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Analysis of penstock design and losses using the Darcy-Weisbach equation in a micro hydro power plant at Wisata Telaga River, Malang

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ABSTRACT

This study presents the design analysis and energy loss calculation of a penstock system for a micro-hydro power plant located at Wisata Telaga River. The analysis involves determining pipe length through geometric estimation, selecting a pipe diameter based on hydraulic parameters, and evaluating energy losses using the Darcy-Weisbach equation. A 0.45 m HDPE pipe was selected, and a gross head of 9.35 m was considered. The calculated flow velocity was 2.67 m/s, yielding a significant head loss of 0.19 m and a minor loss of 0.18 m. The effective head was 8.98 m, resulting in an estimated net power output of 31.22 kW with an efficiency of 96%. These findings demonstrate the technical feasibility and efficiency of the proposed penstock design for rural micro-hydro applications.

Keywords: Darcy weisbach equation; micro-hydro; penstock; renewable energy

INTRODUCTION

Micro hydro power plants (MHPs) are among the most feasible and sustainable solutions for meeting electricity needs in remote or off-grid areas, particularly in developing countries. These systems generate electricity on a small scale—typically under 100 kW (Asiva Noor Rachmayani, 2015). Indonesia, with its abundant natural energy resources, presents significant potential for MHP development (Trissiana & Wilopo, 2019). By utilising the potential energy of flowing or falling water, MHP offers an environmentally friendly and cost-effective alternative to fossil fuel-based energy sources. The estimated total hydropower potential in Indonesia is around 75,000 MW, much of which is concentrated in the upper reaches of rivers (Ernest Putra et al., 2023).

Beyond being economically viable, MHP is also considered environmentally friendly, as it does not produce exhaust gases, hazardous waste, or significant ecosystem disruption. A crucial early step in MHP development is conducting a potential study, which involves collecting data and information to assess whether a river basin is suitable for a micro-hydro installation (Ummah, 2019). One of the key components in such a system is the penstock pressurised pipe that channels water from the forebay or settling tank to the turbine. The design, dimensions, and material selection of the penstock directly influence the efficiency, reliability, and operational lifespan of the entire system.

In a properly designed MHP system, the penstock enables the effective conversion of gravitational potential energy into mechanical energy, driving the turbine. However, inadequate sizing, improper slope, suboptimal diameter, or unsuitable materials can lead to significant energy losses due to friction and turbulence. These losses reduce the overall power output and operational efficiency. Widiana et al. (2020) demonstrated that incorrect pipe sizing results in suboptimal flow velocity and reduced head gain, underscoring the importance of accurate hydraulic calculations (Widiana et al., 2020). Therefore, precise estimation of head, velocity, and friction losses is essential in optimising penstock performance.

This study aims to investigate and evaluate the design of a penstock system for a micro-hydro power plant located in the Wisata Telaga River. Specifically, it seeks to calculate relevant hydraulic parameters, estimate energy losses using the Darcy–Weisbach equation, determine the optimal pipe diameter, and assess the effective head and resulting power output. The research addresses the gap in detailed, site-specific penstock optimisation studies for small-scale hydro projects. It is intended to serve as a practical reference for engineers and planners involved in rural electrification initiatives, particularly in regions with untapped potential for harnessing river energy.

METHODOLOGY

Penstock Function and Hydraulic Design

The penstock is a critical component in a micro-hydro power system, responsible for channelling water from the settling tank or forebay to the turbine chamber. It transports water under pressure by utilising gravitational potential energy, as water flows from a higher to a lower elevation. This elevation drop increases water pressure, which is essential for efficiently driving the turbine blades. Penstocks are typically constructed from durable materials such as steel, PVC, or HDPE to withstand high internal pressures and various environmental conditions (Jawahar & Michael, 2017).

To ensure optimal performance and minimise energy losses, the penstock design must consider several hydraulic parameters, including channel slope (SSS), pipe cross-sectional area (AAA), and hydraulic radius (RRR). These are calculated as follows:

$$S = \frac{Hg}{L} \qquad (1)$$

$$A = \frac{\pi \times (D^2)}{4} \qquad (2)$$

$$R = \frac{D}{4} \qquad (3)$$

Where:

S = *channel slope* (m/m)

A = *flow area* (m^2)

R = *hydraulic radius* (m)

N = *pipe roughness coefficient*

Q = *Discharge* (m^3/s)

Hg = *gross head* (m)

L = *pipe length* (m)

D = *Pipe Diameter* (m)

Flow Velocity Calculation

With the cross-sectional area known, the flow velocity (v) can be calculated using the following equation:

$$v = Q/A \tag{4}$$

Where:

v = *Kecepatan aliran* (m/s)
Q = *Debit* (m^3/s)
A = *luas penampang* (m^2)

It is essential to keep the velocity within recommended limits to avoid excessive friction losses or pipe wear. According to the American Society of Civil Engineers (ASCE, 1993), the optimal velocity range for penstock water flow is between 2 to 3 m/s (McGraw-Hill., 2001). Higher velocities may cause turbulence and energy losses, while lower velocities could reduce kinetic energy delivered to the turbine..

