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**Comparative Numerical Analysis for Prediction of Flow Characteristics of
Butterfly Valve and Vertical-lift Gate at the Penstock Inlet in Rasuwagadhi
Hydropower Project**

by

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A THESIS

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The undersigned hereby certify that they have read, and recommended to the Institute of Engineering for acceptance, thesis entitled “**Comparative Numerical Analysis for Prediction of Flow Characteristics of Butterfly Valve and Vertical-lift Gate at the Penstock Inlet in Rasuwagadhi Hydropower Project**” submitted by Anshu Kshetri in partial fulfillment of the requirements for the Degree of Master of Science, Mechanical System Design and Engineering.

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ABSTRACT

In a hydropower project, either a valve or a gate can be selected as the penstock isolation equipment depending on cost, availability of access roads and other operational preferences. This study presents a comparative analysis of the flow characteristics between the Butterfly Valve and the Vertical-lift Gate at the penstock inlet of Rasuwagadhi Hydropower Project by conducting a three-dimensional study to identify the better alternative. The Gate and the Valve exhibit distinct geometries even in their fully open states resulting in different flow behaviors, which influences the incurred head loss and subsequently the power production and revenue of the project.

The findings of the study reveal that the Vertical-lift Gate outperforms the Butterfly Valve with a higher flow coefficient, lower loss coefficient, and lesser head loss. And, considering the variations in both the initial costs and the revenue loss, the Vertical-lift Gate emerges as the more financially favorable option. The Vertical-lift Gate is found to be a better option from both the hydraulic and financial standpoint. The insights gained from this research can guide future decision-making in hydropower projects, optimizing the efficiency and financial viability of penstock isolation systems.

Keywords: *Penstock Isolation Equipment, Butterfly Valve, Vertical-lift Gate, Gate Slot, Flow Coefficient, Loss Coefficient, Hydropower, Flow Characteristics, Head Loss, Rasuwagadhi Hydropower Project*

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LIST OF SYMBOLS

C_v	Flow Coefficient in US units
K_v	Flow Factor in metric units
K	Loss Coefficient
v	Velocity
g	Acceleration due to gravity
SG	Specific Gravity
Q	Volumetric Flow Rate
P	Static Pressure
$P_{u/s}$	Pressure at upstream
$P_{d/s}$	Pressure at downstream
ΔP	Pressure Drop
h_l	Head Loss
ρ	Fluid Density

LIST OF ACRONYMS AND ABBREVIATIONS

AWWA	American Water Works Association
BoQ	Bill of Quantity
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
HPP	Hydropower Project
MIV	Main Inlet Valve
NPR	Nepalese Rupee
RANS	Reynold-Averaged Navier-Stokes
RGHPP	Rasuwagadhi Hydropower Project
SST	Shear Stress Transport
USD	United States Dollar

CHAPTER 1: INTRODUCTION

1.1 Background

Nepal is a country blessed with immense hydropower potential. However, only a miniscule amount of the available potential has been realized till date. Currently, there are 142 hydropower projects in operation totaling about 2200 MW. And, 264 more projects are under construction. One such project under construction is Rasuwagadhi Hydropower Project in Rasuwa district, boasting a capacity of 111 MW.

In hydropower projects, Penstock isolation (shutoff) equipment is installed at the penstock inlet to facilitate repair and maintenance of the downstream components. Either a valve or a gate can serve as the penstock isolation equipment. Selection of the penstock isolation equipment depends on various factors such as cost, availability of access roads and other operational preferences. In case of valve, either Butterfly Valve or Spherical valve can be selected depending primarily on the range of head. Valves, while likelier to be more expensive, provide better ease of operation than Gates. In terms of construction, valves require to be housed in especially-built valve chambers whereas Gates require Gate Slots to be excavated. Butterfly Valves are manufactured as a single piece, necessitating roads with sufficient width to accommodate their transportation to the installation site. In contrast, Gates can be disassembled into smaller parts and later assembled on-site, making them a viable option for locations with limited access roads.

Hydropower projects, often located in remote and challenging terrains are frequently hindered by lack of proper access roads among many other challenges. In the specific context of Rasuwagadhi Hydropower Project, similar reasons of transportation constraints led to the installation of a Vertical-lift Gate instead of the originally proposed Butterfly Valve. However, this decision was made without a comprehensive hydraulic evaluation.

Even in their fully open states, Butterfly Valve and Vertical-lift Gate offer different geometry to the flow. Due to this, they offer distinct flow characteristics which will reflect into the pressure drop and subsequently the head loss incurred by the project. In case of Butterfly Valve, the disc remains parallel to the flow which restricts the flow to some extent, leading to certain pressure drop. Whereas in case of a fully open gate, the

gate leaf itself will be absent in the flow domain but the presence of Gate Slot will entail some pressure drop.

Computational Fluid Dynamics (CFD) Analysis can be conducted to simulate the flow through the Valve and the Gate Slot to predict their flow characteristics in order to compare their suitability. Moreover, the analysis provides the opportunity to visualize pressure and velocity profiles, offering valuable insights into the behavior of the flow and its interaction with the components.

1.2 Problem Statement

Maximizing hydropower production in any way feasible is instrumental in a developing country like Nepal. Selection of suitable penstock isolation equipment is crucial because it is a continuous source of head loss throughout the operation of the plant. Prospect of reducing head loss directly impacts in the revenue of the hydropower producer which in a broader scenario, is also reflected in the country's economy. A study that can assist in determination of the better alternative for penstock isolation equipment between Butterfly Valve and Vertical-lift Gate can help in maximization of hydropower production.

Moreover, while several individual research studies have been conducted to compute flow characteristics of Butterfly Valve and Gate Slot, there is no existing study that collectively compares both their flow characteristics. Given that hydropower is the primary source of electricity in Nepal, and numerous hydropower projects are under development, this research holds particular relevance and has a potential to contribute to the energy sector's advancement.

1.3 Objectives

1.3.1 Main Objective

The main objective of this research is to conduct a three-dimensional comparative numerical study between Butterfly Valve and Vertical-lift Gate at the penstock inlet of Rasuwagadhi Hydropower project, in their fully open states, for the prediction of flow characteristics.

1.3.2 Specific Objectives

The specific objectives of the thesis are:

1. To perform CFD simulation of the flow through the Butterfly Valve and the Vertical-lift Gate in their fully open states and to analyze the flow behavior
2. To calculate the flow characteristics of the Butterfly Valve and the Vertical-lift Gate to understand their hydraulic performance
3. To conduct a financial analysis and assess the impact on revenue resulting from selection of the Vertical-lift Gate over the Butterfly Valve

1.4 Scope of Work

The work is intended to establish a hydraulic and financial basis for evaluating and determining the better alternative between Butterfly Valve and Vertical-lift Gate as the preferred penstock isolation solution for Rasuwagadhi HPP. This study can also serve as a reference for future hydropower projects to make informed decisions in selection of the most suitable penstock isolation equipment.

1.5 Limitations of the Study

- Since the project is still under construction phase, experimental verification of the simulation results could not be done. Moreover, the actual installation only includes the Vertical-lift Gate, limiting the ability to experimentally validate the findings of the Butterfly Valve.
- Sedimentation in water is not considered in this research.

CHAPTER 2: LITERATURE REVIEW

2.1 Penstock Isolation Equipment

In a hydropower plant, a Penstock Isolation Equipment is positioned between the surge shaft and the penstock inlet as seen in Figure 2.1. Its primary function is to provide a means of isolating the downstream components for maintenance purposes or in emergency situations, without having to drain the entire headrace tunnel which holds a massive volume of water. Penstock isolation equipment may either be a gate or a valve.

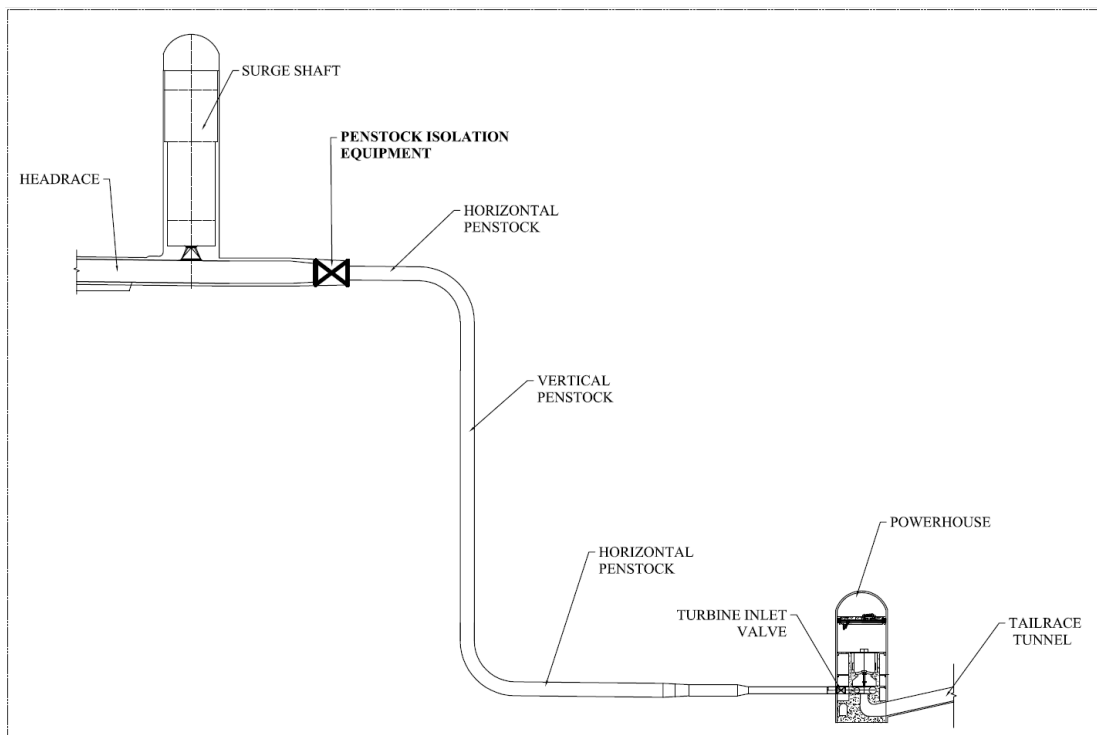


Figure 2.1: Pictorial Representation of a Hydropower Plant and the Location of the Penstock Isolation Equipment

Typically, the penstock isolation equipment remains in the fully open position for the majority of the time, ensuring uninterrupted flow and smooth hydropower generation. When maintenance or repairs are required in turbine inlet valves (also called as Main Inlet Valves or MIV) downstream, the penstock isolation equipment is closed, effectively blocking the flow of water from entering the downstream section. This closure prevents water from reaching the turbines or other components, allowing for safe and efficient maintenance activities to be carried out. Moreover, it is also activated during emergency situations, such as penstock rupture, where it acts as a vital safeguard.

Penstock isolation equipment can also be referred as penstock protection equipment or main shutoff equipment.

2.2 Butterfly Valve

Butterfly Valve is one of the commonly used flow closure devices in pressure conduits due to its compact design and simple structure. It is generally used only as on/off devices and not for flow control (Lewin, 2001). This is especially true in the context of hydropower projects where it is used only as closure devices and not for flow control. In other applications, Butterfly Valve also serves as a throttling device.

2.2.1 Working and Construction

The Butterfly Valve primarily consists of a circular disc or plate positioned within the valve body. The working principle of a Butterfly Valve involves the rotation of the disc within the valve body to control the flow of fluid. Its two main positions are “fully open” and “fully closed”. When the valve is fully open, the disc aligns with the pipe, creating a straight passage for the fluid to flow through. A quarter-turn rotation of the disc results in its “fully closed” position i.e., the flow is obstructed by the disc which acts as a wall. The disc is perpendicular to the flow in the fully closed state. The valve body provides housing and support for the whole assembly of the valve. The disc is mounted on two trunnions: the drive trunnion and the non-drive trunnion. The drive side trunnion transfers the rotating force from the operating lever to the valve disc and the non-drive side trunnion keeps the valve in position and supports the valve disc. The trunnions are inserted in the holes present on the two opposite sides of the valve body. A disc seal is also present between the valve disc and the clamping ring to form a tight joint between the valve body and the disc in the closed position to ensure no leakage of water (Varshney, 2017).

In general, there are two variations of Butterfly Valve:

1. Solid-disc valve, also known as lenticular valve
2. Lattice-blade valve, also known as through-flow valve

The lattice-blade type Butterfly Valve provides a more rigid disc configuration and offers a lower loss coefficient. The Butterfly Valve in this study is also of lattice-blade type.

2.3 Vertical-lift Gate

Gates are movable hydraulic structures that are used to close the openings of hydraulic structures and to control discharges. Among various types of gates, Vertical-lift Gates are used in case of conduits because they offer more flexibility in installation than radial gates (Lewin, 2001) .

