ENERGY DISSIPATION ON LABYRINTH SPILLWAY

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I **AKSHAY KUMAR**, Roll No. 2K16/HFE/03, Of M.Tech (Hydraulics and Water Resources Engineering) hereby declare that the Project Dissertation Titled **"ENERGY DISSIPATION ON LABYRINTH SPILLWAY"** which is submitted by me to the Department Of Civil Engineering, Delhi Technological University 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 prior citation.

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This is to certify that the thesis entitled, "**ENERGY DISSIPATION ON LABYRINTH SPILLWAY**" submitted by **AKSHAY KUMAR** in partial fulfillment of the requirement for the award of **Master of Technology** degree in **Civil Engineering** with specialization in **Water Resources Engineering** at Delhi Technological University (formerly Delhi College of Engineering) is an authentic work carried out by him under our supervision and guidance. To the best of our knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute.

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ABSTRACT

Dams play a very important part in development of a country. A dam is responsible for supply of Drinking water, protection from the floods, power generation from hydroelectric plants, water supply for irrigation purpose and navigation purposes. Sometimes due to unavoidable circumstances the inflow in the dam exceeds safe storage of the dam. For the proper discharge of this storage spillways are needed. Spillways play a very important role in dissipating upstream energy of the dam.

This experimental study was conducted to improve labyrinth spillway design and analyze energy dissipation using physical model based data sets from this and previous studies and by compiling published design methodologies and labyrinth spillway information.

A standard geometric design and analysis of labyrinth spillway is presented in this study. Labyrinth spillways offer great amount of energy dissipation. Thus, it is the main goal of this study to analyze energy dissipation on labyrinth spillways having different sidewall angles.

Two labyrinth spillways having sidewall angles α of 8^0 and 10^0 were designed in this study and compared for energy dissipation. Comparisons were made with linear weirs ($\alpha = 90^0$) to show their energy dissipation efficiency. The effect of sidewall angle of labyrinth spillway on effective crest length and discharge is also stated in this study.

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Notations

D	Apex width
E_O	Total upstream energy
E_1	Residual energy
Fr_1	Downstream Froude number
G	Acceleration due to gravity
H	Water head over weir
H_T	Total head over weir
L	Crest length of a single cycle in labyrinth spillway
N	Number of labyrinth sllway cycles
P	Spillway height
Q	Total discharge passing over weir
V_0	Upstream velocity
V_1	Downstream velocity
W	Width of a single cycle in a spillway
W	Channel width
Y_0	Upstream flow depth
Y_1	Downstream flow depth
A	Sidewall angle and energy correction factor
ΔE	Total dissipated energy
A	Inner apex width
R	Crest curvature radius
C_d	Coefficient of discharge
$\Delta E/E_0$	Energy dissipation rate

CHAPTER 1

INTRODUCTION

1.1 Motivation for the Study

Water management and conveyance are very important for the development of a country. The need for the hydraulic structures increases as per the requirement for the development. The need of the hydraulic structures also increases due to the aging of the infrastructure. There are approximately 3200 dams in India and these dams getting older day by day. This poses threat to the life and environment.

Poor engineering, designing faults, poor foundation conditions, improper designing of foundations, underestimation of load, cavitation, quality of material used, and deterioration of material, leakage and insufficient spillway capacity are common problems linked with the dams.

In last few years, the change in climate has caused some major behavioral changes of water. For example the excessive rainfall has increased due to major climatic changes. The flow of water entering the reservoir keep on changing as it depends on the rainfall intensity. It is a known fact that the water level of the reservoir is dependent on the intensity of the rainfall. As the rainfall intensity increases the water level of the reservoir undergo significant changes. This condition can lead to failure of the dam.

The dams are designed for certain water capacity by studying the historical data. However, the rainfall intensity has no limits as it depends on the climatic changes. The dams need upgradation. Rehabilitation work is necessary for a dam to ensure its longer life.

In addition to these, underestimation of the inflow design flood and change in peak discharge are other more common cases.

Rehabilitation work is necessary in order to maintain dam efficiency and prevent it from failure. Rehabilitation is done to assure safety of the existing dams. Rehabilitation work is done mainly to increase the efficiency of the storage capacity of the existing dams, avoid the chances of seepage, improve conveyance and to withstand the natural calamities like landslide, earthquake etc. Rehabilitation of gates, rehabilitation of penstocks, relining of water passages, repairing of water passages, using roller compacted concrete are some of the methods of rehabilitation.

A dam need to be safe both structurally and hydrologically. Inadequate dam spillway capacity may be the reason making dam unsafe hydrologically. To prevent this, two labyrinth spillways having different sidewall angles will be analyzed and compared in the present study. The labyrinth spillways having sidewall angle of 8^0 and 10^0 are used in this study. Their design procedure and advantages and disadvantages will be discussed in the present study.

Generally, the excess water is drawn from the top of the reservoir created by the dam and conveyed back to the river through an artificially created waterway. In some cases, the water excess maybe diverted to an adjacent river valley. The spillway should be geometrically and hydraulically efficient and should be placed at a location such that the outlet discharge do not erode or Detroit the downstream toe of the dam. The spillway should be constructed in such a way that the surface of the spillway can withstand the scouring or erosion due to the high velocities generated due to the passage of the flow. The function of the spillway is to discharge back the flow from the higher elevation of the dam to the lower elevation of the river on the downstream. Downstream of the spillway is usually provided with an energy dissipation device to dissipate the energy of the discharging water. The water flowing down from the spillways possess large amount kinetic energy. This is generated due to the head loss. The water spilled from the spillway loses its potential head from reservoir level to the downstream level of the river. This energy when not utilized causes major scour and erosion problem on the downstream side of the spillways. Scour and erosion challenges the stability of the dam or the neighboring valley slopes. Energy Dissipators are used to suppress or absorb this high kinetic energy of the water at the downstream toe of the spillways.

Two sets of spillways are provided in some projects. Two sets are called main and Auxillary. The spillway which is responsible for passing the design floods is called main spillway. It is also known as service spillway. The auxillary spillway come into action when the discharge of the river exceeds the discharge of the main spillway. The crest of the auxillary spillway is higher and it is designed for the small discharge capacities. An emergency spillway or fuse plug types of spillway is also provided sometimes. These spillways are usually provided where there are chances of very high flood. These spillways come into use only when there is very high flood which is higher than the design discharge. They also come into use when the normal spillway malfunctions. To avoid the chances of overtopping dam failure the excess of flood is passed through the emergency or plug type spillway.

Generally, gates are provided in the spillways, which helps in providing better control over the discharges passing through. The access to the gates by the personnel is not always possible due to the rainy season or night. In that case ungated spillways are provided in the remote areas. The spillway capacity is generally calculated on the basis of flood routing study of the area.

The capacity of a spillway is dependent on these major factors

- Flood discharge
- Capacity of water stored by the reservoir
- Crest height
- Gated or Ungated

Apart from spillways, which are responsible for passage of the excess flood flow, outlets are also provided for various important purposes. The outlet is provided in the body of the dam to meet irrigation demands, power generation demands, water supply etc. Usually the water is stored in the reservoir and outlets are used for releasing it. The spillways are not required to function for the the flow under design flood. Spillways come into action only when the water flow in the dam increases the design flood or when the discharge is higher than the design capacity of the dam. In the case of large storage reservoirs or large outlets provided the spillway are not used frequently.

Types of Spillways:

I. Straight Drop Spillways
II. Overflow Spillways
III. Chute Spillways
IV. Side Channel Spillways
V. Shaft Spillways
VI. Siphon Spillways
VII. Labyrinth spillways
VIII. Baffled Chute Spillways
IX. Cascade Spillways

I. Straight drop spillways

In straight drop type of spillway the water falls freely from the crest, as in the case of arch dam figure 1.1. It can also be provided with a inclined or vertical downstream face for a decked over flow dam. The crest is in the form of extended overhanging lip to direct small discharges away from the face of over-fall section figure 1.2. Sufficient ventilation is provided in free falling water to prevent fluctuating, pulsating jet. In straight drop or free over-fall spillway the water flows over a relatively thin crest and falls freely on downstream side. These kinds of spillways are usually suitable for the thin dams having almost vertical downstream faces. These kinds of spillways maybe economical for low heads as compared with overflow spillway because of saving in concrete. These spillways are not suitable for the high heads because of the structural instability problems. The water falling freely with high energy may not scour bottom when artificial protection is provided at the loose but scour may occur on the streambeds which are unprotected which will form deep plunge pool. Height of the drop, depth of the tail water and range of discharges affect the depth and volume of the scour hole. An artificial pool can be created using auxillary dam where erosion is intolerable. The straight drop spillway is a weir structure. The flow passes through the opening of a weir, drops to level of stilling basin and then it passes into downstream channel. It is a gully control structure. The straight drop spillway consist of

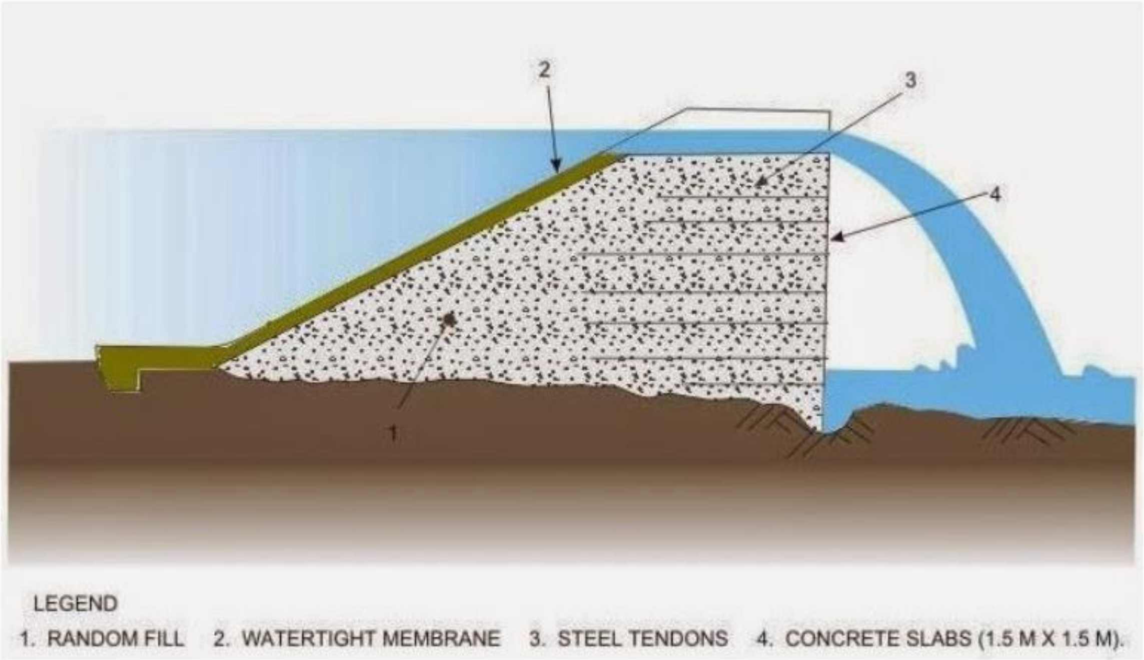

Figure1.1 straight drop spillway

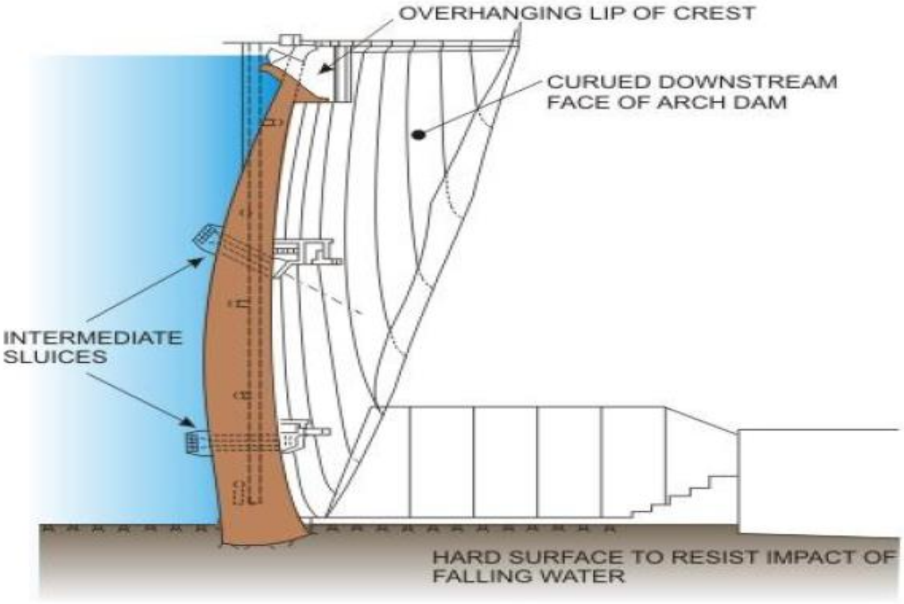

Figure 1.2 short lip provided for overfall spilling

II. Over flow spillways

These types of spillways have ogee or s-shape crest. Hence they are also called ogee shaped or s-shaped spillways as shown in figure 1.3 . The upper curve of the ogee is made to conform closely to the profile of the lower nappe of a ventilated sheet of water falling from a sharp crested weir. The access of air is prevented to underside of the sheet of flowing water due to the reason that the flow over the crest of an over flow spillway is made to adhere to the face of the profile. The shape of the lower nappe of free flowing weir derives the shape of the overflow spillway to be designed. Any discharge greater than the designed flood passing through the overflow spillway would try to shoot forward and get detached from the surface of the spillway due to the presence of negative pressure between the spillway surface and sheet of water. The spillway performs well for the discharge under design flood. Spillway surface profile is in a tangent along a slope to support the sheet of the water flow on the face of the overflow. They are widely used on gravity dams, buttress dams and arch dams. They are of two types gated overflow spillway and ungated overflow spillway.