Head Loss Estimation Using Darcy-Weisbach Equation

In hydraulic systems such as penstocks, head loss refers to the reduction in the total mechanical energy of the water due to friction and flow disturbances along the pipe. The Darcy–Weisbach equation is widely used to estimate both major and minor head losses (Darcy & Weisbach, 2021), defined as follows:

Major Losses (hmajor) = $f\frac{L}{D}\frac{v^2}{2g}$ (5)
Minor Losses (hminor) = $\sum K\frac{v^2}{2g}$ (6)

hmajor = *Kerugian Utama (m)*
hminor = *Kerugian Kecil (m)*
$\sum K$ = *koefisien kehilangan*
f = *Faktor gesekan*
L = *Panjang pipa* (m)
D = *Diameter* (m)
v = *Kecepatan aliran* (m/s)
g = *Gravitasi* ($9.81\ m/s^2$)

The total head loss (h_{total}) is the sum of major and minor losses, which is then subtracted from the gross head to obtain the effective head (H_{eff}). This effective head is subsequently used to calculate the net hydraulic power available for conversion to electricity.

Float Area Method

To estimate discharge (QQQ) in the river, this study employs the Float Area Method, which involves measuring the surface velocity of the flow by tracking a floating object over a known distance. While this method is cost-effective and straightforward, it has limitations. It primarily measures surface velocity, which may not represent the average velocity of the entire cross-section. Furthermore, it is susceptible to external factors such as wind, obstacles, and uneven channel geometry.

To reduce uncertainty, measurements are repeated several times and performed at different cross-sections. Averaging the results can help estimate the actual average velocity and improve the accuracy of discharge estimation.

Flowchart

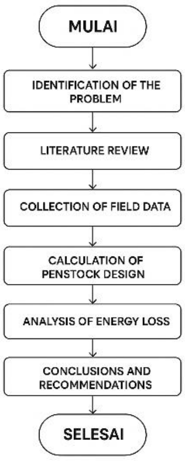


Figure 1. Flowchart

The research process begins with the Start stage, which initiates the entire study. The first step involves conducting a literature review to gather relevant theories, previous studies, and supporting information related to the research topic. Next, the problem identification stage determines the research gap and formulates the objectives. Once the problem is clearly defined, the methodology design is developed, including the selection of data sources, tools, and procedures.

The process then continues with data collection, where primary and/or secondary data are obtained according to the methodology. Afterwards, data analysis is performed using appropriate analytical techniques to generate meaningful insights. The findings are then interpreted in the discussion stage, linking them with the literature and research objectives. The final step is to draw conclusions and provide recommendations based on the results.

RESULT AND DISCUSSION

The analysis of the penstock design for the micro hydro power plant at Wisata Telaga River yields insightful results regarding flow characteristics, energy losses, and system performance.

Geographical Analysis

The project site is situated at the Wisata Telaga River, which presents ideal conditions for a micro-hydro power plant due to its continuous water flow and suitable topography. Google Earth uses satellite data with high accuracy. This technology is widely used in hydrological research, such as in PLTMH research, which uses a lot of Google Earth (Jamali, n.d.).

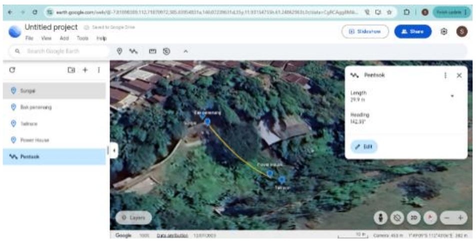
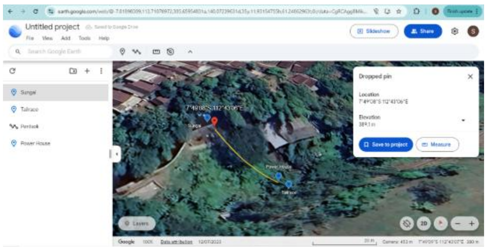


Figure 2. Location of the Penstok pipe on Google Earth.

