefficient. The crest coefficient depends on the total head, weir height, thickness, crest shape, apex configuration and side angle. During the construction and design of a labyrinth, it is obvious that one would want the most “hydraulically” efficient design obtainable; unfortunately, this is not always possible due to increased construction costs or an inability to construct a hydraulically-optimized weir into site topographic, geological and facility constraints. As a result of this, the overall effectiveness of the project is the determining factor for the design of a weir.

1.5. Labyrinth Weir Parameters:

Various designing parameters have been developed by various researchers for optimization and analysis of labyrinth weirs. Many studies had been conducted to study the effect of geometric parameters on the design of the weir. In this section we will be discussing the effects of parameters on the discharge capacity of the labyrinth weirs. In this section detailed information on the geometric factors is given.

In different studies researchers use different names to denote the parameter or parameters are given misleading names. Hence in this section we will clarify and improve designations used for parameters.

In figure 1 & 2 combined, all the geometric features of a labyrinth weir are given. The cycle in the figure consists of series of triangles which are placed next to each other. Number of cycles is 2.

1.5.1. Sidewall angle (α)

The sidewall angle plays a very important role in design of the spillway. The performance and economy of the spillway are very much affected by the sidewall angle. According to the previous studies, the optimal value of the sidewall angle lie between 7° and 16°. Other angles are outside this range are considered to be not efficient. According to the previous studies, the sidewall angle below 7° and above 16° results in increase in the width of the spillway. It was also seen that the length of the labyrinth spillway decreases with increase in sidewall angle. This length decrease of the spillway causes decrease in discharge. It was also seen that in low height reservoirs, having small sidewall angles, there is increase in discharge capacity.

1.5.2. Number of labyrinth weir cycles

Number of labyrinth weir cycles (N) is a very important parameter. This parameter influences the design and the cost of the spillway. As per the previously conducted studies, the coefficient of discharge (Cd) doesn't get influenced much by the number of labyrinth weir cycles. Using too many numbers of labyrinth spillway cycles leads to a design that may not be economical and hydraulically efficient. For this reason, the width ratio should be kept between 3 and 4 to select available weir length.

1.5.3. Discharge coefficient (C_d)

Discharge coefficient (Cd) is an important factor. Discharge coefficient is influenced by sidewall angles, height of the spillway, crest shape, thickness of the wall and flow conditions. For making correct designs, accurate value of Cd plays an important role. In 1995, Tullis et al. conducted study and demonstrated Cd in term of H/P. The study was conducted for labyrinth spillways having triangular shape and for variety of angles.

1.5.4. Head to weir height ratio (H/P)

The total head measured relative to the weir crest elevation, immediately upstream of the weir over the weir height (P). This is known as headwater ratio. In simple words, head water ratio is the ratio of head (H) to the height of the spillway. This is a dimensionless in nature and is very commonly used on the abscissa of a plot that presents the hydraulic performance of a labyrinth spillway. There is a limitation associated with the use of headwater ratio. When the data from two labyrinth spillways having similar discharge rating curves, but different crest height (P), are plotted together. The upper limit of the headwater ratio (H/P) is 0.9 according to the study conducted by Tullis et al. in 1995. Crookston in 2010 stated in his study that for the values equal to or less than 0.4 ($H/P \leq 0.4$) there is increase in efficiency of the labyrinth spillway. It was also stated that the cycle efficiency is maximum at low H/P values. No data above H/P= 0.9 and below H/P=0.1 were used as with increasing head the labyrinth spillways become significantly effective.

Flow magnification ratio (Q/Q_n)

Q/Q_n is defined as ratio of discharge at labyrinth weir to the discharge at normal linear weir for the same head. Hay and Taylor (1970) carried out an experimental study by using a rectangular, trapezoidal, and triangular labyrinth plan form. They presented the results using the variable named flow magnification ratio, Q/ Q_n, defined as the ratio between the labyrinth weir discharge, Q, corresponding to a given head h and the discharge, Qn, flowing by the linear weir for the same head value. Using the ratio Q/ Q_n allows easy evaluation of the effectiveness of the W weir with respect to a linear weir; the performance of the W weir improves when the flow magnification exceeds the unit value. This value shows how much the discharge is increased in labyrinth weir as compared to linear for same width of channel, head, height of weir and other parameters being same.

1.6. Triangular labyrinth weir and it's applications: -

Triangular labyrinth weir's geometry in planform is such that n(cycles) number of isosceles triangles are place in series at width. This placement is symmetrical and is done in such a manner that the base line of triangles are parallel. The length can be magnified up to 4 times as compared to linear weir. The α angles plays the important role in length magnification. The length magnification ratio L/w is equal to 1/sinα. This increased length gives the flowing water more length over which it flows, that too in limited width. Thus, this structure can also be used to contract any channel width. A labyrinth weir is folded in plan view to provide a longer total effective length for a given overall channel width. The variables that need to be considered in designing a triangular labyrinth includes the width and length of the labyrinth, the labyrinth angle, the crest height, the number of cycles, and several other less important variables such as wall thickness, crest shape, and apex configuration.

1.6. Application of Triangular labyrinth weir:

- For reducing water depth level at crest during high floods at same channel width where a normal weir would result in high water level.

- As a "side weir" where water is taken from a channel to another channel for canal systems. A triangular labyrinth weir would result in efficient transfer of water from the feeding channel to receiving channel. Also, when there will be high flows, the weir will carry the large discharge without any significant damage causing rise in water level at crest.

- At existing spillways to increase the discharge carrying capacity. When a reservoir capacity is increased or high flows starts to occur at a spillway, a need of increasing its capacity arises. This can be achieved by constructing a triangular labyrinth weir at the spillway.

- At the intermittent distance in a channel, Triangular labyrinth weir can be constructed to control the flash flood effect downstream. This will result in formation of pools of water at upstream of each weir and will release water in a controlled way so that no major damage occurs at valley downstream.

Layout of a typical triangular weir:

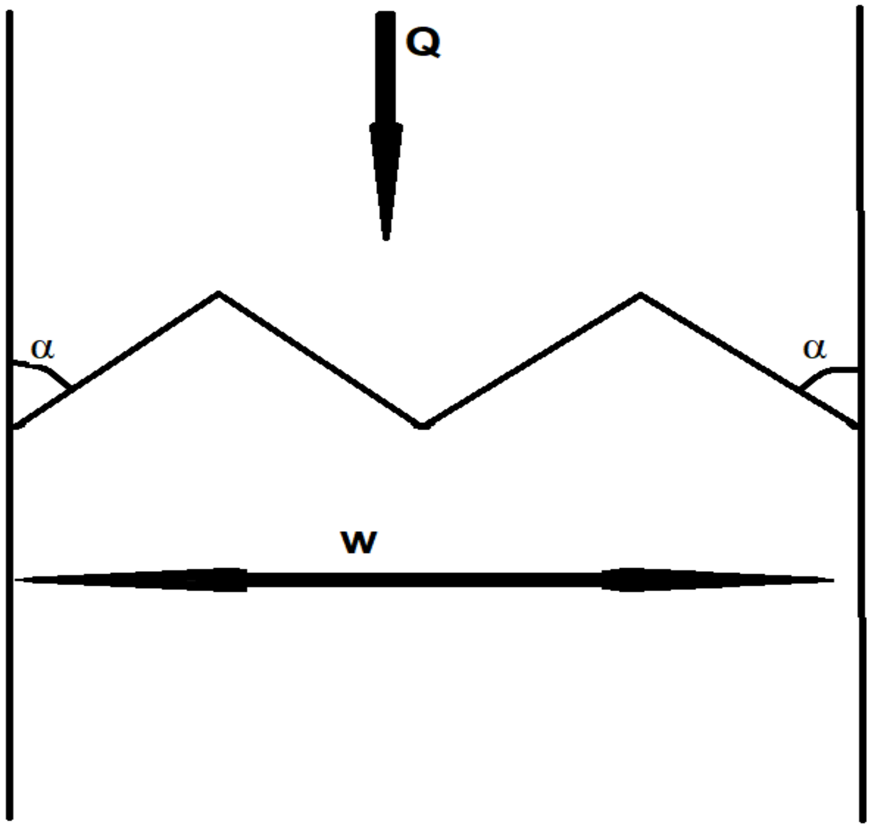

Figure 2: Planform layout of a triangular labyrinth weir

Length magnification ratio:

$$\frac{L}{w} = \frac{1}{\sin \alpha}$$

Q= discharge

W= width of the channel

α = side angle of weir

L = Total Crest Length of the weir

1.7. ANSYS fluent overview

1.7.1 Introduction

ANSYS software program is used to layout merchandise, as well as to create, simulations. ANSYS is a general-purpose software, used to simulate interactions of all disciplines of physics, structural, vibration, fluid dynamics, heat transfer and electromagnetic for engineers. In ANSYS fluent Navier stoke's equations are calculated in flow domain to simulate the flow on the basis of relative values obtained by solving the Navier stoke's equation. In solving Navier Stoke's equation, more the number of iterations more will be the accuracy of the solution because in each consecutive iteration the value of residuals is minimised and error rate is reduced.

1.7.2. Computational fluid dynamics

Computational Fluid Dynamics (CFD) is a set of numerical methods applied to obtain approximate solution of problems of fluid dynamics and heat transfer. CFD is not a science by itself, it is a way to apply the method of numerical analysis to another fluid flow or mass transfer. CFD are used because there are many engineering problems that can't be solved by analytical or experimental approach. CFD solutions can only be as accurate as the physics models on which they are based. "Computational fluid dynamics" (CFD) is a branch of mechanics of fluid, that uses statistical assessment and statistics systems to answer and have a look at issues that involved fluid flows. laptop systems are used to implement the calculations required to, simulate the intercommunication of beverages and gases, with surfaces described through limiting conditions. In computational fluid dynamics, navier stoke's equation is used to find the properties of fluid at a downstream point from the adjacent upstream point.

1.7.3. Methodology

The geometry, and bodily limits of the1issue can be defined the usage of computer aided layout. From there, facts may be certainly processed and the liquid quantity (fluid location) is obtained. The extent involved by the liquid is distributed into discrete1cells.

The work is apparently uniform, or non-uniform, dependent or, unregulated, which include a blend of hexahedral, tetrahedral, chromatic, pyramidal or polyhedral factors. The mechanical modelling is described – as an example, the equations of liquid flow, enthalpy, radiation, kind protection. Boundary states are defined. This requires defining the liquid behaviour and houses at all bounding surfaces of the liquid area. For short troubles, the primary situations are also defined. The simulation is begun and the equations are resolved iteratively as a constant-kingdom or brief. In the long run a postprocessor is used for the evaluation and visualization of the resulting response. "

1.7.4. ANSYS Fluent

Fluent software contains the broad, physical modelling capabilities needed to model flow, turbulence, heat transfer and reactions for industrial applications. These range from air flow over an aircraft wing to combustion in a furnace, from bubble columns to oil platforms, from blood flow to semiconductor manufacturing and from clean room design to wastewater treatment plants. Fluent spans an expansive range, including special models, with capabilities to model in-cylinder combustion, aero-acoustics, turbomachinery and multiphase systems.

ANSYS FLUENT can model the effects of open channel flow (e.g., rivers, dams, and surface-piercing structures in unbounded stream) using the VOF formulation and the open channel boundary condition. These flows involve the existence of a free surface between the flowing fluid and fluid above it (generally the atmosphere). In such cases, the wave propagation and free surface behaviour becomes important. Flow is generally governed by the forces of gravity and inertia. This feature is mostly applicable to marine applications and the analysis of flows through drainage systems.

1.8. Purpose of the study

A labyrinth weir is capable to pass larger flow than a normal weir with same head over the crest. Due to comparatively low construction and preservation costs, and more consistent operation, compared with gated spillways; a labyrinth weir is preferred over other overflow structures. Moreover, it can also be a cost-effective choice in terms of elevation of crest of the dam and reservoir capacity for specified maximum head over the crest. Although it has a broad range of applications, its complex flow conditions and design have been considered a drawback by designers. The labyrinth weir is suitable for situations where the structure length has to be limited or for improvement in performance of existing spillways. This type of weir is characterized by a broken-axis weir in plan, generally with the same polygonal pattern repeated periodically. Hence, for the same total width, the labyrinth weir will present larger crest lengths than the same total width.

Also, the effect of number of cycles and side angle α has not been properly explained and compared with other parameter to obtain a trend of effect on other parameters by the number of cycles of a labyrinth weir.

1.9. Future Scope of the study:

- The triangular labyrinth weir can be analysed to be used to control flow during flash floods. These weirs can be used in series at intermittent distance so large flows don't come downstream instantly.
- Kinetic energy correction factor for models of triangular labyrinth weir can be analysed to get the best model out of tested models.
- Using ANSYS, the triangular labyrinth weir can be tested at the places where other type of labyrinth weirs are currently being used so that comparison can be done among the outcome flow parameters.