A gate consists of three elements: leaf, embedded parts and operating device. The leaf is the main movable part that serves as bulkhead to the water passage. It also contains other support elements such as wheels, rollers, etc. (Erbisti, 2014). Vertical-lift Gates need recessed slots or grooves to facilitate the motion of the gate's guiding rollers or slides. Slot and guide supports are stationary parts also termed as embedments which are fixed in the body of the hydraulic structure and are intended to guide the gates and carry the load imposed on gate support to the structure. Furthermore, an operating device is essential to facilitate the gate's opening and closing processes.

2.4 Performance Parameters

Comparing the Butterfly Valve and the Vertical-lift Gate involves calculation of common performance factors such as Pressure Drop, Head Loss, Flow Coefficient and Loss Coefficient.

2.4.1 Pressure Drop

Pressure drop (ΔP) is the difference in total pressure between two points of a fluid network. It occurs due to resistance encountered by the fluid as it passes through the system.

The pressure drop (ΔP) is calculated at the difference between the upstream pressure ($P_{u/s}$) and the downstream pressure ($P_{d/s}$) as per the equation below:

$$\Delta P = P_{u/s} - P_{d/s} \quad \text{Equation 2.1}$$

It is important to note that this calculation gives a gross measure instead of net measure; i.e., it includes the pressure losses due to the pipe friction length as well.

2.4.2 Head Loss

Head loss is the subsequent reduction in head due to the pressure drop. Head loss is especially relevant in hydropower project because net head is one of its two major

salient features, the other being the design discharge. So, head loss directly impacts the energy generation.

With the pressure drop value, the head loss can be computed from the hydrostatic pressure equation as:

$$h_l = \frac{\Delta P}{\rho g} \quad \text{Equation 2.2}$$

Where, ΔP = pressure drop in Pascals, which is previously computed in Equation 2.1.

ρ = density of the fluid in use, which is water in this case (kg/m^3)

g = acceleration due to gravity (m/s^2)

2.4.3 Flow Coefficient and Flow Factor

The flow coefficient is defined as the flow of water at 60 °F (16 °C) in gallons per minute, at a pressure drop of 1 psi across the device (Bosserman et al., 2012) . The flow coefficient (C_v) allows for easy comparison of flow capacities between the Butterfly Valve and Gate Slots, in the context of the present study.

The flow coefficient of a valve, C_v is defined as:

$$C_v = Q \sqrt{\frac{SG}{\Delta P}} \quad \text{Equation 2.3}$$

Where, Q = discharge flow rate, in gallons per minute

ΔP = Pressure drop, in psi

SG = specific gravity of the fluid (for water, $SG=1$)

The metric equivalent of the flow coefficient is known as the Flow Factor (K_v). It is the flow of water in cubic meter per hour (m^3/hr), at a pressure drop of 1 bar across the device.

The flow factor is calculated as:

$$K_v = Q \sqrt{\frac{SG}{\Delta P}} \quad \text{Equation 2.4}$$

Where, Q= Discharge flow rate, in m³/hr

ΔP = Pressure drop, in bars

SG = Specific gravity (for water, SG=1)

2.4.4 Loss Coefficient

Loss coefficient is also called flow resistance coefficient. It is the measure of resistance to the flow that the obstacle has. Unlike the Flow Coefficient and the Flow Factor, the Loss Coefficient is dimensionless.

$$K = \frac{2gh_l}{v^2} \quad \text{Equation 2.5}$$

where, v= velocity of flow in m/s

h_l =head loss from Equation 2.2

2.5 Review of Related Researches

2.5.1 Flow through Butterfly Valve

Flow through a Butterfly Valve has been the subject of numerous researches in the field of fluid mechanics. Huang and Kim (1996) performed three-dimensional numerical simulation on partially open Butterfly Valves using FLUENT. The simulation yielded velocity and pressure profiles dependent on the valve disc angle. The flow characteristics in various angles of opening of valve disc were presented in the study. Upstream length of two times the pipe diameter and downstream length of eight times the pipe diameter was taken to get sufficient entry length and a fully developed flow downstream. Similarly, Bosserman et al. (2012) suggests taking upstream length of two times the pipe diameter upstream and downstream length of six times the pipe diameter.

Song and Park (2007) also carried out numerical analysis of Butterfly Valve using ANSYS CFX to determine flow coefficients at different valve disc angles. It was found that with the increase in the valve opening angle, the number and regions of vortex decreased and the flow was smoother.

Kimura et al. (1995) successfully carried out an investigation on fluidmechanic performance in a Butterfly Valve with a practical valve model where a theoretical loss coefficient was formulated from a contraction factor. Additionally, cavitation stages were also theoretically predicted in this research.

Eom (1988) investigated the performance of perforated and solid Butterfly Valve and subsequently calculated the loss coefficients at different blockage ratios.

Lin and Schohl (2004) employed commercial software FLUENT for Butterfly Valve at different opening angles to predict lift coefficients, drag coefficients and discharge coefficients, which was verified with experimental data.

Song et al. (2008) used ANSYS CFX for a Butterfly Valve of 2100 mm diameter to observe flow patterns and flow near the valve was observed to be highly turbulent for the nearly fully closed case. They also conducted structural analysis and concluded that a cushion equipment should be designed and installed to mitigate the impact of high pressure drop at low valve opening angle.

Henderson et al. (2007) conducted CFD analysis on penstock isolation Butterfly Valve to compute head loss and torque coefficients at various opening angles with the use of ANSYS CFX. Their results showed a strong vortical flow pattern downstream from the valve.

Del Toro (2012) conducted CFD analysis using STAR-CCM+ on a 48 inch (1219 mm) along with experimental study in an incompressible fluid and found that CFD was able to predict well for mid-open positions (30-60 degrees).

2.5.2 Flow through Gate Slot

The presence of Gate Slots in Vertical-lift Gates is known to lead to hydraulic challenges, particularly at high-velocity flows. As water flows through the slot, flow separation occurs at the leading/entrance edge of the slot, followed by reattachment on its exit side. This phenomenon gives rise to eddies and forms vortices within the slots, resulting in potential cavitation during conditions of high-velocity flow. The flow behavior in the slot is dependent on the shape of the slot's edges and the ratio of cavity depth to its length. The flow through the slot causes a decrease in pressure on the pipe wall just after the slot. Under certain conditions, cavitation may occur either within the

slot itself or in its downstream, especially when flow with high velocity encounters insufficient pressure in the slot region (Lewin, 2001).

Ball (1958) performed laboratory tests on Gate Slots at various positions of gate leaf and deduced that the design of Gate Slots greatly impacts on the turbulence and cavitation and the overall hydraulic characteristics of the flow.

Similarly, Shen et al. (2017) also found that the presence of Gate Slot leads to the formation of the unstable vortex region inside the slot. The vortex inside the slot affects the water flow near the gate and further aggravate the vibration of the gate.

Furthermore, Swamee et al. (1998) conducted experimental investigations specifically focused on flow through rectangular Gate Slots. Their research aimed to develop a discharge equation applicable to partially raised gates and large orifices. This equation proved successful in capturing the flow characteristics through such gate configurations, further contributing to the understanding of Gate Slot hydraulics.

Several other studies have also explored the intricacies of flow through Gate Slots. These investigations have examined parameters such as Gate Slot geometry, flow velocities, and hydraulic conditions. Overall, an extensive literature review reveals the significance of Gate Slot design in relation to turbulence, cavitation, and hydraulic performance.

2.6 SST Turbulence Model

Song and Park (2007) selected $k-\epsilon$ model for its robustness and accuracy and its lack of complex non-linear damping functions unlike other models such as $k-\omega$ and Reynolds Shear Stress model. And in conclusion, they suggest the usage of $k-\omega$ and SST turbulent model because of their advantage of being good at treatment of near-wall.

Lin and Schohl (2004) compared $k-\epsilon$, $k-\omega$, and $k-\omega$ SST turbulence models and concluded that $k-\omega$ SST turbulence model was the most suitable for resolving the Reynolds-averaged Navier-Stokes. Leutwyler and Dalton (2006) used several equations $k-\epsilon$, $k-\omega$ models in Fluent and concluded that SST model of $k-\omega$ produced the best results. Based on this, Henderson et al. (2007) also employed the SST turbulent model for their study.

The SST turbulence model is a widely-used two-equation turbulence model used in CFD simulations. It is known for its ability to accurately predict flow behavior across various flow conditions, ranging from attached boundary layers to separated flows. It combines the k- ω turbulence and the k- ϵ turbulence model and switches between them such that the inner region utilizes k- ω and the free shear flow utilizes k- ϵ . By solving these two equations, the model is known to provide improved predictions of near-wall turbulence and boundary layer behavior.

Based on the literature review, the SST turbulence model was deemed suitable for this study. The governing equations for the SST model are as follows:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = P - \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] \quad \text{Equation 2.6}$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \frac{\gamma}{\nu_t} P - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \frac{\rho \sigma_{\omega 2}}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}$$

Equation 2.7

CHAPTER 3: METHODOLOGY OF RESEARCH

In this chapter, the methodology applied for the work from start to finish is described.

This study follows the methodology as depicted in the flowchart below:

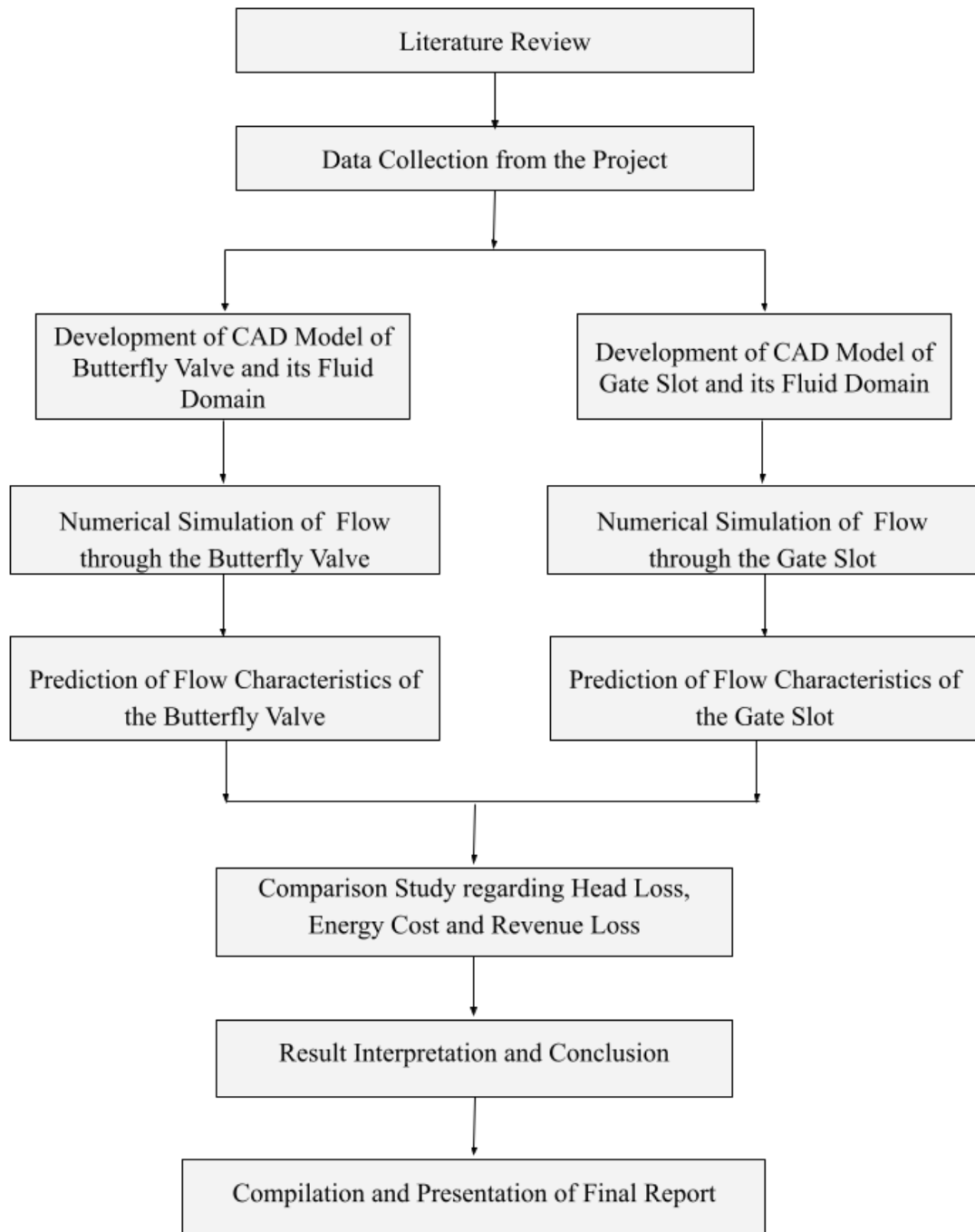


Figure 3.1. General Framework of the Adopted Research Methodology

The above steps have been explained in detail in the succeeding sections.