The profile of an ogee spillway is designed according to the given discharge. When the flow over the spillway is similar to the design discharge, the flow adheres to the surface profile of the spillway with minimum interference from the boundary surface and no access of air to the underside of the water sheet. Under such conditions discharge efficiency is maximum and the pressure along the surface of the spillway is atmospheric. When the water discharge is greater than the design floods then the water sheet tends to separate itself from the spillway surface and produces sub-atmospheric pressure along the spillway surface. Negative pressure increases the effective head as well as the discharges but also causes cavitation and other problems. Under the condition where the flowing discharge is less than the design discharge then positive hydrostatic pressure will occur on the surface of the spillway. A corbel is added to the upstream face of the spillway figure 1.4. The function of the corbel is to shift the nappe backwards. This helps in saving the concrete.

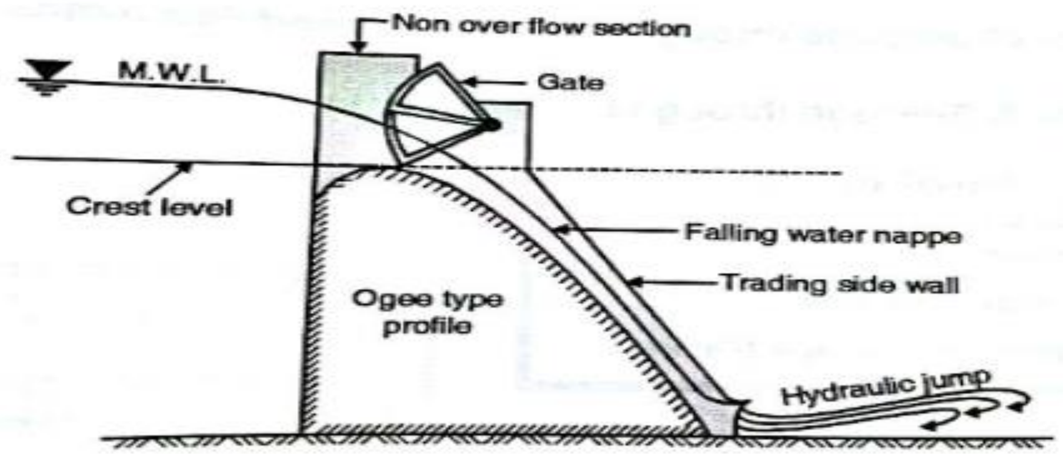

Figure 1.3 ogee type spillway

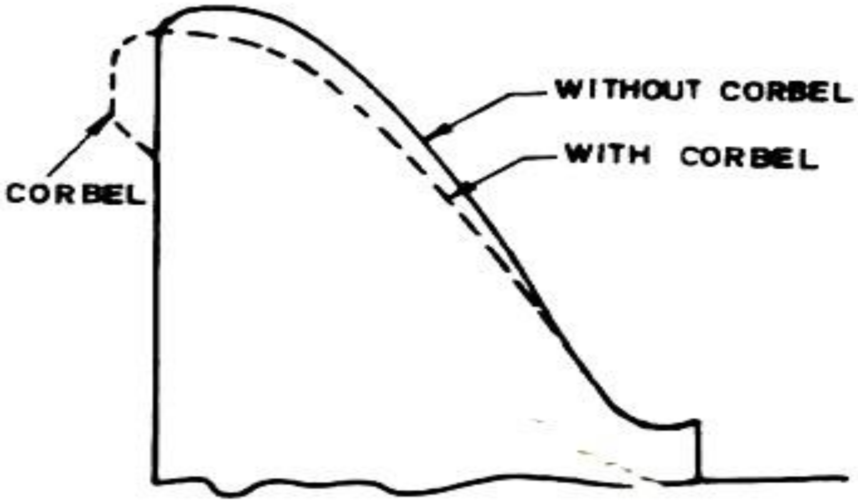

Figure 1.4 ogee spillway with corbel

III. Chute spillway

In chute type of spillway the discharge is conveyed in an open channel starting right from the reservoir to the river downstream fig1.5. The location of the channel is suited either along the abutment of the dam or through saddle. The channel bed must always be kept in excavation. The side slopes of the channel bed should be stable and should be designed factor of safety in mind. The channel should be kept straight as far as possible. Bends should be avoided. If the bend is unavoidable it should be gentle. The overflow crest can work as spillway control structure. Gated orifice or other suitable device can also work as spillway control device. The simplest type of chute spillway has straight center line and constant width. Very often, to suit the topography of the site the axis of either entrance channel or discharge channel is curved. The flow condition changes from subcritical at upstream of controlling crest to critical at the crest and in discharge channel it is supercritical.

The chute spillways are ideally suited with the earth filled dams because:

- They have simple design and the construction is also simple,
- They are good adaptability to all foundations.
- It is overall economical.

Chute spillway can be divided into various parts. The chute spillway consist of an entrance channel, a control structure, a discharging channel, a terminal structure and an outlet channel. Very often, discharge channel axis or entrance channel axis has to be kept curved to fit the topography needs.

Figure 1.5 Alqueva dam chute spillway, Portugal

IV. Side channel spillways

In side channel type of spillways the location of the control weir is set approximately parallel to the discharging channel upper portion. The water discharge from the crest does not directly go to discharging channel. Instead discharge over the crest falls into narrow trough opposite to the weirs, diverts to an approximately right angle and then discharges into the main discharge channel. It is only concerned with the hydraulic action in the upstream reach of the discharge channel. Flow can be directed into an open channel from the side channel. The flow from the side channel can also be directed into a closed conduit or inclined tunnel. Discharge characteristics of an ordinary spillway and side channel spillway are very much similar to each other and are dependent on the selected profile of the weir crest. Side channel spillway is a type of hydraulic structure which has many applications. The most common difference between the standard spillway and a side channel spillway is that in side channel spillway the crest is usually perpendicular to the wall of the dam fig1.6. The water that flows over the crest of the spillway is collected in a channel running along its length. The channel's main function is to convey the water away.

Figure 1.6 Hoover dam, USA

V. Shaft spillway

Shaft spillway is a type of spillway in which water enters over a lip which is horizontally positioned, drops through a sloping or vertical shaft and then is conveyed through a horizontal or nearly horizontal conduit or tunnel to the downstream river channel (fig 1.7). The shaft spillway consists of three main parts. The three main elements are an overflow control weir, a vertical channel and a closed discharge channel. When the shape of the inlet resembles like funnel, the structure is called a morning glory spillway (fig 1.8). The range of the head decides the discharge characteristics of the drop inlet spillway. With the increase in head, the flow pattern changes from initial weir flow over crest to tube flow and finally to the pipe flow in the tunnel. At relatively low heads these types of spillways attain maximum discharging capacity. However, if there is a little increase in the capacity beyond the designed head, flood larger than the selected inflow design flood occurs. At the dam sites where abutment rises steeply, located in the narrow gorges, drop inlet spillway can be used advantageously. At projects where a diversion tunnel or conduit is available, these types of spillways can be used advantageously. The locations where there is no sufficient space for an overflow spillway then shaft spillway may be considered.

Shaft spillways require site conditions where:

- The seismic action should be low. The site should be in the less earthquake prone area.
- The geologic formation should be thick.
- Floating debris should be small in quantity.

Disadvantages of shaft spillway are:

- At condition where the shaft is fully submerged, further increase in head will not result in appreciable increase in discharge.
- Because of the stability problems, these spillways are not suitable for large capacity and deep reservoirs.
- To handle cavitation damage at transition between shaft and tunnel some special designs are mandatory.
- Repair and maintenance are difficult.

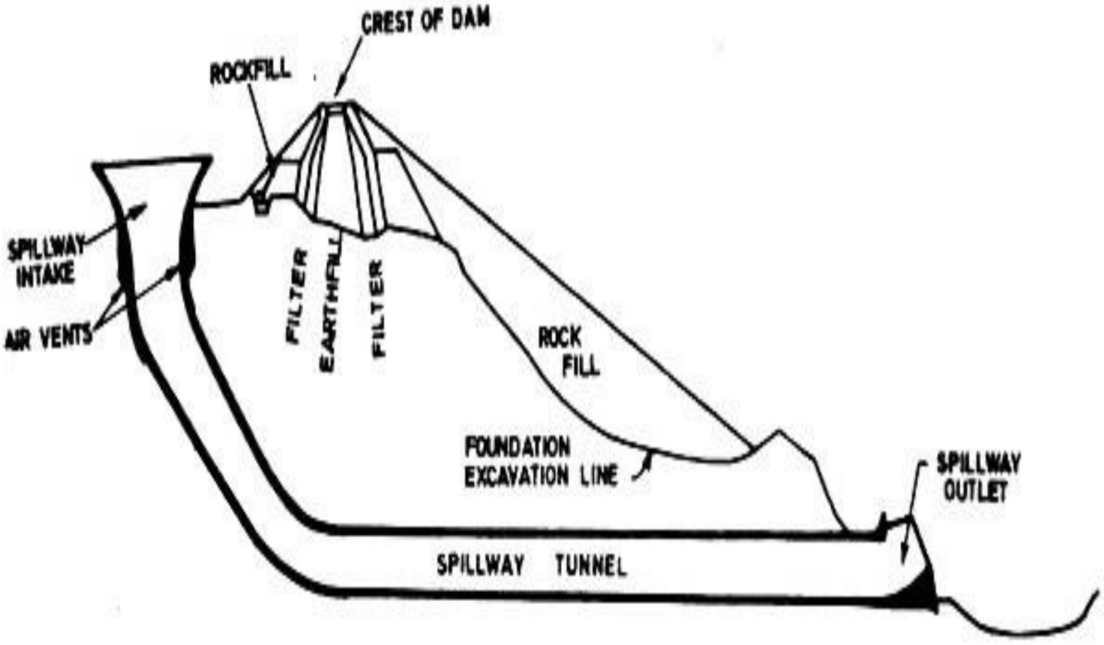

Fig 1.7. Section through a shaft spillway

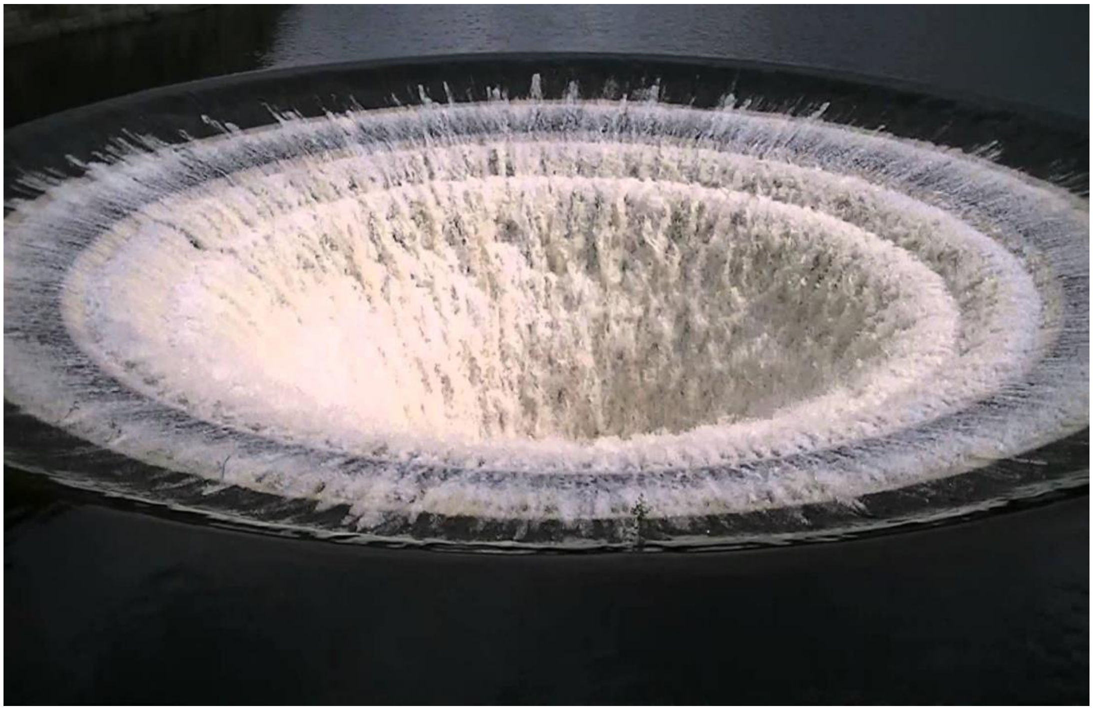

Fig 1.8. Morning Glory Spillway

VI. Siphon spillway

A siphon spillway is a type of spillway in which there exist a system of closed conduit which is in inverted U shape, positioned such that the inside bend of the upper passageway is at normal reservoir storage level (fig 1.9). This type of siphon is also called saddle siphon. As the reservoir level rises above normal, the initial discharges of the spillway become similar to the flow over a weir. After the air in the bend over the crest exhausts then siphonic action comes in action. Due to the gravity pull of the water in the lower leg of the siphon suction effect takes place, which maintain the continuous flow.

Siphon spillways have five major parts. The five main parts are an inlet, a lower leg, an upper leg, control section and an outlet. Siphonic action of the spillway is controlled using a siphon breaker air vent. The function of siphon breaker is to cease operation when the reservoir water surface is drown to normal level. If it is not provided then siphon will continue to operate until air enters the inlet. To prevent the entry of drifting materials and to prevent the formation of drawdowns or vortices which might break the siphonic action the inlet is normally placed well below the full reservoir level.

Siphon spillway may be used as a substitute for overall spillway. It can be placed in the body of the concrete dam when no space is available for the overflow spillway. A siphon spillway can cause damages to the joints of the dam. As the flow in the siphon spillway is primed flow, it causes excessive vibrations in the dam body which further results in weakening of the joints. In siphon spillways are prone to cavitation problem due to the negative pressures. Maintenance and repair work is difficult.