CHAPTER 2

LITERATURE REVIEW

2.1. Previous studies

2.1.1. Kumar C. P. and Pathak S. K. (1987)

They established the relation between discharge coefficient C_M and main channel Froude number for triangular sharp crested side weirs. For broad crested triangular side weirs, this relation is modified by a multiplying factor K which depends only on h/L ratio.

$$K = \frac{C_M \text{ for broad crested triangular weir}}{C_M \text{ for sharp crester triangular weir}} = 0.80 + 0.10\frac{h}{L}$$

Proposed equations of discharge: -

For sharp crested weir:

$$Q_w = 0.5908\, C\sqrt{2g}\, \tan\frac{\theta}{2} h^{5/2}$$

For broad crested weir:

$$Q = 0.5566\left(0.80 + 0.10\frac{h}{L}\right) C\sqrt{2g}\, \tan\frac{\theta}{2} h^{5/2}$$

Where,

$$C = (0.811 - 0.321 \tan \theta/2 + 0.129 \tan^2 \theta/2) - (0.695 - 0.638 \tan \theta/2 + 0.150 \tan^2 \theta/2)F$$

2.1.2. Tullis J. P, Amanian N., and Waldron D. (1995)

They explained that the choice of sidewall angle α and the number of cycles *N* significantly influences the width, length, and other details of the labyrinth. With complete freedom to vary α and *N*, numerous layouts can be generated. The most appropriate design is determined after considering site-specific limitations, completing an economic analysis in parallel with the hydraulic analysis, and routing the flood through the reservoir using the final spillway design.

The capacity of a labyrinth spillway is a function of the total head H the effective crest length L and the crest coefficient C_d. C_d depends on weir height P, total head H, weir wall thickness t, crest shape, apex configuration, and the angle of the side legs.

Also, they talked about flood routing through the concerned spillway. The spillway with a small angle has significantly more capacity at low reservoir elevations. With the increased spillway capacity, more of the flood is passed through the reservoir, which reduces the maximum reservoir elevation. This may allow the spillway length to be reduced, saving construction costs.

The other side of the problem is matching the outflow to downstream flow limitations. An example would be where previous water rights limit releases from the reservoir at floods below the hundred-year flood. If the labyrinth is to be added to an existing reservoir where the downstream requirements limit the flows at low water-surface elevations, a labyrinth with a small angle may provide more capacity than can be tolerated. For such an installation, a large angle labyrinth may better fit the outflow requirements.

2.1.3. Tullis B. P., Young J. C. and Chandler M. A. (2007)

They conducted experiments on submerged labyrinth weirs of different geometries with half-round crest shapes. They described the submerged labyrinth weir head–discharge relationship using the dimensionless sub- merged head parameters and found that the relationship is independent of labyrinth weir sidewall angles.

The dimensionless submerged head relationships developed in this study showed that the submergence did not begin until the tailwater exceeds the crest ($H_d/Ho>0$), that the upstream head is not significantly affected by submergence until H^*/H_d exceeds 0.5, and that at high submergence levels $H_d = H^*$.

2.1.4. Ghare A.D., Mhaisalkar V. A. and Porey P. D. (2008)

Analysis of data from Tullis was been carried out and a new mathematical model equation to work out the optimal coefficient of discharge for labyrinth weir was obtained. The optimum C_d is given by:

$$C_d = 0.1714 \ln (H/P) + 0.8671$$

Proposed design considerations:

(i) From the available control levels, the total head 'H' is to be worked out which include the estimated inlet losses.

(ii) Also crest height ‘P’ can be worked out by subtracting the approach channel elevation from crest elevation of the weir.
(iii) Thickness of the weir wall is based on structural stability considerations and inside apex width shall be assumed in the range of t to 2t for trapezoidal labyrinth weir.

(iv) For weir height ratio, optimal value of ‘C_d’ can be determined by the given equation and the required effective length of control structure ‘L’ can be worked out using:

$$Q = \frac{2}{3} C_d L \sqrt{2g} H^{\frac{3}{2}}$$

2.1.5. Emiroglu M. E., Kaya N., and Agaccioglu H. (2010)

At low Froude numbers, water surface profiles of rectangular side weirs were almost horizontal situation. With an increase in Froude number, water surface profile alongside weir drop slightly at the end of upstream of the weir crest, then rise quickly toward the end of downstream of the weir.

The longitudinal velocity of water moving in active overflow situation from the inner bank toward the outer bank increases due to lateral flow. Discharge coefficient of the labyrinth side weir is 1.5–4.5 times higher than rectangular side weir. The discharge coefficient C_d increases when L/b ratio increases. And, increase on p/b ratio also means increase on the C_d.

2.1.6. Carollo F. G., Ferro V. and Pampalone V. (2012)

This paper reported the results of a laboratory investigation carried out by using sharp-crested w-shaped weirs with the length magnification ratios equal to 1.15, 1.41, 2, and 4.

The comparison, for a given l/w ratio, between sharp-crested and broad-crested W weir pointed out a lower efficiency (lower Q/Q_n values) for the broad-crested case, for which the ratio Q/Q_n is always near to 1. In other words, the tested broad-crested W weirs had practically the same hydraulic behaviour as that of a standard linear broad-crested weir.

In this paper, they talked about flow magnification ratio along with length magnification ratio. Flow magnification ratio was defined as Q/Q_n, where Q is discharge at labyrinth weir with head h and Q_n is discharge at normal weir of same width and height with head equal to h. Because the crest length is greater in the labyrinth weir than the linear weir, a labyrinth weir provides a reduction in the head corresponding to a given discharge.

2.1.7. Crookston B. M. and Tullis B. P. (2012)

This study investigates the concept of labyrinth weir nappe interference and identifies labyrinth weir flow characteristics that decrease discharge efficiency, including local submergence. Parametric methods for quantifying nappe interference region size as a function of weir geometry and flow conditions are presented. A comparison between empirical methods found in the literature for determining the size of the nappe interference region and laboratory-scale experimental data showed a limited correlation.

Nappe interference and local submergence are influenced by nappe aeration conditions, apex length (A_c), sidewall angle (α), and H_t. The effects of nappe interference and consequently apex influence is inherent but not separately quantified in discharge coefficients and rating curves proposed in labyrinth weir design methods. the size of the nappe interference and parametric methods were developed to qualitatively determine if the discharge of a geometrically comparable labyrinth weir cycle may deviate from design method predictions as a result of nappe interference. Such information may either lend confidence to a labyrinth weir design or suggest the need for a model study.

2.1.8. Borghei S. M., Nekooie M. A., Sadeghian H., Ghazizadeh R. J. (2012)

Shown that triangular labyrinth side weir with two cycles decreases the nub length λ over that of a one-cycle side weir with the same effective length 'L' and efficiency of a triangular labyrinth weir is greater than that of a conventional side weir. The effect of anti-vortex plates and aeration for triangular labyrinth side weirs with one and two cycles is important enough to contribute significant differences to the results.

2.1.9. Dabling M. R., Tullis B. P., and Crookston B. M. (2013)

Assessed the accuracy of a simple head-discharge prediction method on the basis of the principle of superposition. The computed $Q_{predicted}$ values were generally within

15% of the experimentally determined Q_{actual}, with maximum errors of 15%. The predictive accuracy was determined to be a function of H_t/P, ΔP_{stage}, l_{stage}, and the low stage location. Although only a single sidewall angle was tested in this study, labyrinth weir literature has documented that discharge is also a function of additional labyrinth geometric parameters, of which α would be a significant parameter in Cd and staged labyrinth weir Q estimations The documented hydraulic characteristics and flow behaviours observed in the laboratory provide new insights and are presumed to generally apply to staged labyrinth weirs. Nevertheless, the experimental results presented herein are limited to the staged labyrinth weir geometries tested. The results are recommended for estimating head-discharge relationships and outflow hydrographs for geometrically similar staged labyrinth weirs and as a first-order approximation for staged labyrinth weirs of different cycle geometries. A physical model study is recommended to confirm hydraulic characteristics of a staged labyrinth weir. Future studies of different nonlinear weir designs will further expand understanding of these complex hydraulic structures.

2.1.10. Bilhan O., Emiroglu M. E. (2016)

Observed that variation of the nappe pressure between sub-atmospheric pressure and atmospheric pressure causes vibrations, oscillations and noise. Although the negative pressures under water nappe partially increase the discharge capacity of the labyrinth weirs, effects of vibration and resonance may cause problems that could threaten the safety of the structure.

Labyrinth weirs provide an effective means to increase the spillway discharge capacity of dams and are often considered for renovation projects required due to an increase in expected flood inflow to the reservoir of an existing dam. Labyrinth weirs can pass large flows at comparatively low heads. The crest shape is one of the most important factors which affect the discharge capacity for labyrinth weirs. According to this experimental study, it was found that the trapezoidal labyrinth weirs are hydraulically more efficient than the circular labyrinth weirs and linear weirs from the perspective of ease of construction and the discharge capacity.

2.1.11. Bilhan O., Emiroglu M. E. and Miller C. J. (2016)

According to this experimental study, it was found that the trapezoidal labyrinth weirs are hydraulically more efficient than the circular labyrinth weirs and linear weirs from perspective of ease of construction and the discharge capacity.

Of course, given unlimited width, greater efficiencies (discharge per head) will be obtained for a linear weir. However, the trapezoidal labyrinth weirs provide much greater weir length in confined space with only limited reductions in efficiency (reduction in Cd). The circular weir is the least efficient of those investigated.

2.1.12. Kardan N., Hassanzadeh Y., Bonab B. S. (2017)

In order to examine the effectiveness of the proposed methodology, optimal design of the Ute Dam labyrinth weir was performed. The optimized volume of labyrinth weir as well as the design variables values was obtained and compared with the real ones. The results indicated that increasing the cycle numbers of labyrinth weir leads to considerable reduction in width and leg of weir in one cycle and as a result to reduction the total volume of labyrinth weir. The optimum volume of the labyrinth weir is 2640 m^3 less than the previous initial volume, i.e., 21.47% less.

2.1.13. Dabling M. R. and Tullis B.P. (2018)

They experimented the effect of angled approach flow on the existing spillways and also during high value of discharges. The results showed that at approach angle 15^0 the effect was almost nil but as the approach angle was increased, the coefficient of discharge reduced as much as 11%. Also suggested that for approach angle $>45^0$, there may be further decrease in the efficiency of the spillway.

Also, at small upstream head, the spillway was slightly more efficient due to utilisation of ogee shaped crest, but at high upstream heads there was a slight decrease in efficiency.

CHAPTER 3
METHODOLOGY

3.1. Model

Labyrinth weir models of different cycle and geometry were designed according to the size of flume available in university Hydraulics lab on "ANSYS Fluent". Three side wall angle α were used and three cycles of each angle were deigned to study the effect of side wall angle and cycle on flow.

ANSYS – Analysis and Simulations

Fluent - It is a part of ANSYS software which deals with fluid flow.

$$\frac{L}{w} = \frac{1}{\sin \alpha}$$

Table1: L/w ratios for sidewall angle α

S.no.	α	$\frac{L}{w}$ ratio	w(mm)	L(mm)
1.	30^0	2	300	600
2.	45^0	1.414	300	424.24
3.	60^0	1.154	300	346.2

Simulation were done according to the geometry of flume.

Flume geometry:

Length – 6000mm

Width – 300mm

Height – 400mm

Weir geometry:

Height of weir – 75mm

Width of weir – 300mm

Effective Length of weir – According to side angle α

Weir Shape: Triangular in planform and Rectangular in elevation i.e. top view is triangular and when a front view is scene, it's walls are rectangular.

Total 9 Models are made for simulations

S.no.	Name	α	cycle
1.	30d1c	30^0	1
2.	30d2c	30^0	2
3.	30d3c	30^0	3
4.	45d1c	45^0	1
5.	45d2c	45^0	2
6.	45d3c	45^0	3
7.	60d1c	60^0	1
8.	60d2c	60^0	2
9.	60d3c	60^0	3

Table2: model details

"30d1c – weir having $\alpha=30^0$ and 1 cycle"

"45d2c – weir having $\alpha=45^0$ and 2 cycles"

"60d3c – weir having $\alpha=60^0$ and 3 cycles"

Variation of sidewall angle α and cycle (N) has been done to make 9 models. All models are tested under similar condition to study the effect on discharge. These significant changes in geometry have a major impact on the flow and also the height of water at the crest of weir which plays a major role in weir flow control. Other parameters like discharge Q, height of weir P, width of channel, material of weir are kept constant to keep the conditions same for all weirs.

3.2. ANSYS Fluent simulation process: -

3.2.1. Designing geometry

3.2.2. Meshing

3.2.3. Setup

3.2.4. Post Processing

3.2.5. Results

3.2.1. Designing geometry: -

Designing of model is done in workbench on design modeler. A proper layout of model is drawn and then "extrude" command is used to make the model in 3d to elevate the weir in third axis.

