Prashant Bhatta

Stepped Large Scale Spillways in Unlined Rock

Master's thesis in Hydropower Development
Supervisor: Elena Pummer
June 2019

Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

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Kunnskap for en bedre verden

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M.Sc. THESIS IN HYDRAULIC ENGINEERING

Candidate: Mr. Prashant Bhatta

Title: Stepped large scale spillways in unlined rock

1. Background

Design of flood diversion on dams internationally, irrespective of if it is concrete or rockfill dams, now and then fails to implement the best solutions and often copy conservative or similar designs from previous projects. A large amount of money has been wasted in some places on wrong solutions, where applied designs led to a massive amount of excavation, concrete, support with sprayed concrete/concrete, rock anchors and other support systems. The hydraulic challenge with bypassing large dams with huge volumes of water generated during floods is to dissipate the energy before it causes an erosion problem downstream the dam.

In Myanmar, the spillway solution is established as a stepped spillway in bedrock, solely making use of the bedrock, blasted in steps for bypassing the floods. The stepped spillway in rock dissipate sufficient kinetic energy and disburse it such that a large stilling pool/basin is not required. Compared to a typical approach with chute and spillway the savings are estimated to be large. On RCC dams; stepped downstream faces constructed as spillways can allow for q = 12 – 15 m^3/s/m discharge and as such can allow for free overflow and avoid construction of additional spillway systems with separate spillway structures. This can enable huge cost savings. Solutions exist where additional energy dissipaters have been established downstream RCC overflow structures ("Robert's Splitters") and proved increase to unit flow 80 m^3/s/m. The cost of establishing such dissipaters (concrete blocks), compared to separate spillways systems (with gate control) could be significant.

The spillway and flood diversion of Kafue Gorge Lower in Zambia and evaluation of the design solution, spillway arrangement and stilling basin is a case study in the thesis work, alternatives to established design and benchmark various solutions with respect to cost/schedule and risk to get a balanced comparison with implemented design.

2. Main content for the thesis

The thesis shall cover, though not necessarily be limited to the main content listed below.

2.1 Literature and desk study

The candidate should study various spillway/diversion systems established on dam projects internationally. Different design concepts must be found and should be separated by parameters as discharge Q, unit discharge q, head H and costs [US$] or others. The projects can be medium to large and should be in regions with typical large floods but also regions with moderate floods. Both concrete/RCC and rock fill dams should be represented. This part will be a brief study with open sources to determine the potential. Furthermore, this should give some indications towards the value of investment in design optimization versus the potential of savings.

2.2 Main tasks

Related to the literature the following must be carried out:

1 Evaluation of design concepts
2 Hydraulic calculations for the concepts
3 Design of a small scale model for experimental use
4 Possible testing of parameters in the physical model
5 Cost evaluation of the concepts
6 Conclusions and presentation

3 Supervision and data input

Associate Professor Elena Pummer will be the main supervisor and Professor Leif Lia and MSc Øystein Lilleland in Norconsult will be the co-supervisors. Technicians in the lab will assist during the possible lab work.

Discussion with and input from colleagues and other research or engineering staff at NTNU, Norconsult, Sintef, NVE, power companies, other consulting engineers etc. is recommended. Significant inputs from others shall always be referred in a convenient manner.

The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context. The candidate and the supervisors are therefore free to introduce assumptions and limitations which may be considered unrealistic or inappropriate in a contract research or a professional context.

4 Report format and reference statement

The report should be written with a text editing software, and figures, tables, photos etc. should be of good quality. The report should contain an executive summary, a table of content, a list of figures and tables, a list of references and information about other relevant sources. The report should be submitted electronically in B5-format .pdf-file in DAIM/Inspera, and three paper copies will automatically be handed into the department. The Master's thesis should be submitted within 20 weeks plus the official holidays during the spring semester.

The executive summary should not exceed 450 words and should be suitable for electronic reporting.

Trondheim 16th of January 2019

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Elena Pummer
Associate Professor
Department of Civil and Environmental Engineering
NTNU

ACKNOWLEDGEMENT

First and foremost, I would like to express my sincere gratitude to my thesis supervisor, Elena Pummer. Her continuous support, helpful suggestions, and encouraging feedbacks played an important part in the timely completion of this study. Thank you for the patience, for the support and guidance throughout the study.

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This part is incomplete without acknowledging the technical as well as the physical help from Geir Tesaker from the Hydraulic Research lab, NTNU. His suggestions regarding the setting up of the model, choosing the measurement methods, and for arranging all the equipment is worth mentioning and I am thankful to him for that. I am also thankful to Trond Høiås for his physical help with setting up the tank and the pump.

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ABSTRACT

Water is an imperative source to human life. The change in climate is affecting the availability of water round the year which combined with increasing water demand has become a global problem. This has rendered water storage as the only option for proper management of water. Construction of dams for the storage helps in the field of, flood control, navigation, power generation, irrigation, drinking water, and recreation. The inability to store all the water in the river streams economically while also maintaining a high level of safety, leads to the problem of conveying the excess water safely to the downstream. Construction of steps on spillway chute, construction of plane chute with stilling basins, flip bucket structures with plunge pool, and construction of energy dissipators like Roberts splitters and baffle blocks are some of the adopted methods for dissipating the energy of the flowing water.

Stepped spillways are efficient at dissipating the flow energy as the water flows down the steps. This design method has been adopted for a long time for its easy to build design, structural stability provided and the energy dissipation ability. In this study, the energy dissipation capability of the stepped spillway was tested in a physical hydraulic model. The effect of discharge rate, step dimension, and surface roughness on the energy dissipation rate has been tested. In addition, the change in energy dissipation with a change in spillway height has been studied. Furthermore, the viability of constructing stepped spillway in an unlined rock has been looked briefly.

The results obtained show a high energy dissipation efficiency for all the steps tested with the dissipation efficiency reaching as high as 93% for a low flow rate. For a constant step height to length ratio and for the same discharge, the dissipation efficiency was found to be higher for the bigger steps. Introduction of surface roughness further improved the dissipation efficiency. The construction of a weir on the steps to create pool of water was found to increase the dissipation efficiency considerably. Dissipation was considerably high for low discharges for which fully developed hydraulic jump was created for the falling jet. An inverse pattern between the discharge and energy dissipation was observed in the test.

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CHAPTER 1 INTRODUCTION

1.1 Water and Dams

Water, a necessity, has always seen a rise in demand from the very starting of civilization and the trend is expected to continue in the future. Through time, the use of water has just diversified. Water demand in all the fields is expected to increase in the years to come (Leflaive 2012). The changing climatic condition is an additional challenge to the proper management of this imperative resource. The changing climatic condition is predicted to make the extreme event more frequent. The droughts will be longer, and the extreme precipitation will be more common causing frequent and severe floods (Easterling et al. 2000). The increasing need and the adverse climatic conditions make it an obligation to preserve, store and manage water in an efficient way. Efficient use, reduced wastage and conservation of water sources are always some of the ways for making the water resource last longer. Some applications of water like drinking supply, hydropower, irrigation and many more require a constant flow and storage to provide the need at any time. The application of water for such purposes makes its retention inevitable. Dams (barriers) are constructed to cease the flow of water to impound the water and form a reservoir.

The attempts to store water have been done for a long time. The history of dams can be traced back to 3000 BC when the first dam was constructed in Jawa, Jordan for the supply of water to the town of Jawa (Schnitter 1994). The purpose of the dams in the initial days was limited to providing water for drinking supply, irrigation and for flood control. In the region with dry riverbeds where the rivers were dry for most time of the year and flooded during the rainy season, dams were used to store water for the year-long use in the dry periods This helped to sustain the civilizations in those areas. The irrigation facility provided by the construction of the Hoover dam in USA helped to convert the arid zones of Imperial Valley and Yuma Plains to rich agricultural land (Takahasi 2009). Construction of Aswan Dam on the Nile has proven to be an important factor for the growth of the Egyptian economy (Takahasi 2009). The dams provide many more advantages in flood protection, transportation and navigation, electricity generation and recreation. These dams, based on the requirement can be small to large and based on the type of construction and the material used, can be of different types.

1.2 Spillway and its Need

The construction of a dam creates a high barrier which prevents the water from flowing downstream. With a higher dam, the water storage increases and so does the difficulty to convey the minimum flow, water exceeding the maximum storage level and flood water to the downstream. The water overtopping is disastrous in case of embankment dams and may even result in the failure of concrete dams in presence of any discontinuities or cracks. Overtopping has been the reason for a large number of the embankment dam failures resulting in large economic losses and casualties (Jandora & Říha 2008). Along with this, the water falling from such a height has enormous kinetic energy which if not dissipated effectively, may result in downstream river stream and riverbank erosion. This erosion in turn may erode the dam toe and collapse the dam itself. Erosion can also occur in the internal dam body which is one of the leading cause of embankment dam failure (Jandora & Říha 2008).

The high-velocity turbulent flow may also affect the nearby structures like powerhouse in case of hydropower plants, water conveyance channels and water treatment plants for drinking water system. These failures are a huge economic loss and may also turn catastrophic for the downstream biodiversity and human settlements. To convey the excess water safely to the downstream and to dissipate the energy before it affects the riverbed and/or the riverbanks, spillways are designed along the dam body or on the sides and a desilting basin is designed at the bottom.

As the climate change elevates the need for dams to store water for the dryer periods, the short-term flood events make it arduous to safely transfer the excess water from these dams to the downstream. People have long tried to find a way to transfer this water with least residual energy to the downstream, either by dissipating the energy of the flowing water on the course of flow, down the slope or, at the stilling basin at the bottom. Different approaches like flip bucket structures with plunge pool, Roberts splitters, and baffle blocks, which increase turbulence and aid in energy dissipation have been tried. Some of the proven design methods to dissipate energy are construction of steps along the spillway or/and to design a stilling basin at the spillway end where hydraulic jump could be developed dissipating a large amount of flow energy (Chanson 2002).

1.3 The objective of the Thesis

The objective of this thesis is to study the literature in the open stepped channels and spillways, understand the flow characteristics like the flow type for different discharges and different step sizes, the mode of energy dissipation in different flow types, on the steps, look into the physical hydraulic modelling done and design a physical model to verify the effectiveness of stepped spillway in dissipating energy. Effect of different parameters like the step size, height of spillway, and the discharge on the spillway, is to be tested and the results to be reported Literature review related to the possibility of constructing stepped spillways in unlined rocks, examples of such construction and the difficulties associated with their construction is also to be investigated

1.4 Organization of the Report

The entire report has been divided into seven (7) chapters and each chapter is further divided into sub-chapters. The 1st chapter deals with the basic introduction to the need for water, dams and spillways. The 2nd and 3rd chapters are literature review. Chapter two focuses on the history of the stepped spillway, the flow characteristics in the stepped spillway, energy dissipation on the steps and on the history and possibility of the stepped spillway in unlined rocks. Chapter three scrutinize the contribution of different researchers in the field of stepped spillways and the outcome of their research in short. The literature is later used to identify the flow types, flow characteristics and to determine the mode of energy dissipation. Chapter four describes the construction of the model, the instruments used, and the steps taken to conduct the test. Chapter five deals with the presentation of results without commenting anything on the obtained result. Chapter six discusses the outcome of the result and chapter seven concludes the work done along with the recommendations for further research in the field.

CHAPTER 2 STEPPED SPILLWAYS

2.1 History and Development

The stepped spillways have been around for a long time now. The first identified stepped spillway were the stepped overflow weirs built in Akarnania, Greece, built around 1300BC (Chanson 2002). The stepped spillways along with the application for energy dissipation were constructed because of their simple design and their additional advantage of providing stability to dam or weir structure. The stepped spillways were developed by many of the ancient civilizations independently, constructing as much as 16 dams with such structures in ancient times (Khatsuria 2004). The spillway height of those structures varied from 1.4 to 50 meters, handling a discharge up to $9000m^3/s$.

The Spanish learnt the art of designing and constructing overflow stepped spillways from the Roman and Moors and applied the knowledge to build the dam with the largest stepped spillway of the time, the Puentes dam in the 18th century. They spread the technology around Europe and North America in the 18th century and a large number of dams with stepped spillways were constructed. More information on the velocity reduction of the steps was gained which led to the adoption of stepped spillways in most of the structures. Towards the starting of the 20th century, the energy dissipation capabilities of hydraulic jump ware discovered. This led to the focus on the construction of the stilling basin and creating jumps to dissipate energy rather than constructing stepped chutes. The repairing required by the stepped spillway was the main reason as the stepped spillways were mainly made up of granite blocks or low strength concrete in those days and eroded often(Chanson 1995).

The development of any new and better construction materials like the Roller compacted concrete and the reinforced gabion towards the 2nd half of the 20th century reignited the interest towards the stepped spillways. The stepped spillways were highly effective in dissipating the flow energy. This meant the reduction in the area required for the stilling basin and reduction in cost and space required. The advantages led to many engineers and scientists to work in the field of stepped spillways. Studies were conducted to understand the flow characteristics over the steps, the efficiency of steps in dissipating energy, optimization methods to make them more efficient and the ways to reduce construction cost for the projects using such spillways.

2.2 Flow types in stepped spillways

The flow over the steps in the stepped spillway is dependent on the chute slope, step height, step length, and the flow rate. Based on the characteristics derived on these parameters, the flow on the steps can be divided into two distinct flows, the nappe flow occurring for flatter slopes and lower discharges, and the skimming flow regime occurring for higher discharges and steeper slopes(Boes & Hager 2003; Chamani & Rajaratnam 1999; Chanson 2002). There exists an intermediate flow regime for the flows between nappe and skimming flow with unstable flow, high splashing and high flow variation.

2.2.1 Nappe Flow

For the low discharge and in the flatter steps with high step height to length (rise/tread) ratio, water flows as a free-falling jet (nappe)(Boes & Hager 2003; Chamani & Rajaratnam 1994; Chanson 2002; Felder 2013; Sorensen 1985). The falling jet falls a certain distance on the next downstream. The point where the falling nappe meets the next step is known as the point of impact. At the point of impact, a hydraulic jump with a roller is created where the falling jet rises again and falls on the next step. Though this is the general phenomenon, as the discharge increases, the flow still remains in the nappe flow regime, but the hydraulic jump may only develop partially or may not develop at all. The falling nappe creates an air cavity behind it and a pool of water beneath the cavity. A figure of a nappe flow on the stepped chute with an air cavity and recirculating water pool is shown in Figure 1.

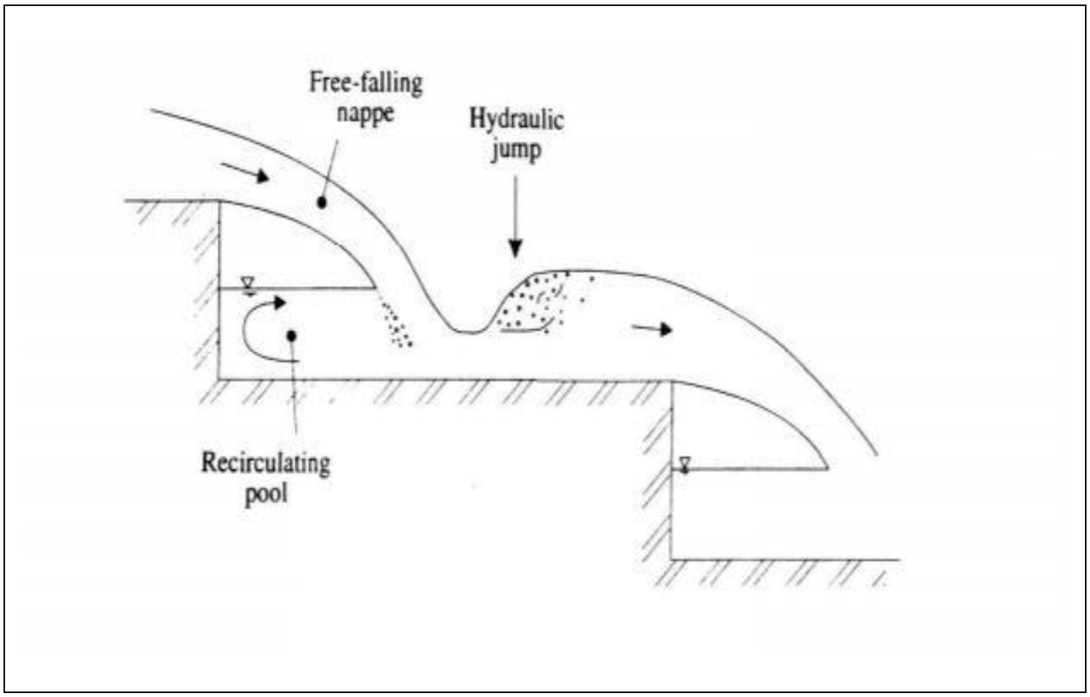

Figure 1: Nappe flow with a hydraulic jump (Chanson 1996)

The energy dissipation in nappe flow occurs due to jet break up in the air, mixing of the jet with the recirculating water on the downstream step and in case of hydraulic jump development, the hydraulic jump dissipates flow energy too (Chamani & Rajaratnam 1994; Chanson 2002; Sorensen 1985). The main characteristics of the nappe flow is the falling nappe and the air cavity below the falling nappe.(Renna & Fratino 2010) Depending on the development of the hydraulic jump, the hydraulic analysis of nappe flow differs.

2.2.2 Skimming Flow

The higher discharge in the spillway prevents the formation of nappe and the flowing water just skims through the step edges as it flows downstream. The fast-flowing water creates a pseudo bottom at the edge of the steps and flows down the spillway as a coherent stream (Boes & Hager 2003; Chamani & Rajaratnam 1999; Chanson 1998; Felder 2013; Sorensen 1985). The air cavity present in the nappe flow is completely displaced and water recirculating vortices are formed beneath the pseudo bottom on the steps. The water flowing creates a shear stress which keeps the water recirculating. Figure 2 shows the skimming flow through the stepped spillway and its gradual aeration. Skimming flows are highly aerated after the inception point and because of this air entrainment, the flow depth bulges.