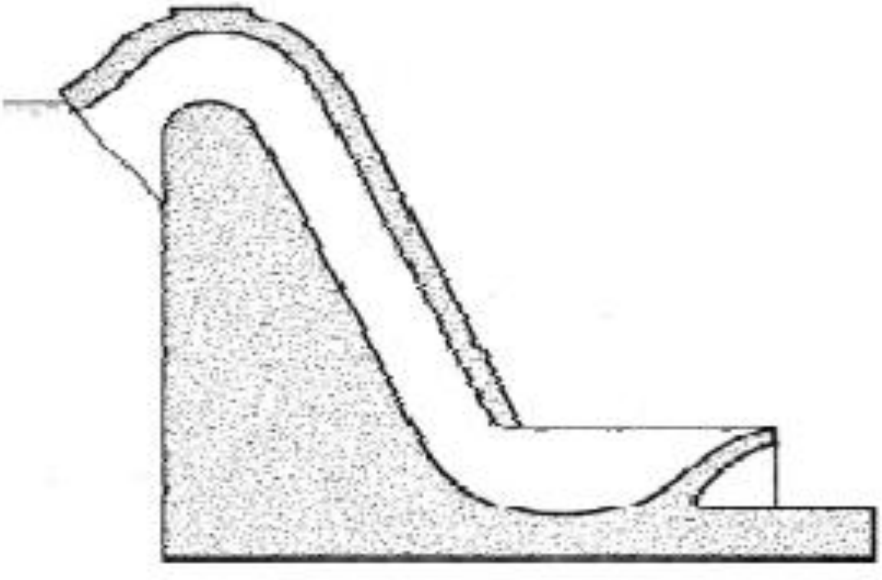

Fig 1.9 Siphon spillway cross section

VII. Labyrinth spillway

The flow capacity of the spillway is majorly controlled by the spillway length and crest shape. A labyrinth spillway is a linear spillway folded in plan-view. The spillways due to their shape have several advantages over linear spillway structures. The main function of the labyrinth spillway is to provide increases crest length for a given width of channel. The increased crest length increases the flow capacity for a given upstream head. In addition to labyrinth spillways, labyrinth weirs also provide effective drop. Labyrinth spillways helps in dissipating energy and also provide flow aeration.

To regulate upstream water elevations labyrinth spillways are often favorable design option. Apart from their hydraulic characteristic, labyrinth spillways encourage a positive landscape addition. Dams have multiple goals to achieve such as water detention, water quality improvement, etc. the labyrinth spillway offers a longer extension because it is formed by polygonal shape of structures constructed side by side as cycles. As a result they need less space. A labyrinth spillway consists of crest formed by series of staggered walls such that a given discharge can pass under a small head large spillway crest length. Flow conditions around labyrinth spillways are very complicated. An example of trapezoidal labyrinth spillway is given in the figure 1.10.

Fig 1.10 The Hartwick Dam

Have several advantages over linear spillway structures. The main function of the labyrinth spillway is to provide increases crest length for a given width of channel. The increased crest length increases the flow capacity for a given upstream head. In addition to labyrinth spillways, labyrinth weirs also provide effective drop. Labyrinth spillways helps in dissipating energy and also provide flow aeration.

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VIII. Baffled chute spillway

A baffled chute spillway is a chute spillway whose surface is covered by a number of densely placed baffle blocks. The baffle blocks works as energy dissipation devices. When the water flows through chute it normally has high kinetic energy. To dissipate this energy and prevent the water damage due to its high velocity baffle blocks are placed all over the channel. Baffle blocks dissipate the energy of the flowing water effectively. The main aim of the energy dissipation devices is to reduce the kinetic energy of the water. This helps in controlling the corrosive nature of the water. An advantage of baffle chute spillway is there is no need of separate stilling basin. A special design in needed to maintain small velocities at the entrance of the chute.

Fig 1.11 Baffle chute spillway

IX. Cascade spillway

Due to recent technology advances we have more complex and big designs of dams, reservoirs and channels. With the increase in size of dams, they need safe disposal of floods and also safe energy dissipation is required. Stepped spillway is commonly used design for above given purposes. Stepped spillway is a modification of a standard spillway (figure 1.12). The downstream portion of the ogee spillway is modified to steps for better energy dissipation. Steps are fitted at some distance in the downstream of the spillway. Steps are placed in such a way that they start from the top and ends at the toe of the spillway. Generally, a stepped spillway is geometry is used where the slope is small. Normally energy dissipation below hydraulic structures is achieved by single fall type stilling basins, roller or trajectory buckets. These cannot be used for high dams. Stepped spillway can be used for any type of dam irrespective of material used. Only disadvantage of this type of spillway is that low pressure may occur and lead to cavitation damage.

Fig 1.11 stepped or cascade spillway

Energy Dissipation

Energy dissipation plays a very important role in design of the hydraulic structures. Energy dissipation occurs when the flow from the upstream passes over the weir/spillway and this flow impacts on downstream forming hydraulic jump. The kinetic energy of the flow is damped when it flows over the spillway and impacts on the downstream side. In labyrinth spillways, the flow passes over the longer crest length than the standard spillway. Labyrinth spillways, due to their increased crest length, have effective energy dissipation rate. Labyrinth spillways are recommended for increasing the capacity of the spillway. The crest length and height of the spillway plays an important role in energy dissipation. Increased crest length offers more capacity than a linear weir.

1.2 Objective of the Study

To ensure the safety of the dam hydrologically and seek protection from excessive flow in the dam, the discharge capacity of the dams are needed to be increased. For increasing discharge capacity of a dam rehabilitation works have been done. The main aim of this study is to find an alternative to efficiently discharge the excessive flow. In this respect, labyrinth spillways of were selected as the method to achieve it.

By using labyrinth spillway the crest length can be increased (fig. 1.2). Therefore, they increase the flow capacity for the given water head. The length of the crest can be increased approximately five times by using a labyrinth spillway instead of standard one. The discharge capacity of the standard spillway is around half as compared to labyrinth spillway. The labyrinth spillways provide better results than the standard spillway.

The Main Objectives of this Dissertation are:

- Provide Design Method For Flat Top Labyrinth Having Sidewall Angles 8° And 10°.
- Analyze The Flow over the Labyrinth Spillway Using Model study.
- Provide Comparison Between energy dissipation over Spillway Designs Chosen.
- Clearly Present And Make Readily Available Results Of This Study So That They May Be Used In Further Practices.

1.3 Description of the Thesis

This thesis consists of six chapters. Chapter 1 is the Introduction part, the problems related to the dams are mentioned and aim of the study is introduced in this part. In Chapter 2, the information obtained from previous studies on labyrinth weirs are provided. Then, in Chapter 3, general information about the spillway rehabilitation methods are explained. In this thesis, labyrinth weirs are used for increasing spillway capacity of the dams wherever applicable. Next, Chapter 4 is about experimental setup and test procedure. In this chapter, all the equipment used in the experiment and test procedure used is stated. Chapter 5 is Results and Discussion part. In this part, different geometric parameters are used to increase spillway capacity. Finally in Chapter 6, conclusions of this study are given.

CHAPTER 2

BACKGROUND AND LITERATURE

In order to understand the subject better, previous studies done for designing and increasing capacity of spillway are examined and summarized.
In this study we will focus on designing labyrinth spillways and comparing them. We will focus on the ways to increase spillway capacity.

In the beginning, the studies conducted on the labyrinth spillways were mostly associated with the spillway characteristics. In 1968, Taylor conducted a study to give important information to the designers. The main aim of his study was to provide most efficient design of labyrinth spillway for any conditions. The whole purpose of the investigation was to obtain the fundamental factors related to the labyrinth spillway for finding the theoretical solution in case of an adverse condition. In this study, the condition for application of the labyrinth spillway are for large discharges with small operating head.

Taylor et al. (1986)

According to the Taylor's (1968) the performance of the spillway depends on the water head. He stated that the performance of the spillway decreases with the increase in water head. It was stated in his study that the discharge capacity of the spillway increases with the growth in length magnification factor (l/w), where l denotes the developed length of one cycle of the spillway and w denotes the width of one cycle of the spillway, however, it results in reduction of design efficiency. It can be stated that an important performance loss can occurs when the vertical aspect ratio (w/p) is small, where p is the crest height and w is the width of the one cycle. If the w/p is greater than 2, this performance loss can disappear. When the w/p is greater than 3, to reach the optimum performance, the sidewall angles should be as large as possible.

Tullis et al. (1995)

At that point, in 1995, Tullis, et al. conducted a study identified with the outline of the labyrinth weirs. The total head (HT), the successful crest length (L) and the crest coefficient (Cd) are expressed as the parameters influencing the release limit. In addition, as indicated by the plan method of the investigation, the proportion of HT/P is around 0.9, and the divider thickness of the crest is P/6, which is adjusted on the upstream corner at a range of P/12. In the event that the geometry of the crest is settled, the release coefficient is impacted by just the head and the labyrinth edge (α). Moreover, release coefficients are substantial for the labyrinth edge in the vicinity of 6° and 35°, for the prescribed weir designs. It is determined that the quantity of cycles (N) and labyrinth edge influence the width, the length and alternate factors of a labyrinth weir and furthermore so as to get the most advantageous and monetary outline, site-particular confinements ought to be respected.

Crookston (2000)

In 2000s Crookston characterized the point of his investigation (2010) to build up a labyrinth weir outline strategy for different introductions, for example, flush, adjusted, channel and anticipating, and enhance geometric plan and pressure driven plan approach. Crookston tried 32 new hydraulic labyrinth weir models in Utah Water Research Laboratory (UWRL). The information were acquired for quarter-round labyrinth weirs. In the channel typical and backwards introduction were utilized and flush, adjusted, delta and anticipating introductions were utilized as a part of the source for the model arrangements. Crookston figured the release by utilizing the conventional weir condition. Be that as it may, he utilized the centerline length of the weir (Lc) rather than the trademark length. The release coefficient information were acquired for quarter-round and half round labyrinth weirs with side divider edges $6° \leq \alpha \leq 35°$. From this test, it was presumed that for the estimations of $H_T/P \leq 0.4$, the expansion in effectiveness, particularly for the half-round crest shape could be seen unmistakably. In this study, cycle effectiveness (ε') was said. In the test outcomes it could be seen that when α diminishes ε' increments and the most extreme ε' values happen at low H_T/P release per cycle.

Crookston et.al (2011)

At that point, Crookston and Tullis (2011) led a study. The principle motivation behind the study was to build up the plan and investigations of labyrinth weirs by utilizing physical demonstrating, accessible information, and current outline strategies to look at the conduct of particular weir geometries.

In the study, the essential condition produced for direct weirs is proposed to show the head-release connections of labyrinth weirs.

$$Q = 2/3\, C_d\, L_c\, h^{1.5} \sqrt{2}g$$

Where,
Q= discharge over the weir (m^3/s)
C_d= coefficient of discharge
L_c= total centerline length of labyrinth spillway (m)
g = acceleration due to gravity (m^2/s)
h = total head on the crest (m)

Cycle effectiveness, ε', speaks to the connection between the diminishing in release productivity and the expansion in release. Diminishing α (sidewall point) causes the decrease in release proficiency and the expansion in the peak length which triggers the increment in the release.

The hydraulic performance of the standard, inverse, anticipating, flush, adjusted channel, and arced orientations were examined and afterward following outcomes were gotten:

i. The release proficiency picks up the best an incentive with an arced labyrinth weir. (~10%-25%)

ii. It can be detectably observed that adjusted projections guarantee the water driven proficiency of the flush orientations.

iii. A performance contrast between the orientations of normal and inverse was not decided.

Crookston et al. (2012)

Crookston, et al. (2012) presented an investigation expanding the HT/P configuration extend. It was planned to assess the hydraulic performance of labyrinth weirs for more prominent HT/P esteems than the most extreme qualities which had been directed in past investigations. Hence, HT/P configuration range could be broadened. This investigation contained both physical and numerical displaying to supply promote approval of the utilization of CFD calculations keeping in mind the end goal to inspect the release qualities of the labyrinth weirs. In the physical displaying $\alpha=15°$ bend fit condition for quarter-round peak shape is won. In the examination, they inferred that CFD was a sensible instrument to assess release performance of the labyrinth weirs. Furthermore, the compliance between the physical demonstrating and the numerical displaying was of 3% to 7%.

Suprapto et al. (2013)

Afterward, Suprapto (2013) led an investigation in order to think about the Ogee write spillways and labyrinth sharp peaked spillways (LSCS). Labyrinth sharp peak spillways comprised of trapezoid write, saws compose and duck mouth compose. Keeping in mind the end goal to ascertain the spillway release, the established conditions of direct weir peak were utilized as a part of the investigation. For different water thicknesses of spillways, stream perceptions of various kinds were resolved. Additionally, the distinctions of releases for a wide range of spillways were watched. It can be closed from the perceptions that the littlest release limit has a place with the Ogee compose spillway, aside from in the stream thickness of under 1.50 m. Besides, the best release limit has a place with the trapezoidal kinds. The hydraulic performance of the conventional labyrinth weirs is notable since they have been considered for quite a while. In any case, a for the most part acknowledged standard outline strategy of the piano key weirs has not been created yet, in view of the absence of deliberate trials and existing information.

Houston et al. (1983)

Houston (1983) led an investigation of Hyrum Dam where the test program included different weir orientations and positions of the labyrinth weir with respect to the supply release channel (ordinary, reverse, flush, and halfway anticipating) of the two cycle labyrinth weir.Houston (1983) found that for channelized approach stream conditions, the typical orientation had 3.5% more noteworthy release than the opposite orientation, and in part anticipating expanded release by 10.4% when contrasted with flush with admission. It ought to be noticed that bended guide dividers or an adjusted channel were utilized quickly upstream of the labyrinth, and that the aftereffects of this investigation might be restricted on the grounds that the weir was included just two cycles. Extra research is expected to give outline direction for labyrinth orientations and situations (including $N \geq 2$), fundamentally in light of the fact that current plan strategies have been produced in channelized stream conditions (research center flumes).

Two investigations were led that gave introductory bits of knowledge into labyrinth weir conduct. Be that as it may, because of the constrained extent of each examination, there were lacking information for general labyrinth weir outline.

Gentilini et al. (1940)

Gentilini (1940) distributed an examination in light of past work on sideways weirs by putting various diagonal weirs together to shape triangular labyrinth weirs. The sharp crested weirs were tried at three sidewall edges (α=30°, 45°, and 60°) and generally small w/P proportions. Because of the extensive working head (contrasted with cycle width), Gentilini's comes about were observed to be subject to w/P and were displayed as an element of h/w.

Kozák and Sváb(1961)

Kozák and Sváb (1961) tried eleven distinctive trapezoidal labyrinth weirs (tw=6mm) with a level finished peak with the two edges chamfered. The tried weirs had the following parameter ranges: $0.05 \leq h/P \leq 0.25$, $5.7° \leq \alpha \leq 20.6°$, $1.23 \leq Lc\text{-}cycle/w \leq 4.35$, $1.15 \leq w/P \leq 4.61$

Kozák and Sváb inferred that the release limit of labyrinth weirs is apparently more noteworthy than a straight weir working under a similar head. They moreover inferred that a bigger number of little cycles are more effective and conservative than a labyrinth weir of proportional length made out of less cycles. It is essential to take note of that this investigation was directed for little working heads where release limit isn't essentially lessened by sidewall point and nappe obstruction.