Based on satellite measurements using Google Earth, as shown in Figure 2, the straight-line distance between the sedimentation tank and the powerhouse is approximately 29.9 meters, marked by the yellow line. This line represents the linear measurement and not the actual route of the penstock, which may be slightly longer due to terrain curvature.



Dropped pin

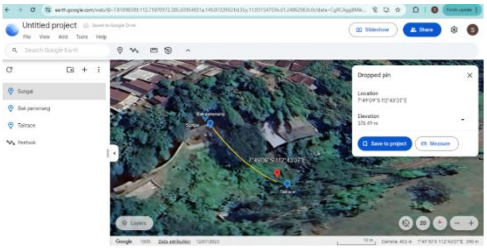
Location
7°49'08"S 112°43'06"E

Elevation
389.1 m

Save to project
Measure

Figure 3. Place where Water Enters the Penstock.

In Figure 3, the geographic coordinates of the sedimentation tank location are 7°49'08"S and 112°43'06"E, which is at an altitude of 389.1 meters above sea level (AMSL). This point serves as the origin of water intake into the penstock system.



Dropped pin

Location
7°49'09"S 112°43'07"E

Elevation
378.49 m

Save to project
Measure

Figure 4. The Place where Water Comes out into the Penstock.

In Figure 4, the powerhouse where the turbine and generator are located is located at coordinates 7°49'09"S and 112°43'07"E, with an elevation of approximately 378.49 meters AMSL. These values indicate a gross head of approximately 10.7 meters, forming the basis of the hydrostatic pressure in the penstock.

Figure 5. Photo on the Field.

Figure 5 further displays the broader landscape, including the river and the proposed settling tank area. This image shows the diversion of water from a nearby river and spring, which is used as a tourist attraction by the local community, into the intake structure. This visual Google Earth documentation helps provide an understanding of the terrain and infrastructure that support the system's water collection before it enters the penstock, which is then directed to the power generation infrastructure.

The average value of the cross-sectional area of the measurement results was set at 1.0934 m^2. This value serves as a representative parameter in various technical analyses, including flow rate calculations, water velocity estimation, and the design of the main components of the micro hydropower system, such as penstocks and turbines.

The measurement of the water flow velocity is carried out using the Float Area Method. (Intermountain Environmental Inc., 2019). This method is used to measure the flow of velocity in an open channel by utilising objects that float on the surface of the water, as in journals that frequently employ this method in hydrological measurements. Based on the measurement data, the water flow time in several experiments averaged 12.3 seconds with a flow distance of 4 meters.

From the measurement data obtained, the water speed (v) is determined using the following calculation.

Given:

$$d = 4 \quad m$$
$$t = 12{,}3 \quad second$$

Then:

$$v = \frac{d}{t}$$
$$v = \frac{4}{12.3} = 0{,}324 \quad {}^{m}/_{s}$$

After obtaining the water flow velocity and previously determining the river's cross-sectional area, the next step is to calculate the water discharge using the following formula.

Given :

$$A = 1{,}093 \quad m^2$$
$$V = 0{,}324 \quad {}^{m}/_{s}$$

Then :

$$Q = A \times V$$
$$Q = 1{,}093 \times 0{,}\ 324 = 0{,}354 \quad {}^{m^3}/_{s}$$
$$Qd = 0{,}354 \times 1{,}2 = 0{,}425 \quad {}^{m^3}/_{s}$$

The calculated discharge values offer insight into the water flow rate within the channel, which varies according to fluctuations in flow velocity. Determination of design discharge (Qd) according to the reference (Leyland, 2014). These discharge values are crucial for water resource planning, both for power generation and other applications that require controlled flow systems.

An important consideration is the potential impact of seasonal flow variations in the Telaga Wisata River. In Indonesia's tropical climate, rainfall is highly seasonal, with significant differences between wet and dry periods that can significantly impact river discharge—reducing generation capacity during the dry months and necessitating careful management during the rainy season. While this study design is based on current flow conditions with strong technical feasibility, incorporating seasonal hydrological modelling would enhance year-round reliability. Rainfall data from April 2024 to April 2025 indicate that measurements in March 2025 coincided with a monthly rainfall of 227.8 mm and a daily average of 7,348 mm. Residents reported that discharge remained stable due to the influence of upstream springs and the catchment system, indicating that rainfall does not directly impact the measured discharge, which reflects actual flow conditions. Designs based on long-term flow data achieve better performance and higher capacity factors. Applying these considerations here would improve efficiency, resilience, and sustainability as a renewable energy source for the community.