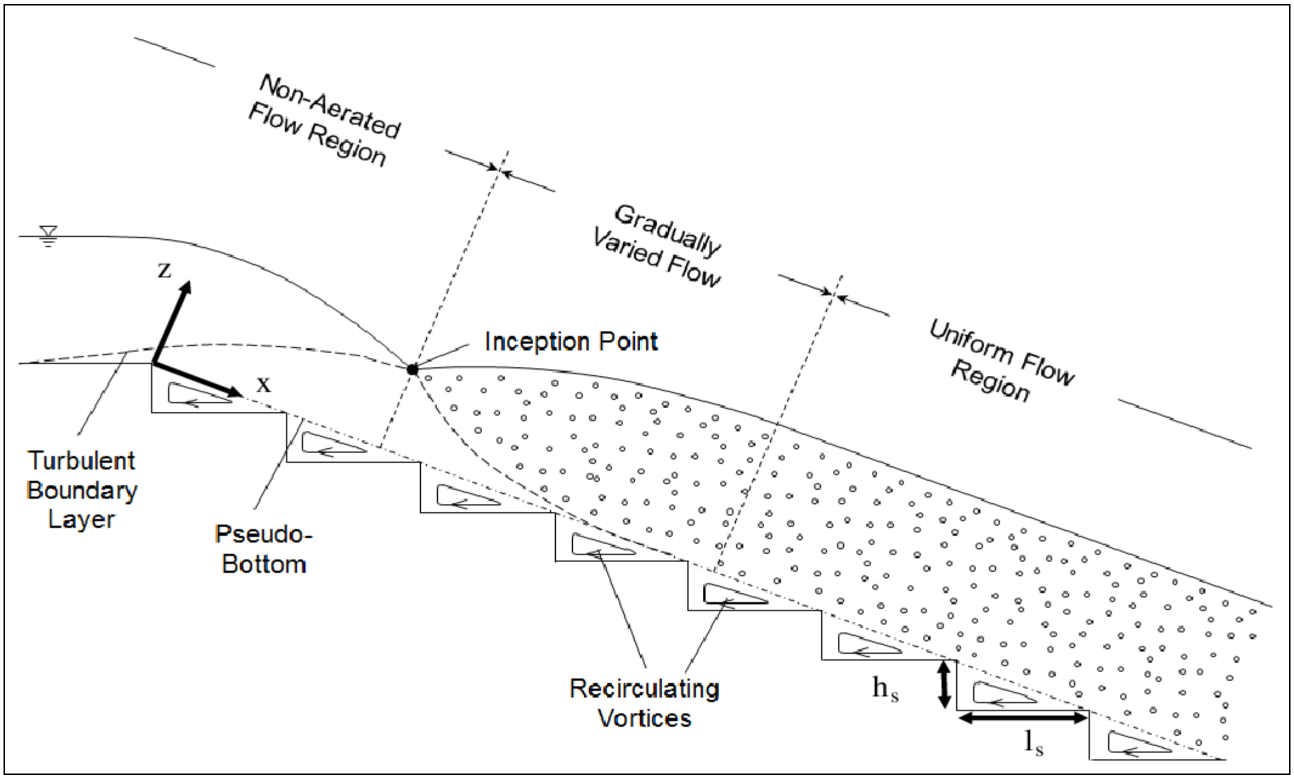

Figure 2: Stages in skimming flow over stepped chute (Van Alwon et al. 2017)

The energy dissipation in skimming flow is caused by the momentum transfer of the flowing water to the recirculating vortices. The entrained air also assists in energy dissipation. Though the dissipation efficiency is higher in nappe and transitional flow regime, spillways are generally designed in skimming flow regime. The flow in the nappe and transitional regime could be unstable, so the spillway is designed in skimming flow regime for maximum discharge (Felder 2013)

2.2.3 Transition flow

The discharge value in the upper range of nappe flow and in the lower range of skimming flow shows a chaotic behavior. The flow shows irregular splashing of water droplets as the water flows on the downstream step after the inception point (Chanson 2002; Chanson & Toombes 2002). The flow though in between the nappe and skimming flow, shows neither the clear free-falling nappe drops, neither the clear skimming characteristics. The air cavities beneath the falling water as seen in the nappe flow are fluctuating in transition flow regime, they are irregular in size and even keep disappearing in between. The falling jet still hits the downstream step edge and the flow seems like coming in the stagnation stage at the point (Khatsuria 2004). The transition flow properties are difficult to predict based on theory only.

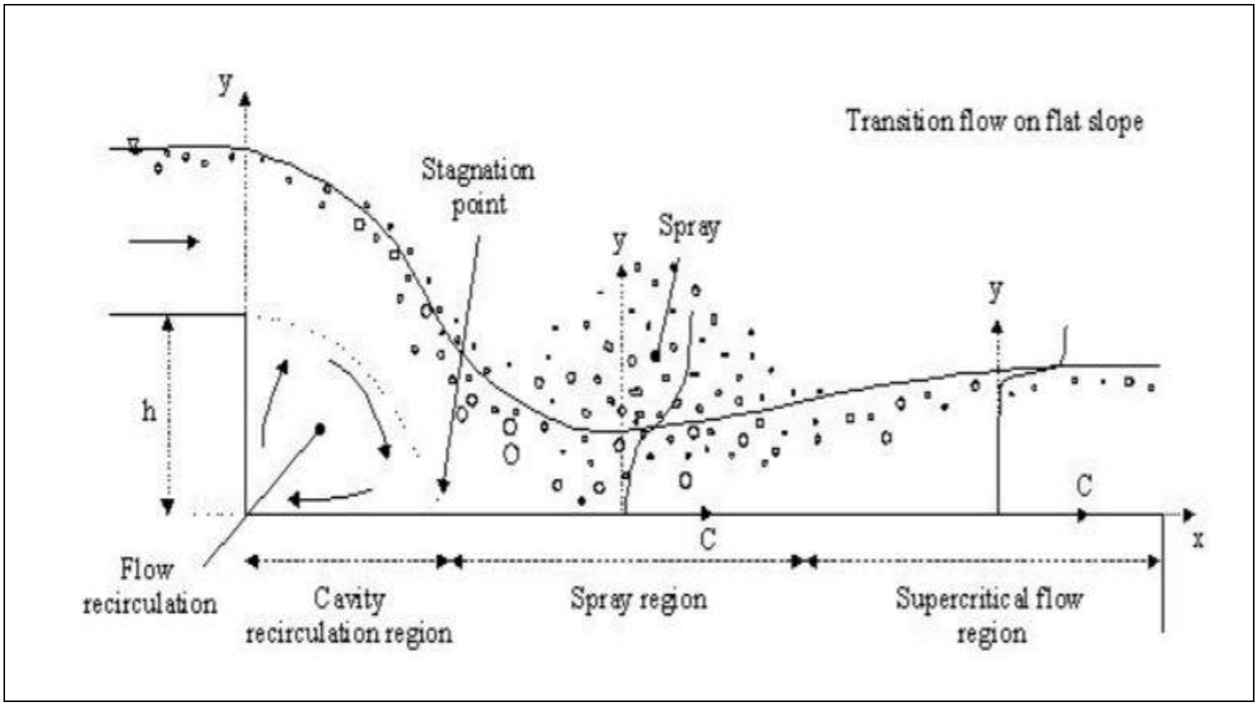

Figure 3: Transition flow regime on a stepped chute (Chanson 2001)

Figure 3 shows the development of the aeration zone for transition flow, and the air entrainment and splashing after the inception point. The design of spillway into this uncertain regime must thus be avoided and if avoiding is not possible, proper physical modelling must be done and attempts must be done to have transition flow only at small discharges (Chanson 2001; Chanson 2002).

2.3 Stepped Spillway in Unlined Rocks

The history of the stepped spillway is old and so is the tradition of making the steps in the rocks. The inceptive days stepped spillways were either cut into the rock itself, made up of cut masonry or were constructed with timber (Chanson 2000a). The unlined spillway of James Bay La-Grande-II project, an immense structure, 1.8km long with 10 steps of 10-12 meters each and a total vertical drop of 110m is shown in Figure 4.

From the development of first unlined spillways in Akarnania, many notable spillways were constructed in unlined rocks. Ternay Dam, France (1968), Gold Creek dam, Australia (1885), Dartmouth dam, Australia (1977), La Grande 2, Canada (1982), and Lower Paunglaung Dam, Myanmar (2004-05) are some of the examples of remarkable dams with unlined spillways(Chanson 2002; Khatsuria 2004). The unlined spillway of Gold Creek dam was damaged by large overflows(Chanson 2002) and the Dartmouth dam spillway was eroded by flow concentration during a flood(Chanson 2000b). The unlined steps were then replaced by concrete lined steps.

Figure 4: James Bay LG-2 spillway (Impregilo 2019)

Developing stepped spillway in unlined rocks need good geological condition. Rock quality, erosion potential, the height of fall, turbulence resulting in varying pressure and velocity must be studied in detail before adopting the unlined stepped spillway. In addition to these parameters, the economic parameter also matters. The usability of the excavated rock in the dam construction could lead to a further reduction in cost and in case of rockfill dams, all or part of the rockfill could be from the excavated material.

2.4 Energy dissipation and advantages

Energy dissipation is one of the most important characteristics of the stepped spillways. Due to the energy dissipation capabilities, many dams were built with stepped steps in the past. But these structures were not durable and needed constant repairing which led designers to use stilling basins instead. The development of new, durable construction materials has reignited the interest in the field of stepped spillways.

On the stepped spillways, when the water flows over the steps, the steps act as the surface roughness, exerting resistance on the flow and thus reducing velocity and as a result, the energy. The flow resistance is mainly because of the flow recirculation, jump development, unsteady momentum exchange and jet mixing. Sorensen (1985), Chamani & Rajaratnam (1999), Chanson (2002), and Felder & Chanson (2009), all conducted physical study of the energy dissipation on the stepped spillways and found a high efficiency for energy dissipation on the steps.

The energy dissipation capability of the stepped spillway reduces the area of the stilling basins required at the bottom. In some cases where the riverbed surface is strong, the steps alone can provide the energy dissipation required and no space for the stilling basin is required. This is highly economical as the excavation for the stilling basin could be costly and, enough space for stilling basins is not always available. The stepped spillways, in addition to the energy dissipation, provide structural stability to the dam structure and are economical compared to other alternatives (Peyras, Royet & Degoutte 1992).

CHAPTER 3 REVIEW OF RESEARCHES IN THE FIELD

The research about the field of stepped spillways started very late in respect to their development. The concept of the stepped spillway is more than 3000 years old with a large number of dams already designed around the world before the initiation of research on the flow characteristics and energy dissipation along the stepped chute.

Essery & Horner (1978) were probably the first researchers trying to study the flow characteristics in the stepped spillway. Physical model tests for several slopes with different step height to width (tread) ratio, different step inclination, and different step numbers were conducted. Velocity measurements were taken downstream of the stepped spillway on the horizontal section where the flow seemed free of entrapped air. The specific energy E_s at the spillway toe was calculated using the velocity as

$$E_s = d + \frac{v^2}{2g} \tag{3.1}$$

Where, d is the flow depth, v is the flow velocity, and g is acceleration due to gravity.

Based on the observations, they also tried to classify the flow into isolated nappe, interference nappy and skimming flow. Different dimensionless parameters were calculated, and several plots were made for the model parameters and the measured and observed values.

Sorensen (1985) conducted physical hydraulic modelling for Monksville dam in New Jersey, USA. Tests were conducted on 3 models of scale 1:10 and 1:25. Since, no data on the energy dissipation efficiency of the steps was available at the time, the main aim of the tests was to see the energy dissipation efficiency and to study the flow transition from smooth ogee crest to stepped chutes. The flow transition was found to be smooth for the desired flow rates and the energy dissipation was found in comparable range with the same spillway model with hydraulic jump and stilling basin at the toe. Inception point and aeration characters were observed but no conclusion on the impacts of these was drawn.

Rajaratnam (1990) used the experimental results from Sorensen (1985) and Essery & Horner (1978). Based on the results, Rajaratnam classified the flows into nappe flow and skimming flow. He identified the flow as nappe when the flow from each step hits the consecutive downstream step as a falling jet and defined skimming flow as the flow with a coherent stream which skimmed through the step edges and created a flow recirculation in between the coherent stream and the steps. According to him, energy dissipation in nappe flow was as a result of jet breakup in the air, jet mixing on the steps with or without formation of hydraulic jump. Similarly, energy dissipation in skimming flow was due to momentum transfer of the flow velocity to the recirculating vortices. Rajaratnam also worked out the equation to calculate the turbulent shear stress in the recirculating flow below the pseudo bottom formed by the flow in skimming flow and the frictional energy loss of the skimming flow.

He expressed the shear stress (τ) in terms of coefficient of fluid friction (c_f) and calculated the energy at the toe of the stepped spillway (E), energy at the toe of the smooth spillway (E') as

$$\tau = c_f \frac{\rho v^2}{2} \tag{3.2}$$

$$E = \left(\frac{c_f q^2}{2gsin\alpha}\right)^{1/3} + \left(\frac{qsin\alpha}{c_f\sqrt{2g}}\right)^{2/3} \tag{3.3}$$

$$E' = \left(\frac{c_f{}' q^2}{2gsin\alpha}\right)^{1/3} + \left(\frac{qsin\alpha}{c_f{}'\sqrt{2g}}\right)^{2/3} \tag{3.4}$$

And, the reduction in energy at the toe of the stepped spillway to the smooth spillway, ΔE is given by:

$$\Delta E = E' - E \tag{3.5}$$

$$\frac{\Delta E}{E'} = \frac{(1-A) + \frac{F_o'^2(A^2-1)}{2*A^2}}{1+\frac{F_o'^2}{2}} \tag{3.6}$$

Where, c_f is the coefficient of fluid friction, F_o' is the Froud number at the toe of spillway, q is discharge per unit length of spillway, ρ is mass density of the fluid, α is the slope of the spillway chute, $A=(c_f/c_f')^{1/3}$ and $\Delta E/E'$ is the relative energy loss.

Rajaratnam estimated the relative energy loss considering a very high Froude number to be equal to ((A^2-1)/A) and got a value of 8/9 suggesting a high energy loss in accordance with the results of Sorensen (1985). From the results of Essery & Horner (1978), Rajaratnam derived the break point for the flow change from nappe to skimming for horizontal steps. He expressed the break point as a ratio of critical depth d_c to step height h. He concluded that for $d_c/h>0.8$ skimming flow occurs and for values below that, nappe flow occurs.

Chanson (2002) has summarized his work as well as the studies done by other researchers in the field of stepped chutes and spillways. In the already present flow types, Chanson introduced a new flow type, the transition flow regime. For a constant step geometry, when the flow rate is increased, the flow regime changes from nappe to skimming. But according to Chanson, there is transition flow regime in between in which the flow characters fluctuate between a nappe and a skimming flow. The flow has a recirculating pool with or without air cavity beneath and the fall has a stagnation point. Immediately after the stagnation point, the water spray is high and water deflection occurs. The flow in this regime changes from step to step and is highly chaotic and unstable. Strong suggestions have been made to avoid transition flow while designing the stepped spillways.

Based on the experimental and observed results, Chanson suggested the range for the nappe, transitional and skimming flow as a dimensionless ratio of critical depth to height (d_c/h). The critical depth d_c is calculated as

$$d_c = \sqrt[3]{\frac{Q^2}{gb^2}} \tag{3.7}$$

where, Q is the discharge (m^3/s) and b is the spillway width (m).

For Nappe Flow,

$$\frac{d_c}{h} < 0.89 - 0.4\frac{h}{l} \tag{3.8}$$

And for Skimming flow

$$\frac{d_c}{h} > 1.2 - 0.325\frac{h}{l} \tag{3.9}$$

For the flows with values in between nappe and skimming flows, transition flow occurs. The derived conditions are tested for slope angle of 3.4°-60° and for the uniform to quasi-uniform flows.

To check for the development of hydraulic jump on the steps in nappe flow regime, equations were developed to see the distance to the jet impact point on the step downstream and the length of the roller created for the jump.

$$\frac{d_1}{h} = 0.54 * \left(\frac{d_c}{h}\right)^{1.275} \tag{3.10}$$

$$\frac{L_d}{h} = 4.30 * \left(\frac{d_c}{h}\right)^{0.81} \tag{3.11}$$

$$\frac{L_r}{d_1} = 8 * \left(\left(\frac{d_c}{d_1}\right)^{3/2} - 1.5\right) \tag{3.12}$$

Here, d_1 is the flow depth at the point of jet impact, L_d is the distance from the drop wall to the impact point and L_r is the length of roller created because of hydraulic jump.

When the sum of the length to impact (L_d) and length of roller (L_r) is less than the length of the step (l), a fully developed hydraulic jump occurs.

And the equation to calculate the rate of energy dissipation or the dissipation efficiency is

For nappe flow in ungated chute

$$\frac{\Delta H}{Hmax} 1 - \frac{0.54\left(\frac{d_c}{h}\right)^{0.275} + 1.715 * \left(\frac{d_c}{h}\right)^{-0.55}}{\frac{3}{2} + \frac{H_{dam}}{d_c}} \tag{3.13}$$

And for skimming flow in ungated chute is calculated as

$$\frac{\Delta H}{Hmax} = 1 - \frac{\left(\frac{f}{8 * sin\phi}\right)^{\frac{1}{3}} * cos\phi + \frac{1}{2} * \left(\frac{f}{8 * sin\phi}\right)^{-\frac{2}{3}}}{\frac{2}{3} + \frac{H_{dam}}{d_c}} \tag{3.14}$$

Annandale (1995) evaluates the erodibility of the earth materials and rocks. A relationship between the energy dissipated in the spillways and the erodibility index has been developed. Filed observation for 137 spillway performance has been incorporated to develop a plot to see the critical threshold for the initiation of the rock erosion. The erodibility index has been derived from the Kristian's rippability index which relates the excavation power of the equipment to the rippability of the rocks and earth material. Both methods are based on the Barton's Q system which determines the rock strength.