3.1 Literature Review

Literature review has been conducted by studying related research papers, journals, thesis reports, books to get an insight about the topic, where the potential research gap lies, and how to address it. Mainly, the following have been studied under literature review:

- Penstock Isolation Equipment
- Working and construction of Butterfly Valve
- Working and construction of Vertical-lift Gate
- Flow characteristics of Butterfly Valve
- Flow characteristics of Gate Slots
- CFD techniques

3.2 Data Collection from the Project

All the necessary data, technical specifications and drawings were collected from the Project. Mainly, following data were collected:

- Relevant Technical specifications
- Relevant Drawings for modelling
- Salient features of the HPP
- Bills of Quantity (BoQs) and Cost of Butterfly Valve and Vertical-lift Gate

3.3 Model Development of Butterfly Valve and Gate Slot

Based on the data collected, the fluid models for fully open states of Butterfly Valve and Vertical-lift Gate have been developed in full-scale, i.e., 1:1 scale in CATIA.

The upstream length of the fluid domain has been taken as two times the pipe diameter and the downstream length has been taken as six times the pipe diameter. The valve has a diameter of 4800 mm. In case of gate, the dimension of the rectangular Gate Slot is 850x1400 mm² on both sides. Additionally, the rectangular cross-section transitions to circular cross-section on both upstream and downstream sides.

The developed model was imported into ANSYS SpaceClaim, where some necessary repairs were made. The models are shown in Figure 3.2 and 3.3.

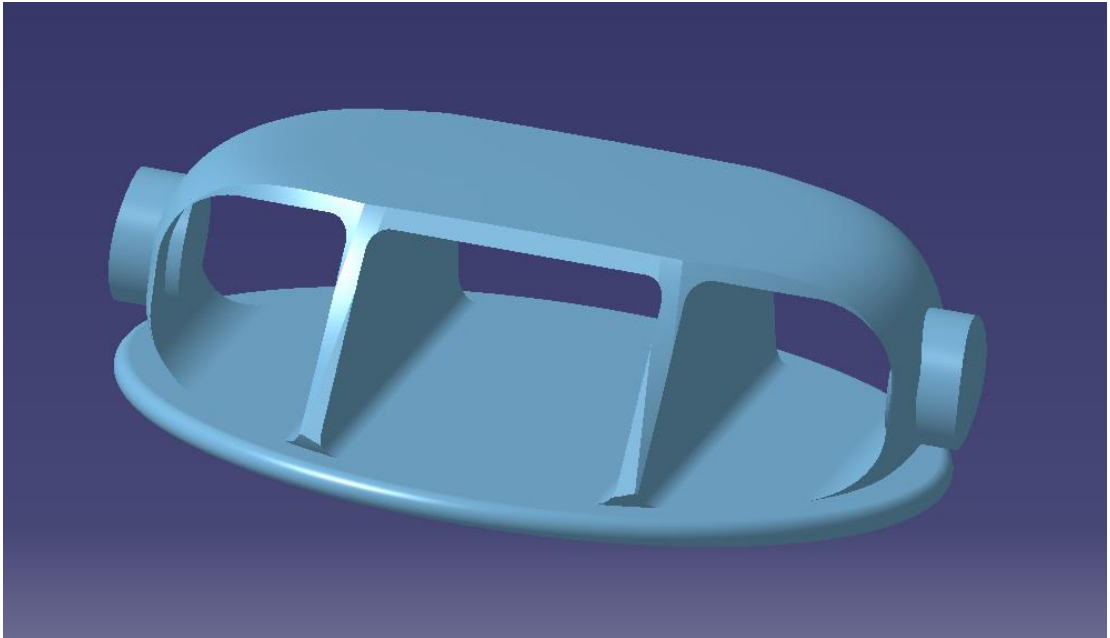


Figure 3.2: 3D Model of Butterfly Valve

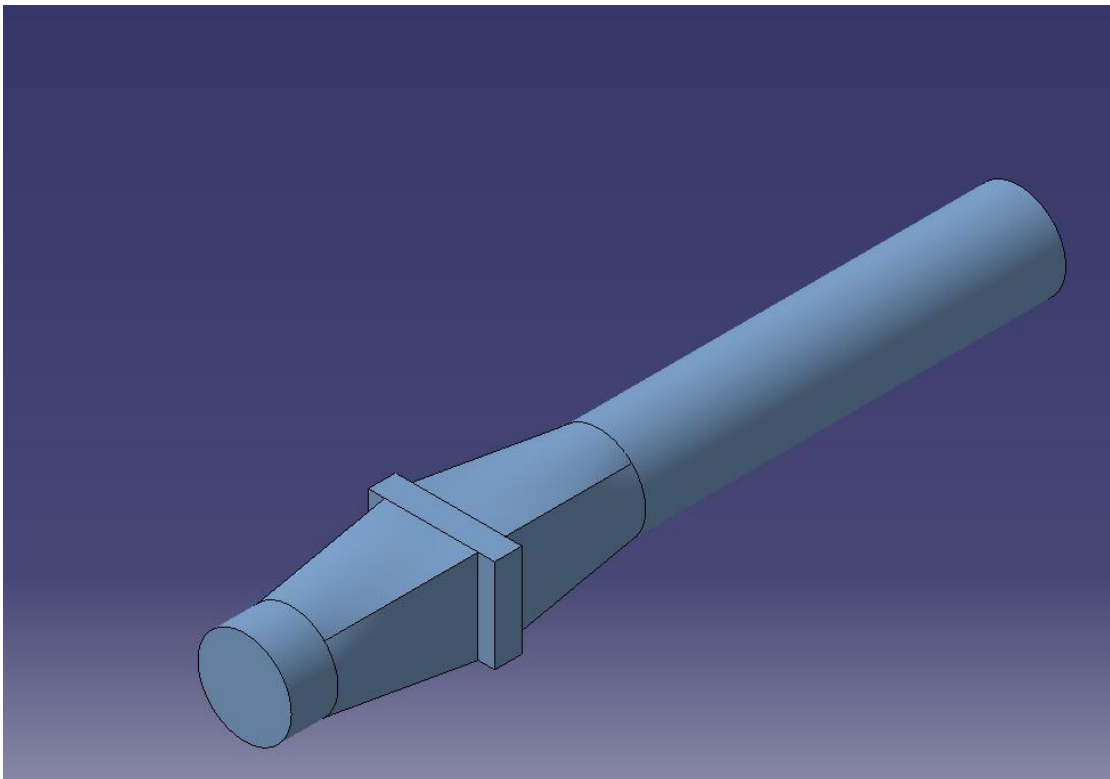


Figure 3.3: 3D Model of Gate Slot Fluid Domain

3.4 Numerical Simulation

Following steps were undertaken for numerical simulation:

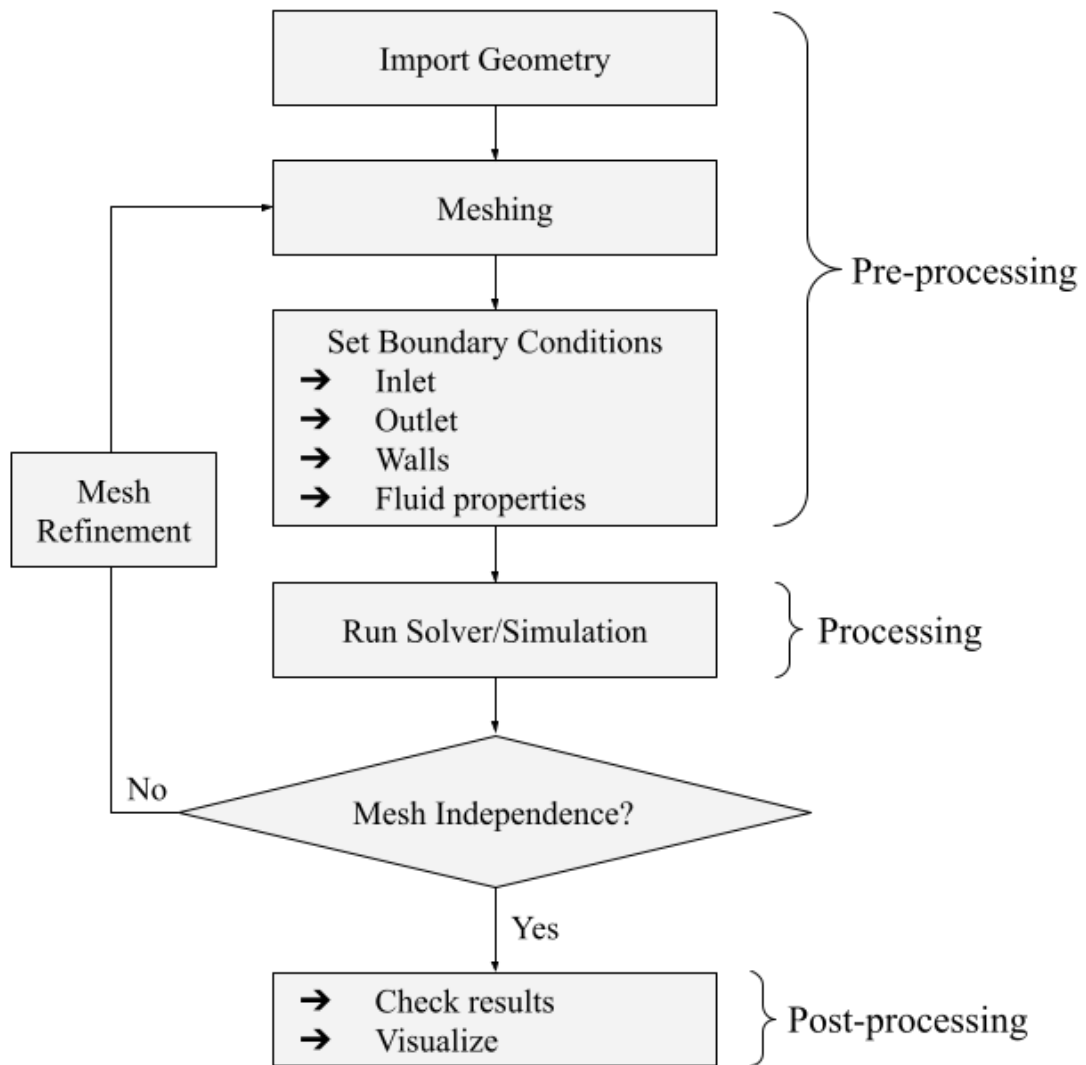


Figure 3.4. Methodology for Numerical Simulation

3.4.1 Meshing

After creating the fluid model, the next step involved meshing the model. The quality of mesh plays a pivotal role in ensuring the accuracy of the simulation. The mesh is refined at the critical areas such as near the Gate Slot and the Valve. The more the number of elements, finer is the mesh and the more qualitative it is considered. However, the downside of the finer mesh is that it will be more computationally taxing (expensive). To strike a balance between accuracy and computational efficiency, a mesh independence test was carried out to determine the optimum number of nodes. By systematically varying the mesh density and evaluating the resulting simulation outputs, the point of diminishing returns can be identified where additional refinement of the mesh does not yield significant improvements in accuracy. In this way, the optimal

mesh configuration was selected that provided the reliable results while also optimizing the computational resources.

3.4.2 Boundary Conditions

The next step in the simulation workflow involves imposing appropriate boundary conditions that represent the real-world operating conditions as close as possible. The boundary conditions of the Inlet, Outlet and Walls must be defined prior to running the simulation. The boundary conditions are tabulated in Table 3.1 to 3.5.

The penstock isolation equipment is situated in a long straight cylindrical section and operated under a static head of 38.15 m relative to atmospheric pressure. The fluid is set as water.

Table 3.1: Details of Default Domain in Flow Analysis

Domain type	Fluid Domain
Fluid Material	Water
Material Morphology	Continuous Fluid
Reference Pressure	1 atm
Buoyancy Model	Non-buoyant
Domain Motion	Stationary

Table 3.2: Details of the Fluid Model

Heat transfer option	Isothermal
Fluid Temperature	25°C
Molar Mass	18.02 kg/mol
Density	997.0 kg/m ³
Dynamic Viscosity	8.90 × 10 ⁻⁴
Turbulence	
Turbulence option	Shear Stress Transport
Wall function	Automatic
Combustion Option	None
Thermal Radiation Option	None

Table 3.3: Boundary Conditions at Inlet

Flow regime Option	Subsonic
Mass and Momentum Option	Normal Speed
Speed	4.41974 m/s
Turbulent Option	Medium (Intensity =5%)

Table 3.4: Boundary Conditions at Outlet

Flow regime Option	Subsonic
Mass and Momentum Option	Static Pressure
Relative Pressure	373128.75 Pa

The upstream and downstream sections are steel penstock pipe which has relatively smooth surface. Similarly, both the Butterfly Valve and the Gate Slot are also made of steel. With this consideration, following boundary conditions are applied at the wall.

Table 3.5: Boundary Conditions at Wall

Mass and Momentum Option	No Slip Wall
Wall Roughness option	Smooth Wall

3.4.3 Simulation

The solver settings were suitably configured for simulation. Several trial runs were carried out to come up with the optimum settings. The simulation was run until convergence was achieved with SST turbulence model.