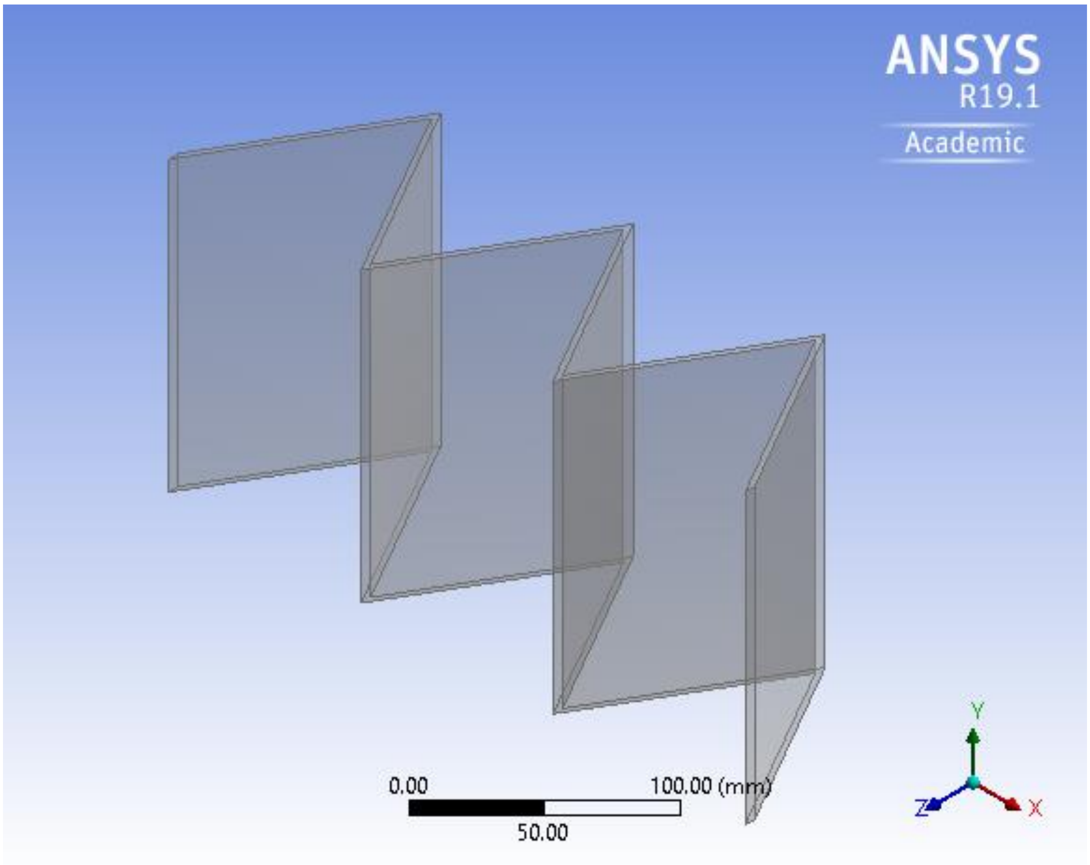

Figure 3: 3D geometry of model

Here, a 3D model of $\alpha=30^{0,}$ 3 cycle weir is shown. In this the width of each cycle is 100mm and the length of one wall is also 100mm.

A flow domain is provided by using “enclosure” command and flow domain dimensions are provided.

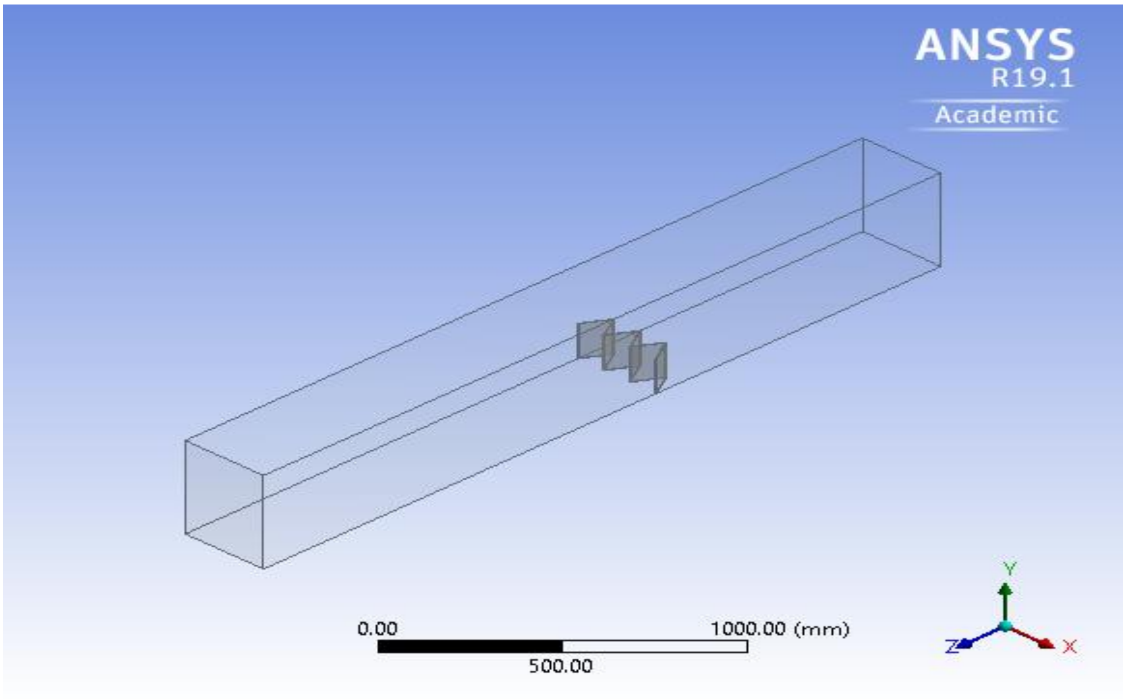

Figure 4: Model in flow domain

Then naming of flow domain faces is done to mention inlet, outlet, walls, etc.

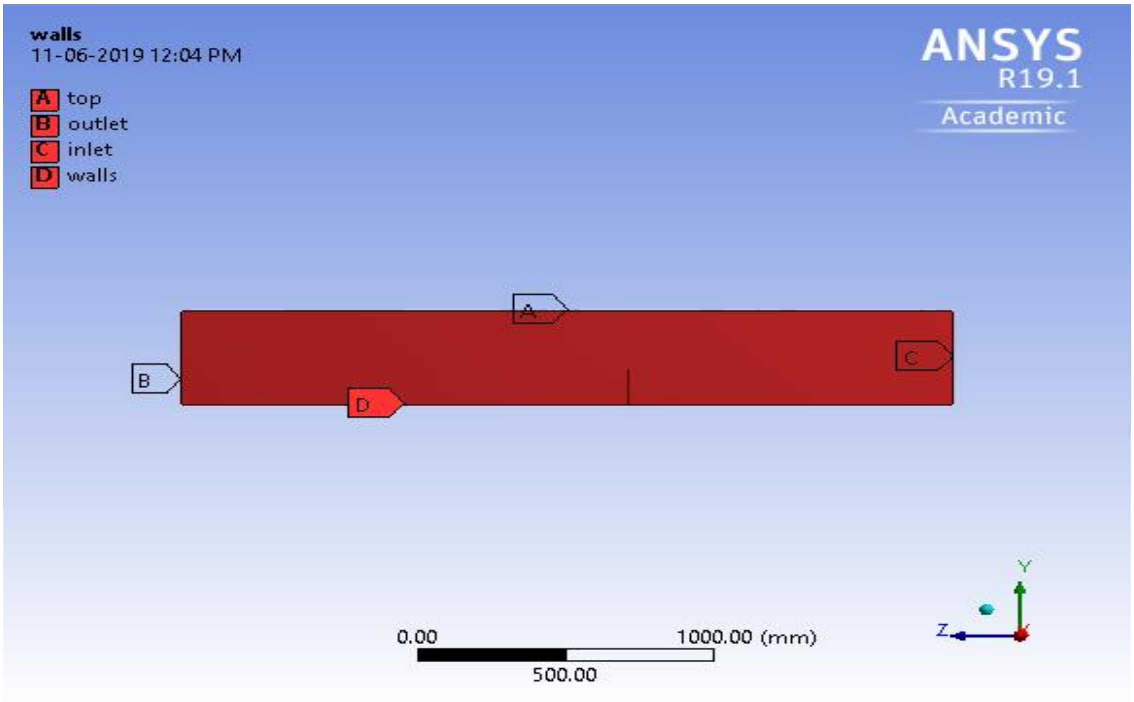

Figure 5: Naming of faces

The named faces are top, walls, inlet and outlet.

3.2.2. Meshing

Meshing is done by generating the mesh command under Mesh component of ANSYS fluent.

The fineness of mesh is increased by inserting "sizing" command in mesh, and then desired size is input and mesh is generated. This decrease or increase the cell size of mesh and desired fineness is achieved.

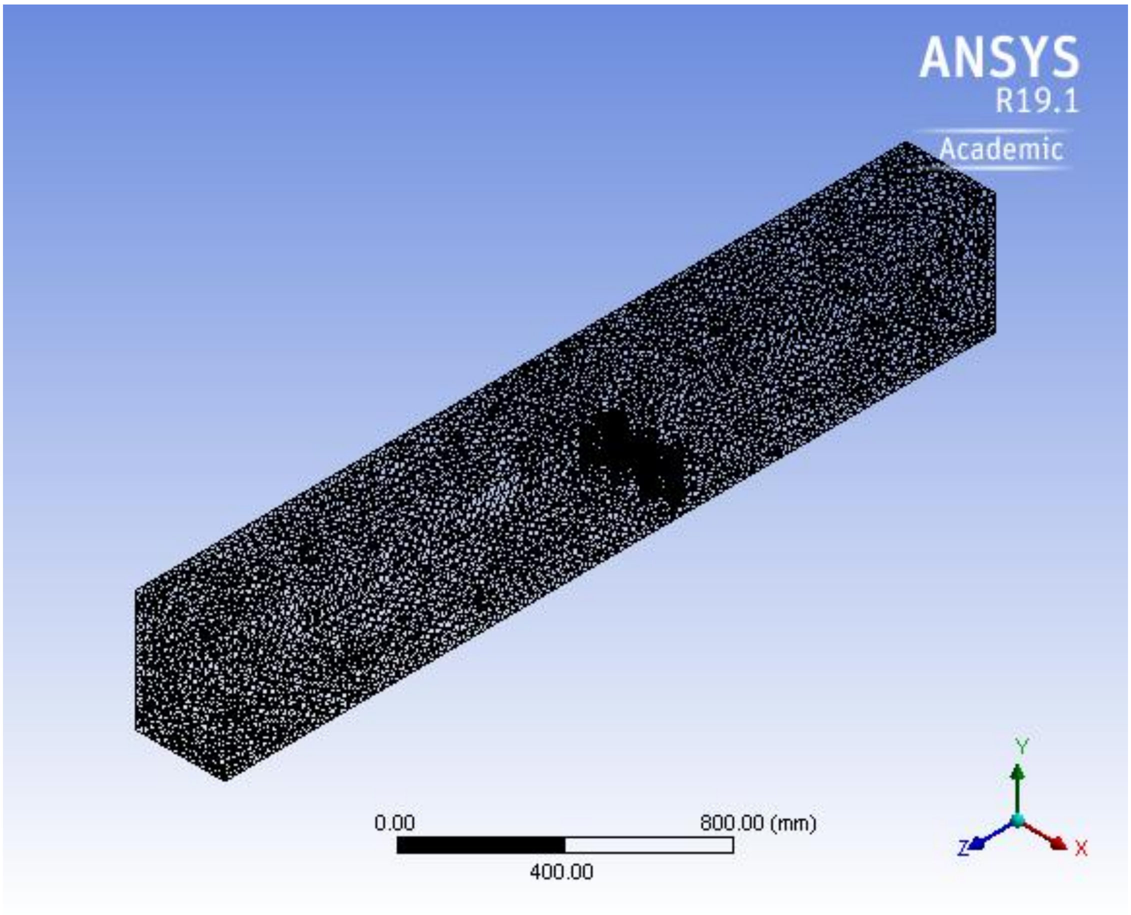

Figure 6: Meshing for CFD in ANSYS

Meshing is done on the model by simply generating the mesh and the sizing command is input under mesh tab to further refine the mesh size.

The mesh settings are as follows:

Element order – Linear

Growth rate – 1.2

Minimum edge length – 5.0 mm

Skewness – 0.9

Smoothing – medium

Transition ratio – 0.272

3.2.3. Setup

(a) General

Under this, general setting is provided on the Fluent model. In this model, Solver type is chosen as pressure based, time is taken as transient, gravity is given in negative Y axis to simulate the model.