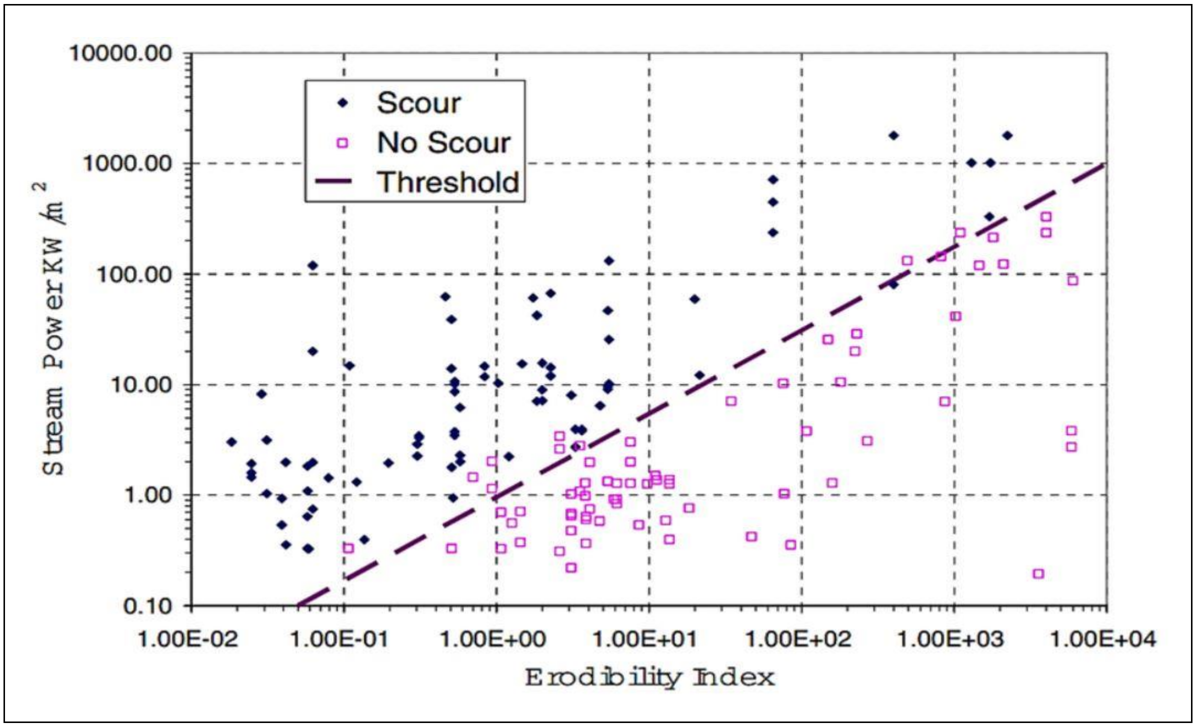

Figure 5: Erodibility threshold for rocks and other strong earth materials (Annandale 1995)

The parameters used to calculate the rippability of the rocks are based on the rock mass strength number M_s, particle block/size number K_b, discontinuity in the rock K_d and relative ground structure number J_s.

The erodibility index (K_h) is calculated as

$$K_h = M_s . K_b . K_d . J_s \tag{3.15}$$

And erosion for a rock material occurs if,

$$P > f(K_h) \tag{3.16}$$

Where, P is the dissipated energy at the rock face.

CHAPTER 4 METHODOLOGY

The knowledge from the theoretical literature was tested practically at the Hydraulic Research Lab at NTNU. A stepped spillway model was built in the lab and tested with different step dimensions and discharges to see the flow characteristics, velocity change and the change in energy head.

4.1 Design of the Model

The model was built on an already existing wooden chute used previously for other experiments. The chute slope was non-adjustable and was fixed at 25º. The steps were so designed that the step height(rise) to width (tread) gave an inclination of 25º, making it stay supported on the slope. The idea of the tests to be conducted was just to see how the water flows over the steps and how it behaves. The model didn’t depict any real prototype and making the choice about the dimensions of the steps was open to the student (me).

The available chute was built on a section 1.45m high and 3.1m long horizontally. The sidewalls were 0.30m high on both sides with some portion of it made with transparent glass while the rest was made up of plywood. The sidewall to sidewall width of the chute was 0.60m. There wasn’t enough space remaining behind the already built up model, so the tank used for the experiment was inclined on the chute itself reducing the length of the available chute for steps. Further, as we were not modeling a real prototype, steps were just built on a fraction of the chute to keep the material usage low. The remaining bottom part of the chute was left untouched and was not considered during the experiment.

4.1.1 The Tank

A rectangular tank of the dimension 1m X 0.6m X 0.6m (lxbxh) was used for the experiment. One end of the tank was removed for the water to flow out to the spillway. The open end was fitted with nets to reduce the undulations and to obtain a laminar flow. A small barrier (12cm) was kept in the middle of the tank length. The water from the pump was collected into the rear part and then flowed into the front part minimizing the effect of pump. The tank was inclined lengthwise on the chute and fixed with the help of screws. The tank had small supports at the bottom (as we used an already available tank) which created some gap between the chute and the tank bottom. A step was placed to make up for the gap and create a uniform level from the tank to prevent the formation of a hydraulic jump in the gap.

4.1.2 The Spillway Model

The chute was fitted with steps over a span of 1.8m. Two sets of steps with different dimensions were used for the test. The first set of steps had a height of 0.047m (4.7cm) and step width of 0.1m (10cm). In the report, these set of steps are identified as “Step A”. The second set of steps were 3 times the size of Step set A with a height of 0.141m (14.1cm) and width of 0.30m (30cm). These set of steps are identified as “Step B” in the report. The third type of steps, pooled steps were created by adding obstruction (weir) to the edge of each step. The weirs were long enough to cover the whole width of the spillway i.e. 0.60m and were 0.016m (1.6cm) in height and 0.03m (3cm) in width. These weirs helped to create a pond on the steps which gave a cushioning effect on the falling water. Pooled steps were tested only for the Step B set and are identified in the report as “Step C”. The step configuration and the model diagrams are shown in Figure 6, Figure 8 and in Figure 7.

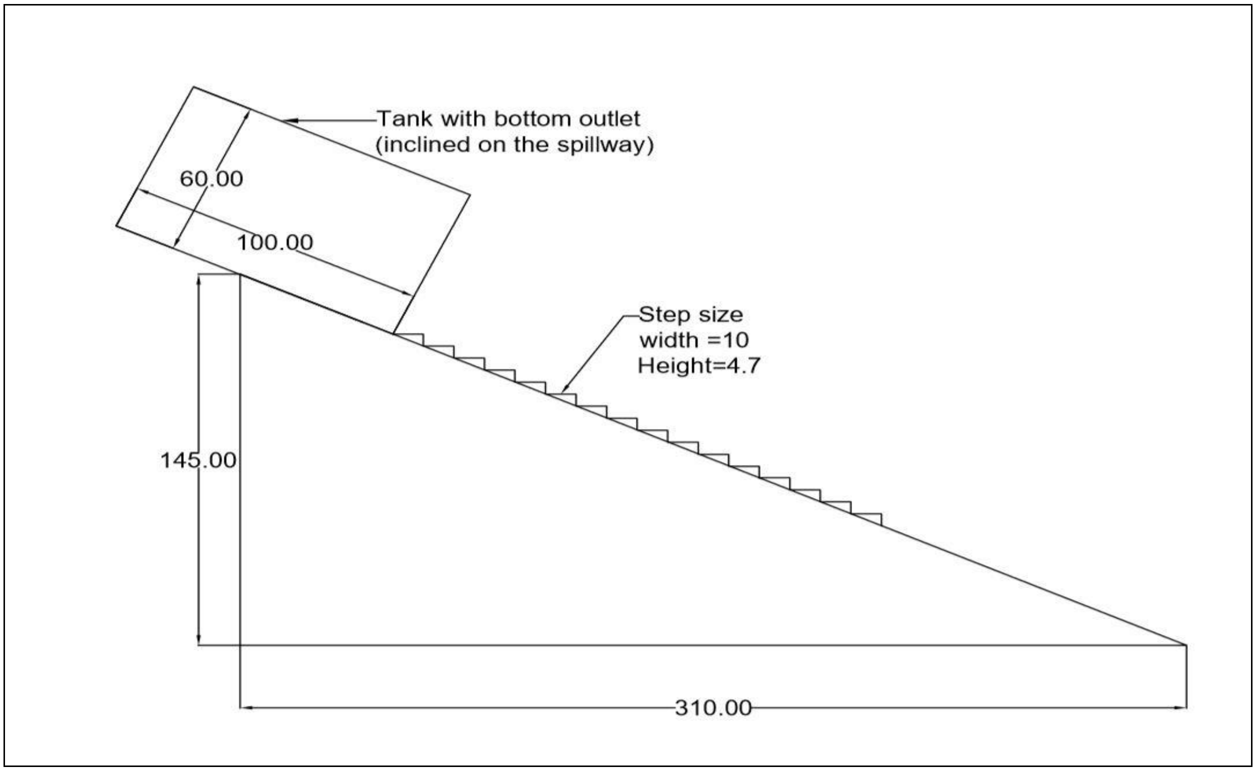

Figure 6: Diagrammatic sketch of model 1 with the step set “A”

For the construction of steps, plywood material was used, and screws were used to hold the steps in position. The aim of the project was to see the working of the stepped spillway in unlined rock. Due to the limitations of time, material and expertise, no tests regarding the rock characteristics and strength under the action of the falling water were possible. To create the feel of working on the cut rocks, tests were also conducted by introducing surface roughness on the steps. The steps were pasted with sand and fine gravel on the horizontal part after conducting the tests on the smooth steps. Epoxy was used to glue the particles on the steps. The test with the surface roughness was conducted for all 3 sets of steps. The steps without this roughness material are identified as smooth steps (S) and the ones with the roughness introduced are identified as rough steps (R) in the report.

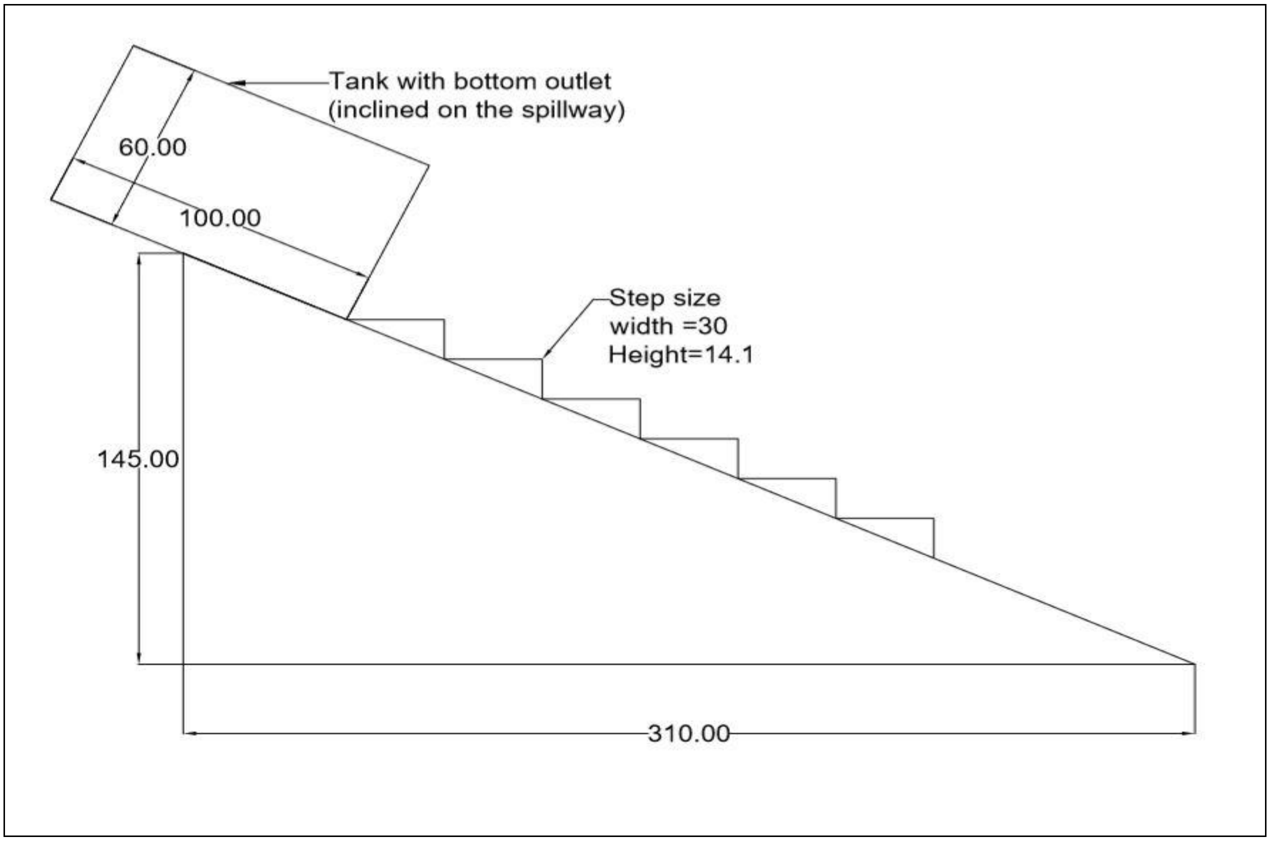

Figure 7: Diagrammatic sketch of model 2 with step set “B”

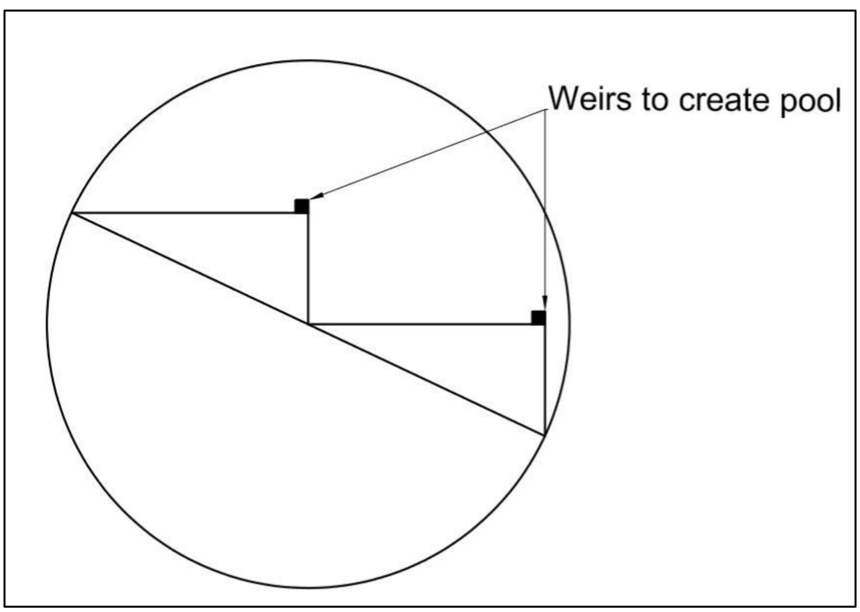

Figure 8: Weirs added at the step edge to create pooled step. Step set “C”

4.2 Selection of Instruments

The primary focus of the experiment was to find the energy dissipation efficiency of the stepped spillway. To calculate the energy head of the flowing water, the main parameters needed were the velocity of the flow, depth of water over the steps and the height of the steps above the spillway bottom.

4.2.1 Velocity Measurement

The velocity in a channel can be measured by a number of methods. Measurement using pitot tube, intrusive probes, conductivity electrodes, and using particle image velocimetry are some of the common methods considered for the purpose of velocity measurement in this study.

Pitot tubes works on the principle of pressure difference of water velocity and static pressure. The flow in the stepped spillways is highly aerated with air bubbles in the flow. These air bubbles obstruct the measurement of the differential pressure required in the pitot tube and result in erroneous results (Felder 2013). Because of this, the idea of using pitot tube in the study was not considered any further.

Phase intrusive conductivity probes are efficient at measuring interfacial flow velocity in aerated water. They are also capable of measuring the air concentration in the flowing water. The air bubble detecting electronic system converts the air/water resistance into voltage signals and these signals are recorded at a high rate (frequency). The acquired data is processed to obtain flow velocity, bubble count, void fraction and turbulence intensity (Felder 2013). For different studies, the intrusive probes were developed in their own research facilities based on the above-mentioned principle. Due to unavailability of the instrument in the lab, limited knowledge about its construction, and the time constraint to finish the study led to giving up on using developing one for this study.

Particle Image Velocimetry (PIV) was suggested as one of the options for velocity measurement. Using PIV required a well-organized set up with a closed section, enough transparent space on the model, high-end cameras and in most cases a laser. The compulsion to use an already existing spillway chute, the aim of making the study economic and the time constraint to finish the study averted the use of this method.

Conductivity electrode method, based on the principle of conductivity through fluid (water being the fluid in this study) was discussed as an option. The staff in the laboratory had some experience with the method and through discussions, it was suggested as the option to move forward with. The method is less prone to the effects of entrained air and provides the least resistance to the flow when designed and placed accurately

4.2.2 Depth Measurement

The measurement of depth in a flow over stepped spillway is a complex process. The presence of high amount of air makes the accurate measurement of depth difficult. Acoustic displacement meters are efficient in measuring the flow depths in both aerated and non-aerated flows. They can be calibrated to measure the difference between the water surface and the flow bed to know the depth. In the studies where the air content of the flowing water is known, it is easy to derive the actual water depth but as we lacked the air content data for our studies, acoustic displacement meters were futile. Measurements with the aerated depth could have been used for the study but the unavailability of the required number of sensors (all the sensors were in use for other projects), the method could not be used.