3.4.4 Post-processing

After successful simulation, the required data was extracted in this step, mainly the pressure drop. The flow was then visualized using pressure profiles, streamlines, contour plots etc. The data was used to compute the flow characteristics such as flow coefficient and loss coefficient.

3.5 Comparison Study

After getting the individual results of Butterfly Valve and Vertical-lift Gate Slot, a comparative study was conducted with respect to their flow coefficient and loss coefficient. Subsequently, the resulting head loss and its implication on revenue loss were calculated.

3.6 Result Interpretation and Conclusion

From the results obtained, the conclusion was derived on which alternative is better between Butterfly Valve and Vertical-lift Gate.

3.7 Compilation and Presentation of Final Report

This was the final step of the research wherein all the information and results collected was compiled and presented in a formal report.

3.8 Research Tools

The research employed software tools described below:

AutoCAD: AutoCAD was employed in this study to make 2D draft of the models. For modelling of the Butterfly Valve, AutoCAD was utilized to come up with the initial 2D drawing of the disc.

CATIA: CATIA is a powerful CAD software widely used in various engineering applications for creating and designing complex 3D models of mechanical components, structures and systems. So, it was opted as the primary CAD tool in this research. It was used to develop the fluid models of Butterfly Valve and the Gate Slot in their fully open states.

ANSYS CFX: ANSYS has been chosen as the simulation software for this research because of its wide application in CFD. Moreover, CFX has been opted for its known robustness.

Microsoft Excel: Microsoft Excel is a versatile tool for data analysis and data organization. It has been used for basic calculations and data analysis. It has also been used for data visualization.

CHAPTER 4: RESULTS AND DISCUSSION

The CFD simulations were conducted using the methodology outlined in Chapter 3. The flow fields were visualized and the performance characteristics were computed.

4.1 Flow through the Butterfly Valve

Overall, the pressure gradient is quite gradual from the inlet to outlet with disturbances observed at the leading edge of the disc, the trunnion and the gap between the trunnion and the disc. The pressure difference at these areas is distinctly observed in the contour visualization in Figure 4.1, 4.2 and 4.3.

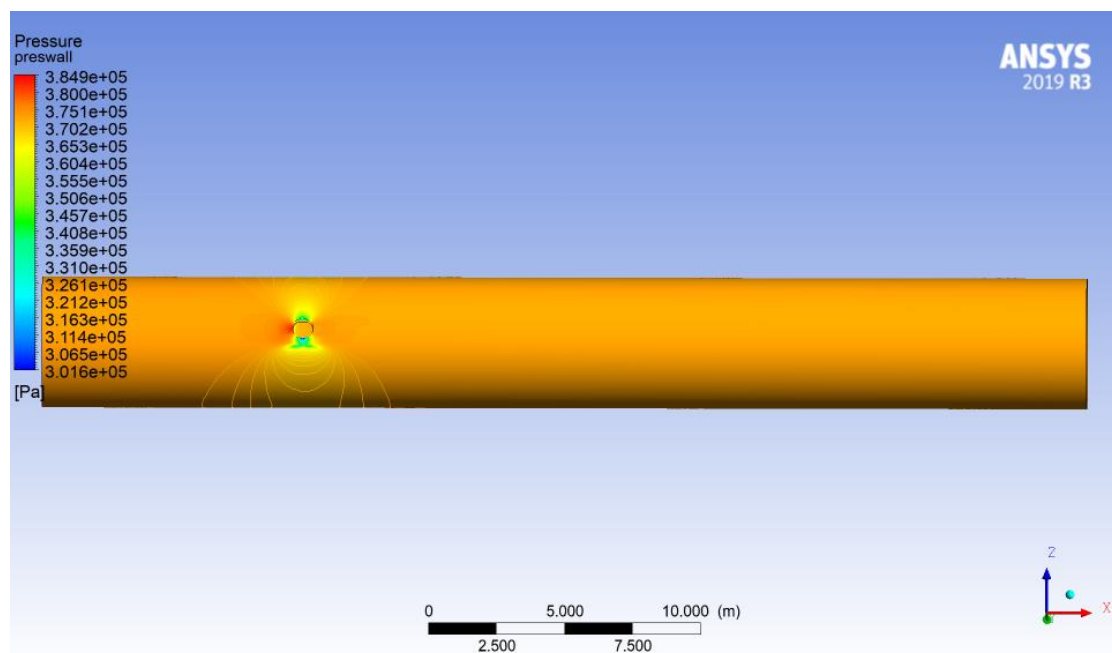


Figure 4.1: Pressure Distributions at the Wall for the Flow through the Butterfly Valve

The sudden presence of trunnion causes disturbance to the flow in case of Butterfly Valve as seen in Figure 4.3. The fluid is forced to flow through the narrow gap between the trunnion and the valve disc where the pressure is observed to be low. In fact, this zone near trunnion seems to be the region of the lowest pressure, which is evident in Figure 4.1. Whereas, the highest-pressure region is distinctly visible at the points where the upstream flow makes initial contact with the disc's lower surface and the upper surface as seen in Figure 4.2. Similarly, the deviation in the velocity's direction can be observed in Figure 4.4 at the same points of contact. Another high-pressure zone appears at the point of contact of the flow with the trunnion cylinder as seen in the Figure 4.1.

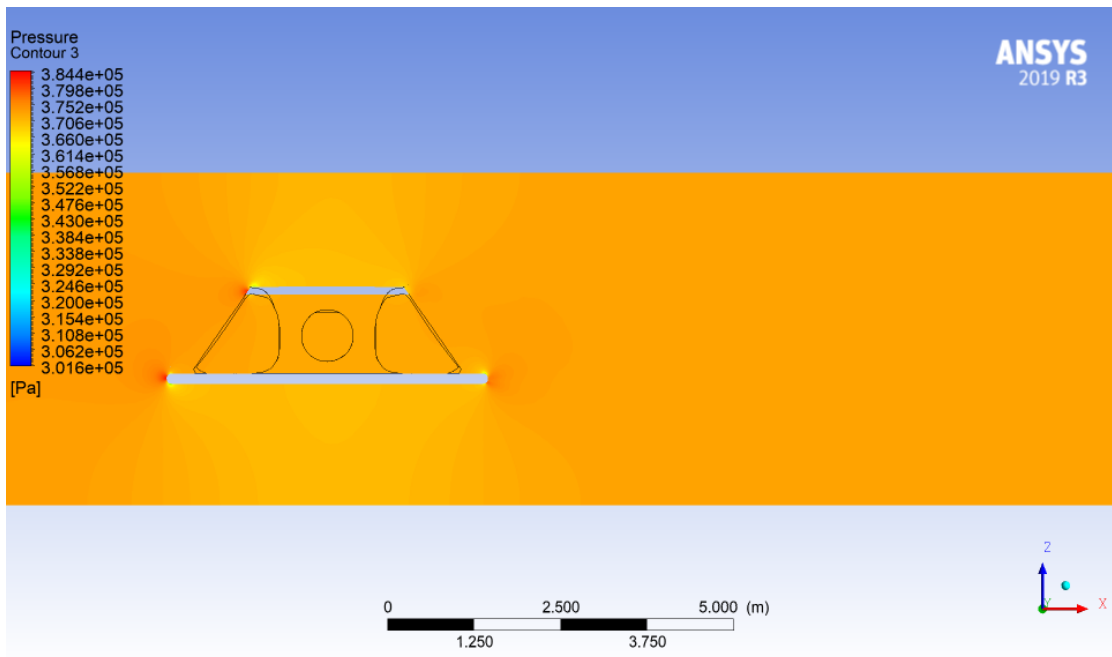


Figure 4.2: Pressure Distribution at the Mid-plane for Flow through the Butterfly Valve

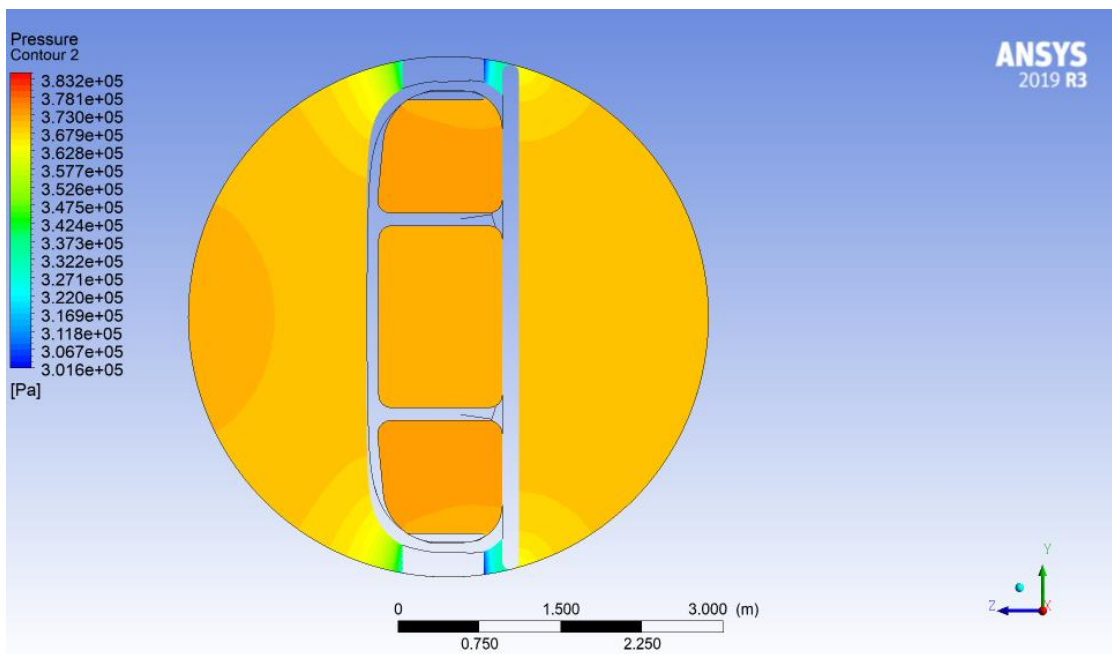


Figure 4.3: Pressure Distribution at the Midsection of the Butterfly Valve

In the streamline visualization in Figure. 4.5, steady streamlines are observed along the upper and lower opening between the valve disc and the wall. However, streamlines along the Butterfly Valve disc seem to deviate, but this effect appears to dissipate gradually downstream. The deviations of the streamlines are observed to be more pronounced from the gap between the trunnion and the valve disc in Figure 4.6.