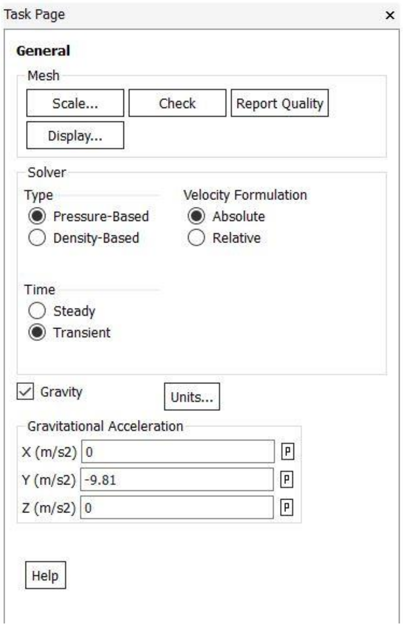

Figure 7: ANSYS setup: general

(b) Model(i)Under Multiphase tab, Volume of fluid model is chosen for 2 phases namely air and water. Sub model is "open channel flow". Formulation is "implicit"

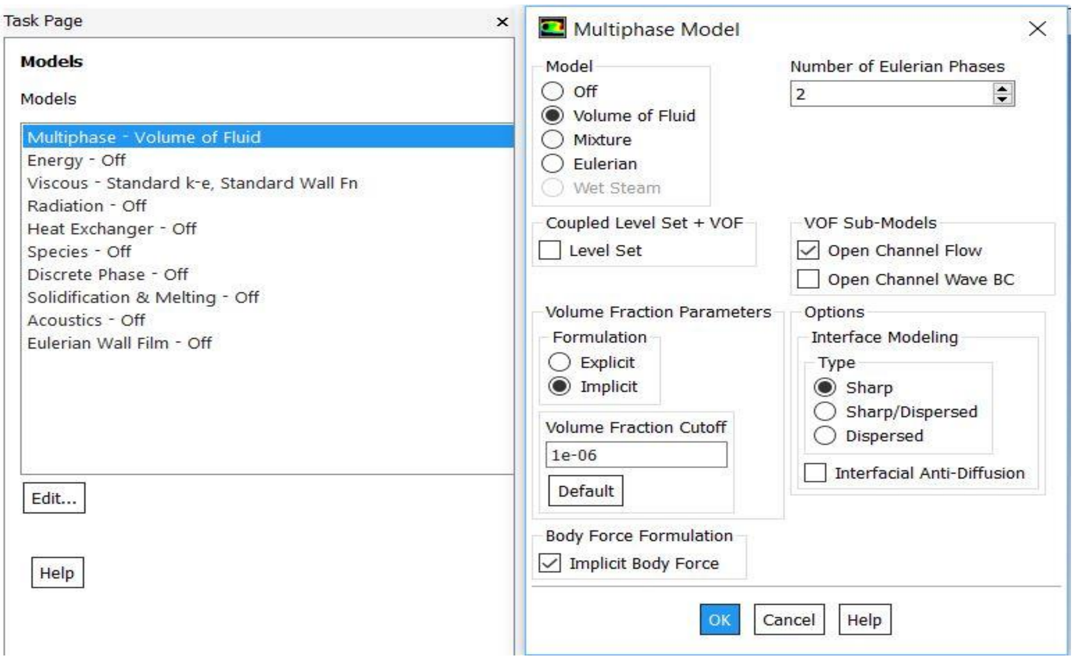

Figure 8: ANSYS setup: multiphase model

(ii) In addition to the multiphase model, Viscous model command is also activated sub model is "k-epsilon". Standard wall function is chosen to consider near wall flow effectively.

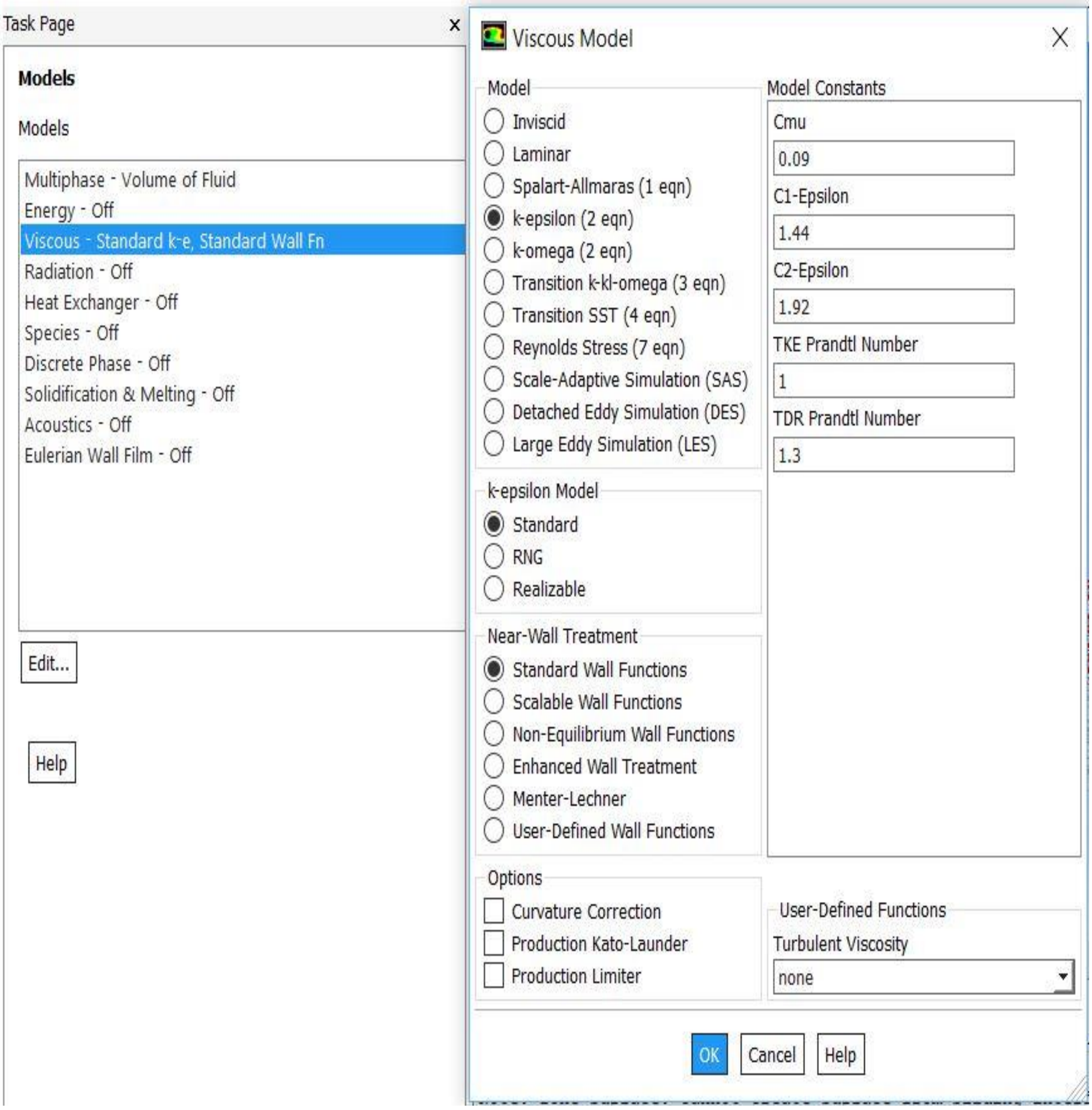

Figure 9: ANSYS setup: viscous model

(c) Under Material tab materials are defined from pre specified database or user defined material. Here, in addition to default material "Air" as primary fluid, "Water" is added from fluent database as secondary fluid.

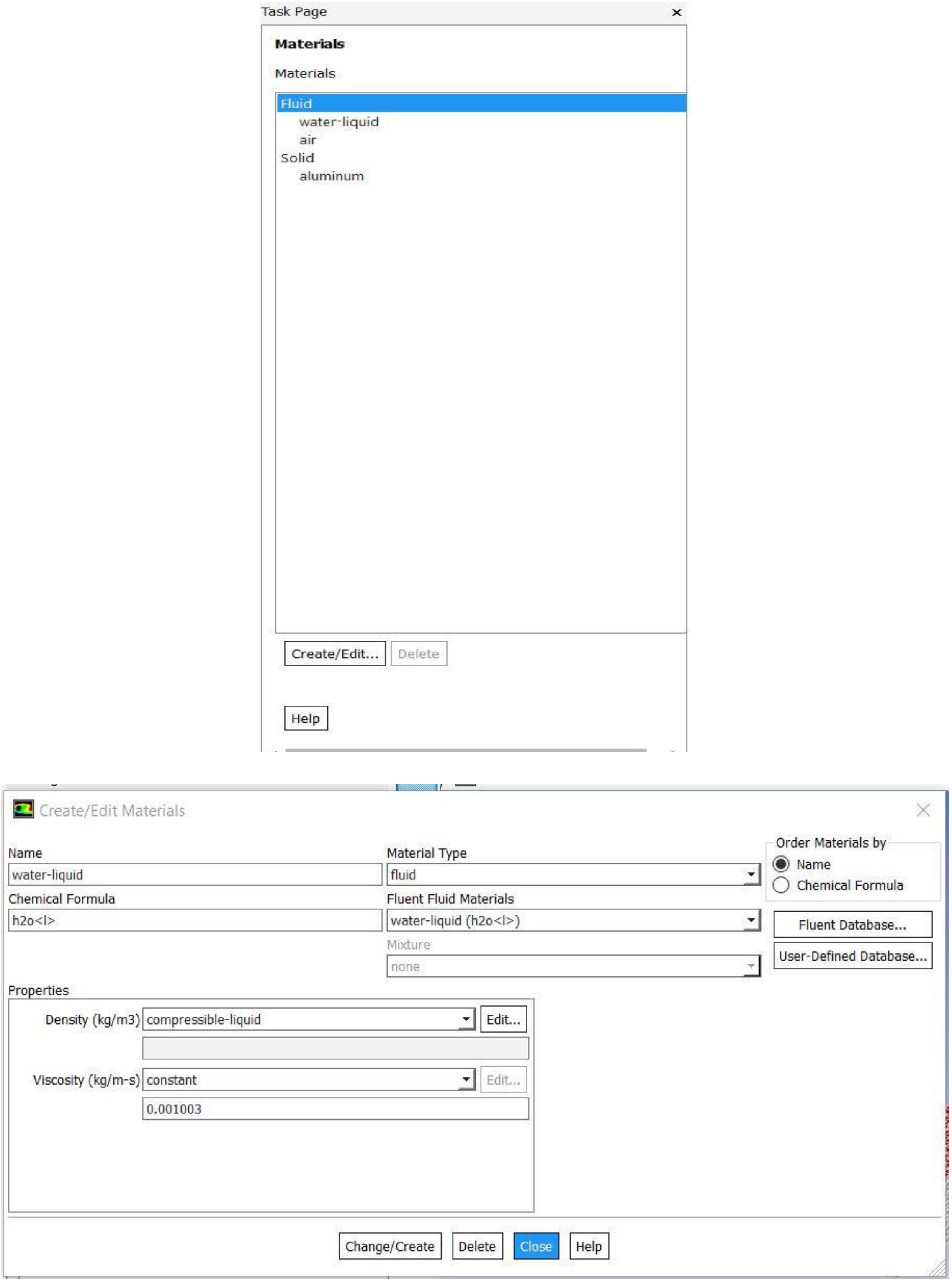

Figure 10: ANSYS setup: material selection

(d) Boundary Conditions

Under this tab, boundary conditions of inlet and outlet are provided to simulate the flow according to the model need.

Inlet is defined as mass flow inlet to input the value of discharge.