A simple measurement technique using a ruler to measure the flow depth on the steps was used as shown in Figure 9. The depth measurement using a ruler on the fluctuating and aerated water is a challenging task. Flow depths near the step edge after the point of impact and before the water starts to flow down to the next step were taken.

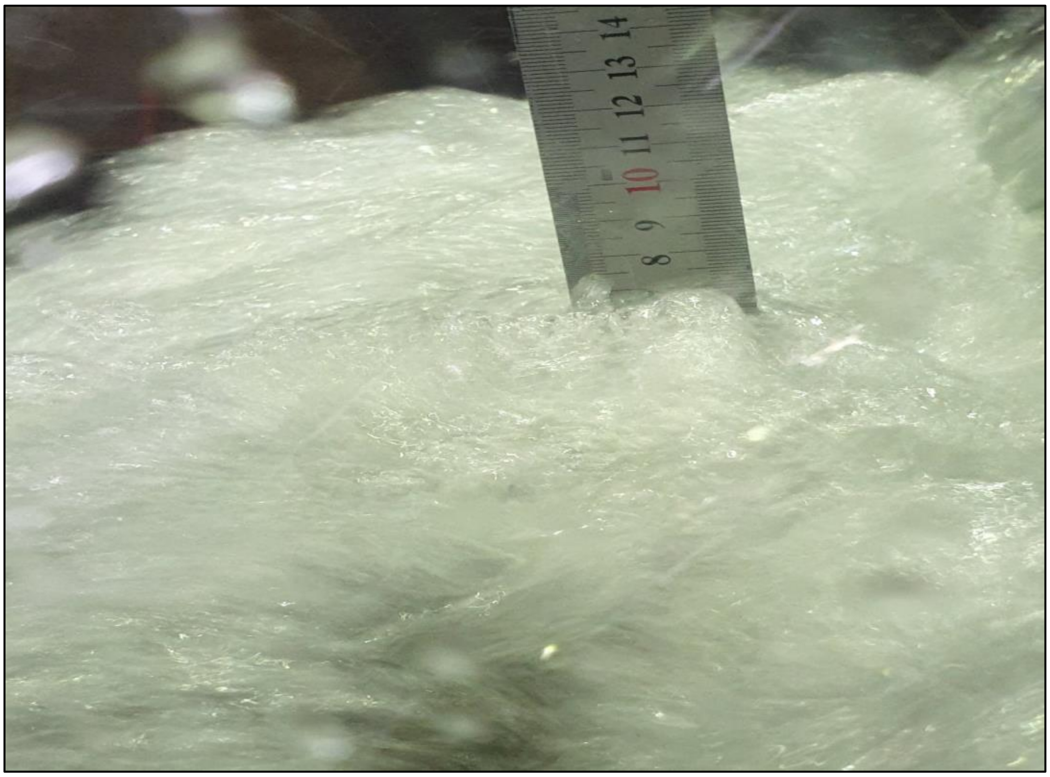

Figure 9: Flow depth measurement using a ruler

4.3 Working of the conductivity electrode method

The basic principle of the conductivity method, the steps in velocity measurement and the setting up of the electrode sensors are defined in this section

4.3.1 Theory of Conductivity

Conductivity refers to the ability of any material to conduct electricity through it. The conductivity in fluids is due to the movement of ions towards the electrically charged electrodes. The conductivity of pure water is negligible due to lack of free ions. Most of the water found around us has some or the other compounds which provide the ions required for the conductivity. As the content of these ions increase, the conductivity of the solution also increases. When two electrodes, positive and negative are immersed in the water and AC current passed through them, the electrical potential difference between the two electrodes is developed which can be read as voltage. Higher conductivity is reflected in the form of higher voltage.

4.3.2 Test Technique

The voltage obtained as mentioned in section 4.3.1 was the main parameter in our study. The conductivity of the flowing water was read using the sensors installed on the steps (installation explained in 4.3.3 Electrode (sensor) Installation). The conductivity was increased by adding saltwater. This resulted in a voltage increase. The voltage values when plotted against the time show a steep increase in the values when the saltwater reaches the sensors (Figure 10). Reading the rises gives the time when the saltwater reaches each sensor and from this time, the time taken by the saltwater to travel from one sensor to other can be calculated. This time interval is one parameter out of two parameters required to calculate velocity in Equation 4.1.

$$velocity = \frac{distance\ travelled}{time\ taken} \tag{4.1}$$

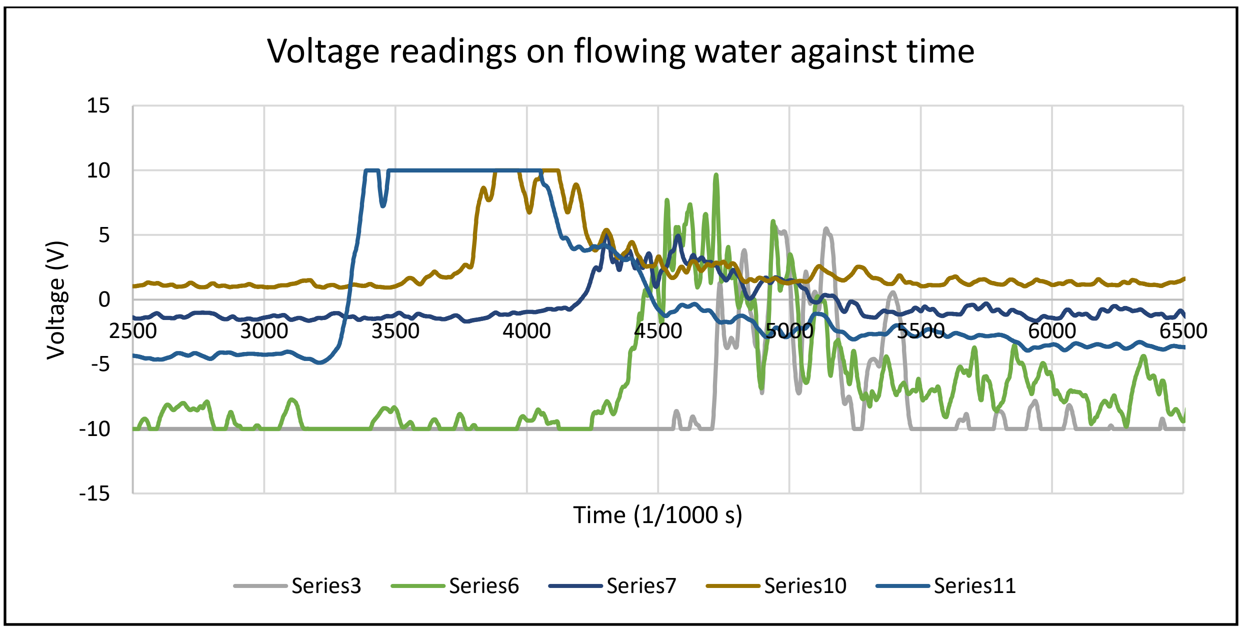

Figure 10: Voltage fluctuation with the change in water quality.

The distance travelled required in Equation 4.1 is measured directly on the steps as the distance between the two sensors can easily be measured using a ruler.

4.3.3 Electrode (sensor) Installation

Electrodes were required in pair whenever used, as two electrodes (one positive and one negative making one set of electrodes) were required to measure the potential difference between them. Additionally, as the velocity measurement is the ratio of the distance between the sensors and the time taken for the water to travel that distance, two sets of electrodes were required at minimum for velocity calculation. Placing the sensor sets far away with many steps in between will average the velocity for that distance. The velocity of the flowing water along the stepped spillway changes from step to step dissipating some energy on each step. Along with the velocity, the depth of flow also varies from step to step. Averaging the velocity over long intervals will limit the ability to see the dissipation pattern over the spillway length and will create confusion with the value of water depth to be used for energy head calculations.

The electrode sets were therefore placed on at least two consecutive steps so that the velocity is not averaged over longer lengths. The sensors were placed near the step edge at an identical distance from the edge on all the steps where electrodes were placed. This made sure the distance between the electrode sets was same and the flow conditions were same on all the electrode sets for the same flow rate.

A total of eight (8) electrode sets were used in the model A which consisted of 16 steps with four velocity measurements done as each velocity measurement required two electrode sets. The model B and C had 6 steps and each of them was equipped with a set of electrodes for the measurements. The position of the installed electrodes is shown in Figure 11.

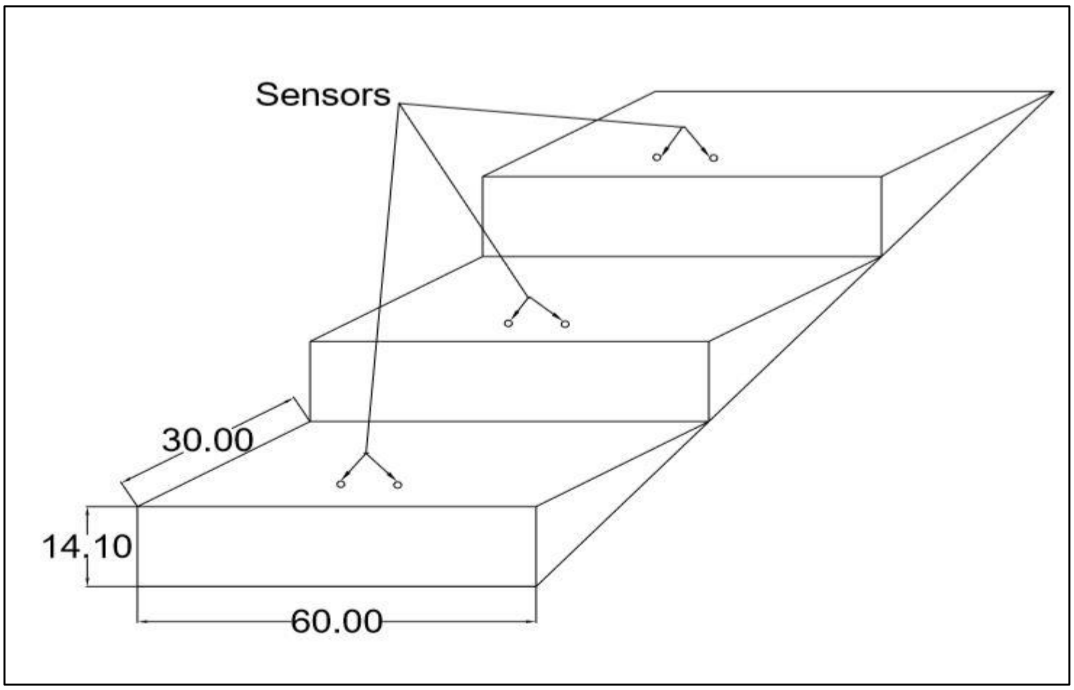

Figure 11: Sketch showing the location of the installed sensor on the steps.

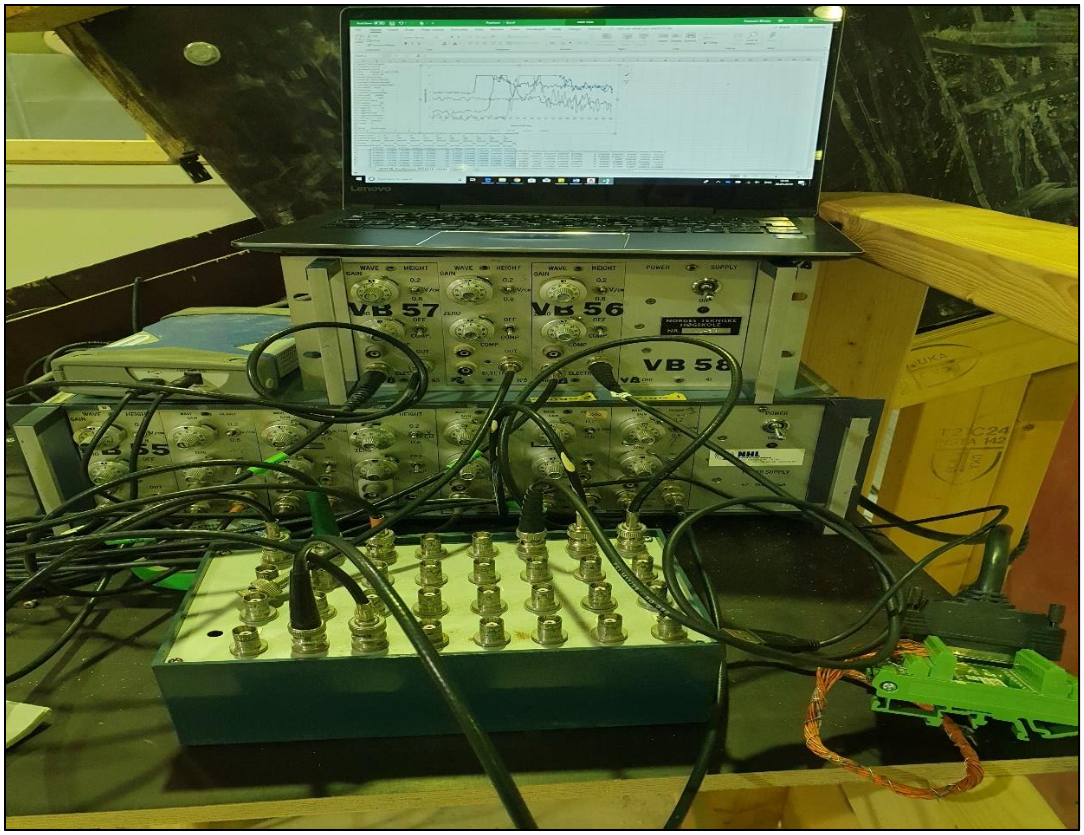

Figure 12: Instrument setup for data collection and recording

Locally available metallic bolts with high conductivity were used as the electrodes. Holes were drilled on the step edge where the electrodes were to be installed as shown in Figure 11. The electrodes were so arranged that their tops were at the same level as the step surface, thus creating the least disturbance to the flow.

These electrodes were connected to the amplifier through the connecting wires. The amplifier in turn was connected to a logger from Agilent technologies. The logger was connected to a personal computer to store the logged data. The whole set up was provided with electricity to function. The discharge was measured using an electromagnetic pump from Siemens with an accurate measurement up to 0.1l/s. A personal laptop was used for storing the logged data through the logger.

4.4 Procedure

Tests were started with the first set of steps, step set A. The electrode sensors were installed on eight of the sixteen steps. The steps with the sensors were so placed that we had two sets of sensors in a continuous series and the sensors were spread over the whole spillway. The position of the steps with sensors was 1,2,4,5,9,10,14 and 15. The electrodes were connected to the wire through which the conductivity signal pass to the amplifiers. A small cut was made on the side of the steps to make enough space to pass the wire out of the step. The wooden steps were then placed on the spillway chute starting from the top end. Measures were taken to check the horizontality of the steps and to level them perfectly to prevent tilting of the steps towards any of the sides. The steps were screwed well to ensure stability during the flow through them. The wires coming out of the steps were taped to the side wall and then passed to the amplifier box. Attempts were made to create minimum disturbance to the flow and the flow velocity. Any gaps present on the spillway were filled with a water-resistant sealing material to prevent the leakage of water out of spillway. The model picture with step set A is shown below in Figure 13.

The tests were then conducted at varying discharges. Five (5) different discharges were used for the test. $0.0032m^3/s$ (3.2l/s), $0.005m^3/s$ (5.0l/s), $0.01m^3/s$ (10.0l/s), $0.015m^3/s$ (15.0l/s), $0.025m^3/s$ (25l/s) flow discharges were used in the tests. The idea behind using the different discharges was to see the working of the model under all the three flow types mentioned by the researchers namely nappe flow, transition flow and skimming flow. The concept of nappe flow with fully developed hydraulic jump was not possible in step set A as the steps were too small even for a discharge as low as 1l/s. It was possible to test the steps in transition flow and skimming flow in the step set A. The step set B and C were too large to attain a transition or skimming flow in the steps even at the maximum test discharge of 25l/s. Testing with a larger discharge was not possible because of the short sidewall height.

The power supply to the measurement system was then turned on. This induced conductivity in the water and the electrical potential difference was measured by the electrodes. The measured signals were amplified by the amplifiers which were then read by the logger and logged into an excel sheet on the storage device (personal computer) as voltage values against time. The conductivity was changed(increased) by adding saltwater to the flowing water in the front part of the tank. This water flowed through the steps and whenever passed an electrode set, a sudden rise in the conductivity was recorded. These sudden rises were studied manually by plotting a graph of conductivity vs time. A sampling rate of 1000 was used to obtain higher resolution data, recording 1000 voltage values for each second of time.

After conducting the tests with all the mentioned discharges, the steps were dried, and the roughness material was pasted on the steps using epoxy. The purpose of the roughness was just to see if the roughness on the stepped spillway has any effect on energy dissipation. No definite particle size was chosen but a sand to fine gravel ratio of roughly 90:10 was used with the maximum sand size of 1mm and gravel size reaching up to 5mm. Figure 14 shows the step set A after applying the roughness material on the surface. The same tests were repeated on these roughened steps with the same discharges and the data was stored for further calculations.

The step set A was then detached and replaced with the second set, the step set B. As there were just 6 steps covering a horizontal distance of 1.8m, only 6 sensors were used, one on each step. The steps were placed with the same precision and screwed with the same accuracy. We missed to include the overlapping length for these set of steps. Because of this, the step length planned to be 30cm, was reduced to 28.5cm due to overlapping. After placing the steps, the sides and any gaps in between were sealed and let dry.