Taylor (1968)

Geoffrey Taylor led a vast report (24 models) fundamentally on triangular labyrinth weirs alongside a predetermined number of trapezoidal and rectangular weirs. Two peak shapes were examined, sharp-peaked and half-round, and Taylor likewise investigated four inclined apron configurations. The weirs were tried for $0.05 \leq h/P \leq 0.55$. Feed and Taylor (1970) characterized the hydraulic performance regarding stream magnification, Q_{lab}/Q_{lin} (Labyrinth weir release/Linear weir release) versus h/P. They introduce effectiveness(E) to decide the points of interest picked up from an expansion in peak length notwithstanding two release relationship diagrams particular to sharp-peaked labyrinth weirs, this outline technique gives suggestions with respect to Lc-cycle/w, submergence, channel-bed height, aprons, and general nappe interference. Notwithstanding, the creators dismissed the velocity component in the driving head (comes about constrained to channels and not counting V2/2g) and inferred that release is moderately autonomous of w/P. They propose utilizing greatest conceivable qualities for α and suggest triangular labyrinth weirs.

Hay and Taylor (1970)

Hay and Taylor (1970) discouraged the utilization of labyrinth weirs where they would work under submerged conditions or with a high tail water that would expel the aeration cavity behind the nappe (based upon hydraulic efficiency).The U.S. Department of Reclamation directed flume investigations of labyrinth weirs to help in the outline of Ute Dam; the plan was past the extent of Hay and Taylor (1970) and it was vital to affirm their outcomes. Errors between examinations were attributed to variation in upstream head definition in his flume examinations.

Hinchliff and Houston (1984)

Labyrinth spillway plan rules (Hinchliff and Houston 1984) were created in light of the consequences of the Ute Dam and Hyrum Dam display examines; including rating bend information displayed in a shape reliable with Hay and Taylor (1970). As already said, the data in regards to weir position gave new bits of knowledge in labyrinth weir outline, regardless of degree constraints (N = 2).

Darvas (1971)

Darvas (1971) presented an observational release condition,to go with an outline diagram. His approach uses HT, and presented Cd-Darvas, a dimensional labyrinth weir release coefficient (ft1/2/s). Results are displayed as Cd-Darvas versus Lc-cycle/w, and incorporate a group of HT/P plan bends ($0.2 \leq HT/P \leq 0.6$) for trapezoidal labyrinth weirs without aprons, and $w/P \geq 2$. The supporting information for this plan strategy are restricted to a substantial quarter-round ($R_{crest} = t_w$) peak shape and depend on physical model investigations of Avon Dam (α = 22.8°) and Woronora Dam (α = 27.5°).

Table 2.1: labyrinth spillway parameters summary from design methods

Study	Crest shape	Type
Hay And Taylor (1970)	Sharp, Half Round	Triangular Trapezoidal Rectangular
Darvas (1971)	Large Quarter Round	Trapezoidal
Hinchliff and Houston(1984)	Sharp,Quarter Round	Triangular Trapezoidal
Lux and Hinchliff (1985) Lux (1984, 1989)	Quarter Round	Triangular Trapezoidal
Magalhães and Lorena (1989)	Truncated Ogee	Trapezoidal
Tullis et al. (1995)	Quarter Round	Trapezoidal
Melo et al. (2002)	Large Quarter Round	Trapezoidal
Tullis et al. (2007)	Half Round	Trapezoidal
Emiroglu et al. (2010)	Sharp	Triangular

Indlekofer and Rouvé(1975)

Indlekofer and Rouvé (1975) investigated the idea of nappe interference by considering sharp-peaked corner weirs (r= 23.4°, 31°, 44.8°, 61.7°). A corner weir can be portrayed as a solitary triangular labyrinth weir cycle with channel limits perpendicular to every sidewall. Indlekofer and Rouvé partitioned the corner weir into two stream areas: a distributed region where the spill out of every sidewall meets (impacting nappes) and a second area where the stream streamlines are perpendicular to the sidewall (i.e., linear weir stream).

Melo, Ramos, and Magalhães (2002)

In view of their investigation of a solitary cycle labyrinth weir situated in a channel with converging walls, Melo et al. (2002) additionally built up the technique of Magalhães and Lorena (1989) by including an alteration parameter. This outline technique presents $k_{\theta\text{-}CW}$ as an element of θ_{CW} (0° – 90°) to incorporate the impact of meeting channel dividers ($1.0 \leq k_{\theta\text{-}CW} \leq 1.4$), which increment labyrinth weir productivity by coordinating a bigger upstream

stream region into a labyrinth weir cycle (merging stream) and enhancing the orientation of the stream lines to the labyrinth weir sidewall (closer to perpendicular).

Amanian M.S. Thesis (1987)

Amanian (1987) tried straight weirs and half-round triangular labyrinth weirs in a channel, including sideways labyrinth weirs (the labyrinth cycles situated at an edge to the moving toward stream, appeared in Fig. 2-3). The weirs were created from fabricated wood, with tw~19.05-mm. In spite of the fact that there are not very many information focuses related with each physical display, Amanian tested eight labyrinth weirs and eleven direct weirs. Patterns seem to have been hard to perceive because of the modest number of information focuses; in any case, Amanian states that good agreement was found between the sharp crested trial comes about and the consequences of past examinations. Restricted data is given in regards to nappe aeration conditions amid testing. Amanian presumed that the release proficiency of labyrinth weirs decreases as HT increments (because of submergence and nappe interference), and proficiency can be expanded with a half-round peak shape (relative to quarter-round, flat, or sharp crest shapes).

Tullis, Young, and Chandler (2007)

Past to the Tullis et al. (2007) study, the direct weir submergence technique created by Villemonte (1947) was ordinarily connected to labyrinth weirs for absence of a more proper option. Tullis et al. (2007) built up a dimensionless submerged set out relationship toward labyrinth weirs that is easy to explain and has a normal prescient mistake of 0.9%

Tullis et al. (2012)

Tullis (2012) explored the idea of labyrinth weir nappe interference. They pronounced that nearby submergence diminishes the release productivity of labyrinth weir. Based upon the trial aftereffects of physical demonstrating, Crookston and Tullis (2013) exhibited a strategy for hydraulic plan and examination of labyrinth weirs. To guarantee hydraulic advancement and to represent potential vibrations, Crookston and Tullis (2013) suggested that nappe conduct ought to be considered in the plan of labyrinth weirs.

B.V Khode and A.R Tembhurkar (2012)

B.V Khode et al. (in 2012) conducted model study on labyrinth spillways having different sidewall angles. In their study they created four labyrinth models having sidewall angle 8^0, 10^0, 20^0 and 30^0. H_T/P value was kept under 0.9 throughout the experiment for all the models. In his study he gave design curves and regression equation for labyrinth spillways having sidewall angle from 8^0 to 30^0.

CHAPTER 3

GENERAL INFORMATION FOR LABYRINTH SPILLWAY

In this chapter the concepts of the labyrinth spillway are discussed. Then, hydraulic and geometric properties of the labyrinth spillway are illustrated. In the end of this chapter the advantages and disadvantages of the labyrinth spillway are discussed.

3.1 Labyrinth Spillway

A labyrinth spillway is linear in plan. Labyrinth spillway has zig zag shape. The main objective of using the labyrinth spillway is to increase discharge capacity of the spillway. This is done by increasing the crest length of the spillway. The crest length increases as the shape of the crest is changed from straight to zig zag which allows it to allow more discharge through it.

The crest length of the labyrinth shaped spillway is around five times of standard spillway. The discharge of the labyrinth spillway is around three times that of the standard spillway. Here are some examples of labyrinth spillway used in practice fig 3.1, fig 3.2 and fig 3.3.

Fig 3.1 Brazos dam, Texas, USA

The gated spillway was replaced by the labyrinth weir designed by Freese and Nichols. This design for the Brazos lake helped in cost cutting and estimated cost was half to the estimated cost of the standard spillway. The innovative design of labyrinth weir allows the reuse of the existing dam site, yielding substantial reduction in construction cost and time. The placement of the labyrinth on the embankment area resulted in an upstream shift across the labyrinth near mid-stream effect, two labyrinth side by side.

In addition to minimizing cost, with the help of phased construction process engineers were able to control disruptions to the lake level during construction. During the construction of left labyrinth the existing gates remained operable and work started on right labyrinth spillway only after the successful completion of left labyrinth spillway.

Fig 3.2 Lake Townsend Dam, Greensboro, North Carolina

Greensboro gets its primary supply from the lake Townsend. The alkali silica reactions (ASR) caused severe deterioration to the spillway concrete. The damage was so serious that it had to replaced or rehabilitated. The dam also could not pass the spillway design flood due to the inadequate spillway capacity. Temporary repairs were done but the complete evaluation recommended the replacement of the spillway and downstream embankments. The labyrinth spillway was selected as the preferred option after evaluation. It was 300 foot wide with the total weir length of more than 1000 feet.

Fig 3.3 Ute Dam, New Mexico

Ute dam was constructed in 1962 and is located in New Mexico. The original spillway design included high gates which were not installed. The water demand of future could not be fulfilled because the gates were not installed to increase the reservoir capacity. To solve this problem a economical alternative was worked out. An economic labyrinth spillway having triangular or trapezoidal cycles was selected to counter the existing problem. This provided an economical solution to the problem because the labyrinth spillway allows more discharge to pass to meet future requirements. The length of the crest was increased using the labyrinth spillway. Due to the increase in crest length the capacity of the spillway increases.

Although there are various types of labyrinth spillways based on their geometric classification but the most commonly used are triangular, trapezoidal and rectangular. According to the study conducted by Crookston in 2010 the triangular and trapezoidal shaped labyrinth spillway (fig 3.4) are more efficient than the rectangular shaped spillway per unit discharge.

A spillway is a simple structure that has been used for a long time to maintain discharge and upstream water depths and flow rate measurement. There are many spillway geometries and a labyrinth spillway is folded in plan-view. By doing this the length of the crest increases which allows more storage.

Labyrinth spillways come in variety of geometric configurations, however, there are three types depending on the cycle shape i.e triangular, trapezoidal and rectangular (fig 2.1). The labyrinth spillways having triangular and trapezoidal shaped cycles are more efficient than then rectangular shaped cycle labyrinth spillway. The geometric features associated with labyrinth spillway are provided in the next chapter of the thesis in detail.

Because of their hydraulic behavior, labyrinth spillways have been of interest to researchers and engineers. They provide an increased crest length which results in increased flow capacity for a given upstream water depth. Labyrinth spillways require less free board than a standard linear spillway. They also help in maintaining a more constant upstream depth. Labyrinth spillway can increase storage capacity of a reservoir under base flow conditions in comparison to linear weir structures such as an ogee crest spillway. They have also been found to be efficient and effective flow aeration control structures, drop structures and energy dissipation. The performance of the labyrinth spillway is directly dependent on the discharge, passed by a linear weir of width,W, equal to the total width occupied by the labyrinth spillway cycles. The discharge passing over labyrinth spillway should be directly dependent on the crest length of the spillway. For example, a length magnification of 3 should allow passage of discharge three times.

Labyrinth spillways occupy less space as compared to ogee spillways which results in reduction of dam’s dimension. Spillways and weirs have a significant cost in the construction of the dam. They require a lot of money. Labyrinth spillways offer economic solution to this cost problem. They are used as a good alternative to reduce the structural cost.

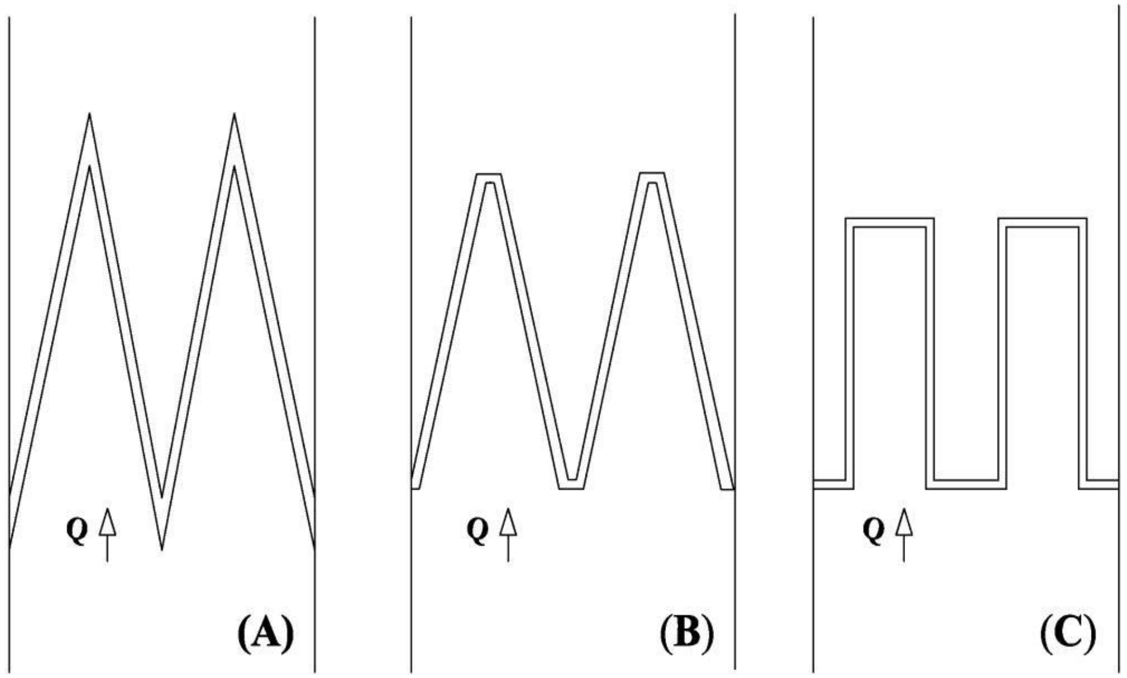
The basic components of a labyrinth spillway are:

- Approach channel – they are for conducting water to the spillway. They provide passage for water to the spillway. They are mostly used when the spillway is located outside the body of the dam.