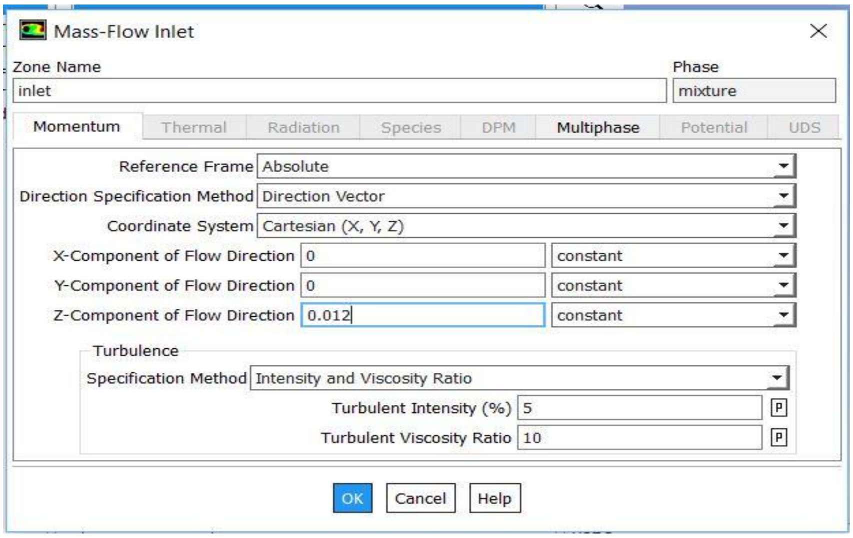

Figure 11: ANSYS setup: inlet boundary condition

Outlet is defined as outflow to provide as discharge outlet

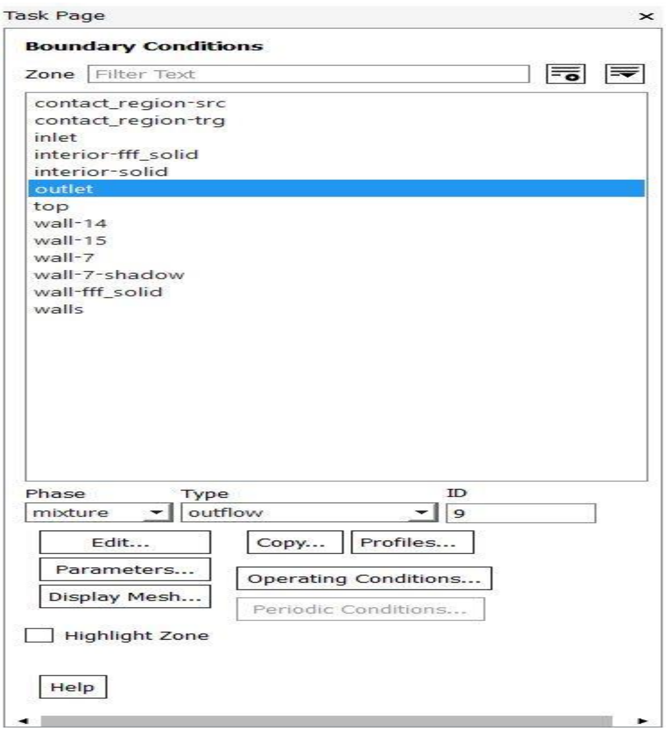

Figure 12: ANSYS setup: outlet boundary condition

(e) Solution initialisation and calculation activity

Hybrid initialisation is provided with calculations starting from inlet and solution is initialised in 10 iterations

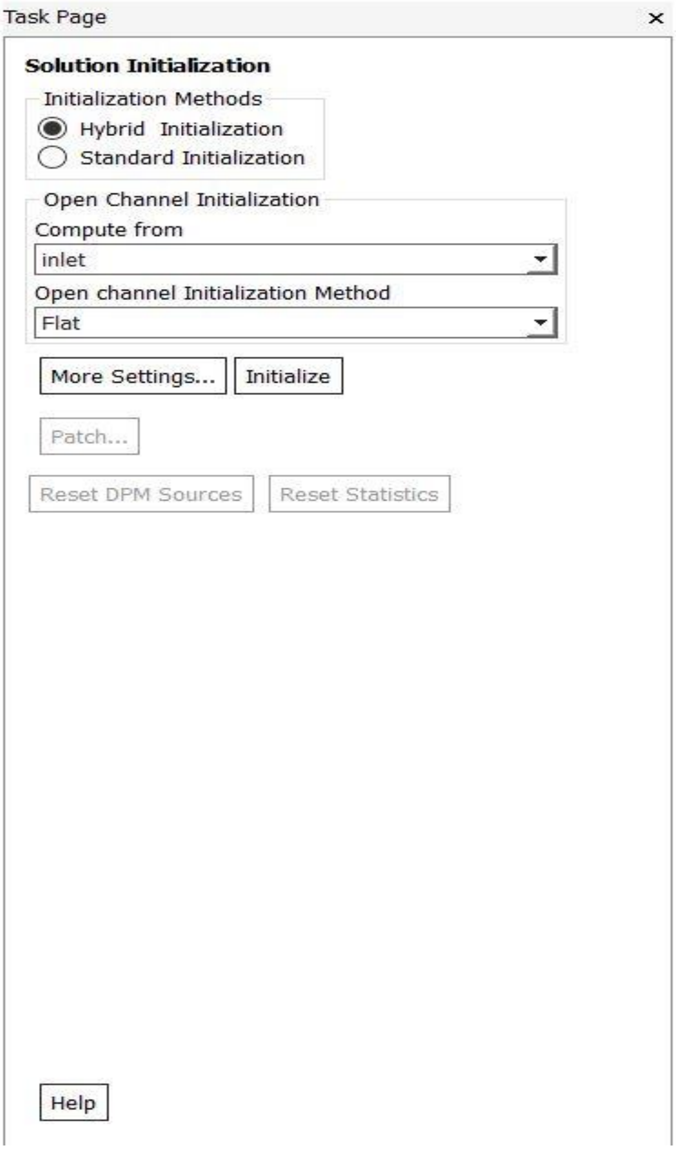

Figure 13: ANSYS setup: Solution Initialisation

Calculation activities

A CFD post file is generated to later open the Fluent solution. In calculation time step size is taken as 0.05s and number of time step is 100.

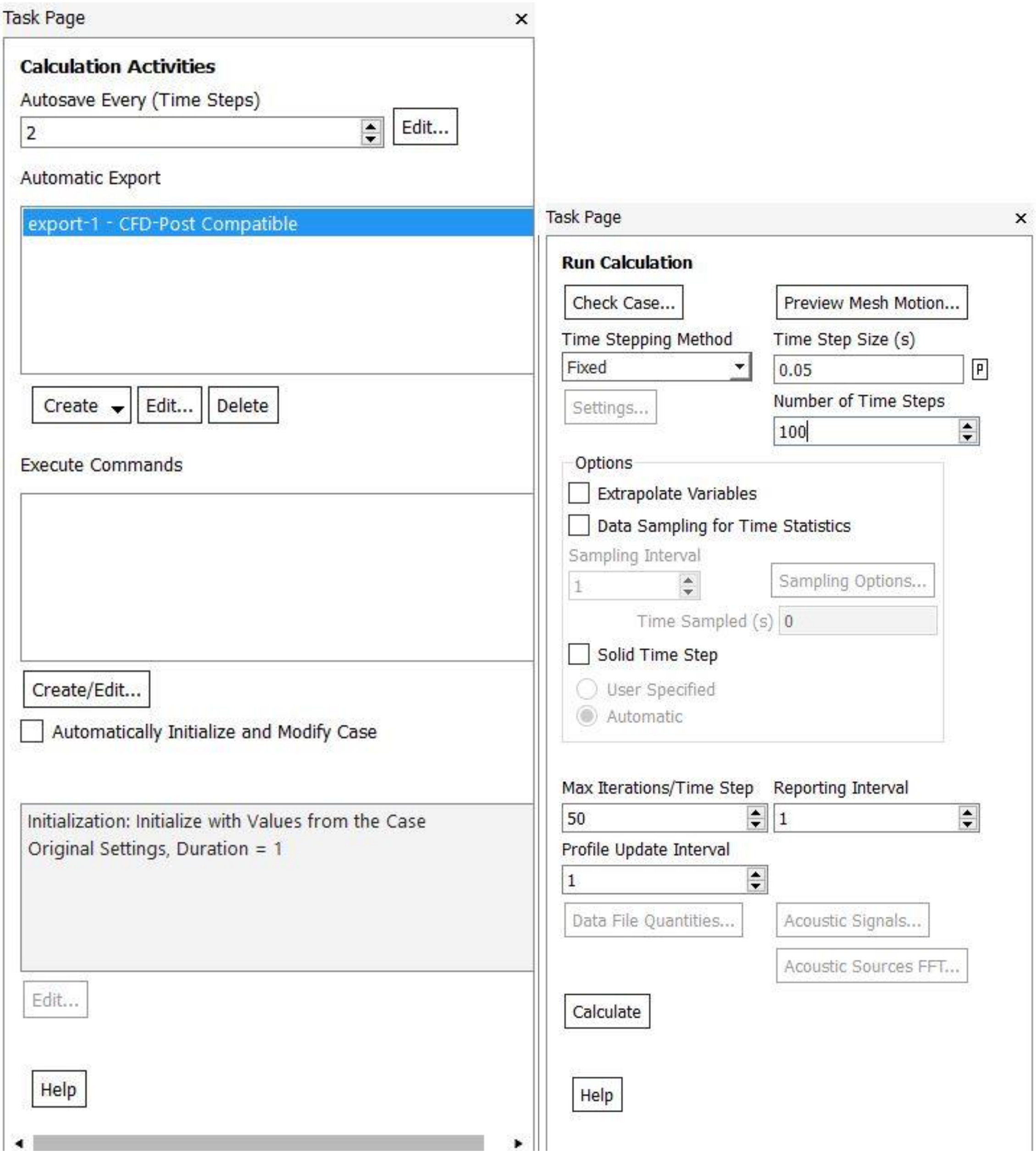

Figure 14: ANSYS setup: Model run and solution export

Design parameters and input values in ANSYS to provide a setup for CFD simulations

TABLE 3: ANSYS model units

Unit System	Metric (mm, kg, N, s, mV, mA) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

TABLE 4: ANSYS Geometry

Model (A3) > Geometry

Object Name	Geometry
State	Fully Defined
Definition	
Source	C:\Users\kaushal\Desktop\MAJOR THESIS FILE\ANSYS files\45d2c\45d2c_files\dp0\FFF\DM\FFF.agdb
Type	DesignModele r
Length Unit	Meters
Bounding Box	
Length X	300. mm
Length Y	400. mm
Length Z	3580. mm
Properties	
Volume	4.296e+008 mm^3
Scale Factor Value	1.
Statistics	
Bodies	2
Active Bodies	2
Nodes	5321
Elements	24688
Mesh Metric	None
Update Options	
Assign Default Material	No
Basic Geometry Options	

Parameters	Independent
Parameter Key	
Attributes	Yes
Attribute Key	
Named Selections	Yes
Named Selection Key	
Material Properties	Yes
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	Yes
Coordinate System Key	
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	Yes
Compare Parts On Update	No
Analysis Type	3-D
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	No

TABLE 5: Parts of the model

Model (A3) > Geometry > Parts

Object Name	Solid	Solid
State	Meshed	
Graphics Properties		
Visible	Yes	
Transparency	1	0.1
Definition		
Suppressed	No	
Coordinate System	Default Coordinate System	
Behavior	None	
Reference Frame	Lagrangian	
Material		
Assignment		

Fluid/Solid	Defined By Geometry (Solid)	Defined By Geometry (Fluid)
Bounding Box		
Length X	300. mm	
Length Y	75. mm	400. mm
Length Z	80. mm	3580. mm
Properties		
Volume	1.1231e+005 mm³	4.2949e+008 mm³
Centroid X	7.0098 mm	6.9531 mm
Centroid Y	37.5 mm	200.04 mm
Centroid Z	-40. mm	210.07 mm
Statistics		
Nodes	66	5255
Elements	115	24573
Mesh Metric	None	

TABLE 6: ANSYS Workbench Coordinates

Model (A3) > Coordinate Systems > Coordinate System

Object Name	Global Coordinate System
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0.
Origin	
Origin X	0. mm
Origin Y	0. mm
Origin Z	0. mm
Directional Vectors	
X Axis Data	[1. 0. 0.]
Y Axis Data	[0. 1. 0.]
Z Axis Data	[0. 0. 1.]