Figure 13: Smooth steps (set A)

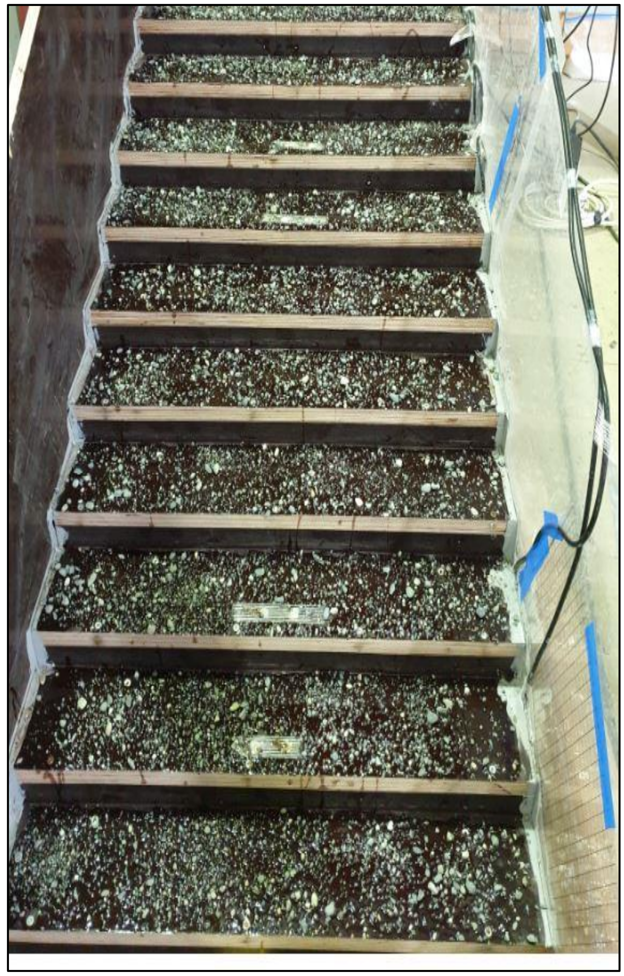

Figure 14: Rough steps (set A)

Tests with the same discharges were conducted for these set of steps. After completing the first set of tests, a weir equal in length to the spillway width and having a height and width of 1.6cm was introduced at the step edge by screwing it to the installed steps. The weir covered the whole step length so that water can be retained without any leakage, creating a pool of water on the steps when the tests were run. Test under the same discharges were conducted on these pooled steps too. After running tests with all the required flow rates, the roughness surface was introduced for these steps as well. Same procedure as adopted for step set “A” was followed for the step set “B” and “C”. The test results were stored for further calculations.

CHAPTER 5 RESULTS.

The results obtained from the tests were plotted as graphs as shown in Figure 10. The graphs were then read manually to see the rise in the voltage values indicating the arrival of saltwater. To get a more accurate value and to minimize the human or instrumental errors if any, each test was repeated four times. Four values of velocity were obtained for each case from the readings and an average velocity was used for the energy head calculation. Discrepant values which showed the possibility of errors were not considered for the calculations. A total of 120 tests were conducted for six different step types with each step type tested for five different flow rates.

Flow velocity and depth were measured based on the procedure mentioned in CHAPTER 4, and these parameters were used to find the energy head at different steps. Equation 3.1 is used to calculate the energy head. The equation 3.1 is a derivation of the Bernoulli's principle and calculates the energy at the toe of the spillway only. As we needed to calculate the energy head at different heights, the corresponding height from the spillway toe (in our tests, the height from the bottommost sensor) was added to the equation.

The velocity values and the calculation table for all the step types are kept in Appendix A1-A6. Picture showing the model and flow modes in the steps are also kept in Appendix B. Only the results and the graph plots are presented here.

The description of the steps used are below:

Step A: Step set with step height (h) = 0.047m and width (l) = 0.1m

Step B: Step set with step height (h) = 0.141m and width (l) = 0.285m

Step C: Pooled step set with step height (h)= 0.141 and width (l) =0.285 with added weir at step edge of thickness (t) = 0.016m

The letters S and R are used with the step sets to define the roughness on the steps.

S = Smooth steps **R** = Rough steps

The energy dissipation efficiency for the three different step sets was calculated and compared to see how it varies with change in step size. The obtained dissipation efficiencies for the tests conducted are presented in Table 5-1. The dissipation over the whole length of the spillway has been considered for the calculation of these values.

Table 5-1**:** Energy dissipation efficiencies for different step types at different discharge

Discharge (l/s)	Energy Dissipation Efficiency					
	Step A		Step B		Step C	
	Smooth	Rough	Smooth	Rough	Smooth	Rough
3.2	82.0	84.3	92.2	93.1	93.1	93.1
5	70.4	78.2	84.3	89.2	91.3	92.2
10	64.9	74.8	82.7	83.8	87.4	88.3
15	63.1	71.8	77.2	75.4	84.7	84.1
25	55.9	61.1	59.6	70.9	73.3	73.3

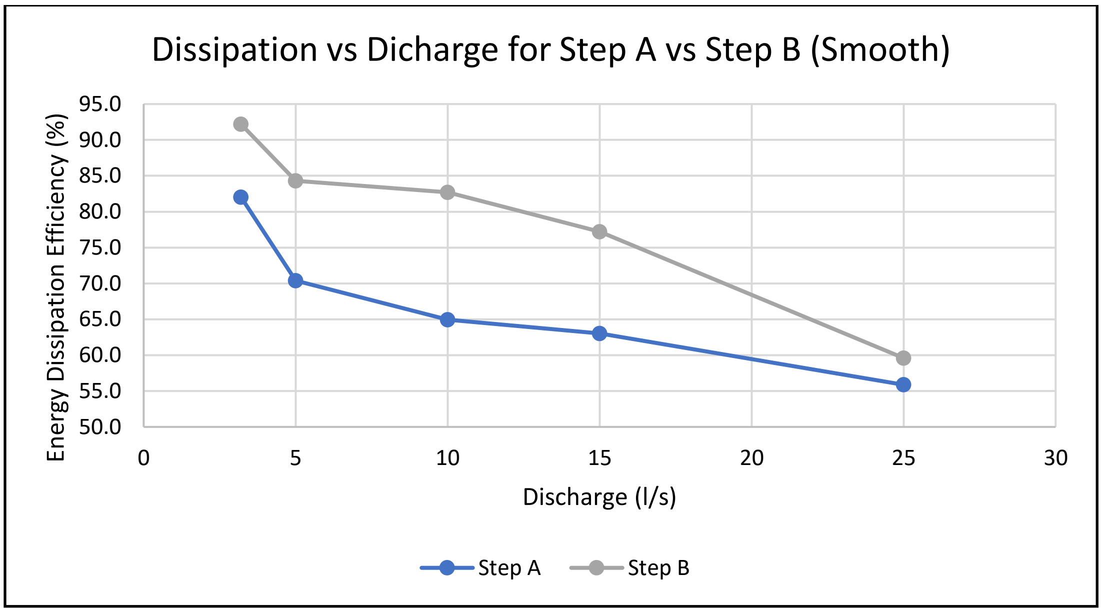

Figure 15: Comparison between the energy dissipation efficiencies of step set A and B

Figure 15 shows the change in energy dissipation with the change in step sizes. The inclination of the spillway in both the cases is same, only the step height and width has been changed. Along with the change in step size, the effect of creating a pool on the steps was also tested. The dissipation efficiency for the plain steps of step set B and pooled steps of step set C is compared as they have the same step size. Figure 16 shows how the energy dissipation efficiency changes by the creation of pool on the step.

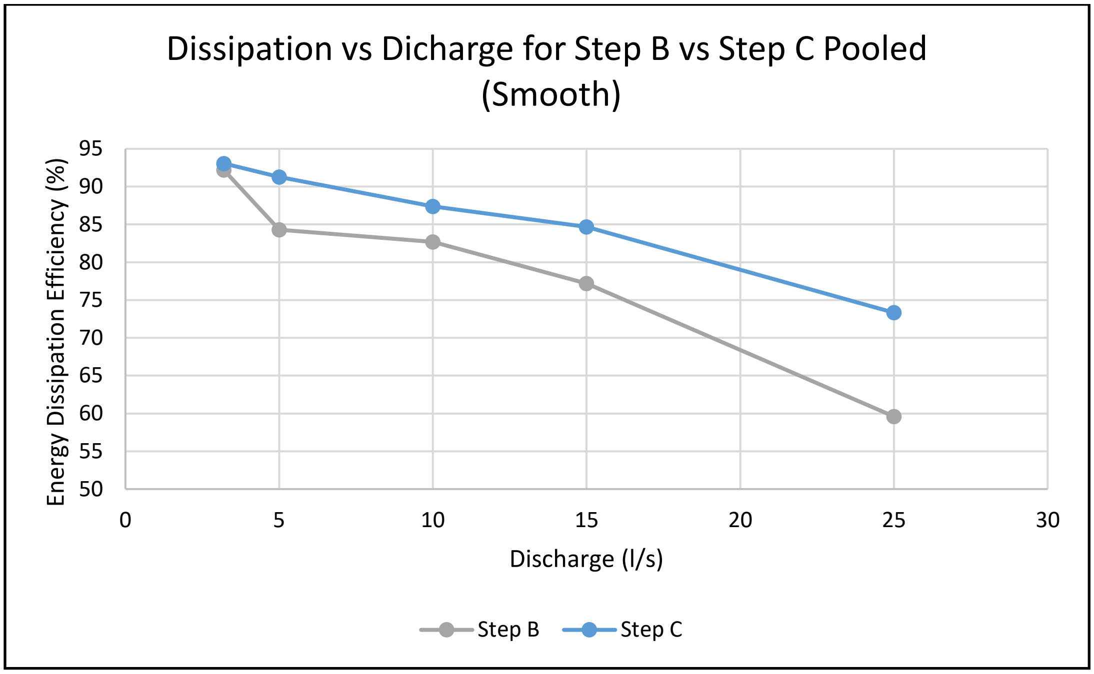

Figure 16: Change in dissipation efficiency by creating pool on the steps

The effect of introducing roughness on the step surface was also experimented with. To see how the energy dissipation in the natural spillways could be affected due to the roughness or small unevenness on the flow surface, tests were conducted by introducing some sand and fine gravel on the steps.

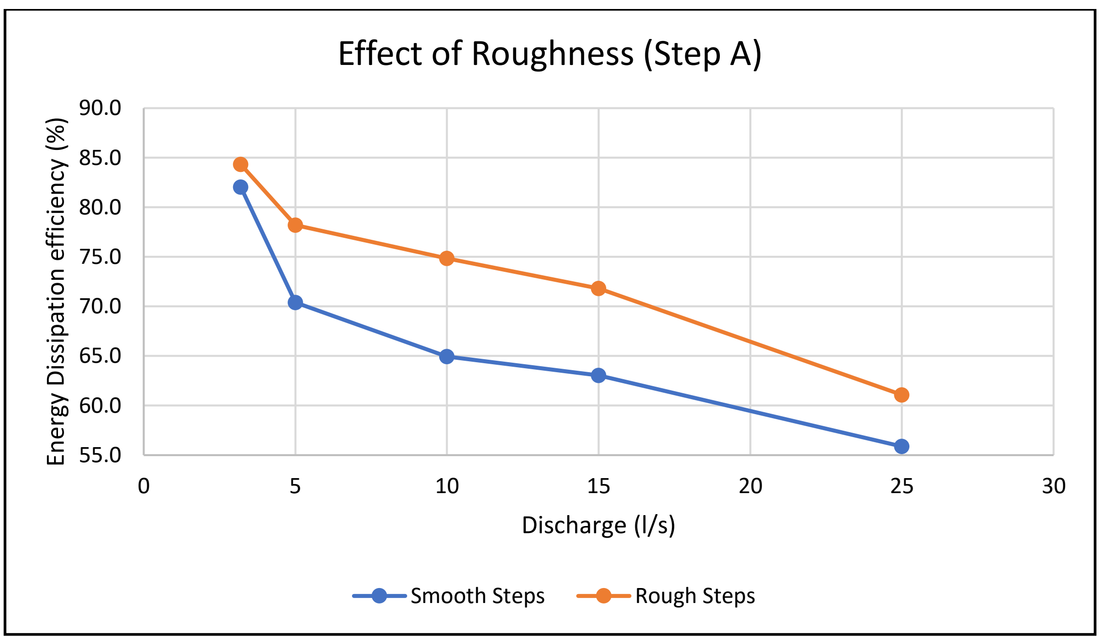

Figure 17: Energy dissipation efficiency comparison between smooth and rough steps (Step set A)

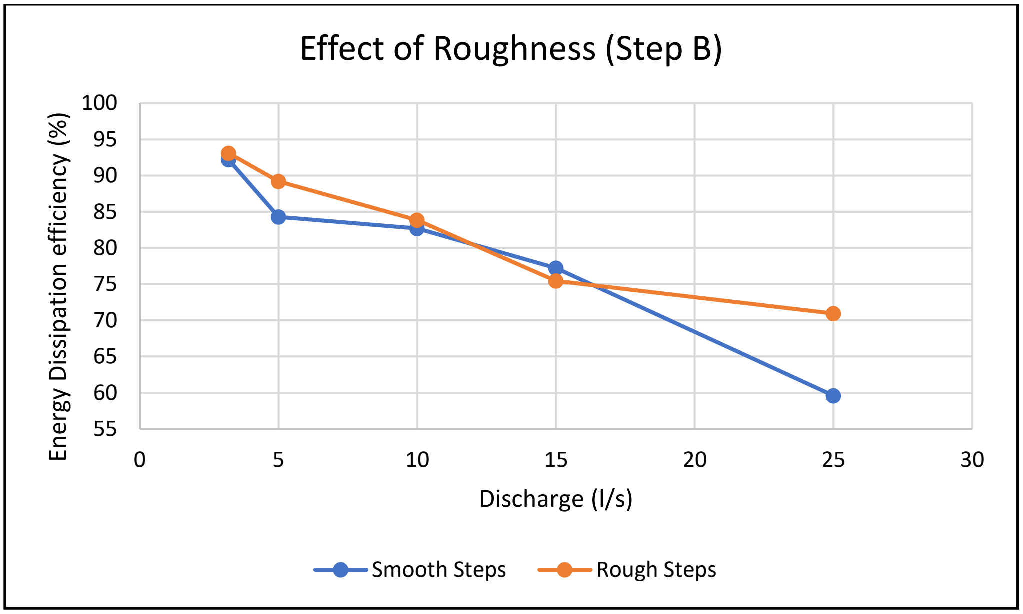

Figure 18: Energy dissipation efficiency comparison between smooth and rough steps (Step set B)

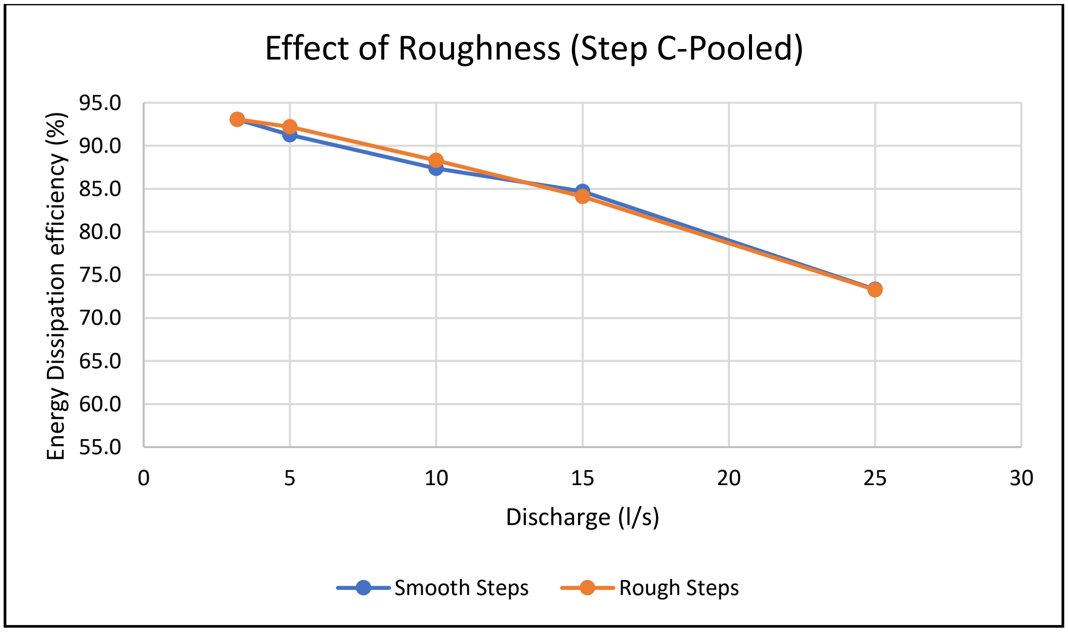

Figure 19: Energy dissipation efficiency comparison between smooth and rough pooled steps (Step set C-Pooled)

The data obtained from the tests for the three step sets has been shown in Figure 17, Figure 18, and Figure 19. To get a total overview of all the tests conducted, the energy dissipations for all the step types have been presented in Figure 20.