- Control structure – this part is responsible for the controlling the water level in the reservoir. It is the main part of a spillway.

- Downstream chute – the main purpose of this part is to carry water from the spillway back to the streambed.

- Dissipation structure – this part is responsible for the dissipation of the energy. This part contains various obstacles to dissipate the energy of the water.



Triangular shape trapezoidal shape rectangular shape

Fig 3.4. Classification of labyrinth spillways

The design of a labyrinth spillway depends on various geometric factors. Some of the important geometric factors are the angle of sidewalls, crest shape, length of sidewall, H/p ratio etc. The geometric features of the labyrinth spillways are discussed in the next chapter.

3.2 Labyrinth Spillway Parameters

Numerous design parameters have been developed by various researchers for optimization and design process of labyrinth spillway. Many studies have been conducted for studying the effect of geometric parameters on the design of the spillway. In this section we will be discussing the effects of parameters on the discharge capacity of the labyrinth spillway. 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 3.4 all the geometric features of a labyrinth spillway are given. The cycle in the figure consists of series of trapezoids which are placed next to each other.

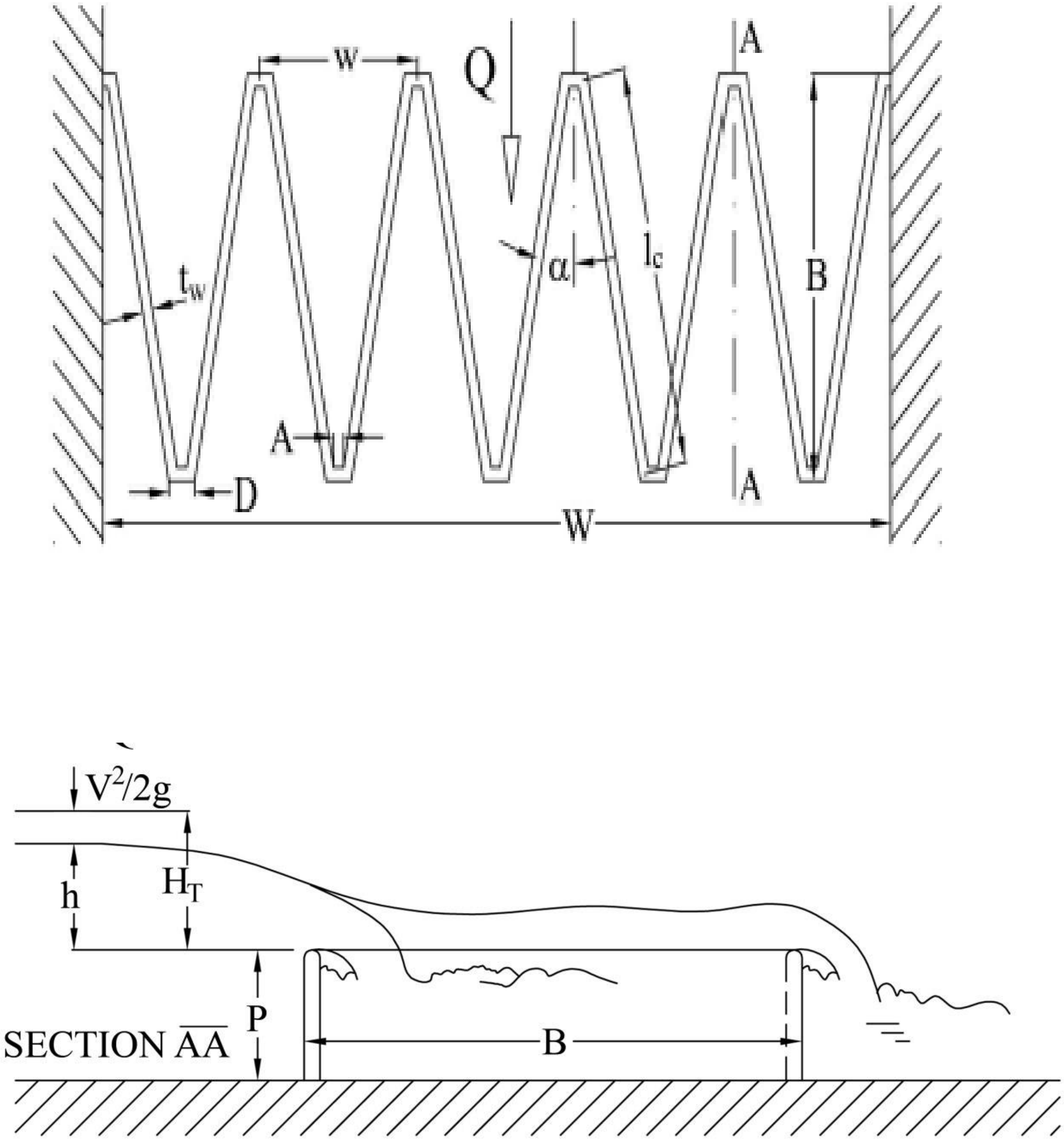


Figure 3.5 geometric parameters

t = wall thickness (m)
w = width of one cycle of spillway (m)
W = total width of labyrinth spillway (m)
α = angle of labyrinth (degree)

A = inside apex width (m)
D = outside apex width (m)
B = apron length (m)
P = height of the spillway
L_1= actual side length (m)
R = radius of crest curvature (m)

Headwater ratio (H_T/P).

The total head measured relative to the weir crest elevation, immediately upstream of the weir over the weir height (P) fig 3.5. This is known as headwater ratio. In simple words, head water ratio is the ratio of total head (H_T) to the height of the spillway. This is a dimensionless in nature and is very commonly used o the abscissa of a plot that presents the hydraulic performance of a labyrinth spillway. Total head of the spillway is gven by $H_T = h+V^2/2g$. 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_T/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 ($H_T/P \leq 0.4$) there is increase in efficiency of the labyrinth spillway. It was also stated that the cycle efficiency is maximum at low H_T/P values. No data above H_T/P= 0.9 and below H_T/P=0.1 were used as with increasing head the labyrinth spillways become significantly effective. In study, it is also stated that finding the value of coefficient of discharge (C_d) is very hard at $H_T/P<0.1$

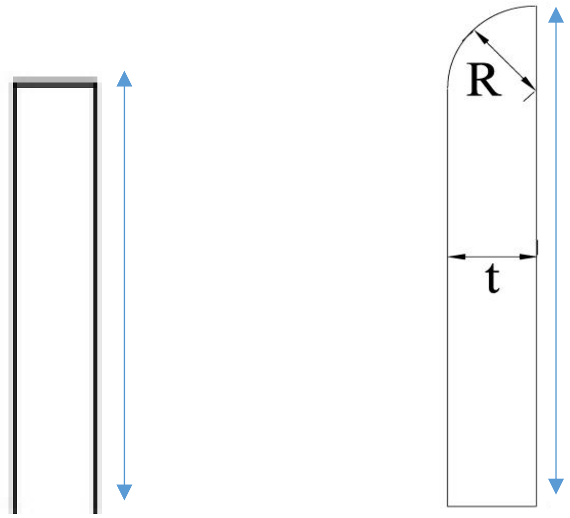


Fig 3.6 cross section of a labyrinth spillway showing crest height (P)

Cycle width ratio (w/P)

Ratio of width of one cycle of a labyrinth spillway (w) to the spillway height (P) is called cycle width ratio. In 1968, Taylor suggested that the cycle width ratio (w/P) should be greater than 2 in order to avoid important performance loss. In 2010, Khode and Tembhurkar also suggested that the cycle width ratio should not be less than 2.5 for triangular shaped labyrinth weir and not be less than 2 for trapezoidal shaped labyrinth weirs. In 1995, Tullis et al. study showed that the design will be hydraulically efficient and economical when the w/P lies between 3 and 4. In 1989, Lux found from his experiments that the discharge coefficient and cycle width ratio depends on each other. He found out that coefficient of discharge (C_d) decreased with cycle width ratio (w/P) decreased.

Number of labyrinth spillway 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 (C_d) doesn’t get influenced by the number of labyrinth weir cycles. This situation eases up the design of the project. Using too many number 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 spillway length.

Discharge coefficient (C_d)

Discharge coefficient (C_d) 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 C_d plays an important role. In 1995, Tullis et al. conducted study and demonstrated C_d in term of H_T/P. The study was conducted for labyrinth spillways having trapezoidal shape and for variety of angles.

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.

Nappe interference

Nappe interference refers to the interaction of flow passing over a weir in a converging flow situation. This occurs in the vicinity of the upstream apex of a labyrinth weir cycle. In this process when the flow passes over the labyrinth spillway the discharge over one spillway wall interacts with discharge of an adjacent wall of spillway. The flow usually impacts with other flow of adjacent wall. This creates localized submergence effects. In the case of trapezoidal spillway, the nappes occurring from the sidewall not only collide, but also interacts with the nappe of the apex. Nappe aeration provided on the downstream side of the spillway affects the nappe collision. Therefore the area of collision does not increase linearly with increment of H_T.

Figure 3.7 Nappe interference

3.3 Design Procedure for Labyrinth Spillway

A labyrinth spillway is used to increase the crest length of the standard spillway. In the given width only, the labyrinth spillway increases the crest length for given width of spillway. As the crest length increases, the discharge capacity of the spillway also increases.
Eq.(3-1) is the general equation for the linear weir and this was used by Tullis et al. (1995) for designing labyrinth weirs. In this section steps for designing the labyrinth spillway are given.

$$Q = \frac{2}{3}\, C_d L \sqrt{2g} H^{\frac{3}{2}} \qquad (3\text{-}1)$$

Where,
Q –discharge over the weir
C_d –discharge coefficient
L –crest length

g –acceleration due to gravity
H_T – total head on the crest

This equation was derived assuming steady one-dimensional flow, an ideal fluid, atmospheric pressure behind nappe, hydrostatic pressure, horizontal and parallel stream lines at the crest.

Steps for design

1. The H_T/P ratio should be less than 0.9. It is necessary to limit the H_T/P to maintain the effectiveness of labyrinth spillway. Labyrinth spillway still functions at headwater ratio greater than 0.9 but the advantage of labyrinth design continue to decrease with increase in headwater ratio. A labyrinth spillway tends to operate with a slight negative pressure at headwater ratio between 0.1 and 0.2.
2. w/P should be between 3 and 4. This step is used to find out the number of cycles. In this study the 'w' cannot be changed as we have limited width of flume. So the number of cycles are considered according to the flume.
3. The wall thickness (t) is equal to P/6. (J. paul Tullis et al.)
4. Crest shape of the labyrinth spillway is flat. For quarter round spillway, radius of curvature is equal to P/12.
5. The value of inside apex width is between t and 2t.
6. Labyrinth angle is usually chosen from 8^o to 16^o.
7. Outside apex width is calculated by eq.3-2

$$D = A + 2t \tan(45-\alpha/2) \quad (3\text{-}2)$$

8. Actual length of side length is calculated by eq. (3-3), (3-4) and (3-5)

$$\sin \alpha = x/ L_1 \quad (3\text{-}3)$$

$$X = (w\text{-}D\text{-}A)/2 \quad (3\text{-}4)$$

$$L = (D/2+ 2L_1+ A+D/2)\, N \quad (3\text{-}5)$$

9. Determine C_d using graph provided by Tullis et al. (1995)

10. Calculate discharge over labyrinth spillway using eq.(3-1)

In this experimental study we used two labyrinth spillway models having sidewall angles of 8^o and 10^o. During designing of these spillways the width was calculated according to the width of the flume available.

CHAPTER 4

EXPERIMENTAL SETUP AND TESTING PROCEDURE

4.1 Testing Facilities

All research for this study was conducted in hydraulics testing lab located on Delhi Technological university campus. Rectangular flume facility was used for channelized application. In this study great care was taken to minimize systematic and random errors. Prior knowledge of this experiment was gained by reviewing published literature.

4.2 Experimental setup

4.2.1 Rectangular Tilting Flume

The tilting flume is designed to perform various experiments. Tilting flume is an open channel which is used to perform various experiments. The tilting flume has glass walls and fabricated stainless steel bed. Rectangular tilting flume used for this study has working section of 300mm wide by 400mm deep and length available was of 8m (figure 4.1). The dimensions are from center to center of the flume frame.

Figure 4.1 rectangular tilting flume used for study

The flume comprises of moulded inlet and discharge tanks, a pump, a jacking system and a control console. The working section of the flume has walls fully glazed with large panels of clear toughened glass. This allows excellent visibility and allow visualization of the flow for good experiment understanding. The glass panels give full view of the flow upto the working height of the flume. The glass panels are completely sealed which allows leak proof flow in the flume. Rigidity and stability is very important for the flume. For this the bed is manufactured to high tolerances. To connect the sections of the flume rigid dowelled joints are used. The stability and rigidity of the design reduces repairs and maintenance. The flume is also provided with instrument rails along its working length. Along the length of one of the rails, a continuous scale calibrated in millimeters.

At the downstream end of the flume a recirculation tank is placed which ensures continuous supply of water in the flume figure (4.2). The circulation tank stores water and passes it to the flume through pipes.

Figure 4.2 Recirculation tank

With the help of centrifugal pump placed at downstream end of the flume, the water from recirculation tank is supplied to the flume. The whole process of transferring water is done with the help of pipes that connect recirculation tank to the upstream of the flume. The rectangular flume is tilting in nature. The tilt can be given with the help of the motor placed below the upstream side. A scale is also provided at the upstream side to note down the tilt. The flume also consists of two gates i.e. head gate and tail gate. Head gate is provided on the upstream side of the flume and tail gate is provided on the downstream end of the flume. Both the gates help in maintaining the flow depth in the flume.

Figure 4.3 centrifugal pump

4.2.2 Point Gauge

Point gauge is an instrument used for determining the depth in the flume (figure 4.3). It is generally used to determine flow depths in the flume. Point gauge is used to measure vertical readings. Point gauge used in the flume moves along the length of the flume with the help of rails provided on the top of the flume. The point gauge has a vertical scale on which the numbers are engraved for measuring depths. The scale is movable with the help of dial provided on it. The point gauge movement along the width is also free. Zero error should be taken care of prior taking any measurements.