Penstock Calculation

The following calculation is for the penstock pipe, starting with the determination of the length of the penstock pipe (L), which is calculated using the Pythagorean theorem, as this system is analogous to the right triangle. By knowing the height of the water fall (Hg) and the horizontal distance or base of the triangle (a), and also the height of the fall cut by the depth of the stilling tank because the location of the stilling tank is 15 cm above the surface of the stilling tank to prevent sediment from entering, the pipe can calculate the length of the penstock pipe.

Given:

Head (Hg) = 10,7 m
Distance (a) = 30 m
Settling tank depth (h) = 1,5 m
Pipe height from the bottom = 0,15 m

Then:

Net head (Hgnet) = *10,7-(1,5-0,15)*
Net head (Hgnet) = *9,35 m*

Penstock length (L) = $\sqrt{hg(bersih)^2 + a^2}$
Penstock length (L) = $\sqrt{9{,}35^2 + 30^2}$
Penstock length (L) = *31,42 m*

Based on the calculations, the penstock length (L) was determined to be 31.42 meters. The pipe diameter (D) was selected by testing various values and evaluating the resulting discharge (Q) to achieve optimal efficiency. Prior to calculating discharge, key supporting parameters were identified, including channel slope (S), cross-sectional area (A), and hydraulic radius (R).

Given:

Roughness coefficient of HDPE pipe (N) = *0.009*
Discharge (Q) = *0.425 m³/s*
Net head (Hgnet) = *9.35 m*
Pipe length (L) = *31.42 m*
Pipe diameter (D) = *0.45 m*

Channel slope (S) = Hg/L
Channel slope (S) = $31{,}42/9{,}3$
Channel slope (S) = *0,297 m/m*

Cross-sectional area (A) = $\frac{\pi\ x\ (D^2)}{4}$
Cross-sectional area (A) = $\pi\ x\ \frac{(0{,}45}{2}$
Cross-sectional area (A) = *0.159 m²*

Hydraulic radius (R) = $D/4$
Hydraulic radius (R) = $0{,}45/4$
Hydraulic radius (R) = *0,1125 m*

*Flow velocity (**v**)* = Q/A
*Flow velocity (**v**)* = $0{,}425/0{,}1$
*Flow velocity (**v**)* = $2.67\ m/s$

This velocity value of 2.67 m/s is within the recommended range by ASCE (American Society of Civil Engineers), which suggests flow velocity in penstocks should be between 2 and 3 m/s.

Head Loss Calculation Using the Darcy-Weisbach Equation as follows

Major Losses Given:

Friction factor (f) = 0.007 (pipa HDPE)
Panjang pipa (L) = 31,42 m
Diameter (D) = 0,45 m
*Flow velocity (**v**)* = $2.67\ m/s$
Gravity (g) = $9.81\ m/s^2$

Then :

hmajor = $f\frac{L}{D}\frac{v^2}{2g}$
hmajor = $0{,}007\frac{31{,}42}{0{,}45}\frac{2{,}67^2}{2.9{,}81}$
hmajor = 0.178m

Minor Losses Given :

Loss coefficient (∑K) = *0.5 (due to one 45° bend and one valve)*

Flow velocity (v) = $2.67\, {}^{m}/_{s}$

Then :

$$hminor = \sum K \frac{v^2}{2g}$$

$$hminor = 0{,}5 \frac{2{,}67^2}{2.9{,}81}$$

$$hminor = 0.18\ m$$

Power and efficiency are determined by the adequate power that can be utilised after accounting for power losses in the Penstock, as follows.

Given :

Water density (ρ) = 1000 *kg/m³*

Gravity (g) = 9.81 ${}^{m}/_{s^2}$

discharge (Q) = 0.354 ${}^{m^3}/_{s}$

Head loss (Hloss) = *Hminor+Hmajor*
= *0,18 + 0,19*
= *0.36 m*

Gross head (Hggross) = 9,35 m

Effective head (Heff) = *Hgross- Hloss*
= *9,35 – 0,36*
= *8,98 m*

Then :

$$Peff = \rho.g.Q.heff$$
$$Peff = 1000 \times 9.81 \times 0.354 \times 8{,}98$$
$$Peff = 31{,}219\ kW$$

$$Pbruto = \rho.g.Q.heff$$
$$Pbruto = 1000 \times 9.81 \times 0.354 \times 9{,}35$$
$$Pbruto = 32{,}47\ kW$$

$$Ploss = Pbruto - Peff$$
$$Ploss = 32{,}47\ kW - 31{,}21\ kW$$
$$Ploss = 1{,}25\ kW$$

Based on these calculations, the adequate power that the flow at Wisata Telaga River can generate is approximately 31.22 kW, while the gross theoretical power is 32.47 kW. The power loss within the penstock system is estimated at 1.25 kW.