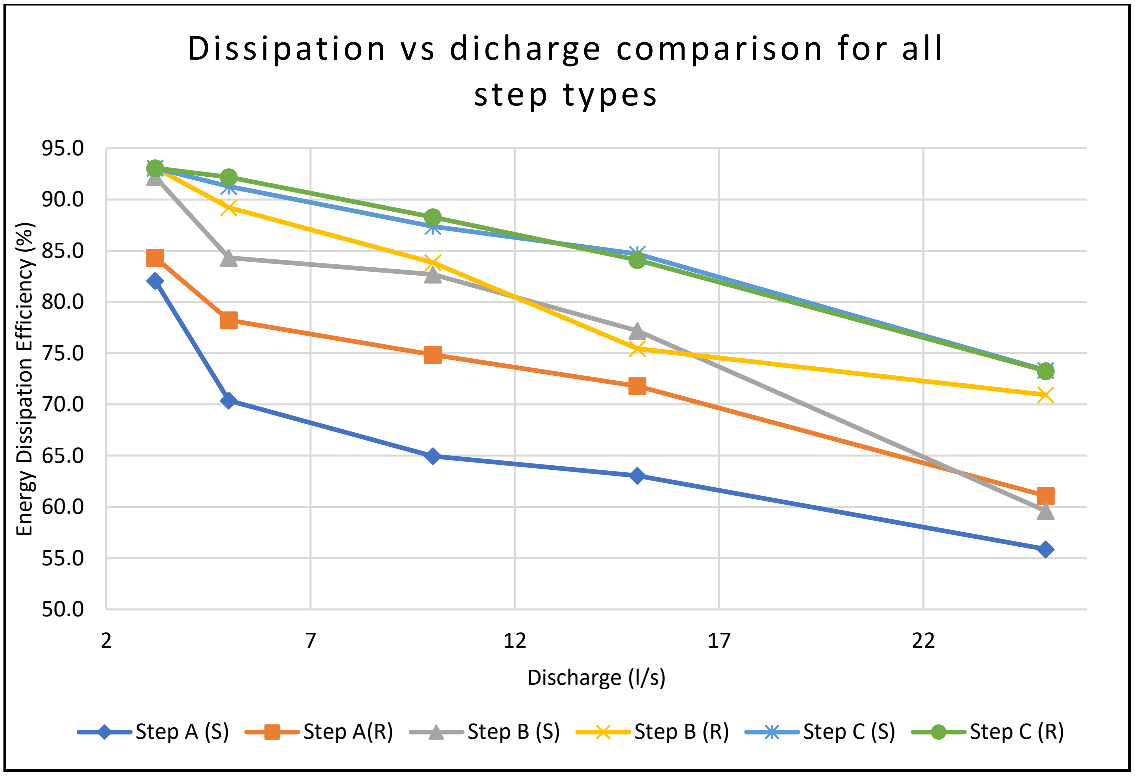

Figure 20: Dissipation efficiency variation on six different step types tested

A comparison between the obtained experimental data and the data obtained from the calculations based on Chanson (2002) have been compared. Among the tests conducted, except for the flow on step set A for 0.015m^3/s (15l/s) and 0.025m^3/s (25l/s), the flow was in nappe flow regime according to the criteria set by Chanson and Rajaratnam (Chanson 2002; Rajaratnam 1990). There are not many studies on nappe flow except the ones by Chanson, so the comparison only with the studies by Chanson has been done. The values calculated based on the equation 3.13 and 3.14 have been summarized in Table 5-2.

Table 5-2: Energy dissipation efficiency value calculated from the literature of Hubert Chanson (Chanson 2002)

Discharge (l/s)	**Step A (Smooth)**	**Step B (Smooth)**
3.2	91.7	84.6
5	90.3	82.4
10	87.7	78.3
15	85.8	75.6
25	82.9	71.7

The data obtained in Table 5-2 has been compared with the experimental results from Table 5-1. The graph showing a comparison between the theoretical and experimental values is shown in Figure 21and Figure 22.

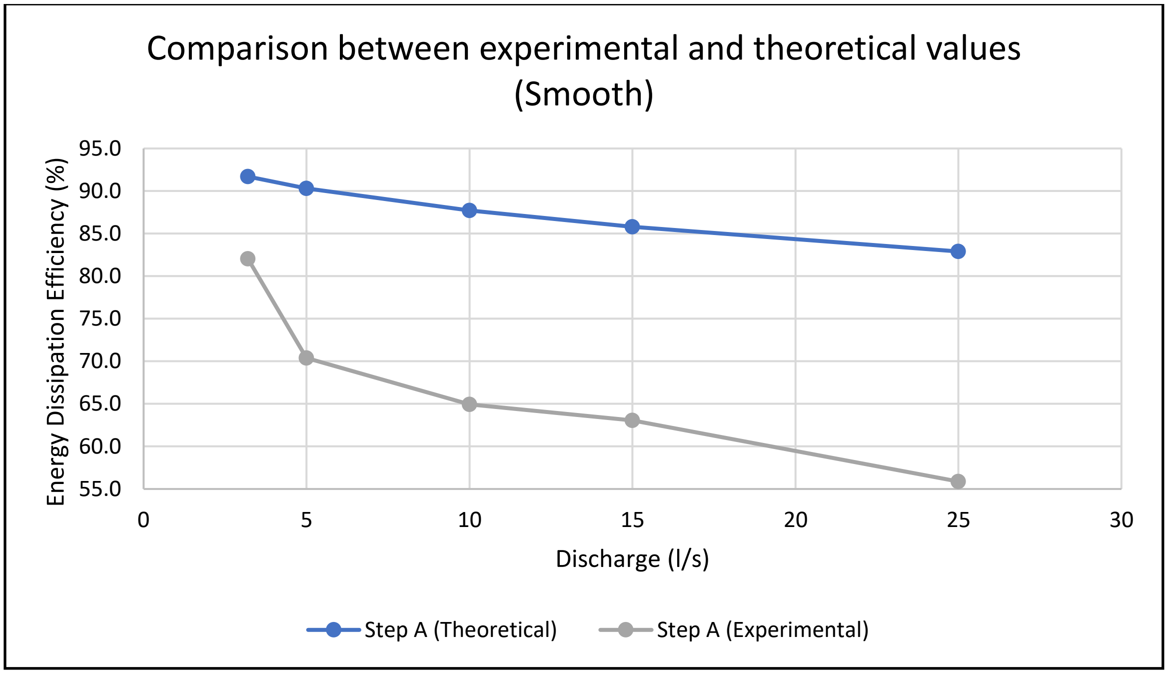

Figure 21: Experimental vs Theoretical dissipation efficiency values for step set A

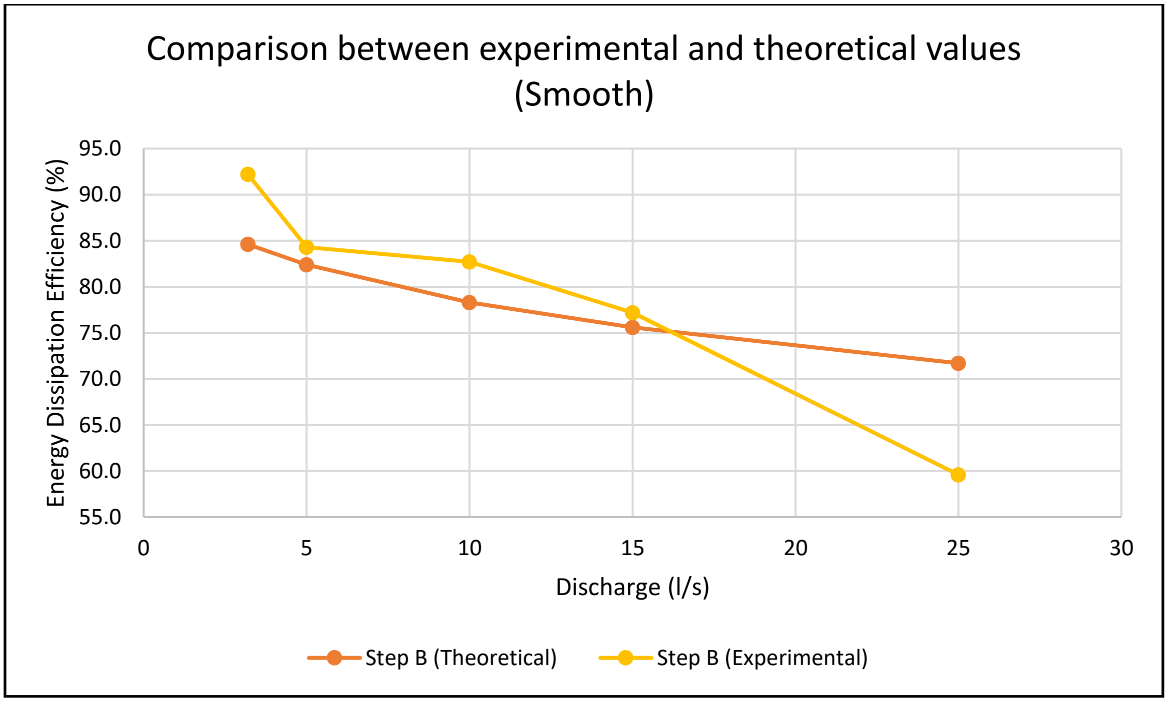

Figure 22: Experimental vs Theoretical dissipation efficiency values for step set B

In addition to these, tests were conducted to see the effect of spillway length in the energy dissipation. Based on the velocity measurements on different steps on the spillway, relative energy dissipation in comparison to the energy head at the top step has been calculated. The calculation showing the head and the energy dissipation is presented in the Table 5-3. Instead of using the total height of the spillway, the effective height for the length of which energy was dissipated, has been considered for the calculations.

Table 5-3: Energy dissipation change with spillway height.

Number of steps	Effective height of spillway (m)	Energy dissipation Efficiency (%)			
		Step B		Step C	
		3.2l/s	25l/s	3.2l/s	25l/s
3	0.141	68.6	37.8	77.3	31.4
4	0.282	82.1	46.9	87.1	58.0
5	0.423	87.0	55.8	91.1	67.1
6	0.564	92.2	59.6	93.1	73.3

(a)

Number of steps	Effective height of spillway (m)	Energy dissipation Efficiency (%)	
		Step A	
		3.2l/s	25l/s
5	0.141	54.7	22.4
10	0.282	65.1	43.3
15	0.423	82.0	55.9

(b)

The data has been plotted as shown in Figure 23 and Figure 24. Figure 23 shows the change in energy at a low flow rate of 0.0032m^3/s (3.2 l/s) and Figure 24shows the change in energy dissipation at a high flow rate of 0.025m^3/s (25 l/s).

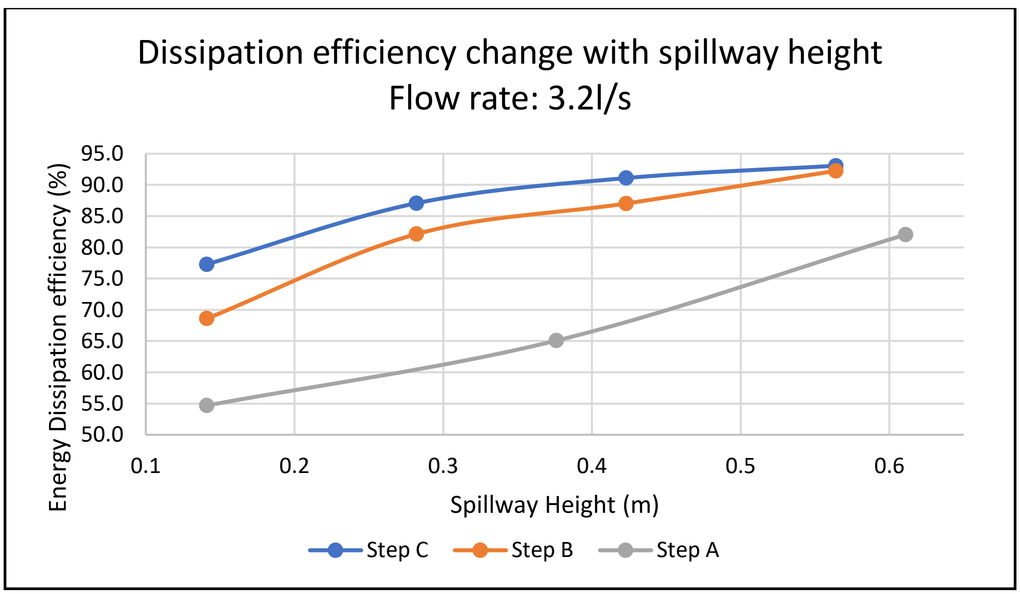

Figure 23: Energy Dissipation change with change in spillway height at low flow

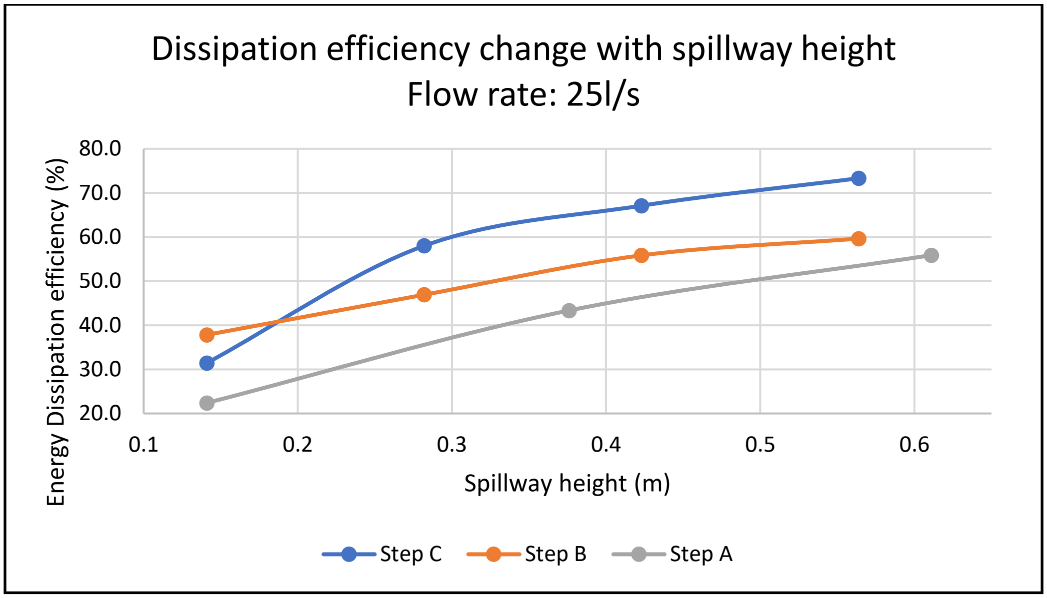

Figure 24: Energy Dissipation change with change in spillway height at low flow

Furthermore, the effect of water depth on the energy dissipation was studied. Since the task of measuring water depth for the turbulent flow over the steps is challenging, there was a possibility of errors in the measured depth. So, an "If Case" study was done to check how an overestimation or an underestimation of the flow depth could affect the energy dissipation. The test results for step set B (Smooth) were used for the calculations and the results are presented in Table 5-4.

Table 5-4: Effect of flow depth on energy dissipation

Discharge (l/s)	Energy dissipation at measured d (%)	Energy dissipation at 1.5*measured d (%)	Energy dissipation at 0.5*measured d (%)
3.2	92.24	92.03	92.46
5	84.26	84.00	84.53
10	82.67	81.94	83.40
15	77.21	76.25	78.19
20	59.65	58.81	60.51

The obtained energy dissipation values for all the cases were close enough and a line plot would not have been a wise choice to present such data. The data is thus presented as a bar graph in the

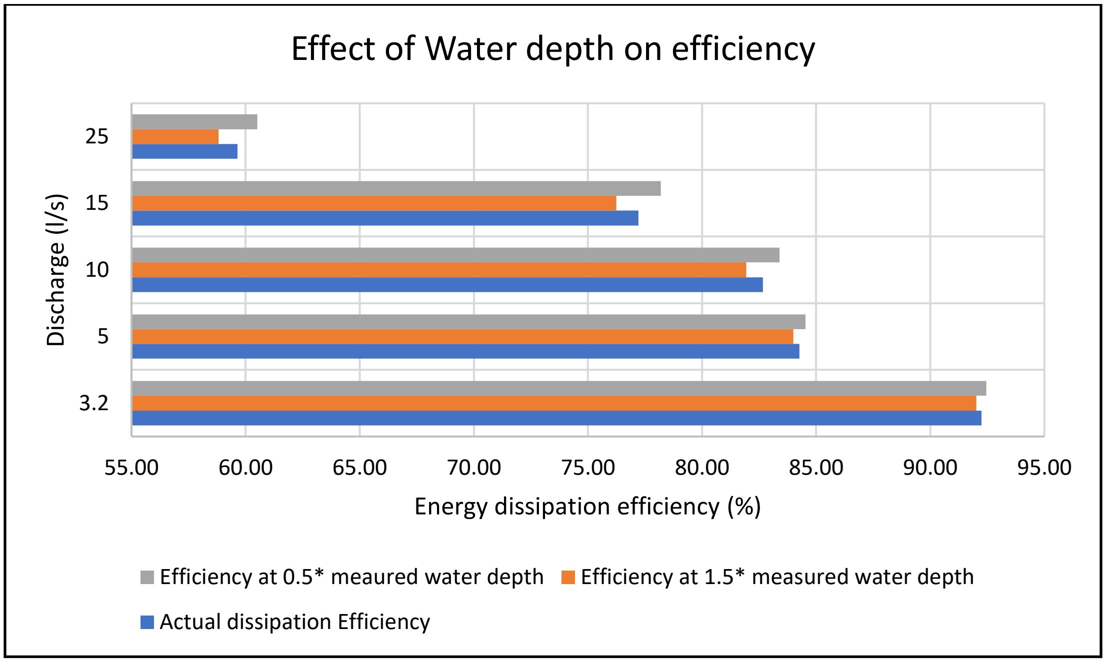

Figure 25: Efficiency change with flow depth

The measured depth was also compared with the depth obtained from the calculation based on the basic flow rate measurement formula given in Table 5-5.

$$Flow\ rate(Q) = velocity * cross - sectional\ area \tag{5.1}$$

Where, cross-sectional area is the product of the spillway width (0.60m) and the depth of the flow (d).