Figure 4.4 point gauge

4.2.3 Flow Probe Velocity Meter

Flow probe velocity meter was used in experiment to determine the velocity. This device is highly accurate in measuring velocity in open channels and partially filled pipes. The flow probe has a propeller attached on the lower end, which is submerged in the water to measure velocity. The flow probe has adjustable height and can be extended from 1.12 m to 1.82 m. The flow probe has a telescopic rod made up of light weight material (anodized aluminium). The probe has a ergonomical design which helps in easy handling of the device. This device works on the principle of propeller movement.

Figure 4.5 flow probe velocity meter (source: www.globallw.com)

4.2.4 Labyrinth spillway model

Labyrinth spillways were designed according to the recommended design procedure of a model study conducted at UWRL of the standley lake labyrinth spillway. The original design of spillway for Standley lake was based on a model study of the Ritschard dam labyrinth. Geometry of labyrinth spillways in this study are similar to that of used by B.V Khode et al. in 2012. The geometry of the spillways was designed according to the flume size. The width of the flume available was 30 cm in this experiment. The total width of the spillway crest is kept 30cm. Number of labyrinth spillway cycles are kept limited to 2. The cycles are designed such that they fit in the flume easily. Two models of labyrinth spillways were used in this experimental study. Height of both the models were kept same for fulfilling the criteria $3 \leq w/P \geq 4$. Two models of labyrinth spillway were designed having side angles of 8^0 and 10^0. The crest shape of the labyrinth spillways was kept flat. The weirs were made of wood with thickness of 6mm having flat top crest.

Geometrics used for the labyrinth spillways in the present experimental study are given in the table 4.1 and table 4.2

Table 4.1: geometrics for the labyrinth weir having sidewall angle 8°

Sidewall angle	8°
Height of the weir (P) (m)	0.10
Number of cycles	2
Apex width (A) (m)	0.03
Actual side leg (L_1) (m)	0.286
Effective side leg (L_2) (m)	0.280
Total length	1.344
Effective crest length L= N($2L_2$+2A) (m)	1.242
Crest shape	Flat

Table 4.2: geometrics for labyrinth weir having sidewall angle 10°

Sidewall angle	10°
Height of the weir (P) (m)	0.10
Number of cycles	2
Apex width (A) (m)	0.03
Actual side leg (L_1) (m)	0.230
Effective side leg (L_2) (m)	0.225
Total length	1.120
Effective crest length L= N($2L_2$+2A) (m)	1.020
Crest shape	Flat

Table 4.3 geometrics for linear weir

Sidewall angle	90°
Height of the weir P (m)	0.10
Width of weir (m)	0.30
Crest length (m)	0.30
Crest shape	Flat

Figure 4.6. 8° labyrinth spillway model

Figure 4.7. 10° labyrinth spillway model

As clearly visible in the photo given below, the crest length of the 8° labyrinth spillway is more than that of 10°. The width available for the spillway was 30cm. The spillways are designed according to the width of the flume available.

Figure 4.8 labyrinth spillways

4.3 Test Procedure

In this experimental study our main objective is to find out the energy dissipation rate for the labyrinth models having different sidewall angle. The values of labyrinth models is further compared to the linear spillway values for better understanding of the energy dissipation. The discharge is kept constant throughout the experiment. By keeping discharge constant we can compare results obtained from the different experiments. The rectangular tilting flume is used for conducting experiment. The flume has a working section of 0.30m wide by 0.40m depth and the length of the flume is 8m. At the downstream end of the flume there is a water storage tank from which the water is supplied to the flume using centrifugal pump. This tank is also called recirculation tank. This tank is responsible for continuous circulation of water to the flume with the help of centrifugal pump. The slope of the flume is kept horizontal (0°) throughout the experiment. The flume should be horizontal before starting the experiment otherwise it will affect the observation readings. The flume side walls is made up of toughened glass. This glass is provided so that the flow can be analyzed visually. Section A and B were marked on the side glass so that readings could be taken easily. Any leakage must be detected before conducting the experiment otherwise, the results would get affected. Before placing the models in the flume the discharge of the flume was checked and kept constant throughout the experiment. Firstly, the spillway with sidewall angle 8° was placed at a distance of 3.5m from the inlet section of the flume. Labyrinth models were made of plywood having thickness of 6mm. The spillway was placed with the help of double sided tape and the sides of the spillway were sealed with sealant (m-seal). Downstream face of weirs was well ventilated. Water was allowed to flow freely downstream of the weirs and was not controlled by gate, baffle walls etc. Flow depth on the upstream (section A) and downstream (section B) was measured with the point gauge to ± 1 mm reading accuracy. The water surface profile at these sections were horizontal. Section A was marked on upstream at a distance of 1m from the weir and section B was marked on the downstream side at a distance of 1m from the weir. Velocity profile on section A and B was measured with flow probe digital velocity meter to make sure that the approach flow was fully developed. The depths at section A and B were measured by changing the water flow with head gate.

Similarly, for labyrinth spillway having sidewall angle 10° was placed at 3.5m distance from the upstream and readings were taken carefully at 1m distance on the upstream side (section A) and at 1m distance on the downstream side (section B). A model of linear weir was also tested in the same flume for comparison purpose.

Flow probe velocity meter was used to measure velocity at section A and section B point. The discharge during all three experiments was kept constant and only the depth of the flow was varied by using head gate of flume. The tail gate of the flume was kept fully open.

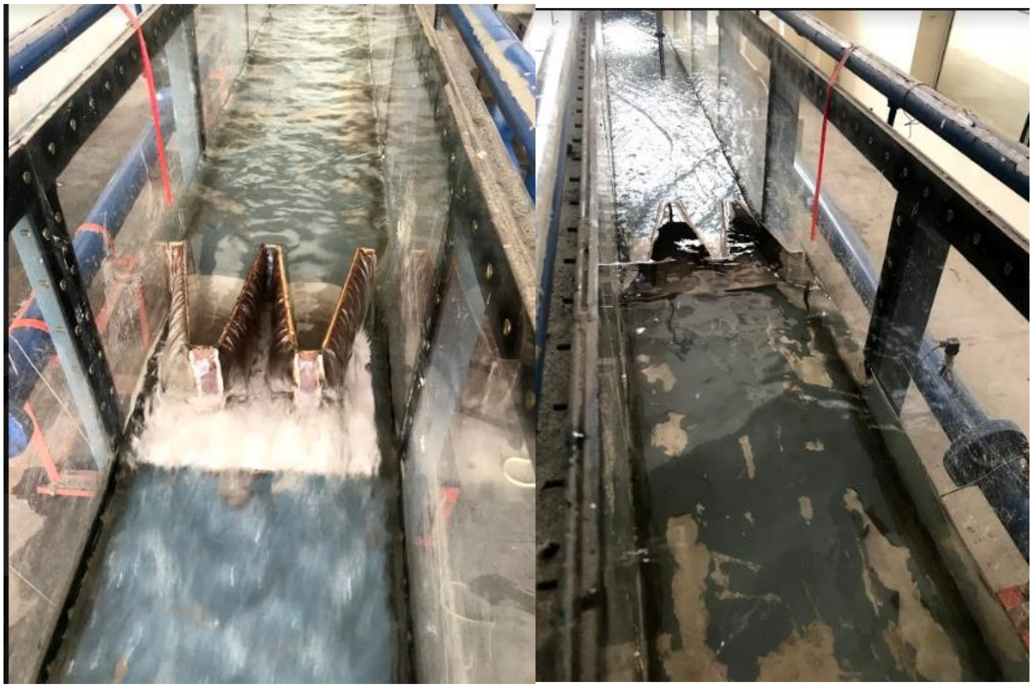


Figure 4.9 flow over 8° labyrinth spillway

Figure 4.9 shows the flow over the labyrinth spillways having sidewall angle 8°. The photo on the left side shows flow from the direction opposite to the flow and the photo on right shows flow from the upstream side of the channel.

Figure 4.10 flow over 10^0 labyrinth spillway

Figure 4.10 shows the flow over labyrinth spillway having sidewall angle of 10º. The photo on the left side was taken from the downstream side of the spillways and the photo on the right was taken from upstream side of the spillway.

Figure 4.11 flow visualization from the side view

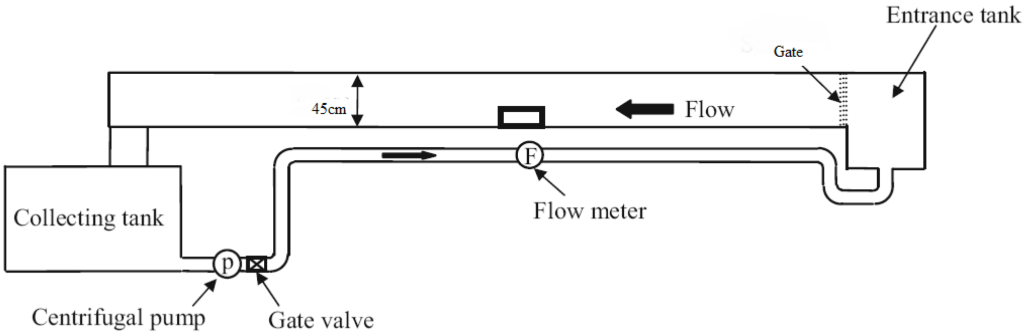


Figure 4.12 schematic diagram of experimental setup

4.4 Calculation of Energy Loss

For calculation of the energy loss two points were selected at a distance of 1m upstream and downstream of the spillway. All the measurements were done on these two points. Point gauge was used to calculate depth and flow probe velocity meter was used to measure velocity at points.

4.4.1. Assumptions:

- The channel is horizontal, rectangular and straight.
- The fluid is incompressible.
- Velocity distribution is non-uniform over upstream and downstream section.
- Channel banks are fixed.
- Wall and bed friction are neglected.
- One dimensional steady flow.

4.4.2. Energy loss

Taking horizontal floor of the flume as reference level and considering energy correction factor $\alpha = 1$, total upstream energy E_0, total downstream energy E_1, total dissipated energy on the spillway and downstream Froude number are calculated using general equations:

$$E_0 = y_0 + V_0^2/2g \qquad (4.1)$$

$$E_1 = y_1 + V_1^2/2g \qquad (4.2)$$

$$\Delta E = E_0 - E_1 \qquad (4.3)$$

$$\Delta E = (y_0 + V_0^2/2g) - (y_1 + V_1^2/2g) \qquad (4.3)$$

$$F_{r1} = V_1/\,(gy_1)^2 \qquad (4.4)$$

Where,

E_0 - total upstream energy

E_1 – total downstream energy

y_0 – upstream flow depth (m)

y_1 – downstream flow depth (m)

V_0 – upstream flow velocity (m/s)

V_1- downstream flow velocity (m/s)

g- Acceleration due to gravity (m^2/s)

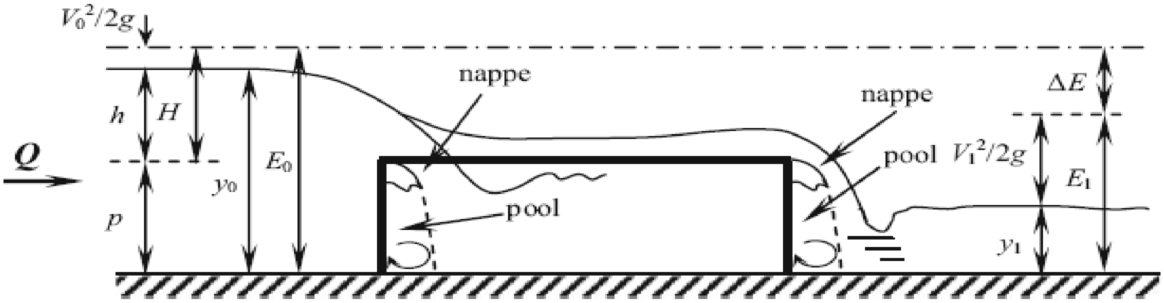


Figure 4.13 flow over labyrinth spillway with all parameters

CHAPTER 5

RESULTS AND DISCUSSIONS

In this chapter, all the data obtained during the experiments for different models is presented in the form of tables and graphs. The data is obtained for different models on the upstream side and downstream side of the spillways. All the other important factors are calculated using this data and are represented here. All the formulae used for calculating important parameters are given in section 4.4 of this dissertation. For each model, 7 reading were taken by keeping the discharge same throughout the experiment. Best efforts were made to keep the readings free from error of any nature.