Given :

Pbruto = *32,47 kW*

Peff = *31,219 kW*

Then :

$$\eta = \frac{Peff}{Pbruto} x\ 100\%$$
$$\eta = \frac{31{,}219}{32{,}47} x\ 100\%$$
$$\eta = 96\%$$

Design Specification

Based on the specifications from the previous calculation, the penstock pipe can be designed as follows.

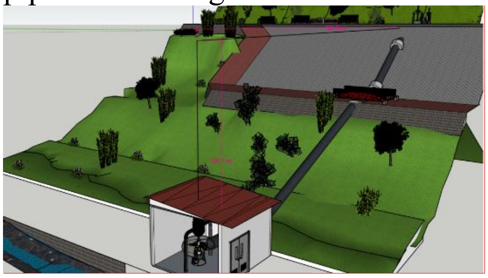


Figure 6. Penstok.

Illustrates the overall design of the micro-hydro power system, starting from the forebay tank located at the upper elevation, the penstock pipe directing water flow downhill, to the powerhouse, which contains the turbine and generator. The penstock is designed with an optimal slope to maximise the potential energy of the water before it is converted into electricity by the turbine. This visualisation provides a clear overview of the flow path and the main components of the micro-hydro installation.

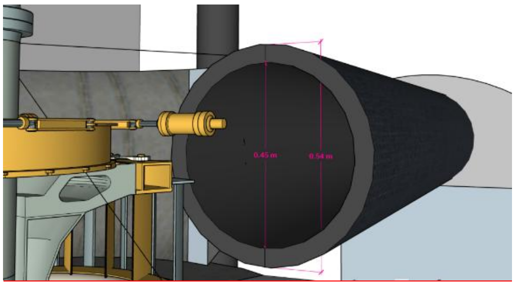


Figure 7. Penstok Pipe.

Detailed view of the penstock pipe connected to the turbine inlet. The pipe has an outer diameter of 0.54 meters and an inner diameter of 0.45 meters, corresponding to the design specifications used in the hydraulic calculations. This cross-sectional view illustrates the scale and structural integration of the penstock with the turbine system, ensuring efficient water delivery under pressure.

Performance Analysis

The analysis shows that the penstock design is hydraulically efficient and technically feasible. With a velocity of 2.67 m/s within the ASCE standard and a total head loss of only 0.36 m, the system achieves an efficiency of approximately 96%. Power loss is minimal at 1.25 kW, reflecting optimal pipe diameter selection and layout. Overall, the design effectively harnesses the site's topography and water potential for reliable micro-hydro power generation.

When compared with other studies, the performance is competitive. In the project at Kedung Kayang waterfall, Central Java, the penstock had a diameter of 0.2677 m and a discharge of 0.143 m³/s under a net head of 19.5 m, but it only delivered 18 kW of electric power (Nugroho et al., 2017). Although the head was higher, the reduced discharge and smaller diameter limited output. Conversely, the Sungai Poreng micro-hydro project in Jember optimised its penstock design (0.45 m diameter), achieving as much as 52.16 kW of power generation through improved hydraulic efficiency and cost-effectiveness. (Pratama et al., 2021).

At Wisata Telaga, the penstock has a diameter of 0.45 m, with a discharge range of approximately 0.354–0.425 m³/s and a net head of about 9.35 m, resulting in around 31 kW with a high hydraulic efficiency of 96%. This demonstrates that a well-balanced combination of penstock diameter and discharge can significantly enhance power output, even when the head is moderate.

CONCLUSION

This study concludes that the design and calculation of the penstock system for the micro-hydro power plant at Wisata Telaga River meet both technical and hydraulic feasibility standards. With a gross head of 10.7 m and an effective head of 8.98 m, the selected HDPE penstock pipe, with a diameter of 0.45 m, provides optimal flow conditions. (Córdoba et al., 2019; Feng et al., 2025). The resulting water velocity of 2.67 m/s aligns with ASCE standards, and the total head loss of only 0.36 m ensures efficient energy transfer. The system generates an effective power output of 31.22 kW from a gross theoretical power of 32.47 kW, yielding a high efficiency of 96%. These results confirm that the penstock design is both reliable and well-suited for implementation in rural micro-hydro applications.

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