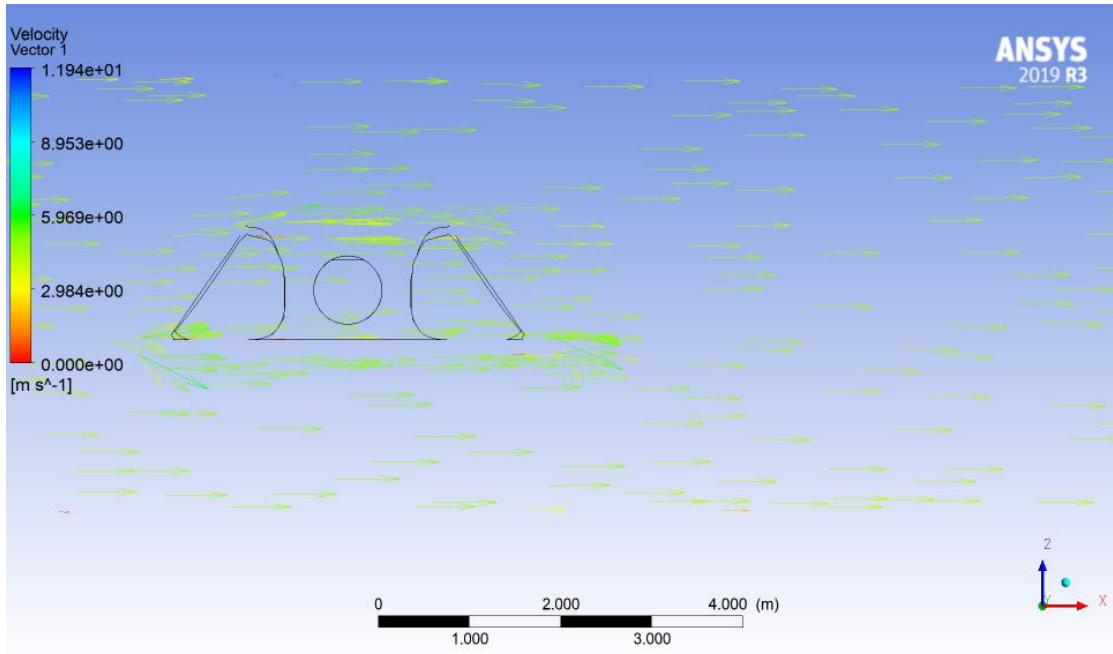


Figure 4.4: Velocity Vectors in the Mid-plane of Butterfly Valve Fluid Domain

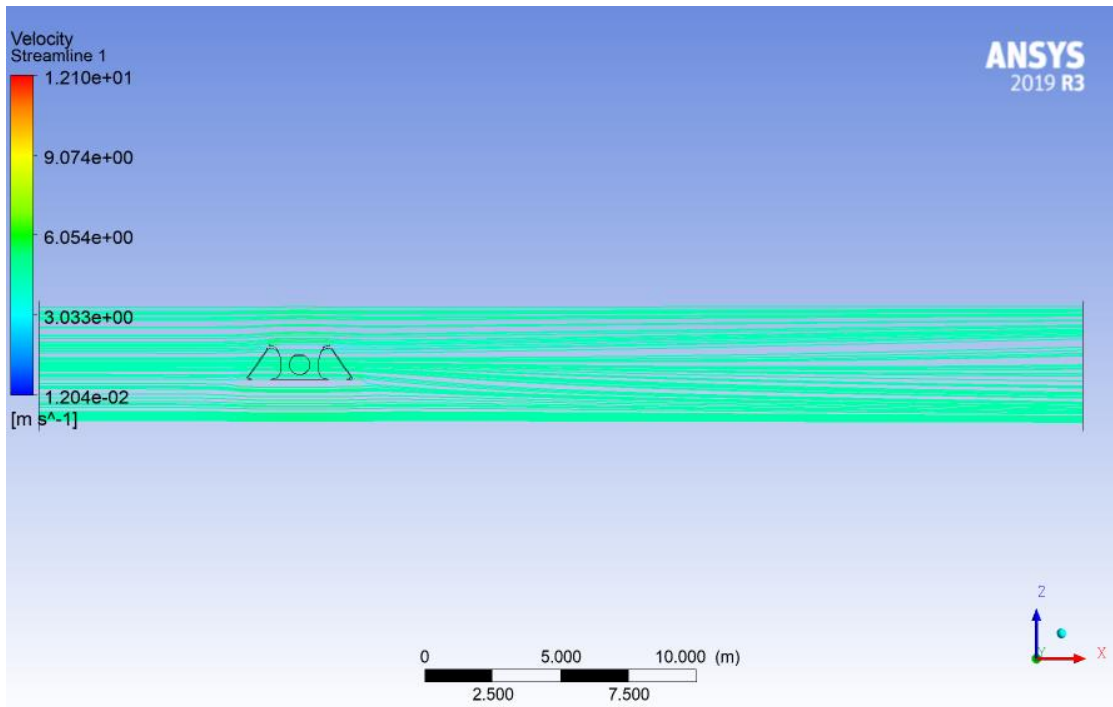


Figure 4.5: Velocity Streamlines in Mid-plane (Side-view) of Butterfly Valve Fluid Domain

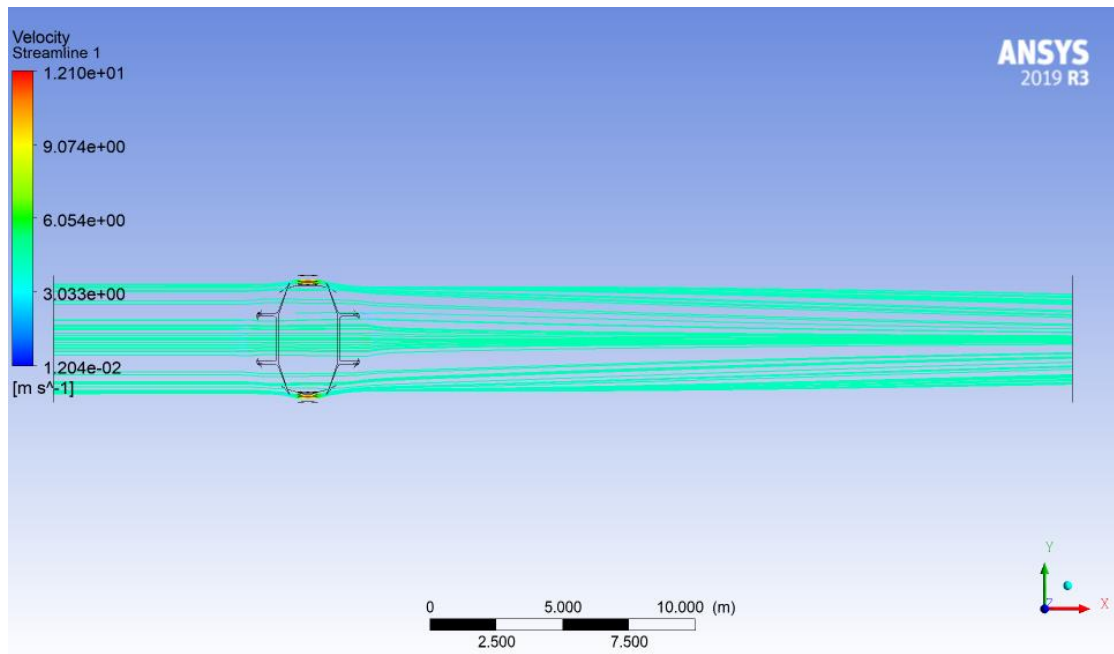


Figure 4.6: Velocity Streamlines in Mid-plane (Top-view) of Butterfly Valve Fluid Domain

4.2 Flow through the Gate Slot

Distinct low-pressure zones are observed both upstream and downstream where the pipe has transitioned from circular to rectangular cross-section and vice-versa as seen in the pressure contours on the wall in Figure 4.7. The effect of transition, however has dissipated in the mid-sections of the fluid as seen in Figure 4.8.

The dominantly high-pressure zone is distinctly seen in the Gate Slot area and the area peripheral to it. This is in accordance with Bernoulli's principle. The sudden enlargement in the flow area because of the presence of Gate Slot causes the velocity to decrease and pressure to increase. The other highest-pressure zone is observed to be concentrated at the corners of Gate Slots and the wall. Again, this effect is observed to be have dissipated in the mid-sections of the fluid flow.