TABLE 7: Model Connections

Model (A3) > Connections

Object Name	Connections
State	Fully Defined
Auto Detection	

Generate Automatic Connection On Refresh	Yes
Transparency	
Enabled	Yes

TABLE 8: Connections in 3D geometry

Model (A3) > Connections > Contacts

Object Name	Contacts
State	Fully Defined
Definition	
Connection Type	Contact
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Auto Detection	
Tolerance Type	Slider
Tolerance Slider	0.
Tolerance Value	9.0369 mm
Use Range	No
Face/Face	Yes
Face Overlap Tolerance	Off
Cylindrical Faces	Include
Face/Edge	No
Edge/Edge	No
Priority	Include All
Group By	Bodies
Search Across	Bodies
Statistics	
Connections	1
Active Connections	1

TABLE 9: Faces and contact regions

Model (A3) > Connections > Contacts > Contact Regions

Object Name	Contact Region
State	Fully Defined
Scope	
Scoping Method	Geometry Selection

Contact	9 Faces
Target	9 Faces
Contact Bodies	Solid
Target Bodies	Solid
Protected	No
Advanced	
Small Sliding	Program Controlled

TABLE 10: Meshing parameters

Model (A3) > Mesh

Object Name	Mesh
State	Solved
Display	
Display Style	Body Color
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Linear
Element Size	Default (180.74 mm)
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Use Adaptive Sizing	No
Growth Rate	Default (1.2)
Max Size	Default (361.47 mm)
Mesh Defeaturing	Yes
Defeature Size	Default (0.90369 mm)
Capture Curvature	Yes
Curvature Min Size	Default (1.8074 mm)
Curvature Normal Angle	Default (18.0°)
Capture Proximity	No
Bounding Box Diagonal	3614.7 mm
Average Surface Area	1.9222e+005 mm²
Minimum Edge Length	5.0 mm
Quality	
Check Mesh Quality	Yes, Errors

Target Skewness	Default (0.900000)
Smoothing	Medium
Mesh Metric	None
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Assembly Meshing	
Method	None
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Straight Sided Elements	
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled
Topology Checking	Yes
Pinch Tolerance	Default (1.6266 mm)
Generate Pinch on Refresh	No
Statistics	
Nodes	5321
Elements	24688

TABLE 11: Flow domain face naming

Model (A3) > Named Selections > Named Selections

Object Name	free surface	outlet	inlet.	walls
State	Fully Defined			
Scope				
Scoping Method	Geometry Selection			
Geometry	1 Face			5 Faces
Definition				
Send to Solver	Yes			
Protected	Program Controlled			
Visible	Yes			
Program Controlled Inflation	Exclude			
Statistics				
Type	Manual			
Total Selection	1 Face			5 Faces
Surface Area	1.074e+006 mm^2	1.2e+005 mm^2		3.9373e+006 mm^2
Suppressed	0			
Used by Mesh Worksheet	No			

CHAPTER 4

OBSERVED DATA AND CALCULATIONS

1. The iterations are done within ANSYS software and graph of residuals during calculation for some variables is shown.

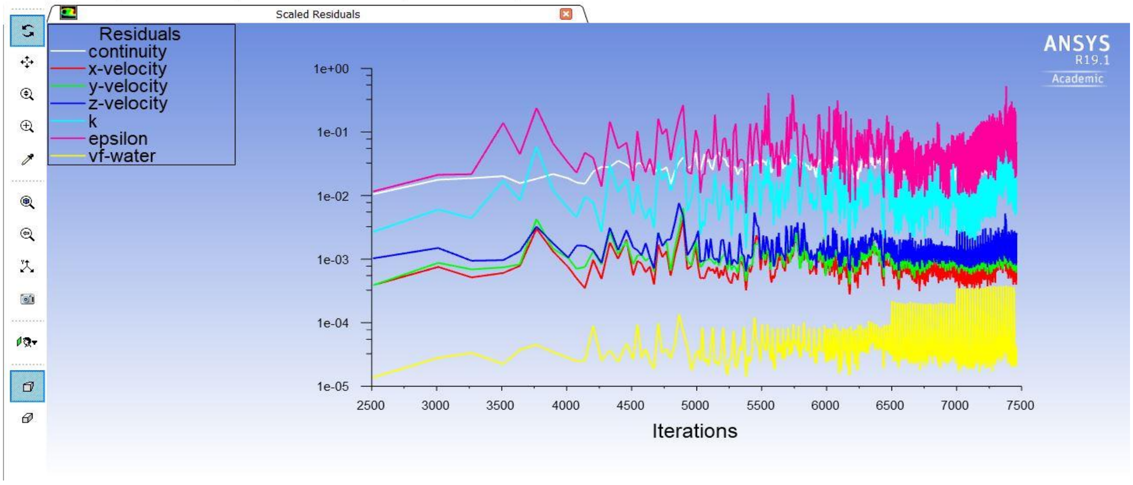

Figure 15: ANSYS calculation and residuals

2. After calculations are done and the solution is exported to CFD post file. The results are opened to view and analyse the various parameters. In this a graph of water volume fraction is shown in which the part where water is flowing is shown and the dark blue part shows there is no water there, hence the other material i.e. Air would be present there.

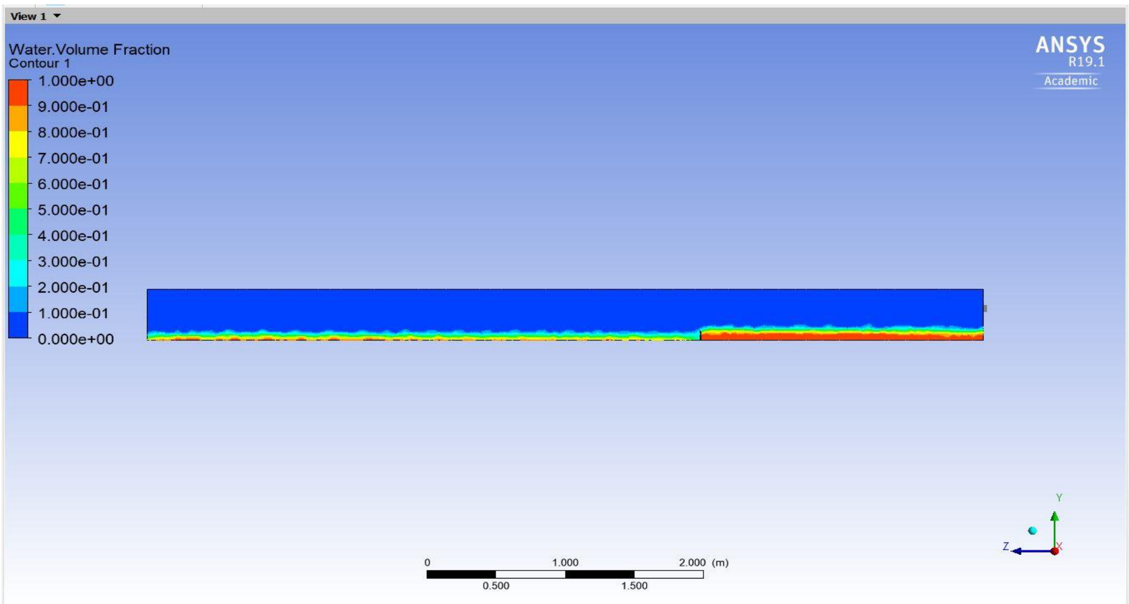

Figure 16: Volume fraction of water phase

3. In this figure, the velocity contours are shown to indicate the velocities at different points.

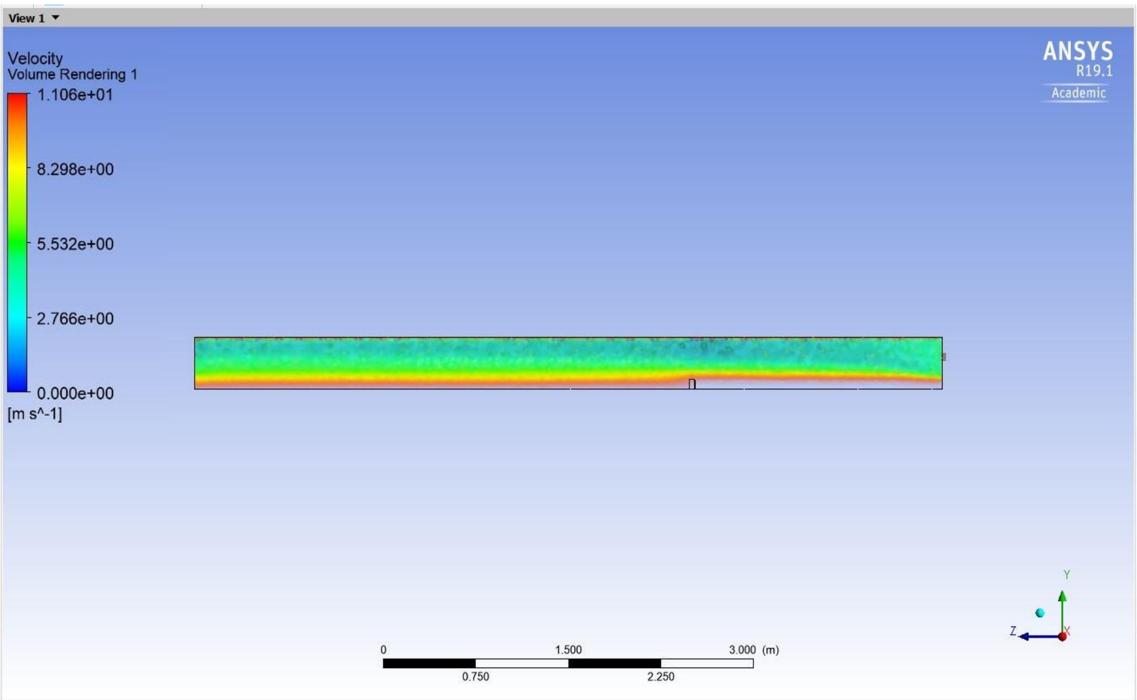

Figure 17: Velocity contours

4. Velocity streamlines are shown in the below given figure. That clearly shows the velocities at different depths of the designed channel.

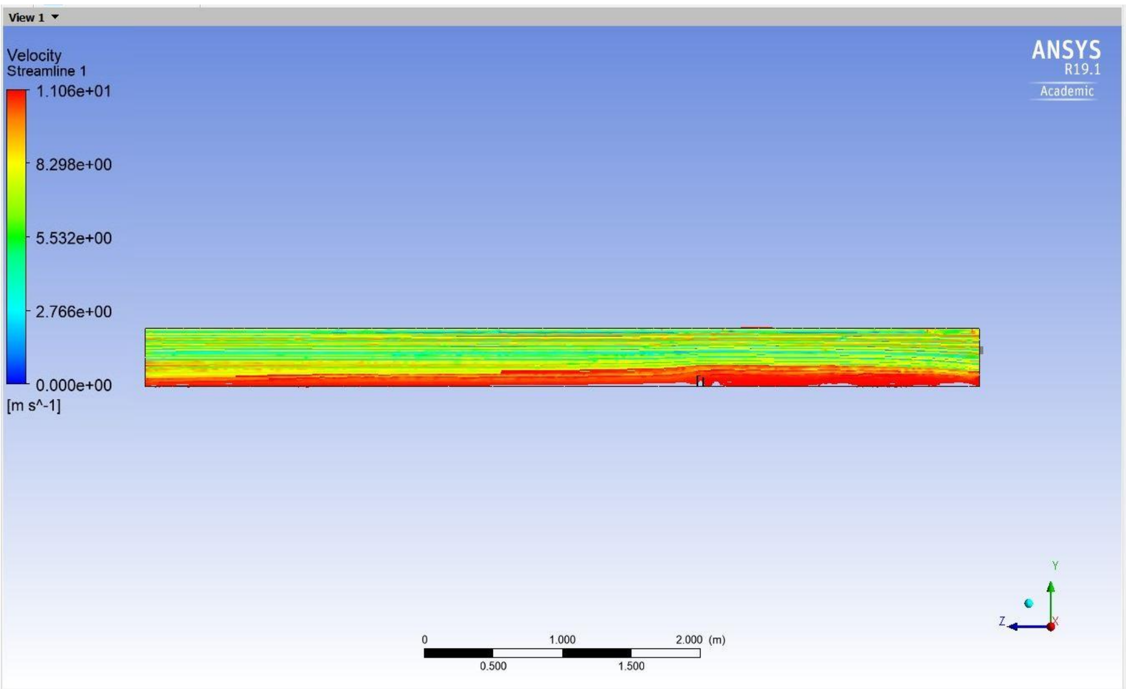

Figure 18: Velocity streamlines

5. Pressure contours are shown in the below given figure. This shows the pressure distribution in the whole flume

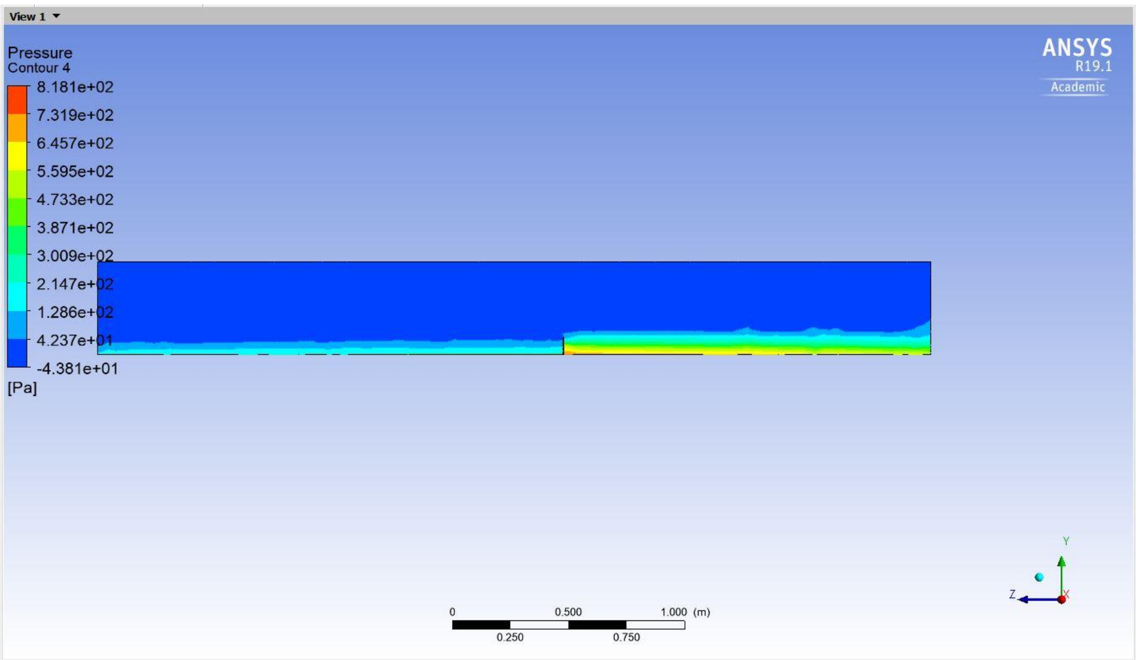

Figure 19: Pressure contours

Discharge given at inlet (Q) – 0.012 m^3/s

Height of weir (P) – 0.075 m

Width of flume (w) – 0.3 m

Depth of water at just upstream of weir - y

Height of water at crest of weir(H) = (y-P)