Table 5-5: Comparison between measured and calculated depth

Discharge (l/s)	Measure depth (m)	Calculated depth (m)
3.2	0.0030	0.0058
5	0.0040	0.0040
10	0.0110	0.0039
15	0.0160	0.0033
25	0.0190	0.0024

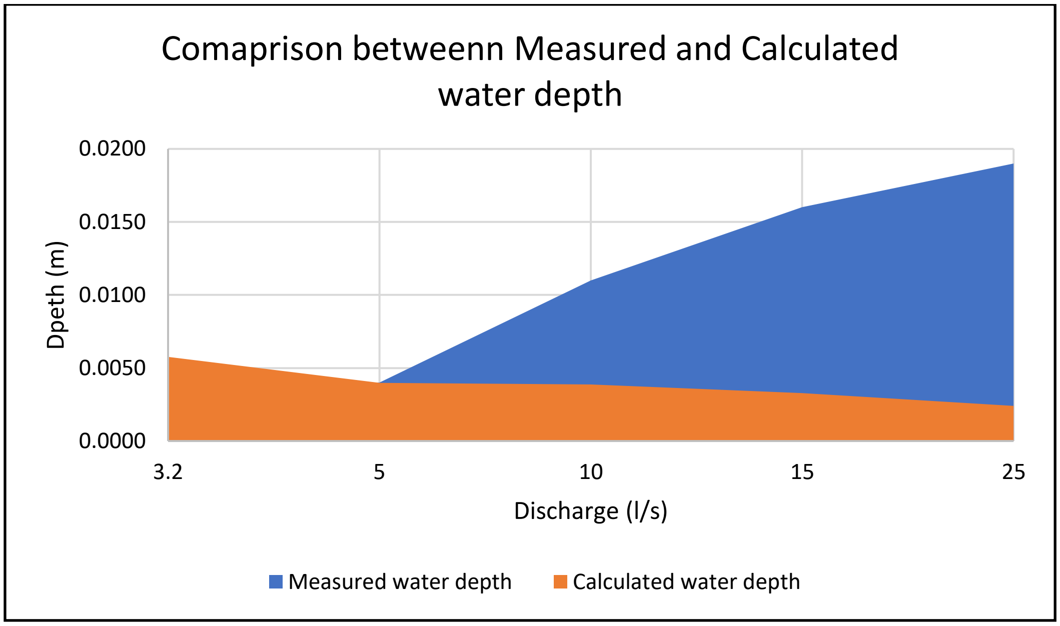

Figure 26: Flow depth deviation from the theoretical values

The data from Table 5-5 has been presented in Figure 26 showing how the flow depth deviates from the theoretical depth calculated based on the flow rate equation. .

CHAPTER 6 DISCUSSION

6.1 Energy dissipation

The experiments conducted show a considerable energy dissipation for all the step types. Values as high as 93.1% for energy dissipation were obtained in the step sets B and C.as seen in Table 5-1. The dissipation efficiency decreased as the flow volume increased with the flow rate. This is in accordance with the results from all the researches mentioned in the literature. As the flow increases on the steps, the steps play a lesser role in the energy dissipation. For nappe flow, with the increase in flow rate, the development of jump subsides and reduces the energy dissipation efficiency of the stepped chute. Similarly, in skimming flow, the water depth increases with higher flow and renders the cushioning effect of the recirculating fluid in between the steps and pseudo bottom less effective for the increased flow.

The comparison between the step set A and B in terms of energy dissipation (shown in Figure 15), shows that the step set B with larger step sizes is more effective. The slope (h/l) for both the step sets is same but under the same discharge, the energy dissipation values obtained are different. The larger steps provide longer length for the hydraulic jump to develop (partially or fully) compared to the smaller steps. This allows for additional energy dissipation and thus the variation in the dissipation values.

The initial values in the step set B and C are very high. The 4 different types tested for the step sets B and C show a dissipation efficiency of 93% for a discharge of $0.0032 m^3/s$ (3.2 l/s). The high efficiency can be credited to the fully developed jump. Based on the calculations using the equations mentioned in the literature (Chanson 2002), the combined length to jet impact and the length of roller for the hydraulic jump created was found to be less than the step length. This satisfies the criteria for nappe flow with a fully developed hydraulic jump. The falling nappes drop as supercritical flow, strike the downstream step, create a hydraulic jump and the flow changes from super to subcritical. This flow again reaches a critical state at the step edge and changes to supercritical as it flows down to the next step as a falling jet. A fully developed flow is created on each step which assists in higher energy dissipation.

Creating a pool on the same step dimensions perform better with the energy dissipation for a wide range of discharge. Pooled water provides a cushioning effect to the falling jet, taking away part of the falling energy. Other nappe characteristics remain the same and the energy dampening by the water provides additional dissipation capability. The tests conducted on the pooled steps were all within the nappe flow threshold. Though a nappe with a fully developed hydraulic jump was just created for the least test discharge (3.2 l/s), all other tested discharges also had a low critical depth to step height value suggesting a nappe flow with a partially developed hydraulic jump. As the flow rate increases, the water just skims over the step edges forming a pseudo bottom. As there won't be a jet falling on the water cushion, the pooled water would not affect the dissipation much. Due to the limitation of the training walls, no higher discharge could be tested in the lab.to see how the pooled steps perform under skimming flow conditions.

Introduction of surface roughness on the steps by applying some sand and fine gravels had a positive impact on the energy dissipation. Considerable increase in the dissipation values were obtained for the step set A and B. The step set A showed an increase of more than 5% in average for all the flow rates (Figure 17) while the increase wasn't so pronounced for in step set B (Figure 18). Considering a larger step length for the flow, a higher impact of the roughness created was expected.in step set B. The dissipation efficiency increases for the low flows, goes down in the middle and again increases at high flows. The discrepancies in the intermediate values could be the result of the errors during the data collection and interpretation.

For the pooled step set, a minor increase in the energy dissipation was recorded (Figure 19) As the roughness creating materials are drowned beneath the pool of water, they have little to no effect in the exerting resistance to the flow. The same property has been shown by the pooled steps in the tests conducted.

Another pattern observed in the collected data was the change in energy dissipation with the change in spillway length. As the slope was fixed, change in length meant the change in height of the spillway. The energy dissipation increased with the increase in step height. The spillway height was changed by considering the number of steps for the effective height calculation. The results in Figure 23and Figure 24 show an increasing trend of dissipation efficiency with the spillway height. The flow at the initial steps is affected by the flow condition from the inlet tank as no heed to the boundary conditions has been given. This might be the reason for lower dissipation and as the flow develops, the dissipation increases.

Flow aeration in the stepped spillways inflates the water depth. This water depth in the flow over the stepped spillways is higher than the usual water depth at the same discharge and flow velocity. The same phenomenon is shown in Figure 26. The water depth at low flow rates look more or less similar for both the calculated and measured values but as the flow rate increases, the measured flow depth is higher than the calculated water depth. This is an important phenomenon to be considered during the design and construction of the stepped spillway. Flow depth inflation and the splashing of turbulent water flow might lead water to spill on the sides leading to erosion or other problems. So, the proper design of the sidewalls on the stepped spillway considering the aeration and water splashing is a must.

The effect of errors while measuring the water depth in the flow over the steps was also considered. A 50% underestimation and a 50% overestimation cases while measuring the depth were tested. For the flow rates and the step dimensions used in this study, the tested flow depths had minimal effect on the energy dissipation. In Figure 25, identical energy dissipation values for all three depths tested can be seen.

6.2 Unlined stepped spillway

The steps in the stepped spillway are subjected to larger hydraulic forces compared to a smooth spillway (Chanson 2000b). This results in damage of the spillway more often than the smooth spillway and needs regular maintenance. This makes a high quality of construction and high strength of the construction material imperative for the durability of the stepped spillway.

The rock surface to be used for unlined steps must have a very high strength and high resistance to erosion. Tests for the worst-case scenarios should be done and the spillway stability under such conditions should be checked. The construction of unlined steps can be highly effective when the rock can sustain the hydraulic forces of the falling water and the erosion forces acting on the rock surface. The unlined spillway could reduce the cost of the concrete required and the cost of the stilling basin by reducing the space required and the decreased excavation for the basin. The project could be highly economical if a rockfill dam utilizing all or part of the excavated rock could be built.

The examples of the La-Grande II project, Canada with a spillway capacity of 16140m^3/s (Chanson 2002) and Lower Paunglaung project, Myanmar with a spillway capacity of 10000m^3/s (Khatsuria 2004) are operating safely even after years of construction.

Proper design of the steps, extensive rock tests and flood modelling and optimization of the spillway slope could result in durable, efficient and economical means for energy dissipation.

CHAPTER 7 CONCLUSION AND RECOMMENDATION

7.1 Conclusion

The energy dissipation rate of stepped spillways for the water flowing through the steps is high. The statements were verified with the model test conducted. The tests with low discharges had nappe flow with fully developed hydraulic jump conditions, for these flows a dissipation rate as high as 93% was obtained. The dissipation on all the tested step types and the flow rates depicted more than 50% energy dissipation. Introduction of the surface roughness increased the dissipation. This concept can be easily tried in the projects by creating some unevenness on the steps

The pooled steps proved to be highly efficient in dissipating energy. Pooled steps for the same step dimensions as plain steps showed a further increase in energy dissipation. In average, more than 5% increase in the dissipation rate was recorded. The pools were efficient for all the discharges tested (3.2l/s-25l/s).

The project areas with good rock condition, high rock strength and high erodibility index, can prove to be self-sufficient in handling the flows without any support system provided. The existing examples of unlined steeped spillways designed for high discharges portray the durability of such structures and can act as the epitome of the strength of unlined rocks in stepped spillways. In addition, the possibility to use the excavated material in the rockfill dams, reduction in the cost and space required for stilling basin and easy construction process can help to attract designers to this energy dissipation alternative. If required, some part of the steps or some steps could be lined with support materials based on the design requirement.

7.2 Recommendation

Looking from the research point of view, the concept of the stepped spillway is still new. Though some researches have been done in last three decades concerning the flow types, aeration, the effect of aeration and energy dissipation in stepped spillways, there is still a lot that can be done in this field to understand the different process on stepped spillways better.

The current physical model test was done on a single slope with slope angle and the step height to length ratio being constant. Tests could be done varying the slope, observing the effects of varying step height and lengths with varying inclination of slope. The Pooled steps showed a high rate of energy dissipation. Further study in the field with the possibility to build spillways on flat slopes allowing the nappe flow type with fully developed hydraulic jump should be done.

The same tests can be done with a CFD model and the results compared with the results from the physical model. Observed data can be used for calibrations required and the CFD model can be used to test further parameters reducing the time and money required for the tests. Similar recent works from Valero Huerta (2018) and Felder (2013) are noteworthy in the field and can be good reference materials for further study.

REFERENCES

Annandale, G. 1995, 'Erodibility', *Journal of hydraulic research*, vol. 33, no. 4, pp. 471-94.

Boes, R.M. & Hager, W.H. 2003, 'Hydraulic design of stepped spillways', *Journal of Hydraulic Engineering*, vol. 129, no. 9, pp. 671-9.

Chamani, M. & Rajaratnam, N. 1999, 'Characteristics of skimming flow over stepped spillways', *Journal of Hydraulic Engineering*, vol. 125, no. 4, pp. 361-8.

Chamani, M.R. & Rajaratnam, N. 1994, 'Jet flow on stepped spillways', *Journal of Hydraulic Engineering*, vol. 120, no. 2, pp. 254-9.

Chanson, H. 1995, 'History of stepped channels and spillways: a rediscovery of the "wheel"', *Canadian Journal of Civil Engineering*, vol. 22, no. 2, pp. 247-59.

Chanson, H. 1996, 'Prediction of the transition nappe/skimming flow on a stepped channel', *Journal of Hydraulic Research*, vol. 34, no. 3, pp. 421-9.

Chanson, H. 1998, 'Review of studies on stepped channel flows'.

Chanson, H. 2000a, 'Historical development of stepped cascades for the dissipation of hydraulic energy', *Transactions of the Newcomen Society*, vol. 72, no. 2, pp. 295-318.

Chanson, H. 2000b, 'A review of accidents and failures of stepped spillways and weirs', vol. 142, Citeseer, pp. 177-88.

Chanson, H. 2001, 'A transition flow regime on stepped spillways? The fact', Citeseer.

Chanson, H. 2002, 'The hydraulics of stepped chutes and spillways.(2002)', Lisse, AA Balkema publishers, 2002.

Chanson, H. & Toombes, L. 2002, 'Experimental investigations of air entrainment in transition and skimming flows down a stepped chute', *Canadian Journal of Civil Engineering*, vol. 29, no. 1, pp. 145-56.

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R. & Mearns, L.O. 2000, 'Climate Extremes: Observations, Modeling, and Impacts', *Science*, vol. 289, no. 5487, pp. 2068-74.

Essery, I.T.S. & Horner, M.W. 1978, *The hydraulic design of stepped spillways*, Construction Industry Research and Information Association.

Felder, S. 2013, 'Air-water flow properties on stepped spillways for embankment dams: Aeration, energy dissipation and turbulence on uniform, non-uniform and pooled stepped chutes'.

Felder, S. & Chanson, H. 2009, 'Energy dissipation, flow resistance and gas-liquid interfacial area in skimming flows on moderate-slope stepped spillways', *Environmental fluid mechanics*, vol. 9, no. 4, pp. 427-41.

Impregilo, S. 2019, 'James Bay Hydroelectric Project on the la Grande River', *https://www.salini-impregilo.com/en/projects/completed/dams-hydroelectric-plants/james-bay-hydroelectric-project-on-the-la-grande-river.html*.

Jandora, J. & Říha, J. 2008, *The failure of embankment dams due to overtopping*, Vutium.

Khatsuria, R.M. 2004, *Hydraulics of spillways and energy dissipators*, CRC Press.

Leflaive, X. 2012, 'Water Outlook to 2050: The OECD calls for early and strategic action'.

Peyras, L.a., Royet, P. & Degoutte, G. 1992, 'Flow and energy dissipation over stepped gabion weirs', *Journal of hydraulic Engineering*, vol. 118, no. 5, pp. 707-17.

Rajaratnam, N. 1990, 'Skimming flow in stepped spillways', *Journal of Hydraulic Engineering*, vol. 116, no. 4, pp. 587-91.

Renna, F.M. & Fratino, U. 2010, 'Nappe flow over horizontal stepped chutes', *Journal of Hydraulic Research*, vol. 48, no. 5, pp. 583-90.

Schnitter, N. 1994, 'A history of dams—The useful pyramids. Rotterdam', Brookfield: AA Balkema Verlag.

Sorensen, R.M. 1985, 'Stepped spillway hydraulic model investigation', *Journal of hydraulic Engineering*, vol. 111, no. 12, pp. 1461-72.

Takahasi, Y. 2009, *Water Storage, Transport, and Distribution*, EOLSS Publications.

Valero Huerta, D. 2018, 'On the Fluid Mechanics of Self-Aeration in Open Channel Flows', Université de Liège, Liège, Belgique.

Van Alwon, J., Borman, D., Sleigh, A. & Kapur, N. 2017, 'Experimental and numerical modelling of aerated flows over stepped spillways', International Association for Hydro-Environment Engineering and Research (IAHR).

Appendix

Appendix -A1: Calculation sheet for Type 1: Step set A (Smooth)

Discharge (l/s)	Step Number	Average Velocity (m/s)	Height from the bottommost step (m)	Water depth on the step (m)	Energy Head (m)	Dissipated energy (m)	Energy Dissipation (%)
3.2	2	0.518	0.611	0.060	0.685		
	5	0.855	0.470	0.060	0.567	0.117	17.146
	10	1.307	0.235	0.070	0.392	0.293	42.731
	15	1.019	0.000	0.070	0.123	0.562	**82.048**
5.0	2	0.724	0.611	0.070	0.708		
	5	1.364	0.470	0.070	0.635	0.073	10.302
	10	1.215	0.235	0.070	0.380	0.328	46.283
	15	1.595	0.000	0.080	0.210	0.498	**70.387**
10	2	0.787	0.611	0.100	0.743		
	5	0.848	0.470	0.110	0.617	0.126	16.957
	10	1.627	0.235	0.120	0.490	0.253	34.021
	15	1.536	0.000	0.140	0.260	0.482	**64.941**
15	2	0.676	0.611	0.160	0.794		
	5	0.670	0.470	0.180	0.673	0.121	15.281
	10	1.279	0.235	0.190	0.508	0.286	35.997
	15	1.354	0.000	0.200	0.293	0.501	**63.052**
25	2	0.814	0.611	0.280	0.925		
	5	1.019	0.470	0.300	0.823	0.102	11.015
	10	1.335	0.235	0.300	0.626	0.299	32.328
	15	1.456	0.000	0.300	0.408	0.517	**55.876**

Appendix -A2: Calculation sheet for Type 2: Step set A (Rough)

Discharge (l/s)	Step Number	Average Velocity (m/s)	Height from the bottommost step (m)	Water depth on the step (m)	Energy Head (m)	Dissipated energy (m)	Energy Dissipation (%)
3.2	2	0.666	0.060	0.61	0.694		
	5	0.672	0.060	0.47	0.553	0.141	20.270
	10	0.865	0.060	0.24	0.333	0.360	51.973
	15	0.978	0.060	0.00	0.109	0.585	**84.320**
5.0	2	0.846	0.070	0.61	0.717		
	5	1.003	0.070	0.47	0.591	0.126	17.591
	10	1.458	0.070	0.24	0.413	0.304	42.396
	15	1.301	0.070	0.00	0.156	0.561	**78.213**
10	2	1.075	0.100	0.61	0.770		
	5	0.874	0.100	0.47	0.609	0.161	20.899
	10	2.142	0.100	0.24	0.569	0.201	26.115
	15	1.281	0.110	0.00	0.194	0.576	**74.847**
15	2	1.054	0.180	0.61	0.848		
	5	0.938	0.180	0.47	0.695	0.153	18.020
	10	1.948	0.170	0.24	0.598	0.249	29.402
	15	1.245	0.160	0.00	0.239	0.609	**71.800**
25	2	1.046	0.280	0.61	0.947		
	5	1.127	0.250	0.47	0.785	0.162	17.114
	10	1.861	0.270	0.24	0.682	0.265	28.014
	15	1.390	0.270	0.00	0.368	0.578	**61.083**