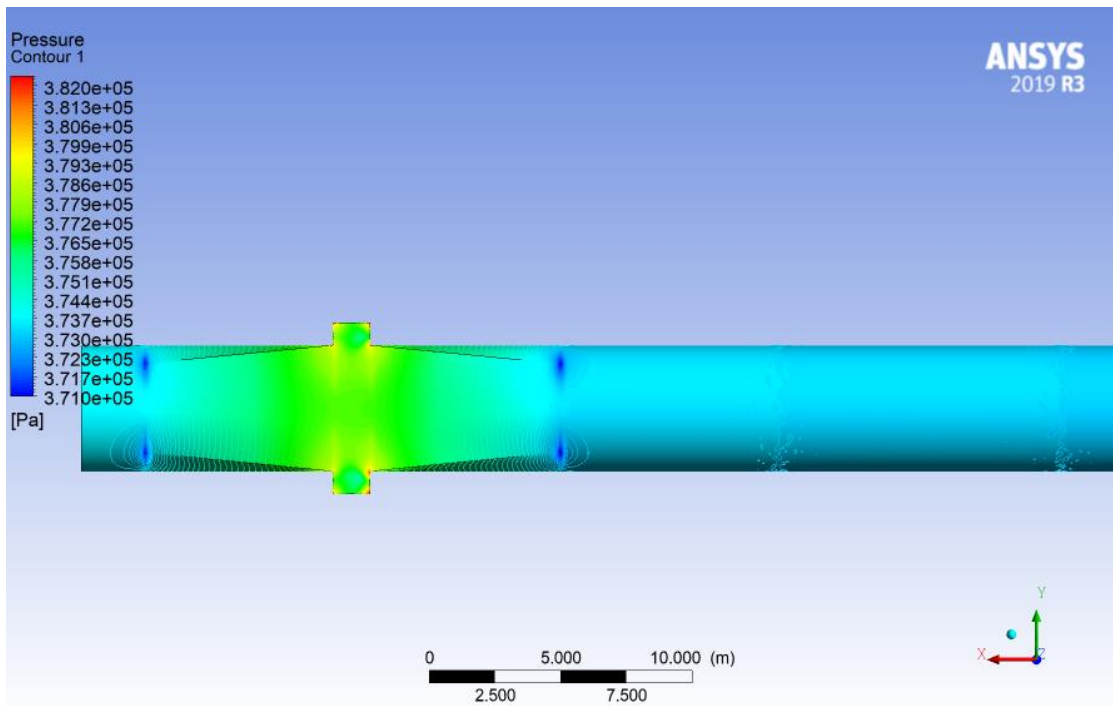


Figure 4.7: Pressure Contours on the Walls for Flow through the Gate Slot

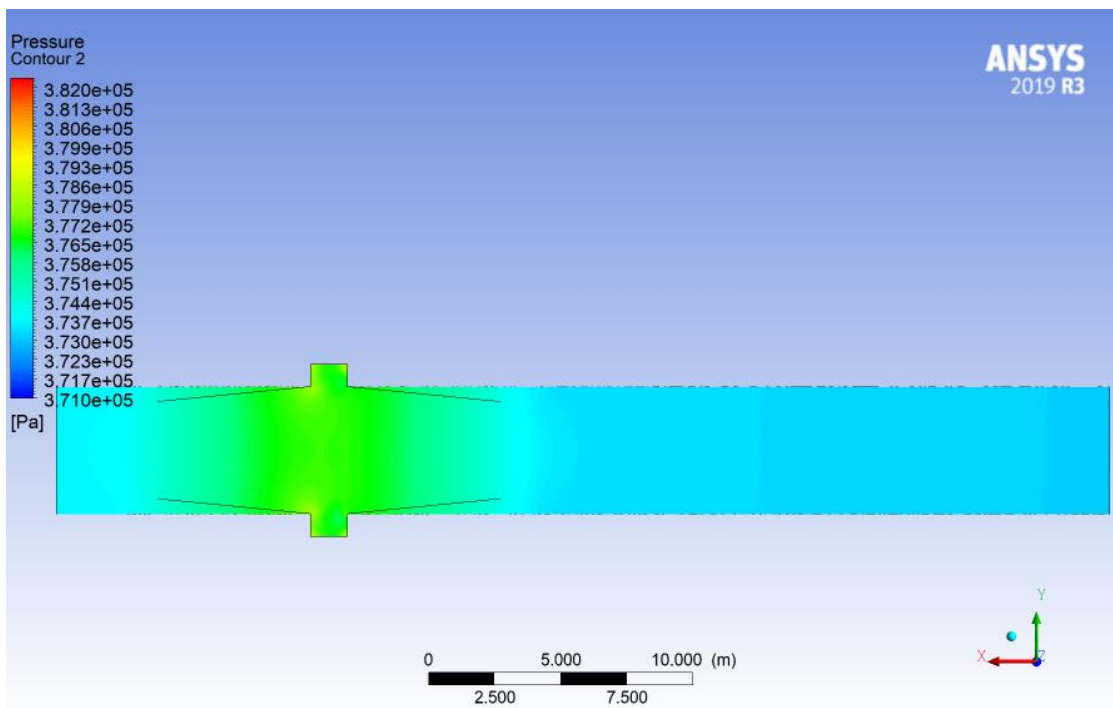


Figure 4.8: Pressure Contour on the Mid-plane for the Flow through the Gate Slot

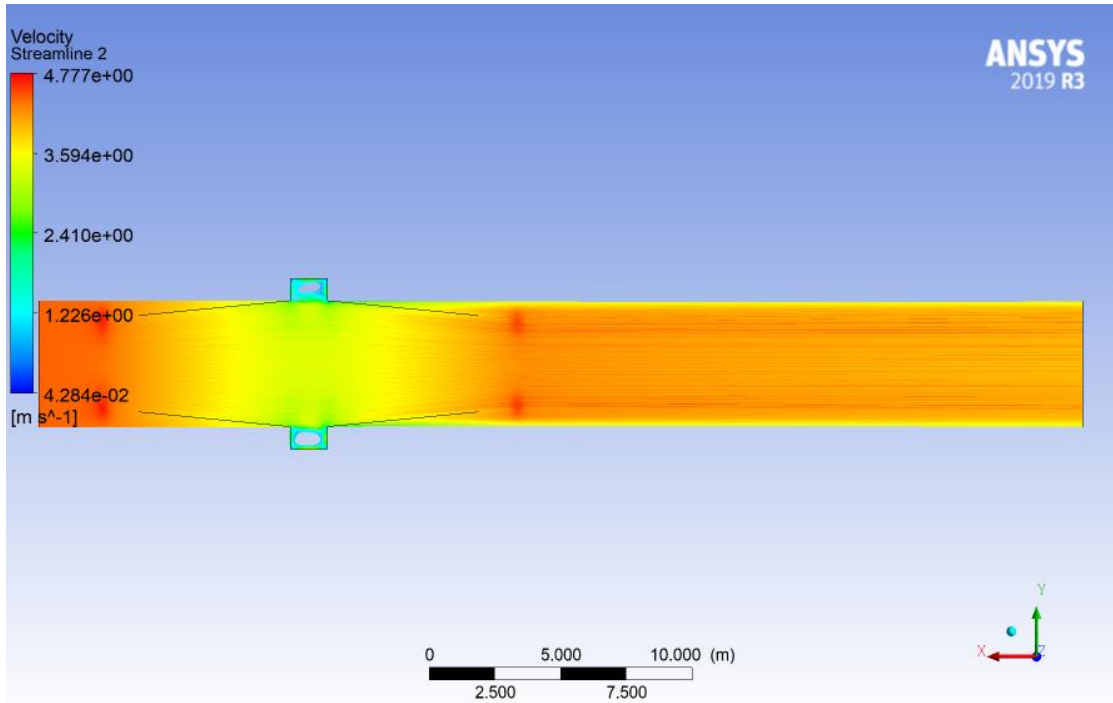


Figure 4.9: Velocity Streamlines for Flow through the Gate Slot

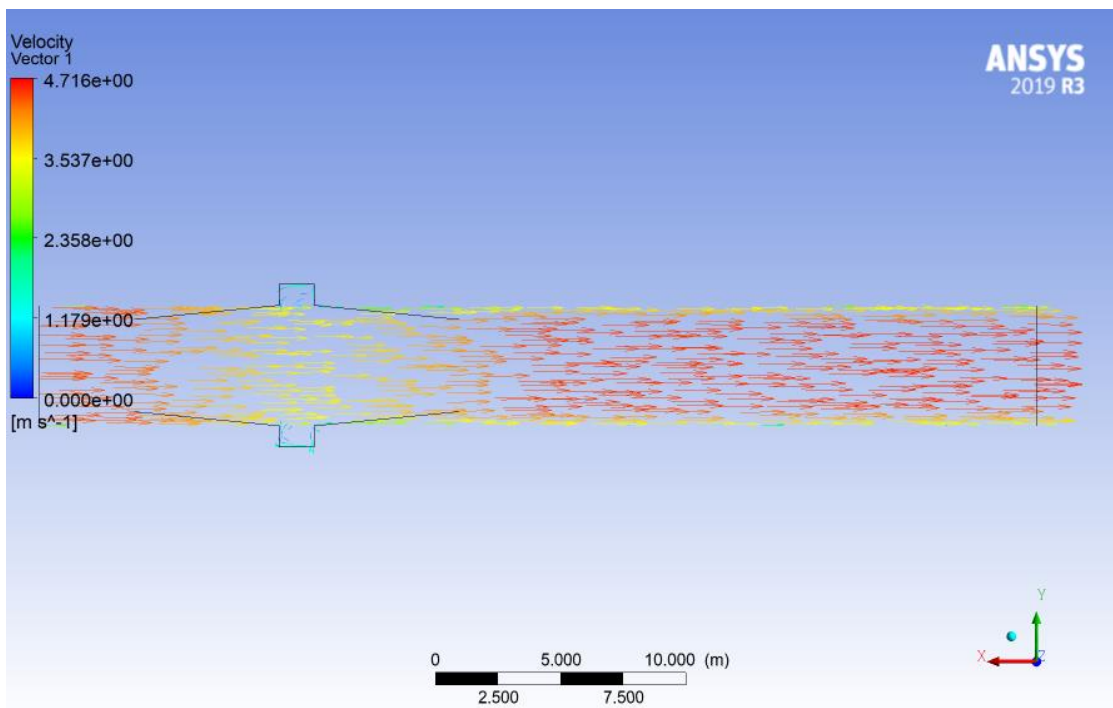


Figure 4.10: Velocity Vector Visualization of Flow through the Gate Slot

Vortex formation is observed in Gate Slots when water flows through the slots of a vertical-lift gate in Figure 4.9 and 4.10. The presence of Gate Slots leads to the creation of an unstable vortex region inside the slot. This vortex can have several effects on the flow. While it will have relatively minimal effect on the gate leaf itself as it is situated

very far up, it may still impact the embedments, i.e., the slot areas. The vortex inside the Gate Slot affects the flow near the gate, altering its characteristics. It can cause disturbances and turbulence in the immediate vicinity of the Gate Slot, influencing the flow patterns.

4.3 Performance Parameters

After obtaining the values of Pressure drops from the simulation, the Performance Parameters of Butterfly Valve and Gate Slot have been calculated, as tabulated in Table 4.1.

Table 4.1: Comparison of Performance Parameters

Parameter	Butterfly Valve	Gate Slot	Difference
Pressure drop (Pa)	933.00	549.00	384.00
Pressure drop (psi)	0.1353	0.07963	0.05569
Pressure drop (bars)	0.00933	0.00549	0.00384
Flow Coefficient, C_v (gals/min)	3,447,035.455	4,493,661.971	-1,046,626.515
Flow Factor, K_v (m^3/hr)	2981615.695	3886926.385	-905,310.690
Loss Coefficient, K	0.0955	0.0559	-0.03914
Head Loss (m)	0.09539	0.05613	0.03926
Head Loss (mm)	95.39	56.13	39.26

The Gate Slot is seen to have significantly higher flow coefficient than the Gate Slot. A higher flow coefficient value signifies that a device can handle a larger volume of fluid flow for a given pressure drop. In this context, it means that the Gate Slot has a higher flow capacity compared to the Butterfly Valve. It suggests that the Gate Slot can accommodate a higher volumetric flow rate of approximately 4,493,661.971 gallons per minute, while the Butterfly Valve can handle a comparatively lower volumetric flow rate of 3,447,035.455 gallons per minute, i.e., the Gate Slot can accommodate 1.3 times of volumetric flow rate as compared to the Butterfly Valve. This information is crucial for understanding and selecting the appropriate penstock isolation equipment in hydropower projects. It implies that the Gate Slot has a higher potential for fluid flow and may be better suited for applications that require higher flow rates.

The loss coefficient of Butterfly Valve is higher than that of the Gate Slot by about 1.7 times, which basically implies that the resistance to the flow caused by the Butterfly Valve is 1.7 times more than that of the Gate Slot.

4.4 Financial Analysis

4.4.1 Initial Costs

In terms of initial equipment cost, considering that the Butterfly Valve has more weight and has a more complex geometry, it is more expensive than the Vertical-lift Gate. However, the cost disparity extends beyond the equipment itself. The required housing for each option significantly influences the overall cost, particularly concerning the surge shaft and installation expenses. The housing and installation cost of the Valve is more than that of the Gate. For the Gate, the excavation of Gate Slots in addition to the surge shaft construction escalates the cost of surge shaft compared to the Butterfly Valve. Additionally, since the Butterfly Valve comes in a single-piece, it demands wider access roads leading to significantly higher access road expenses. In contrast, the Gate's assembly on-site allows for cost-effective access roads, rendering it more economical in this aspect. Consequently, when factoring in the significant cost differences in access roads, the Vertical-lift Gate emerges as the more cost-effective option. In total, the Vertical-lift Gate is estimated to cost USD 203,385 less than the Butterfly Valve. The cost breakdown and comparison are represented in Figure 4.11.

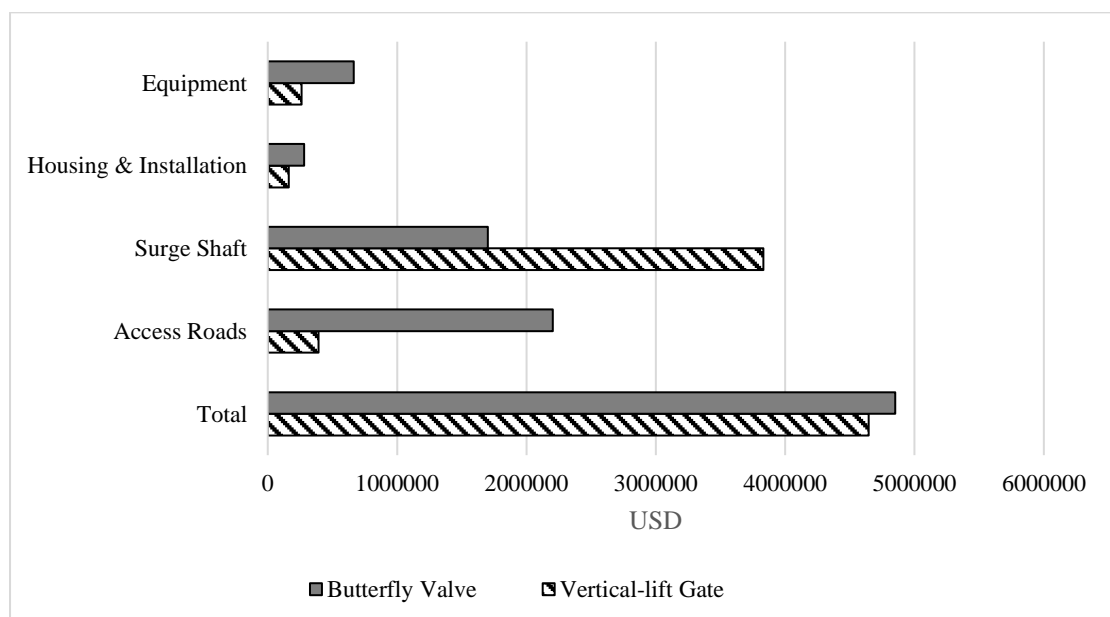


Figure 4.11: Initial Cost Comparison of Butterfly Valve and Vertical-lift Gate

4.4.2 Revenue Loss

Because of different head losses imposed by the Butterfly Valve and the Gate in their fully open states, there are differences in the generation loss and thereby in the revenue loss too. This is presented in the Table 4.2.

Table 4.2: Comparison of Head Loss and Revenue Loss

Parameter	Butterfly Valve	Gate Slot	Difference
Head loss (m)	0.09539	0.05613	0.03926
Revenue loss in a day (USD)	100.32	59.03	41.29
Revenue loss in a month (USD)	3009.62	1770.94	1238.69
Revenue loss in a year (USD)	36,617.10	21,546.40	15,070.70
Revenue loss in 10 years (USD)	366,171.02	215,463.98	150,707.04
Revenue in 30 years (USD)	1,098,513.06	646,391.93	452,121.13
Initial Cost (USD)	4,849,768.74	4,646,383.00	203,385.74
Revenue in 30 years + Initial Cost (USD)	5,948,281.80	5,292,774.93	655,506.87

From the calculation, the Butterfly Valve offers more pressure drop and subsequently higher head loss, which is almost 1.7 times than that of the Gate Slot. As a result of this, the difference in the revenue loss comes to USD 15,070 per annum, i.e., with the use of the Vertical-lift Gate, RGHPP saves yearly USD 15,070 more than what it would have if the Butterfly Valve were installed. In the hydropower producer's plant-owning lifecycle which is generally 30 years in the context of Nepal, the revenue loss difference due to head loss amounts to USD 452,121 and the total difference is USD 655,506.87.

The financial impact difference accounting the initial costs is presented in Figure 4.12. It shows an initial gap of USD 203,385.74 in Year 0. Additionally, owing to the Vertical-lift Gate's lower head loss, it incurs a reduced revenue loss compared to the Butterfly Valve. As a result, the disparity between the revenue losses of the Butterfly Valve and the Vertical-lift Gate widens significantly over time.

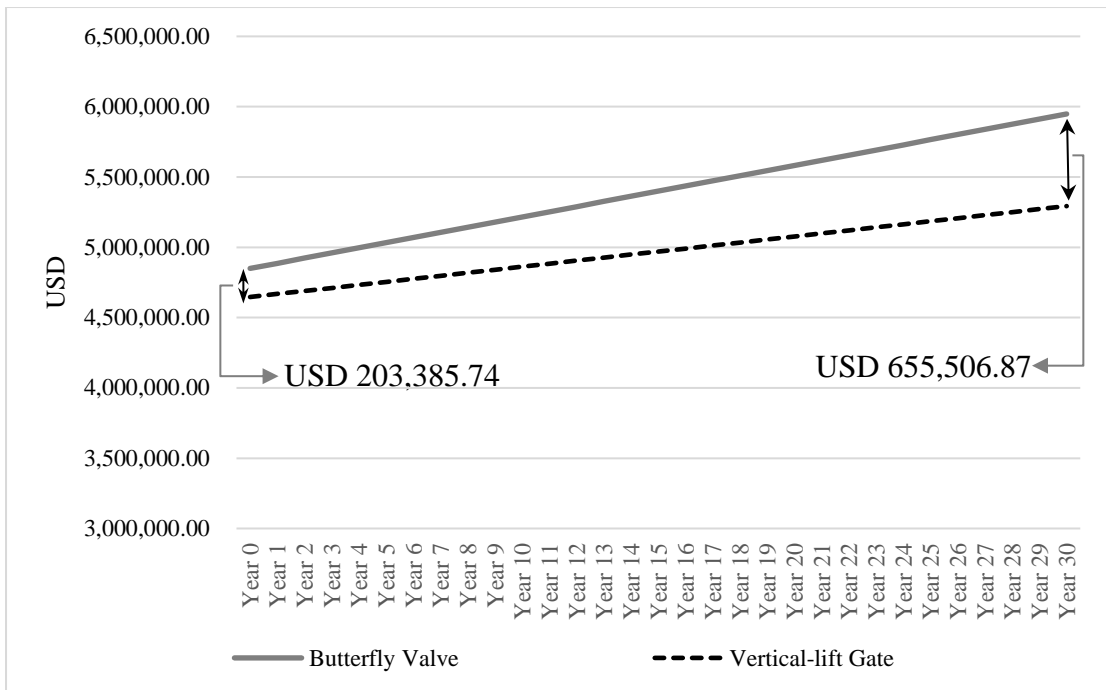


Figure 4.12: Revenue Losses of Butterfly Valve vs. Vertical-lift Gate over 30 Years

As compared to the total revenue generated by the HPP, the revenue loss caused by the Butterfly Valve is 0.06% of the total revenue. Similarly, the revenue loss caused by the Vertical-lift Gate accounts to 0.04% of the total revenue. This information is presented in Table 4.3 below. Based on this, it can be argued that the revenue loss differences are not very significant.