Effective length L = w * magnification ratio

Magnification ratio $(\frac{L}{w}) = \frac{1}{\sin \alpha}$

Angle between flow direction and weir wall = α

S.no.	α	$\frac{L}{w}$ ratio	w(m)	L(m)
1.	30^0	2	0.3	0.6
2.	45^0	1.414	0.3	0.425
3.	60^0	1.154	0.3	0.346

Table12: Crest length for sidewall angles

Head values for different crest lengths:

Crest length (L)	Upstream Head (H)
0.35	0.066
0.425	0.06
0.6	0.045

Table13: Head values for cycle (N=1)

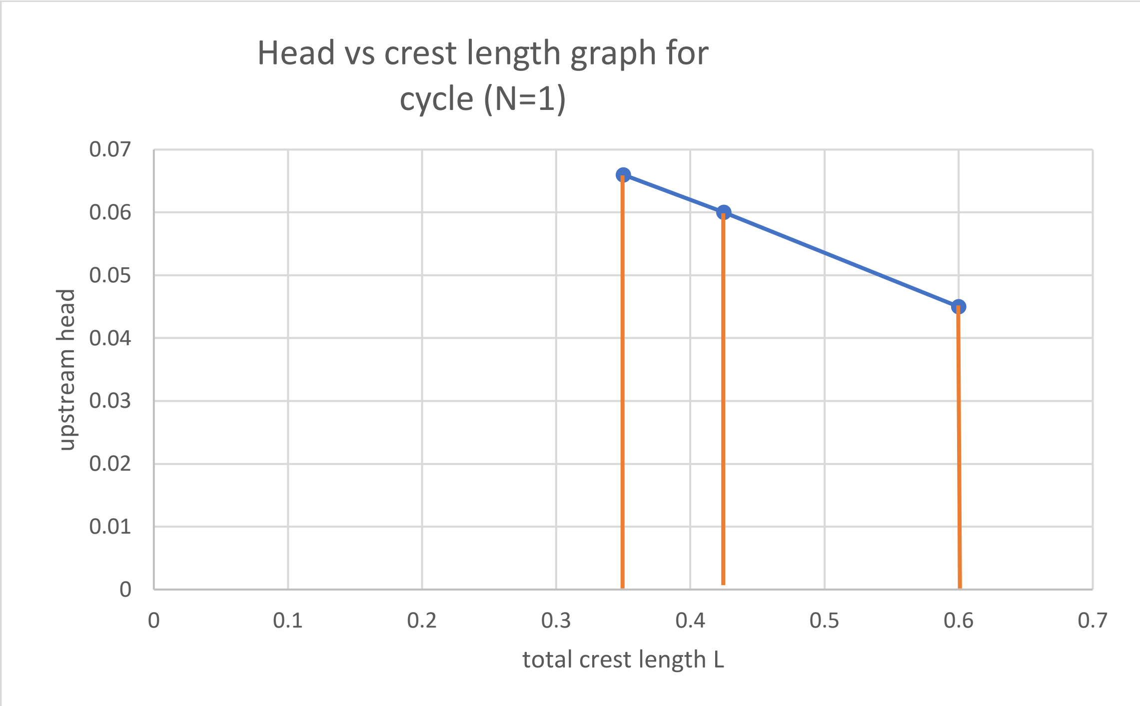

Figure20: Head values for cycle N=1

Crest Length (L)	Upstream Head (H)
0.35	0.065
0.425	0.058
0.6	0.043

Table14: Head values for cycle (N=2)

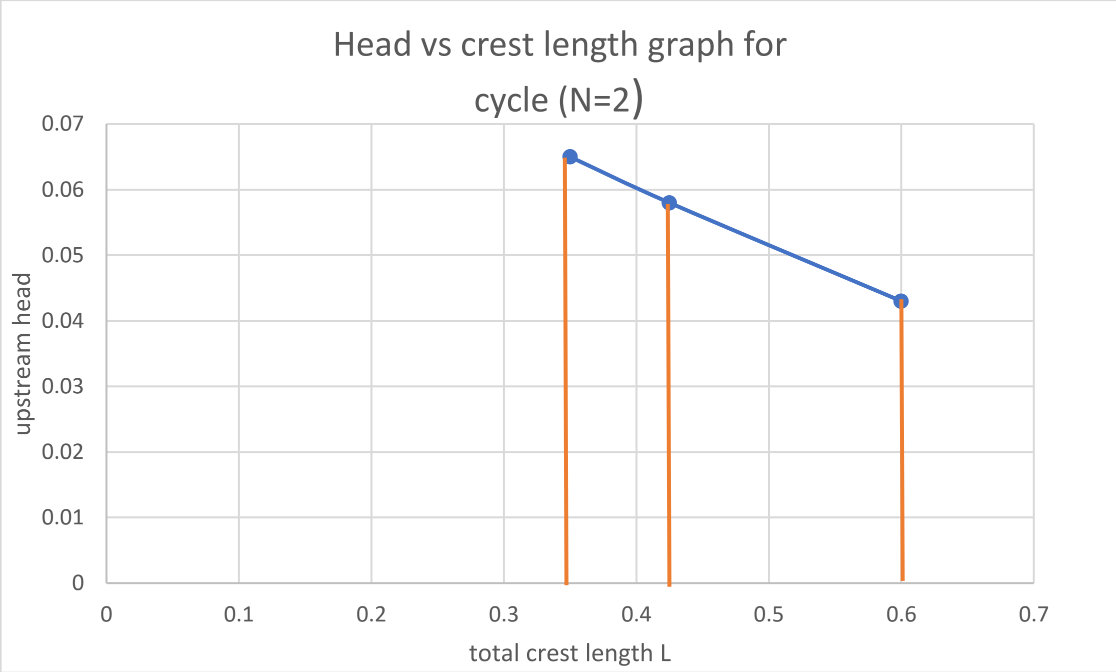

Figure21: Head values for cycle N=1

Crest Length (L)	Upstream Head (H)
0.35	0.063
0.425	0.055
0.6	0.042

Table15: Head values for cycle (N=3)

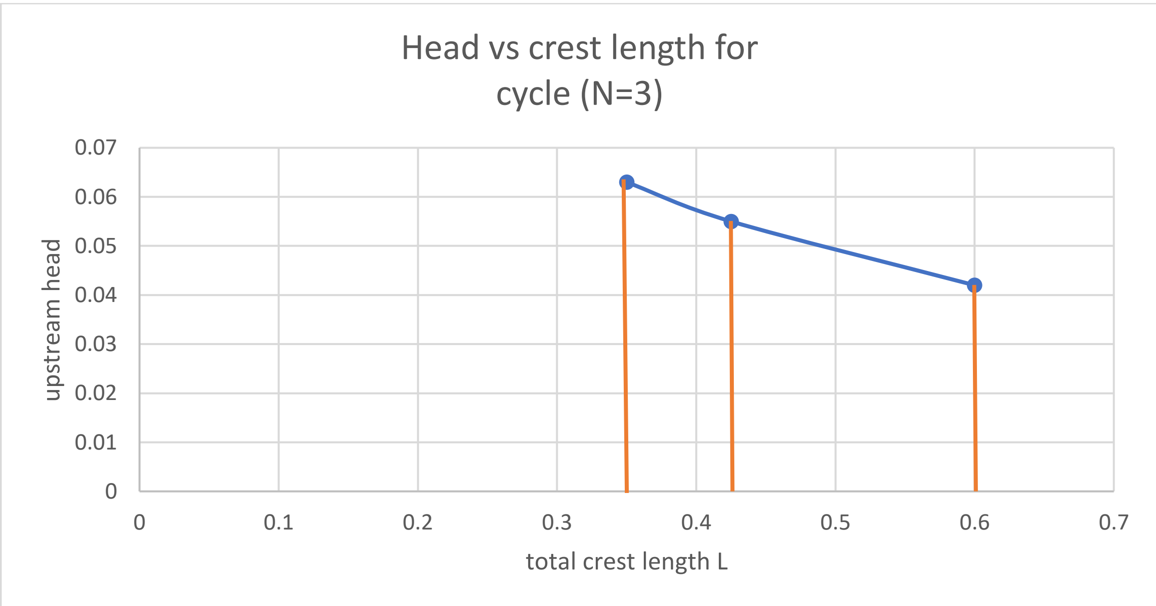

Figure22: Head values for cycle (N=3)

UPSTREAM HEAD VALUES:

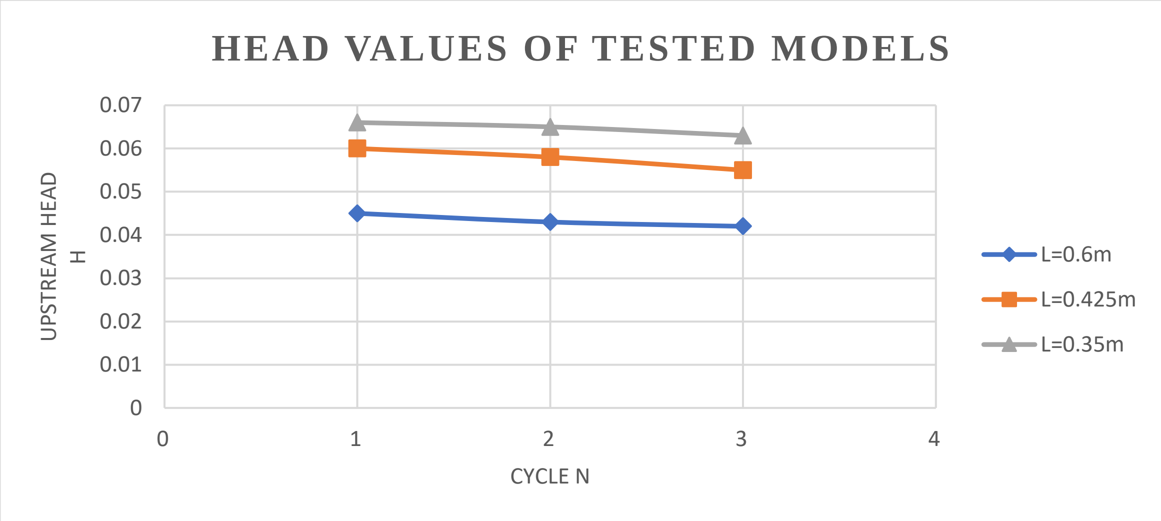

Figure23: Head values of tested models

Length	cycle	H	%decrease
0.6m	1	0.045	------------
0.6m	2	0.043	4.44%
0.6m	3	0.042	2.32%
0.425m	1	0.06	------------
0.425m	2	0.058	3.33
0.425m	3	0.055	5.17
0.35m	1	0.066	------------
0.35m	2	0.065	1.51
0.35m	3	0.063	3.07

Table16: Percentage decrease in head

H/P ratio for the tested models

Table 17: H/P ratio

cycle	L=0.6m	L=0.425m	L=0.35m
1 cycle	0.6	0.8	0.88
2 cycle	0.573	0.773	0.867
3 cycle	0.56	0.733	0.84

Table: H/P ratio

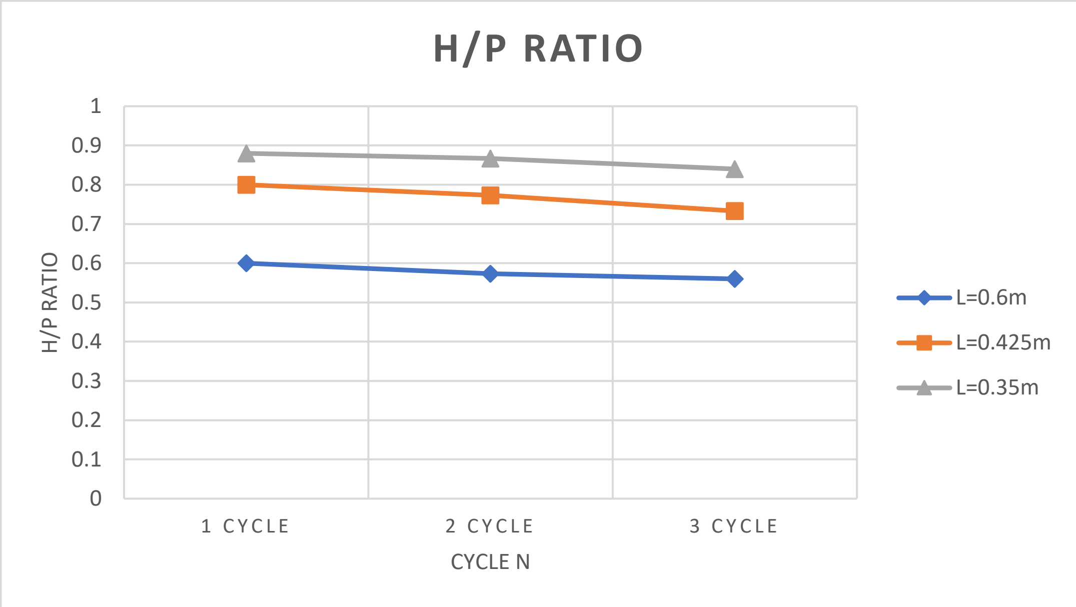

Figure24: H/P ratios

Calculation of C_d for the tested models:

S. No.	Cycle	w(m)	L(m)	Y(m)	H(m)	C_d
1	1	0.3	0.6	0.12	0.045	0.733
2	2	0.3	0.6	0.118	0.043	0.759
3	3	0.3	0.6	0.117	0.042	0.81

Table 18: Calculation table for of the weir ($\alpha=30^0$)

S. No.	Cycle	w(m)	L(m)	Y(m)	H(m)	C_d
4	1	0.3	0.425	0.135	0.06	0.65
5	2	0.3	0.425	0.133	0.058	0.684
6	3	0.3	0.425	0.13	0.055	0.741

Table 19: Calculations for the weir ($\alpha=45^0$)

S. No.	Cycle	w(m)	L(m)	Y(m)	H(m)	C_d
7	1	0.3	0.35	0.141	0.066	0.68
8	2	0.3	0.35	0.14	0.065	0.7
9	3	0.3	0.35	0.138	0.063	0.734

Table 20: Calculations for the weir ($\alpha=60^0$)

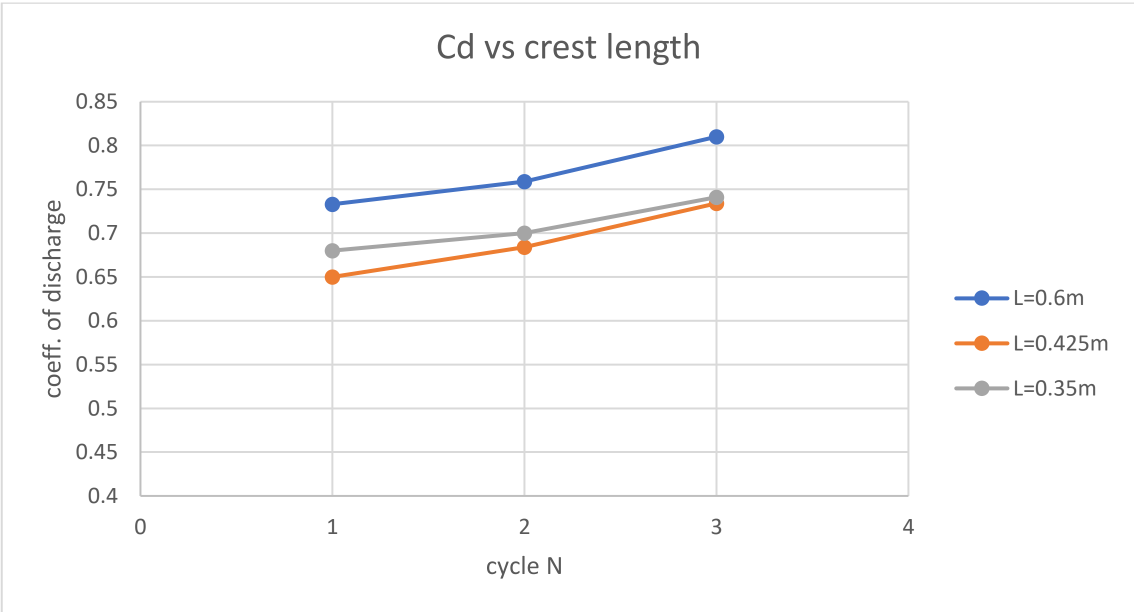

Figure 25: C_d values

- C_d values lies between 0.65 to 0.81.
- C_d increases with increase in cycle.
- C_d increases with increase in crest length.
- C_d does not show linear behaviour on increasing cycle or crest length. This value purely corresponds to various parameters like weir geometry, height, and other flow parameters.

NORMAL DISCHARGE Q_n

To explain the result in flow magnification ratio (Q/Q_n), the discharge Q_n is defined as a discharge outflowing over a linear weir occupying the channel width L, can be expressed by the following relation

$$Q_n = 0.41\sqrt{2g}LH^{1.5}$$

This discharge value indicates the value of discharge that is flowing over a linear weir at channel width L and other parameters are same as in the case of the considered triangular labyrinth weir such as height of water at crest.

Model	Q	Q_n	Q/Q_n
30d1c	0.012	0.010402	1.153665
30d2c	0.012	0.009715	1.235183
30d3c	0.012	0.009378	1.279527
45d1c	0.012	0.011343	1.057948
45d2c	0.012	0.010781	1.113072
45d3c	0.012	0.009955	1.205372
60d1c	0.012	0.010777	1.113445
60d2c	0.012	0.010533	1.139239
60d3c	0.012	0.010051	1.193921

Table 21: Q/Q_n values

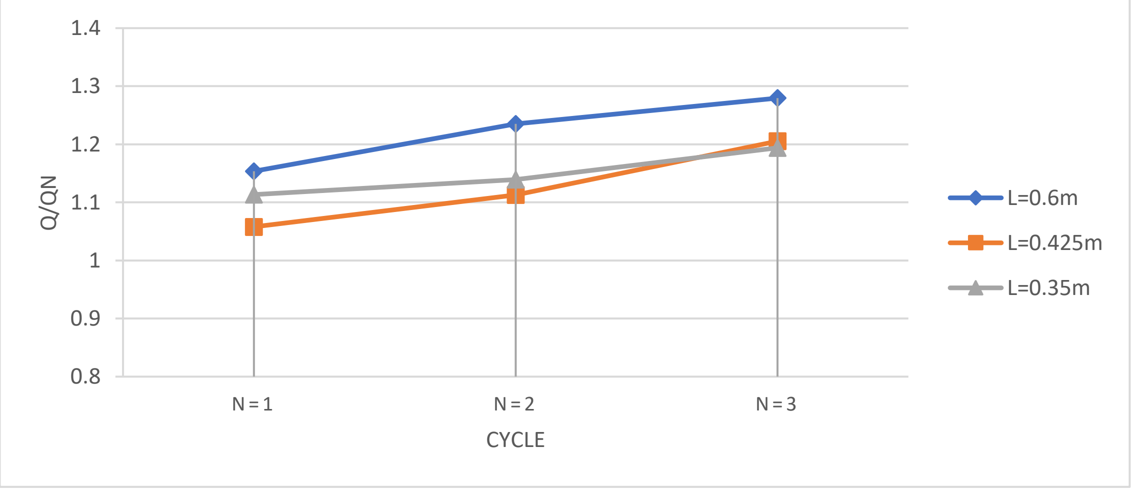

Figure 26: Q/Q_n ratio graph

CHAPTER 5

RESULTS & DISCUSSIONS

Following results have been obtained from observation of flow simulation in Triangular labyrinth weir.

- A range of side angle α is used, keeping other parameters constant to observe the variation in flow parameters, such as height of water at crest level, coefficient of discharge, etc.
- Upstream head H decreases with increase in crest length in the case of a particular cycle.
- H/P ratio lies between 0.56 and 0.88.
- H/P ratio decreases slightly with increase in cycle.
- Decrease in depth of water at the downstream of weir shows that the weir can be used as a good flow control structure.
- Coefficient of discharge for triangular labyrinth weir may be shown as a function of effective weir length, discharge, and head upstream using discharge equation.
- C_d values of tested models lies between 0.65 and 0.81.
- C_d value increase with decrease in side angle α.
- C_d value slightly increase with increase in cycle.
- Using the simulated model and its outcome parameters, relation between coefficient of discharge and crest length is established.
- Result confirms that the coefficient of discharge of triangular labyrinth weir increases with increase in effective length of the weir.

CHAPTER 6

CONCLUSION

- Labyrinth geometry resulted in a increased crest length which increases the discharge capacity of weir.
- The discharge coefficient Cd totally dependent on crest length and water depth at crest because discharge and other parameters are kept constant.
- Water Phase contour from ANSYS post processing show the considerable reduction of water depth at downstream, which shows that this weir controls the flow very efficiently.
- All dimensionless parameters like H/P, w/P ratio are in accordance with previous studies.
- Effective crest length is a function of side angle α, which can be increased or decreased for the specific site location to meet the required need.
- Trend from present study is similar to that from previous studies, hence it can be concluded that the present work is reliable.
- Further research can be performed changing the plan geometry of labyrinth weir to get more efficient weir than triangular labyrinth weir.
- The utility of increment of cycle is observed in the case of constructing a labyrinth weir at an existing spillway. Increment of cycle reduces the pitch of the weir and reduces the area of construction.
- L/w ratio will decrease on increasing the sidewall angle till the 90^0, beyond that the L/w ratio increases but the weir is inverted. i.e. the $\alpha=120^0$ weir will be same as $\alpha=30^0$ but in inverted position.

REFERENCES

[1] Chandra Prakash Kumar and Santosh Kumar Pathak (1987). Triangular Side weirs. Journal of Irrigation and Drainage Engineering, Vol. 113, No. 1, February, 1987.

[2] J. Paul Tullis, Nosratollah Amanian and David Waldron (1995). Design of labyrinth spillways. Journal of Hydraulic Engineering, Vol. 121. No.3. March. 1995.

[3] B. P. Tullis, J. C. Young and M. A. Chandler (2007). Head-Discharge Relationships for Submerged Labyrinth Weirs. Journal of Hydraulic Engineering, Vol. 133, No. 3, March 1, 2007.

[4] A.D. Ghare, V. A. Mhaisalkar and P.D. Porey (2008). An Approach to Optimal Design of Trapezoidal Labyrinth Weirs. World Applied Sciences Journal 3 (6): 934-938, 2008.

[5] M. Emin Emiroglu, Nihat Kaya and Hayrullah Agaccioglu (2010). Discharge Capacity of Labyrinth Side Weir Located on a Straight Channel. Journal of Irrigation and Drainage Engineering, Vol. 136, No. 1, January 1, 2010.

[6] Francesco Giuseppe Carollo, Vito Ferro, and Vincenzo Pampalone (2012). Experimental Investigation of the Outflow Process over a Triangular Labyrinth-Weir. Journal of Irrigation and Drainage Engineering, Vol. 138, No. 1, January 1, 2012.

[7] B. M. Crookston, and B. P. Tullis (2012). Labyrinth Weirs: Nappe Interference

and Local Submergence. Journal of Irrigation and Drainage Engineering, Vol. 138, No. 8, August 1, 2012.

[8] S. Mahmood Borghei, Mohammad Ali Nekooie, Hadi Sadeghian, Mohammad Reza Jalili Ghazizadeh (2013). Triangular labyrinth side weirs with one and two cycles. Water Management volume 166, January 2013, Issue WM1.

[9] M. R. Dabling, B. P. Tullis, B. M. Crookston (2013). Staged Labyrinth Weir Hydraulics. Journal of Irrigation and Drainage Engineering, Vol. 139, No. 11, November 1, 2013.

[10] Omer Bilhan M. Emin Emiroglu (2013). Experimental Studies on Determination of Discharge Capacity of Circular Labyrinth Weirs Located on A Straight Channel.

International Journal of Electronics, Mechanical and Mechatronics Engineering Vol.6 Num.3 - 2016 (1227-1239).

[11] Omer Bilhan, M. Emin Emiroglu, Carol J. Miller (2016). Experimental Investigation of Discharge Capacity of Labyrinth Weirs with and without Nappe Breakers. World Journal of Mechanics, 6, 207-221.

[12] Nazila Kardan, Yousef Hassanzadeh, Babak Shakooei Bonab (2017). Shape Optimization of Trapezoidal Labyrinth Weirs Using Genetic Algorithm. Arab J Sci Engg. (2017) 42:1219–1229

[13] Francesco Giuseppe Carollo, Vito Ferro, and Vincenzo Pampalone (2017). Testing the Outflow Process over a Triangular Labyrinth Weir. J. Irrigation and Drainage Engg., 2017, 143(8): 06017007.

[14] M. R. Dabling, and B. P. Tullis (2018). Labyrinth Weirs with Angled Approach Flow. J. Hydraulic Engineering, 2018, 144(12): 06018014.