Appendix -A3: Calculation sheet for Type 3: Step set B (Smooth)

Discharge (l/s)	Step Number	Average Velocity (m/s)	Height from the bottommost step (m)	Water depth on the step (m)	Energy Head (m)	Dissipated energy (m)	Energy Dissipation (%)
3.2	2	0.801	0.005	0.564	0.602		
	3	1.021	0.003	0.423	0.479	0.123	20.371
	4	1.031	0.003	0.282	0.339	0.263	43.637
	5	1.056	0.003	0.141	0.201	0.401	66.627
	6	0.926	0.003	0	0.047	0.555	**92.242**
5	2	0.863	0.005	0.564	0.607		
	3	1.096	0.004	0.423	0.488	0.119	19.564
	4	1.214	0.004	0.282	0.361	0.246	40.495
	5	1.264	0.004	0.141	0.226	0.381	62.695
	6	1.340	0.004	0	0.096	0.511	**84.262**
10	2	0.975	0.011	0.564	0.623		
	3	1.280	0.011	0.423	0.518	0.106	16.993
	4	1.307	0.011	0.282	0.380	0.243	39.034
	5	1.350	0.011	0.141	0.245	0.379	60.713
	6	1.380	0.011	0	0.108	0.515	**82.668**
15	2	1.256	0.014	0.564	0.658		
	3	1.426	0.015	0.423	0.542	0.117	17.747
	4	1.502	0.015	0.282	0.412	0.246	37.422
	5	1.561	0.015	0.141	0.280	0.378	57.456
	6	1.622	0.016	0	0.150	0.508	**77.209**
25	2	1.288	0.019	0.564	0.668		
	3	1.616	0.019	0.423	0.575	0.093	13.861
	4	1.909	0.019	0.282	0.487	0.181	27.098
	5	2.047	0.019	0.141	0.374	0.294	44.048
	6	2.216	0.019	0	0.269	0.398	**59.648**

Appendix -A4: Calculation sheet for Type 4: Step set B (Rough)

Discharge (l/s)	Step Number	Average Velocity (m/s)	Height from the bottommost step (m)	Water depth on the step (m)	Energy Head (m)	Dissipated energy (m)	Energy Dissipation (%)
3.2	2	0.567	0.014	0.564	0.594		
	3	0.768	0.014	0.423	0.467	0.127	21.429
	4	0.763	0.014	0.282	0.326	0.269	45.211
	5	0.689	0.014	0.141	0.179	0.415	69.849
	6	0.728	0.014	0	0.041	0.553	**93.100**
5	2	0.800	0.014	0.564	0.611		
	3	0.858	0.014	0.423	0.474	0.136	22.293
	4	0.895	0.014	0.282	0.337	0.274	44.838
	5	0.997	0.014	0.141	0.206	0.405	66.316
	6	1.009	0.014	0	0.066	0.545	**89.206**
10	2	1.035	0.016	0.564	0.635		
	3	1.190	0.016	0.423	0.511	0.123	19.446
	4	1.230	0.016	0.282	0.375	0.259	40.885
	5	1.300	0.016	0.141	0.243	0.391	61.686
	6	1.303	0.016	0	0.103	0.532	**83.848**
15	2	1.139	0.018	0.564	0.648		
	3	1.340	0.018	0.423	0.533	0.116	17.839
	4	1.456	0.018	0.282	0.408	0.240	37.042
	5	1.504	0.018	0.141	0.274	0.374	57.670
	6	1.664	0.018	0	0.159	0.489	**75.448**
25	2	1.387	0.027	0.564	0.689		
	3	1.676	0.027	0.423	0.593	0.096	13.906
	4	1.757	0.027	0.282	0.466	0.223	32.311
	5	1.791	0.027	0.141	0.332	0.358	51.883
	6	1.844	0.027	0	0.200	0.489	**70.939**

Appendix -A5: Calculation sheet for Type 5: Step set C (Smooth)

Discharge (l/s)	Step Number	Average Velocity (m/s)	Height from the bottommost step (m)	Water depth on the step (m)	Energy Head (m)	Dissipated energy (m)	Energy Dissipation (%)
3.2	2	0.354	0.039	0.564	0.609		
	3	0.256	0.039	0.423	0.465	0.144	23.639
	4	0.256	0.039	0.282	0.324	0.285	46.778
	5	0.232	0.039	0.141	0.183	0.427	70.011
	6	0.253	0.039	0	0.042	0.567	**93.065**
5	2	0.445	0.046	0.564	0.620		
	3	0.424	0.046	0.423	0.478	0.142	22.888
	4	0.414	0.046	0.282	0.337	0.283	45.693
	5	0.414	0.046	0.141	0.196	0.424	68.434
	6	0.398	0.046	0	0.054	0.566	**91.281**
10	2	0.706	0.048	0.564	0.637		
	3	0.723	0.048	0.423	0.498	0.140	21.930
	4	0.737	0.048	0.282	0.358	0.280	43.890
	5	0.684	0.048	0.141	0.213	0.425	66.611
	6	0.799	0.048	0	0.081	0.557	**87.368**
15	2	0.796	0.064	0.564	0.660		
	3	0.853	0.064	0.423	0.524	0.136	20.631
	4	0.842	0.064	0.282	0.382	0.278	42.123
	5	0.844	0.064	0.141	0.241	0.419	63.450
	6	0.853	0.064	0	0.101	0.559	**84.690**
25	2	0.952	0.066	0.564	0.676		
	3	1.453	0.066	0.423	0.597	0.080	11.775
	4	1.397	0.066	0.282	0.447	0.229	33.820
	5	1.470	0.066	0.141	0.317	0.359	53.105
	6	1.498	0.066	0	0.180	0.496	**73.329**

Appendix -A6: Calculation sheet for Type 6: Step set B (Rough)

Discharge (l/s)	Step Number	Average Velocity (m/s)	Height from the bottommost step (m)	Water depth on the step (m)	Energy Head (m)	Dissipated energy (m)	Energy Dissipation (%)
3.2	2	0.263	0.04	0.564	0.608		
	3	0.272	0.04	0.423	0.467	0.141	23.167
	4	0.249	0.04	0.282	0.325	0.282	46.479
	5	0.212	0.04	0.141	0.183	0.424	69.831
	6	0.204	0.04	0	0.042	0.565	**93.068**
5	2	0.367	0.044	0.564	0.615		
	3	0.364	0.044	0.423	0.474	0.141	22.948
	4	0.346	0.044	0.282	0.332	0.283	45.986
	5	0.294	0.044	0.141	0.189	0.425	69.193
	6	0.280	0.044	0	0.048	0.567	**92.193**
10	2	0.614	0.047	0.564	0.630		
	3	0.757	0.047	0.423	0.499	0.131	20.781
	4	0.771	0.045	0.282	0.357	0.273	43.307
	5	0.753	0.048	0.141	0.218	0.412	65.428
	6	0.725	0.047	0	0.074	0.556	**88.288**
15	2	0.859	0.064	0.564	0.666		
	3	0.877	0.064	0.423	0.526	0.139	20.948
	4	0.905	0.064	0.282	0.388	0.278	41.750
	5	0.958	0.058	0.141	0.246	0.420	63.073
	6	0.970	0.058	0	0.106	0.560	**84.088**
25	2	1.017	0.048	0.564	0.665		
	3	1.255	0.048	0.423	0.551	0.113	17.060
	4	1.303	0.048	0.282	0.416	0.248	37.345
	5	1.471	0.048	0.141	0.299	0.365	54.973
	6	1.595	0.048	0	0.178	0.487	**73.269**

Appendix B: Model Pictures

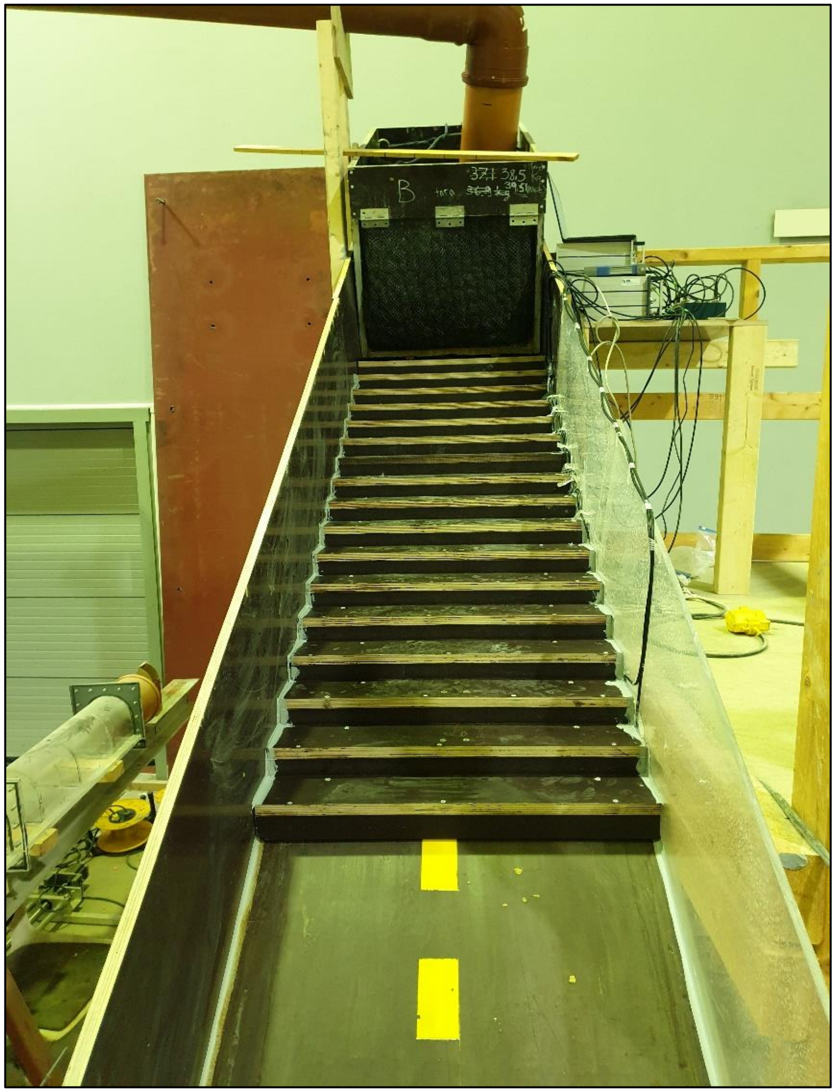

Figure 1: Physical model picture with step set A

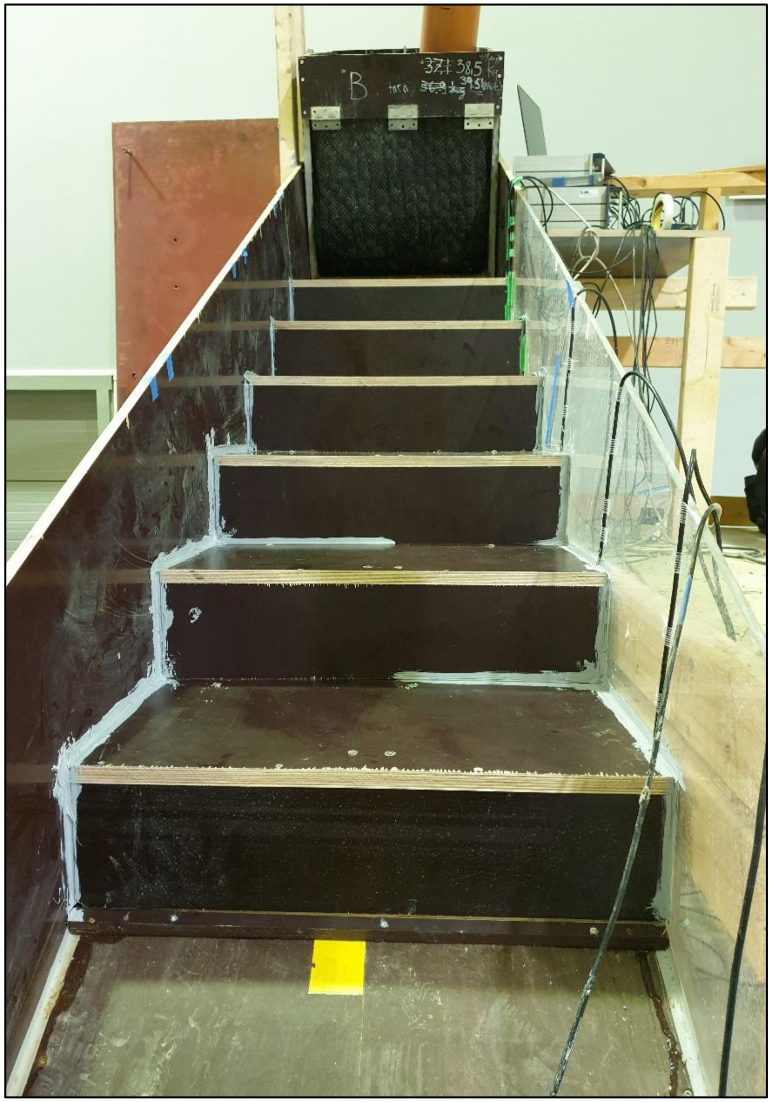

Figure 2: Physical model picture with step set B

Figure 3: Physical model picture with step set C

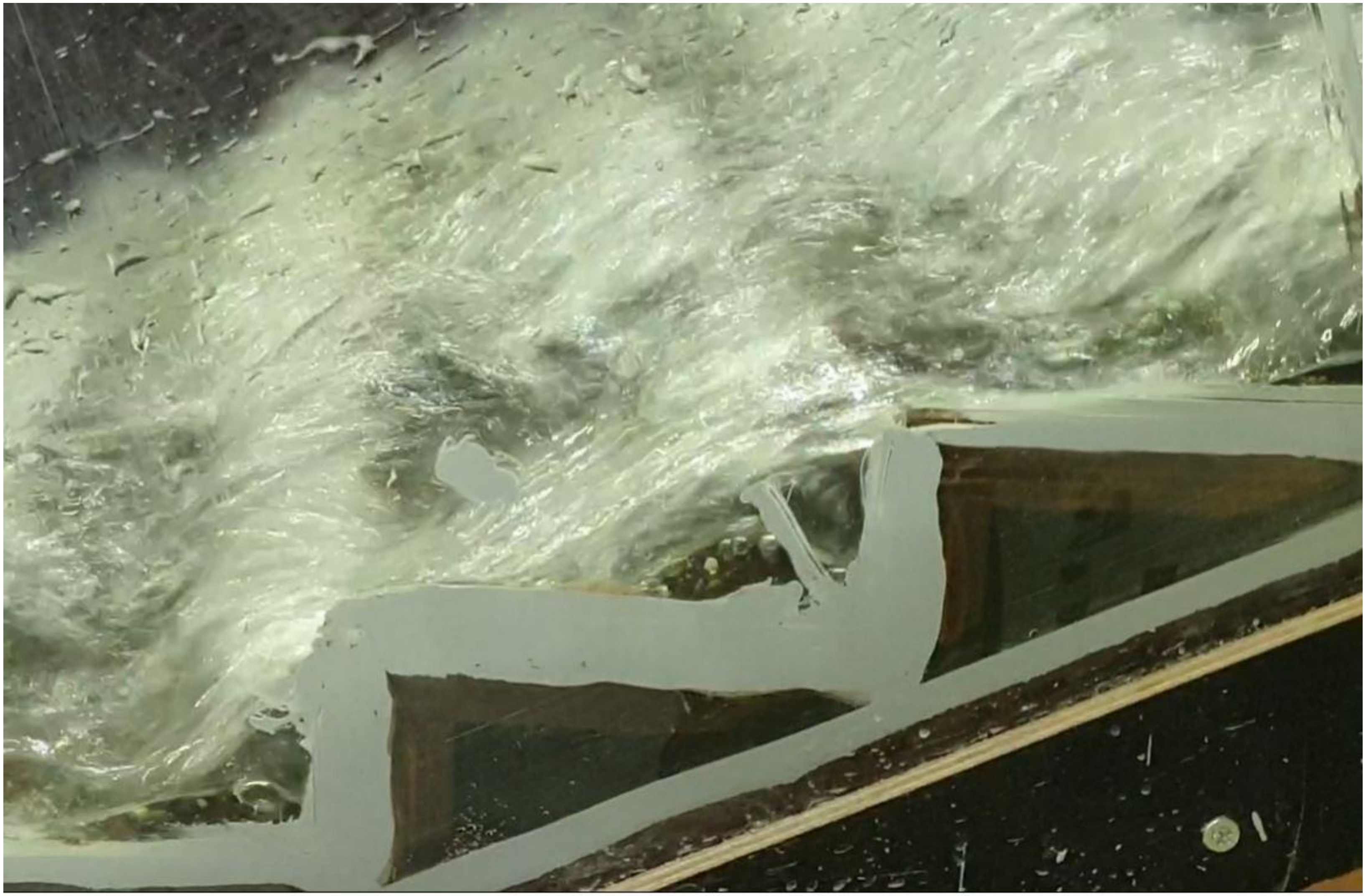

Figure 4: Low flow of 3.2l/s on step A. Partial jump taking place and air cavity beneath the falling nappe present

Figure 5: Large flow rate of 25l/s on step A.

Air cavity disappeared and water recirculation observed below the flow bottom created

Figure 6: Fully developed hydraulic jump on step set C (Polled steps) at 3.2l/s

Figure 7: Large flow rate (25l/s) on step set C (Pooled steps).

Partially developed hydraulic jump still exists and air cavity beneath the flowing nappe exists.