Table 4.3: Revenue Loss in Comparison to Revenue Generated

Parameter	Butterfly Valve	Vertical-lift Gate	Difference
Head loss (m)	0.095393213	0.056131698	0.039261515
Annual Revenue (USD)	60,796,623.80	60,811,694.50	(15,070.70)
Annual Revenue Loss (USD)	36,617.10	21,546.40	15,070.70
Revenue Loss (%)	0.06 %	0.04 %	0.02 %

The Vertical-lift Gate shows a clear advantage over a 30-year period, exhibiting lower head loss and higher energy generation. Moreover, its initial cost is also lower compared to the Butterfly Valve. Taking these factors into consideration, the Vertical-lift Gate emerges as the better alternative, proving to be the more financially viable option in both the short-term and long-term perspectives.

4.4.3 Alternative Case Scenario: Presence of Access Roads

In a hypothetical scenario where the implications on access roads are not factored in, the initial cost of the Butterfly Valve is significantly lower, presenting a cost difference of USD 1.6 million compared to the vertical-lift gate. Thus, in cases where wide access roads already exist or if the cost of access roads remains constant for both options, the Butterfly Valve would be the cheaper option initially.

Because of the lower head loss incurred by the Gate, the annual revenue loss caused by the Gate is USD 15,071 lower than that of the Valve. However, even over a 30-year span, the gate cannot surpass the Butterfly Valve due to the substantial initial cost disparities. In fact, it would take the project approximately 106 years to make up for the initial cost differences as illustrated in the graph in Figure 4.13. In other words, the vertical-lift gate would only become a more financially advantageous option in the 107th year.

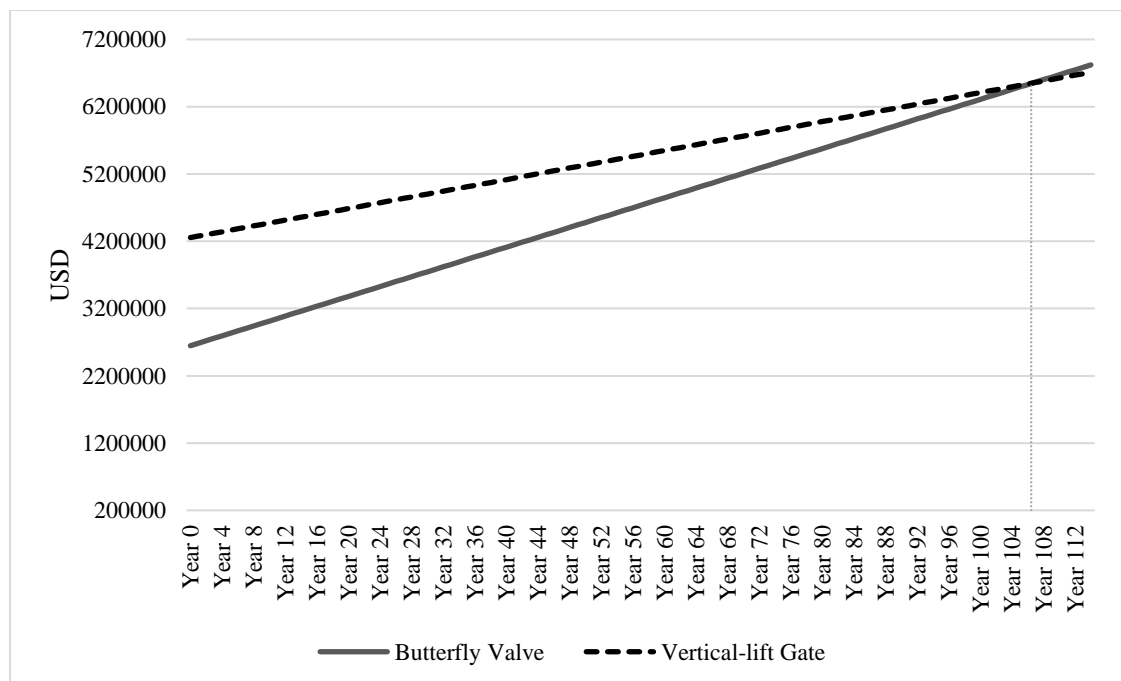


Figure 4.13: Financial Analysis in a Case Scenario of Presence of Access Roads

Thus, in this case scenario, the Butterfly Valve emerges as a favorable option from a financial standpoint. This result also underscores the pivotal role played by the access roads in influencing cost differences and financial analysis.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The numerical simulation provided insights into the distinct flow behaviors of flow through the Butterfly Valve and the Gate Slot. In case of the vertical-lift gate, the presence of vortices in the Gate Slot could pose some challenges such as vibrations and cavitation. In addition to the slot, the presence of transition from rectangular to circular cross-section and vice-versa also contributed to some flow disturbance. Whereas in case of the Butterfly Valve, the presence of the disc itself in the flow causes some minor disruptions.

Based on the findings of this thesis, it can be concluded that the Gate Slot offers much higher flow coefficient than the Butterfly Valve which suggests that the Gate Slot can handle a larger volume of fluid flow for a given pressure drop. Similarly, the Gate Slot exhibits a lower head loss compared to the Butterfly Valve. Consequently, the loss coefficient of the Gate Slot is also lower than that of the Butterfly Valve. From a hydraulic perspective, the gate emerges as the winner in terms of minimizing head loss and optimizing the efficiency of the penstock isolation system.

Moreover, the different head losses are directly reflected into the electricity production and revenue generation of the Rasuwagadhi Hydropower Project. Notably, the initial cost of Vertical-lift Gate is lower compared to the Butterfly Valve. And in addition, the Vertical-lift Gate incurs lesser revenue loss than the Butterfly Valve which adds up over the years. So, from the financial point too, the gate stands out as the superior alternative for the penstock isolation equipment. However, the impact on the revenue is not very significant when compared to the total revenue generated. It is also seen that the access roads play a major role in the financial analysis and in a hypothetical case where wider access roads were already available, Butterfly Valve would emerge as a more financial viable option.

5.2 Recommendations

Despite the clear hydraulic and financial advantages of the Vertical-lift Gate, it is essential to consider other factors when selecting the penstock isolation equipment for the hydropower plant. Factors such as maintenance requirements, reliability, and operational considerations should be carefully evaluated. Additionally, it is important

to consider the phenomenon of vortex formation in the Gate Slots. Therefore, the decision-making process should involve a comprehensive analysis that weighs the hydraulic advantages of the gate against the potential drawbacks and advantages associated with the Butterfly Valve. It is recommended to conduct a thorough cost-benefit analysis, taking into account the initial investment, lifecycle costs, and potential impact on overall plant performance.

Furthermore, the transportation constraint led to the selection of the Vertical-lift Gate in Rasuwagadhi Hydropower Project. Similarly, the decision-making process for any other project should be guided by a comprehensive understanding of the project's specific needs and objectives, ensuring the selection of the penstock isolation equipment that optimizes both hydraulic performance and overall operational feasibility.

Future research can focus on analyzing the performance of both options under varying operating conditions and exploring innovative technologies or modifications that may enhance the efficiency and reliability of the selected equipment. Additionally, an in-depth investigation into the impact of vortices, particularly in relation to their effect on cavitation and turbulence at the gate would also contribute on the advancement of hydropower industry.

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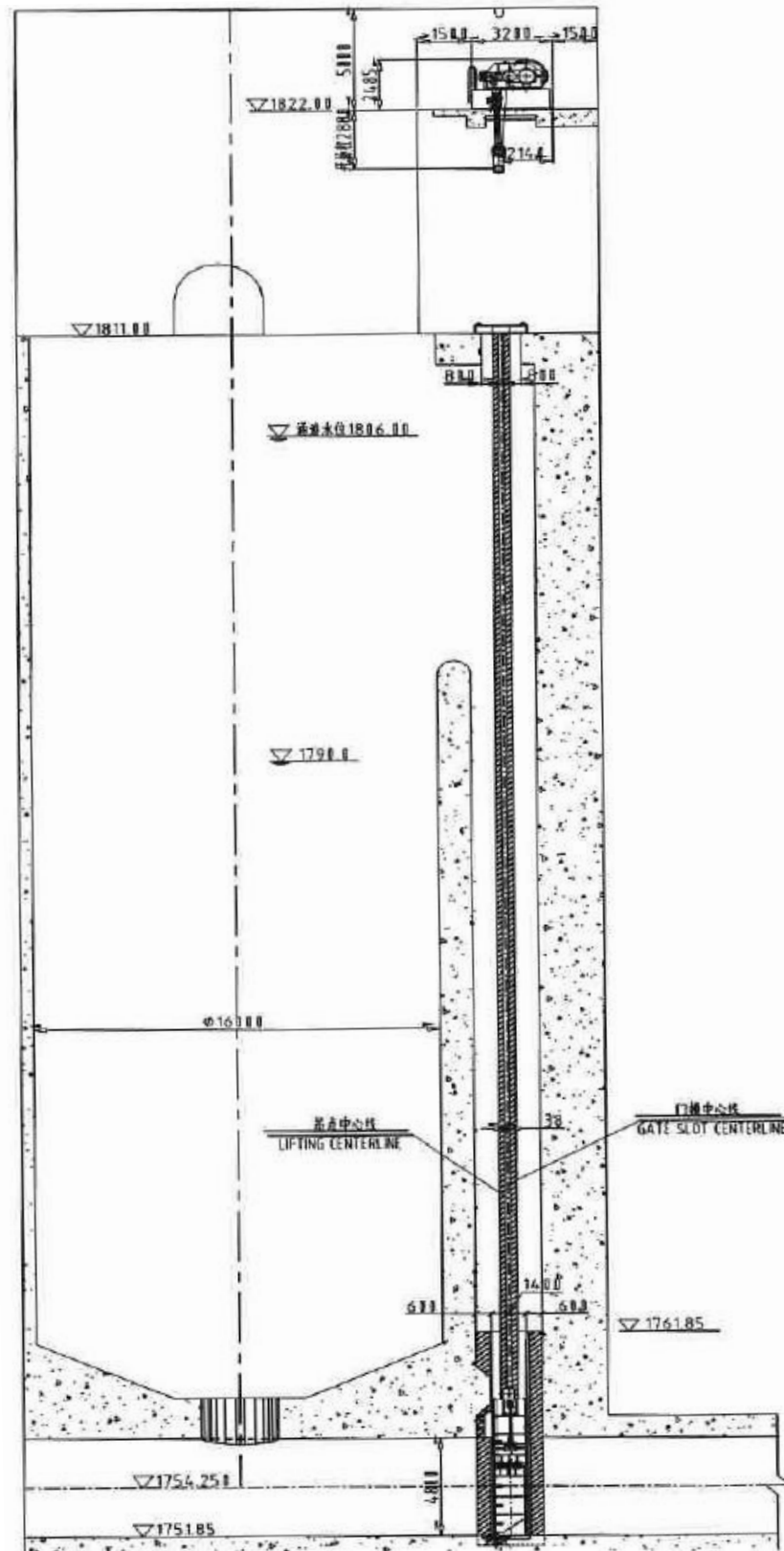
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APPENDIX A: Salient Features of RGHPP

1 General	
Name of the Project	Rasuwagadhi Hydropower Project
Location	Thuman & Timure V.D.C of Rasuwa district
Type of Project	Run-of-river
2 Hydrology	
Catchment Area (Dam Site)	3300 km ²
Design Flow (Q40)	80.00 m ³ /s
Design Flood (100 years)	1167.00 m ³ /s
3 Head	
Gross Head	167.90 m
Net Head	158.48 m
4 Headrace Tunnel	
Length	About 4.2 km long
5 Surge Tank	
Type	Underground, restricted orifice
6 Penstock	
Type	Underground
Number	1 No. steel Pipe with 3 branches
7 Powerhouse	
Type	Underground
No. of turbine-generator units	3
Turbine efficiency	92%
Generator efficiency	98%
8 Transformer Cavern	
Type	Underground
9 Tailrace Tunnel	
Length	About 600 m