5.1. Data Collected

Table 5.1. Data for 8° Labyrinth Spillway

Y_0 (m)	Y_1 (m)	B (m)	Q (m^3/s)	Fr_1	E_0	E_1
0.11	0.02	0.3	0.00302	1.136334	0.110427	0.032913
0.115	0.03	0.3	0.00302	0.618542	0.115391	0.035739
0.123	0.034	0.3	0.00302	0.512664	0.123341	0.038468
0.145	0.043	0.3	0.00302	0.360453	0.145246	0.045793
0.16	0.05	0.3	0.00302	0.287472	0.160202	0.052066
0.172	0.055	0.3	0.00302	0.249177	0.172175	0.056707
0.18	0.063	0.3	0.00302	0.203255	0.180159	0.064301

Table 5.2 Data for 8° Labyrinth Spillway

V_0 (m/s)	V_1 (m/s)	ΔE (m)	A_0 (m^2)	A_1 (m_2)	ΔE/E0	Fr_0
0.091515	0.503333	0.077514	0.033	0.006	0.701951	0.088097
0.087536	0.335556	0.079652	0.0345	0.009	0.690279	0.082415
0.081843	0.296078	0.084873	0.0369	0.0102	0.688118	0.074506
0.069425	0.234109	0.099452	0.0435	0.0129	0.684718	0.05821
0.062917	0.201333	0.108136	0.048	0.015	0.674997	0.050219
0.058527	0.18303	0.115467	0.0516	0.0165	0.67064	0.045057
0.055926	0.159788	0.115858	0.054	0.0189	0.643086	0.042086

Table 5.3 Data for 10^{o} Labyrinth Spillway

Y_0 (m)	Y_1 (m)	B (m)	Q (m^3/s)	Fr_1	E_0	E_1
0.11	0.03	0.3	0.00302	0.618542	0.110427	0.035739
0.12	0.04	0.3	0.00302	0.401755	0.120359	0.043228
0.125	0.045	0.3	0.00302	0.336692	0.125331	0.047551
0.14	0.052	0.3	0.00302	0.271048	0.140264	0.05391
0.147	0.055	0.3	0.00302	0.249177	0.147239	0.056707
0.16	0.062	0.3	0.00302	0.208192	0.160202	0.063344
0.18	0.072	0.3	0.00302	0.166361	0.180159	0.072996

Table 5.4 Data for 10^{0} Labyrinth Spillway

V_0 (m/s)	V_1 (m/s)	ΔE (m)	A_0 (m^2)	A_1 (m_2)	$\Delta E/E0$	Fr_0
0.091515	0.335556	0.074688	0.033	0.009	0.676357	0.088097
0.083889	0.251667	0.077131	0.036	0.012	0.640839	0.077318
0.080533	0.223704	0.07778	0.0375	0.0135	0.620598	0.072725
0.071905	0.19359	0.086353	0.042	0.0156	0.615651	0.061356
0.068481	0.18303	0.090532	0.0441	0.0165	0.614861	0.057026
0.062917	0.162366	0.096858	0.048	0.0186	0.604601	0.050219
0.055926	0.139815	0.107163	0.054	0.0216	0.594824	0.042086

Table 5.5 Data for Linear Weir

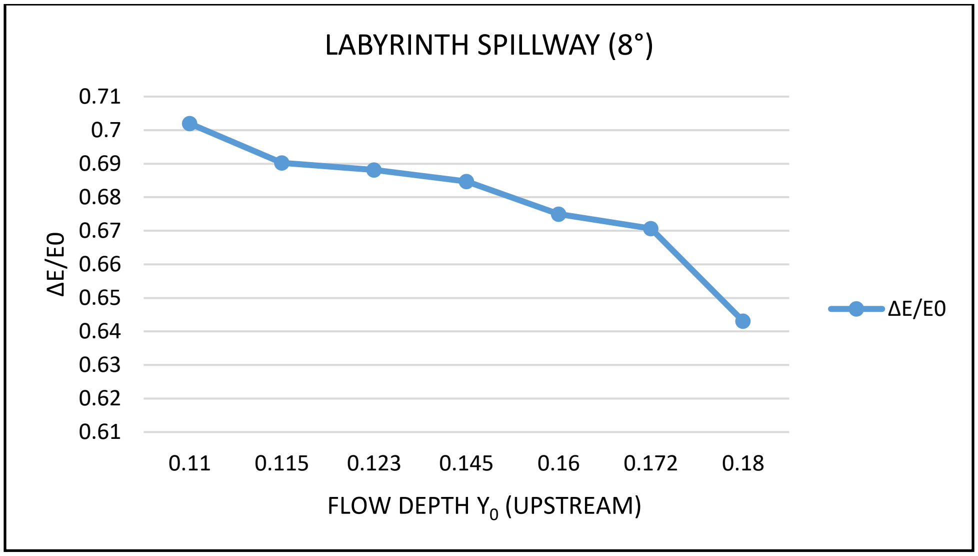
Y_0 (m)	Y_1 (m)	B (m)	Q (m^3/s)	Fr_1	E_0	E_1
0.11	0.04	0.3	0.00302	0.401755	0.110427	0.043228
0.12	0.049	0.3	0.00302	0.296317	0.120359	0.051151
0.125	0.055	0.3	0.00302	0.249177	0.125331	0.056707
0.14	0.064	0.3	0.00302	0.198509	0.140264	0.065261
0.15	0.07	0.3	0.00302	0.173542	0.15023	0.071054
0.16	0.079	0.3	0.00302	0.144747	0.160202	0.079828
0.18	0.091	0.3	0.00302	0.117082	0.180159	0.091624

Table 5.6 Data for Linear Weir

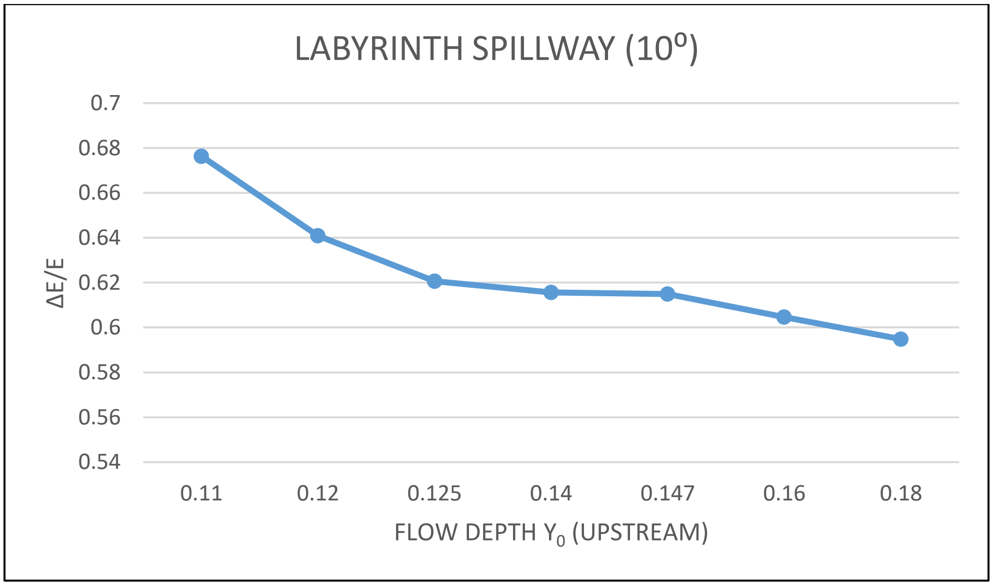
V_0 (m/s)	V_1 (m/s)	ΔE (m)	A_0 (m^2)	A_1 (m_2)	$\Delta E/E0$	Fr_0
0.091515	0.251667	0.067199	0.033	0.012	0.021779	0.608536
0.083889	0.205442	0.069207	0.036	0.0147	0.021779	0.57501
0.080533	0.18303	0.068623	0.0375	0.0165	0.021779	0.547537
0.071905	0.157292	0.075003	0.042	0.0192	0.021779	0.534726
0.067111	0.14381	0.079175	0.045	0.021	0.021779	0.52703
0.062917	0.127426	0.080374	0.048	0.0237	0.021779	0.501706
0.055926	0.110623	0.088536	0.054	0.0273	0.021779	0.49143

5.2 Graphical Representation

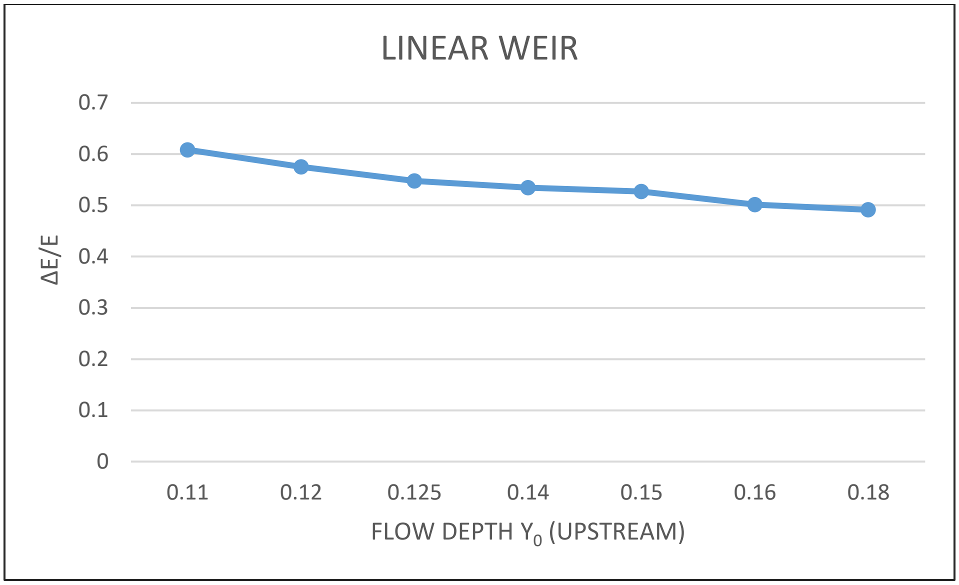
In this section, the tabular data presented in the above section is represented in graphical form for comparison purposes. Graphs in this section shows change in energy dissipation rate, energy dissipation and Froude number with other factors.



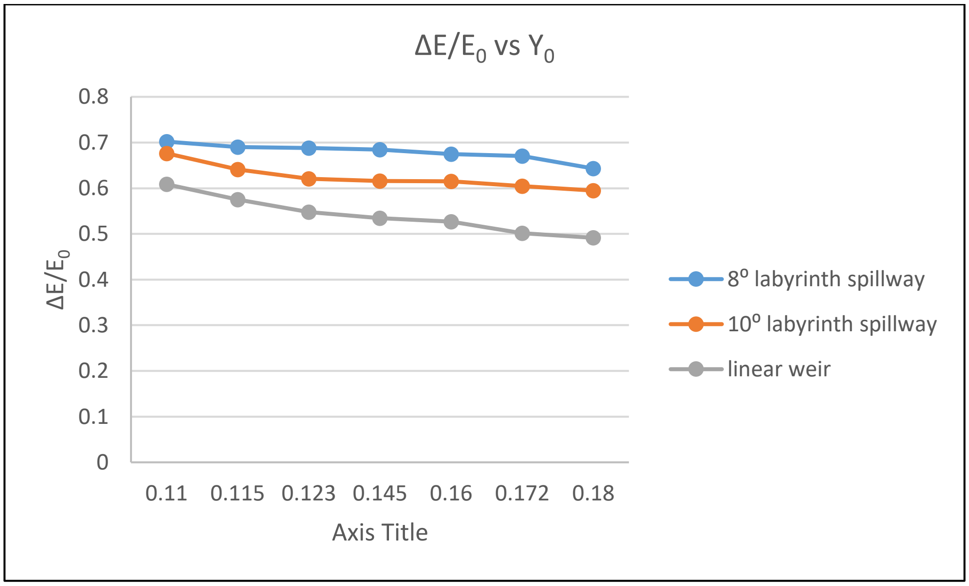
Graph 5.1 Graphical representation of energy dissipation rate $\Delta E/E_0$ for 8^0 labyrinth spillway with respect to upstream depth Y_0



Graph 5.2 Graphical representation of energy dissipation rate $\Delta E/E_0$ for 10^0 labyrinth spillway with respect to upstream depth Y_0

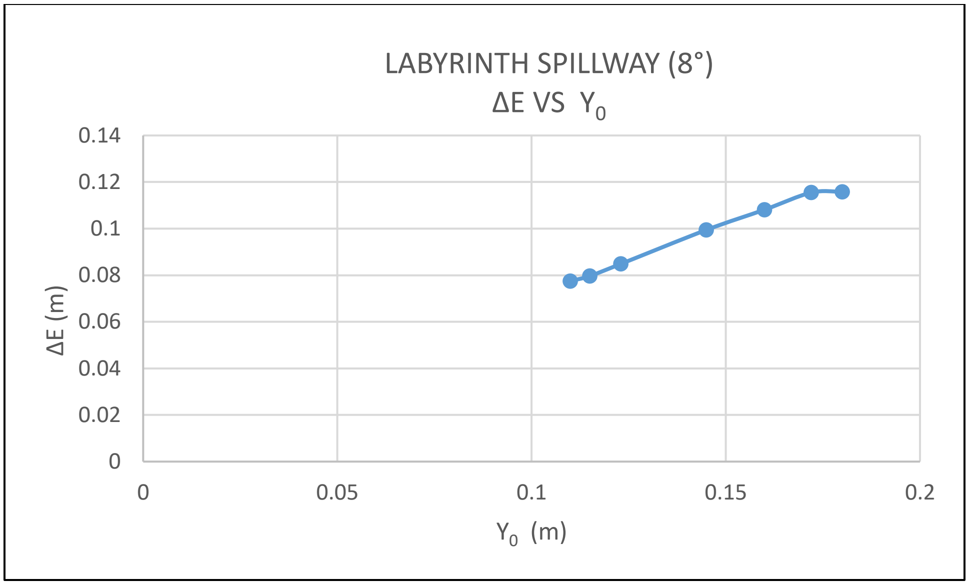


Graph 5.3 Graphical representation of energy dissipation rate $\Delta E/E_0$ for Linear weir with respect to upstream depth Y_0