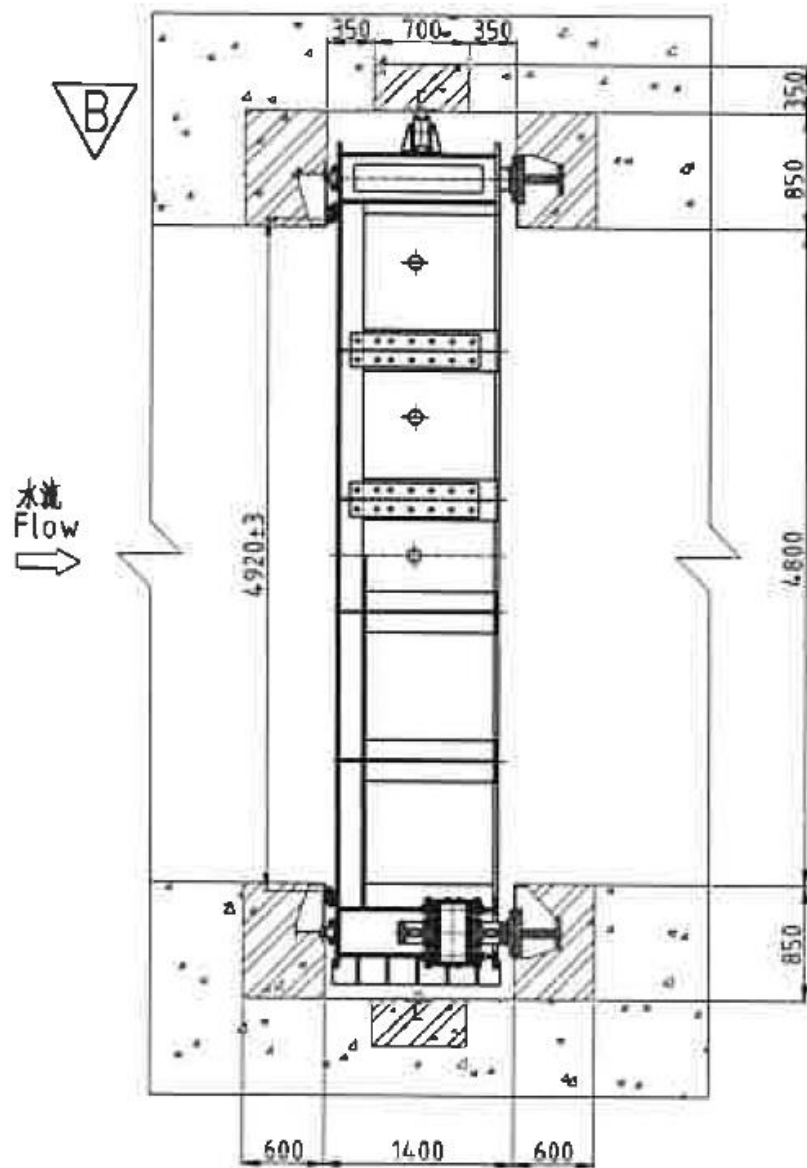
APPENDIX B: Drawings

B-1. Drawing of Vertical-lift-Gate's Arrangement



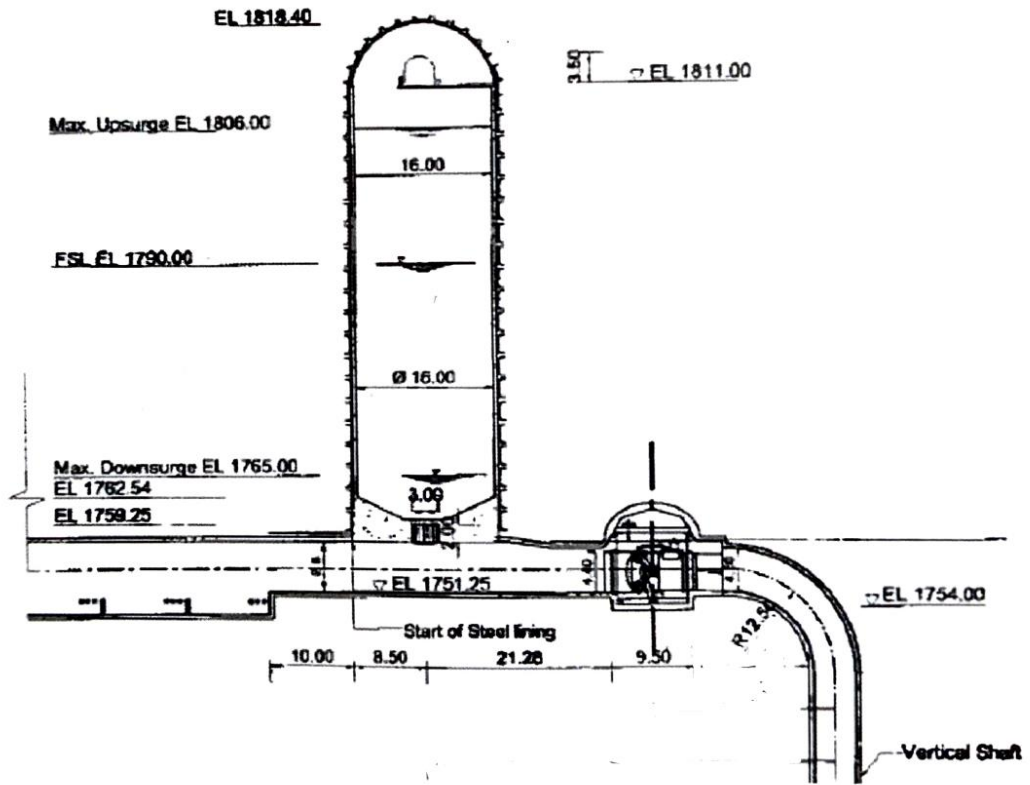
(Source: RGHP Contract documents)

B-2. Drawing of Gate Slot



(Source: RGHP Contract documents)

B-3. Drawing of Butterfly Valve's Arrangement



(Source: RGHPP Contract documents)

APPENDIX C: Cost Breakdowns of Butterfly Valve and Vertical-lift Gate

C-1. Detailed Cost Breakdown of Butterfly Valve, Construction and Access Road

SN	Item	Sub-total (USD)
1	Surge Shaft	
1.1	Tunnel excavation	869,086.37
1.2	Grouted Bars	52,854
1.3	Shotcrete C30	121,314.16
1.4	Pressure Relief Holes	1528.62
1.5	First Stage Concrete C25	270,047.22
1.6	Second stage Concrete C30	0
1.7	Reinforcement	190,965.34
1.8	Consolidation grouting	
2	Valve Chamber	
2.1	Civil Works	
2.1.1	Tunnel excavation	89,495.71
2.1.2	Shotcrete C30	28,210
2.1.3	Reinforcement	53,511.83
2.1.4	Ø25mm L=3m Type 2-Grouted Bar	1440
2.1.5	Concrete C25	75,644.24
2.1.6	Pressure Relief Holes	315.36
2.2	Hydro-Mechanical Equipment	
2.2.1	Isolation Valve	588,285.71
3	Access Roads	
3.1	Rock Excavation	1,604,511.98
3.2	Backfilling	47,644.69
3.3	Gravel cushion	25,006.14
3.4	Asphalt pavement	87,428.70
3.5	Drainage ditch	87,390.45
3.6	Retaining wall	97,150.21
4	Sub-total	4,291,830.74
5	VAT	5,57,938.00
6	Total	4,849,768.74

(Source: RGHPP- Contract documents)

C-2. Detailed Cost Breakdown of Vertical-lift Gate, Construction, Access Road

SN	Item	Sub-total (USD)
1	Surge Shaft	
1.1	Tunnel excavation	1,384,765.97
1.2	Grouted Bars	71,055.00
1.3	Shotcrete C30	137,823.52
1.4	Pressure Relief Holes	11,843.52
1.5	First Stage Concrete C25	835,983.25
1.6	Second stage Concrete C30	10,552.26
1.7	Reinforcement	597,841.60
1.8	Consolidation grouting	341,508.48
	Sub-total (Surge Shaft)	3,391,373.59
2	Hydro-Mechanical Equipment	
2.1	Gate manufacturing	230,279.43
2.2	Gate installation	22,477.80
2.3	Gate groove installation	33,074.40
2.4	Counterweight installation	13,137.25
2.5	Gate fixed hoist manufacturing	72,255.57
2.6	Gate fixed hoist installation	2793.64
	Sub-total (Hydro-mechanical Cost)	374,018.09
3.	Access Roads	
3.1	Rock Excavation	102,175.30
3.2	Backfilling	6490.24
3.3	Gravel cushion	14,749.73
3.4	Asphalt pavement	0.00
3.5	Drainage ditch	37,829.90
3.6	Retaining wall	185,206.51
	Sub-total (Access Roads)	346,451.68
4	Sub-total	4,111,843.36
5	VAT	5,34,539.64
6	Total	4,646,383.00

(Source: RGHPP Contract documents)

APPENDIX D: Boundary Conditions Calculation

D-1. Velocity at inlet

Total flow rate (Q)	80.00	m ³ /s
Mass flow rate	80000	kg/s
Cross-sectional Area	18.10286	m ²
Velocity	4.41974	m/s

D-2. Pressure at outlet

Weir Level (h _w)	1790	m
Sill Level (h _s)	1751.85	m
Head (h=h _w -h _s)	38.15	m
Density of water (ρ)	997	kg/m ³
Acceleration due to gravity (g)	9.81	m/s ²
Pressure at outlet (P _i = ρ.g.h)	373128.7455	Pa

APPENDIX E: Revenue Calculation

E-1. Calculation of Revenue Loss due to Head Loss

Parameters	Butterfly Valve	Gate Slot	Difference
Head loss (m)	0.164169215	0.053975535	-0.1102
Head Loss (mm)	164.17	53.98	-110.1937
Net head (m)	158.3158308	158.4260245	0.1102
MW	114.1900424	114.2695229	0.07948
Year generation (kW.hr)	1000304772	1001001021	696249.1577
Revenue in a year (USD)	8,0024,38,173	8,00,80,08,167	55,69,993.26
Revenue loss in a day (USD)	100.32	59.03	41.29
Revenue loss in a month (USD)	3009.62	1770.94	1238.69
Revenue loss in a year (USD)	36,617.10	21,546.40	15,070.70
Revenue loss in 10 years (USD)	366,171.02	215,463.98	150,707.04
Revenue in 30 years (USD)	1,098,513.06	646,391.93	452,121.13

Assumptions taken for Revenue Calculation:

- 1 kW.hr = 1 unit = NPR 8
- 1 USD= 131.7 NPR

E-2. Calculation of Cumulative Yearly Revenue Loss (in USD)

Year	Butterfly Valve	Vertical-lift Gate	Variation	Remarks
Year 0	4,849,768.74	4,646,383.00	203,385.74	Factoring the initial costs for Year 0
Year 1	4,886,385.84	4,667,929.40	218,456.45	
Year 2	4,923,002.94	4,689,475.79	233,527.15	
Year 3	4,959,620.05	4,711,022.19	248,597.86	
Year 4	4,996,237.15	4,732,568.59	263,668.56	
Year 5	5,032,854.25	4,754,114.99	278,739.26	
Year 6	5,069,471.35	4,775,661.38	293,809.97	
Year 7	5,106,088.45	4,797,207.78	308,880.67	
Year 8	5,142,705.56	4,818,754.18	323,951.38	
Year 9	5,179,322.66	4,840,300.58	339,022.08	
Year 10	5,215,939.76	4,861,846.97	354,092.79	
Year 11	5,252,556.86	4,883,393.37	369,163.49	
Year 12	5,289,173.96	4,904,939.77	384,234.19	
Year 13	5,325,791.07	4,926,486.17	399,304.90	
Year 14	5,362,408.17	4,948,032.57	414,375.60	
Year 15	5,399,025.27	4,969,578.96	429,446.31	
Year 16	5,435,642.37	4,991,125.36	444,517.01	
Year 17	5,472,259.47	5,012,671.76	459,587.72	
Year 18	5,508,876.58	5,034,218.16	474,658.42	
Year 19	5,545,493.68	5,055,764.55	489,729.13	
Year 20	5,582,110.78	5,077,310.95	504,799.83	
Year 21	5,618,727.88	5,098,857.35	519,870.53	
Year 22	5,655,344.98	5,120,403.75	534,941.24	
Year 23	5,691,962.09	5,141,950.14	550,011.94	
Year 24	5,728,579.19	5,163,496.54	565,082.65	
Year 25	5,765,196.29	5,185,042.94	580,153.35	
Year 26	5,801,813.39	5,206,589.34	595,224.06	
Year 27	5,838,430.49	5,228,135.73	610,294.76	
Year 28	5,875,047.60	5,249,682.13	625,365.46	
Year 29	5,911,664.70	5,271,228.53	640,436.17	
Year 30	5,948,281.80	5,292,774.93	655,506.87	