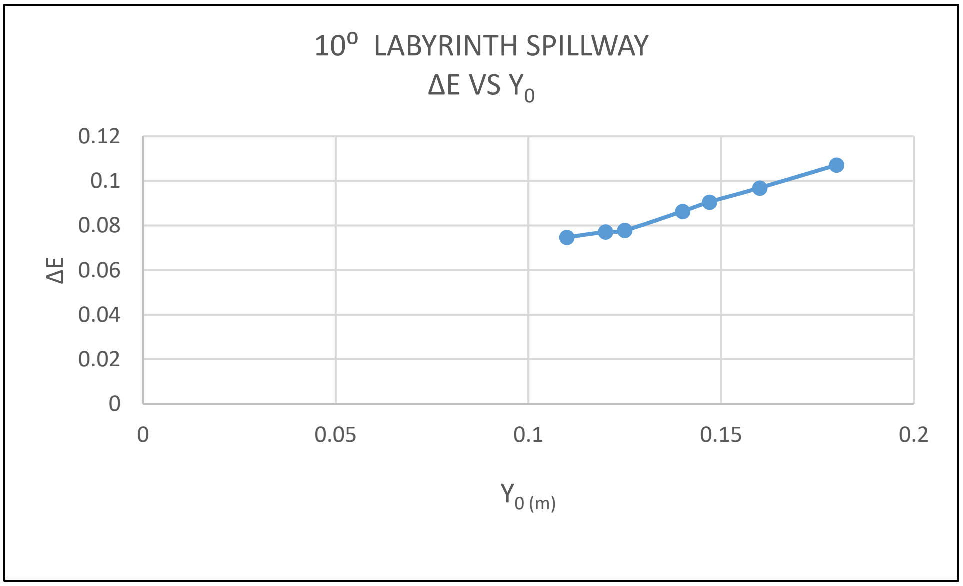


Graph 5.4 Comparison of energy dissipation rate $\Delta E/E_0$

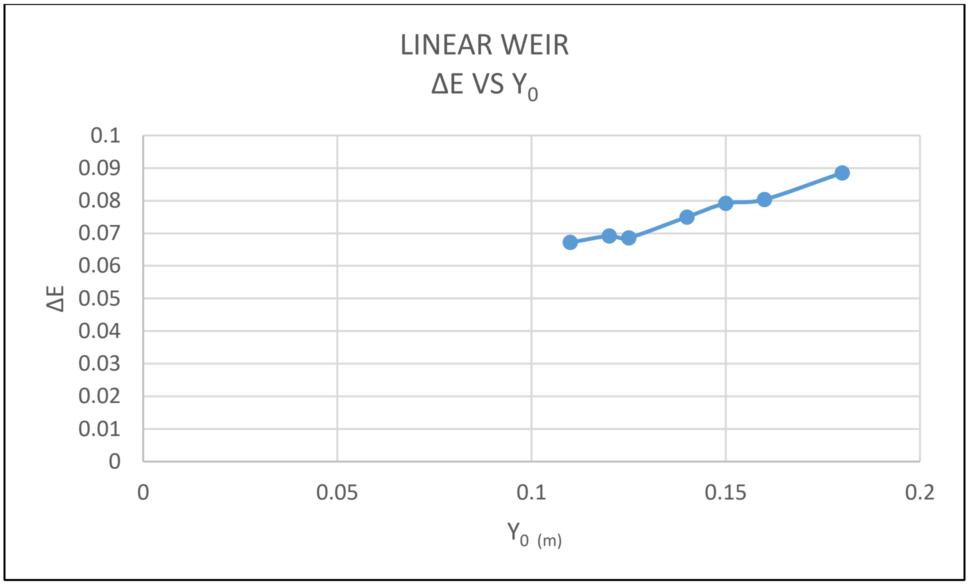
The energy dissipation rate $\Delta E/E_0$ of all the models are compared to know the efficiency of the spillways. The energy dissipation rate $\Delta E/E_0$ of the 8^o labyrinth spillway is greater than the other two spillways. After 8^o labyrinth spillway, then comes the energy dissipation rate of 10^o labyrinth spillway. Linear weir has lowest energy dissipation rate in comparison to others. This means that the energy dissipation efficiency of 8^o labyrinth spillway is better than that of 10^o labyrinth spillway and linear weir.



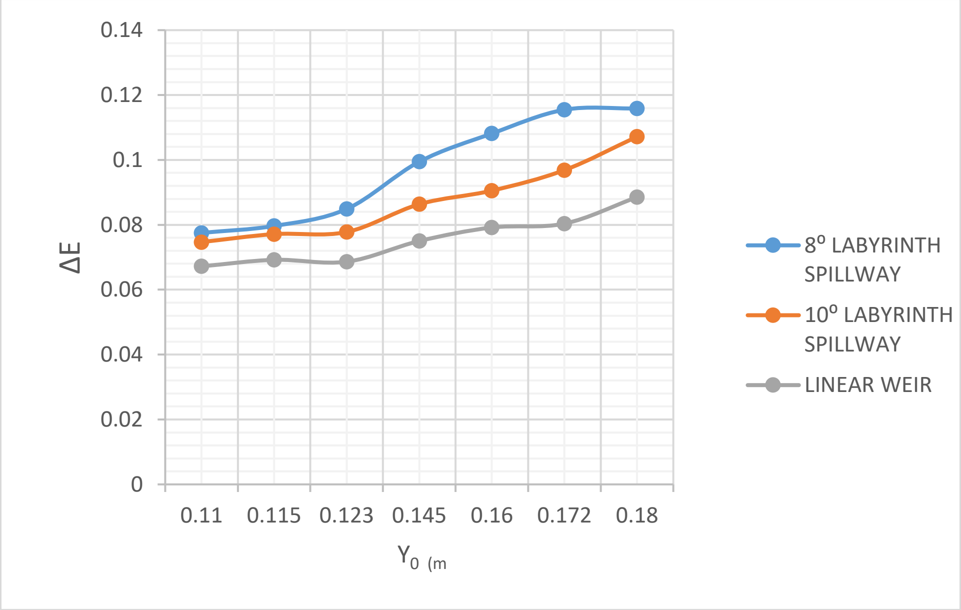
Graph 5.5 Graphical representation of energy loss ΔE for 8^{o} labyrinth spillway with respect to upstream depth Y_0



Graph 5.6 Graphical representation of energy loss ΔE for 10^{o} labyrinth spillway with respect to upstream depth Y_0

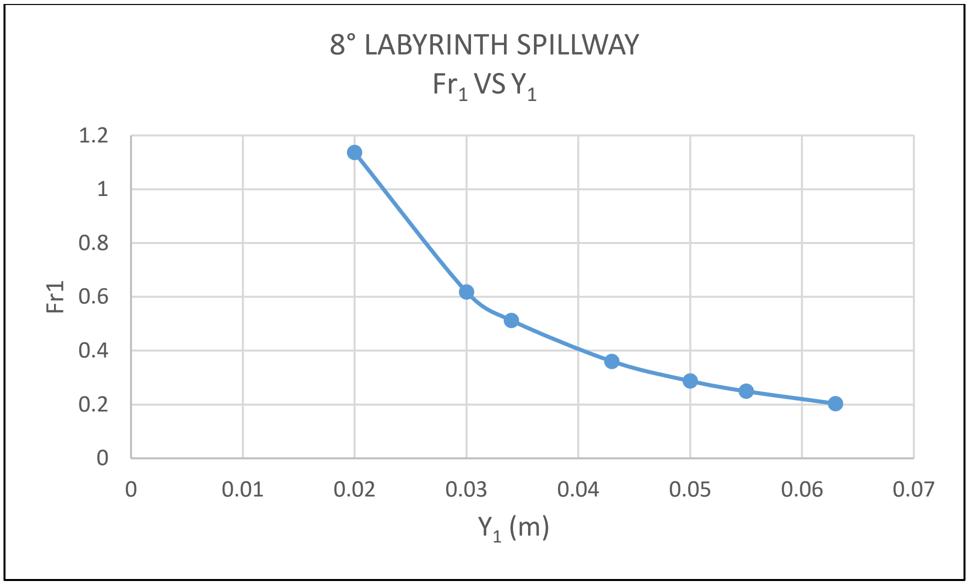


Graph 5.7 Graphical representation of energy loss ΔE for linear weir
With respect to upstream depth Y_0

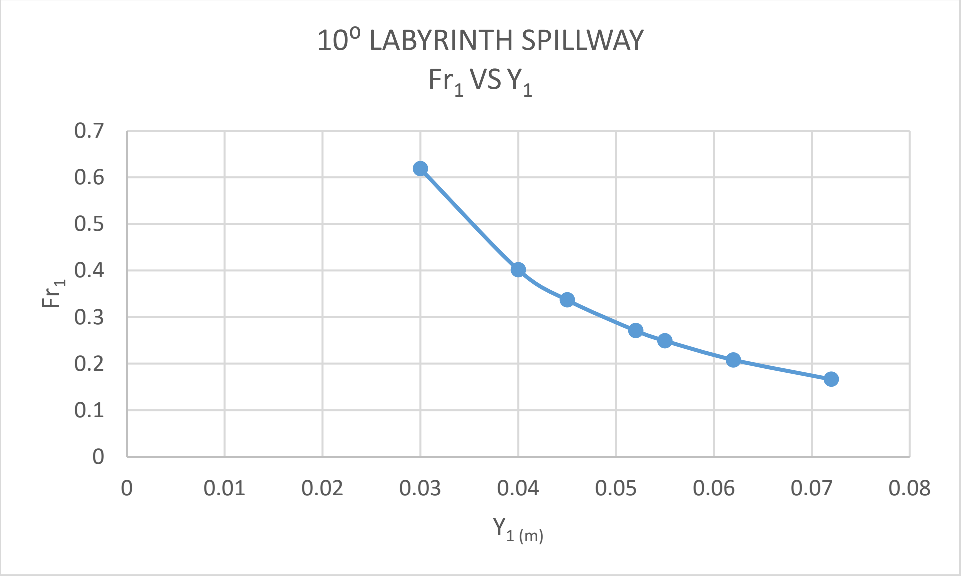


Graph 5.8 Comparison of energy loss ΔE

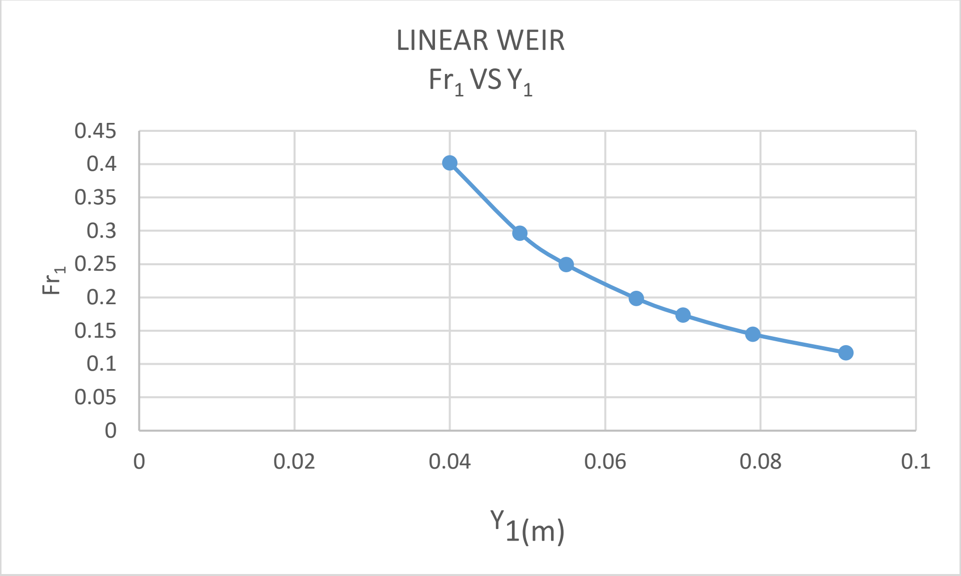
The energy loss calculated was negative in nature. For the better representation in graphical form the loss is descripted in positive nature. The energy loss ΔE for 8º labyrinth spillway is greatest as compared to others. This shows that the 8º labyrinth spillway perform better than other two for dissipation of energy. Then comes 10º labyrinth spillway in terms of energy loss. And lastly linear weir has lowest energy losses.



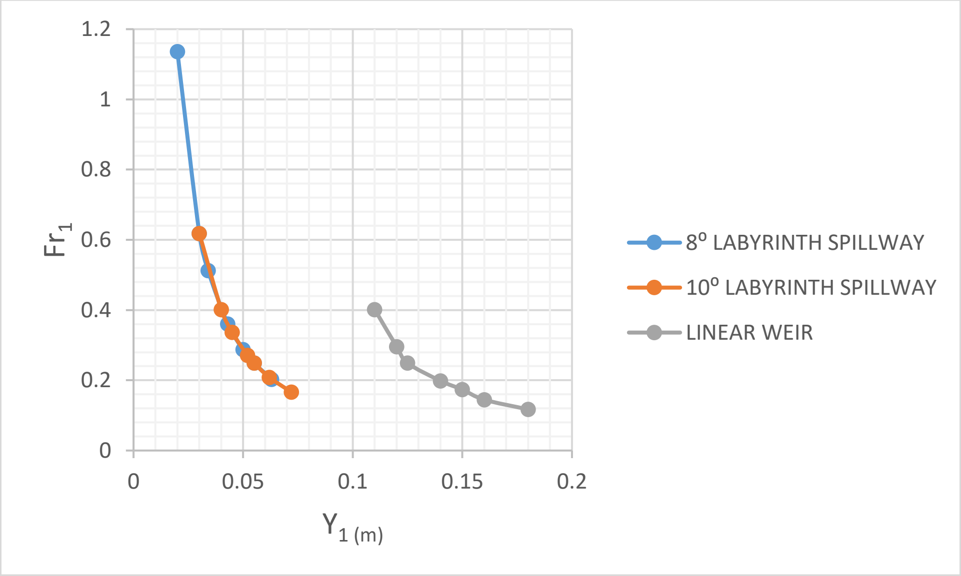
Graph 5.9. Graphical representation of Froude number downstream for 8^0 labyrinth spillway with respect to downstream depth Y_1



Graph 5.10 Graphical representation of Froude number downstream For 10^0 labyrinth spillway with respect to downstream depth Y_1



Graph 5.11 Graphical representation of Froude number downstream
For linear weir with respect to downstream depth Y_1



Graph 5.12 comparison of Froude numbers

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CHAPTER 6

CONCLUSION

In the present investigation, downstream flow regime and energy dissipation on labyrinth weirs are examined. Due to the collision of diagonal supercritical flows at the base of nappes, a powerless hydraulic jump is made on downstream of labyrinth weir. This hydraulic jump balances out the subcritical flow regime on downstream of the weir.

- Labyrinth spillways provide an increase of crest length for a given width of spillway. This allows to increase the flow capacity for a given water head. The capacity of a labyrinth spillway is a function of crest length. Therefore, the crest length and discharge capacity of a spillway can be increased by using a labyrinth spillway.

- In addition to the large discharge capacity, extensive energy dissipation can likewise be said as an advantage of utilizing labyrinth spillways. The extensive energy dissipation on labyrinth spillway can be credited to collision of nappes close to the upstream apexes that make an oblique hydraulic jump, impacting sideways supercritical flows at the base of the nappes that make a powerless hydraulic jump and circulating flow in the pool made behind the nappes.

- Generally, Energy dissipation structures are not required on the downstream of the labyrinth spillway due to extensive energy dissipation. Nappes play an important role in the dissipation of energy.

- It is also seen that the sidewall angle α of a labyrinth spillway effects the crest length of the spillway. The sidewall angle α also influences energy dissipation of the labyrinth spillway. The labyrinth spillways, for a given width, having lower sidewall angles tends to perform better in terms of energy dissipation. Labyrinth spillway having $\alpha = 8^0$ performs better than spillways having sidewall angle $\alpha = 10^0$ and 90^0 (linear weir).

- Labyrinth spillway having sidewall angle $\alpha = 10^0$ performs better than linear weir ($\alpha = 90^0$). This proves that the labyrinth spillways have better energy dissipation rate than the standard spillways. As α (sidewall angle) of the labyrinth spillway increases the effective crest length and discharge capacity of the spillway decreases.

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