Buletin Profesi Insinyur 9(2) (2026) 050–057
http://dx.doi.org/10.20527/bpi.v9i2.317

ISSN 2654-5926

Comparative Hydraulic Performance of Pipe Materials Based on Equivalent Roughness and Energy Losses in a High-Flow Penstock System

Vania Agustin Rousallen[1] Rakhmat Yusuf[1] Mardiani[1]

[1] Department of Civil Engineering, Faculty of Technical and Industrial Education, Universitas Pendidikan Indonesia

✉ vaniaagustinrousallen@upi.edu

This study evaluates the influence of material-dependent equivalent roughness on the hydraulic performance of a high-flow penstock system in an existing mini-hydropower installation in West Java. Eight representative pipe-material roughness scenarios were analysed under identical operating conditions using the Reynolds number, Swamee–Jain equation, Darcy–Weisbach equation, and local-loss coefficients. The penstock has a diameter of 1.90 m, a length of 1,870.403 m, a discharge of 8.26 m^3/s, and a gross head of 138.077 m. The calculated Reynolds number of approximately 6.22×10^6 confirmed fully turbulent flow. The commercial steel/wrought iron reference scenario produced a major head loss of 4.315 m and turbine power of approximately 8.98 MW. Among the evaluated scenarios, riveted steel generated the highest major head loss, 12.73 m, and the lowest power output, 8.41 MW, whereas Plastic/Glass produced the lowest major head loss, 3.71 m, and the highest power output, approximately 9.02 MW. However, the difference between Plastic/Glass and drawn tubing was marginal, indicating diminishing hydraulic benefits as the surface approaches the hydraulically smooth regime. The LINGO-based hydraulic selection model confirmed the Plastic/Glass scenario as the hydraulic optimum under the specified conditions. Overall, equivalent roughness influences penstock energy transmission, but local losses and pipeline geometry should also be considered in hydraulic performance evaluation.

Keywords: equivalent roughness; friction factor; head loss; penstock; turbine power

Submitted: 2 July 2026
Revised: 31 July 2026
Accepted: 2 September 2026
Published online: 3 September 2026

Introduction

The hydraulic efficiency of a hydropower system is strongly influenced by energy losses during water conveyance through the penstock. In high-flow systems, even relatively small reductions in the available hydraulic head may affect the energy delivered to the turbine and ultimately reduce power generation. Energy losses in pressurized pipelines consist mainly of distributed friction losses along the pipe wall and local losses associated with bends, joints, valves, expansions, and other hydraulic components (Madeira, 2020; Animashaun et al., 2022). Consequently, accurate estimation of these losses is essential when evaluating the hydraulic performance of a penstock system.

Among the parameters governing distributed energy loss, the internal surface condition of the pipe is particularly important. It is commonly represented by the equivalent roughness, which, together with the Reynolds number and pipe diameter, determines the friction factor under turbulent-flow conditions. The Darcy–Weisbach equation remains one of the most physically representative approaches for estimating frictional head loss because the friction factor incorporates both flow characteristics and relative pipe roughness (Haktanir & Ardıçlıoğlu, 2004; Abdulameer et al., 2022). Recent investigations continue to demonstrate the importance of accurately determining the friction factor in engineering pipeline analysis. De Souza Mendes (2024) reconsidered the physical interpretation of the moody diagram and emphasized the relationship between turbulent-flow characteristics and mechanical energy dissipation, while recent developments in friction-factor formulations have continued to improve the prediction of head losses over different Reynolds numbers and relative roughness conditions.

The determination of the turbulent friction factor remains particularly relevant for large-diameter hydraulic structures such as penstocks. Ferreri (2024) demonstrated that the Colebrook–White relationship continues to provide a fundamental reference for

How to cite this article:
Rousallen V.A., Yusuf R., Mardiani (2026) Comparative Hydraulic Performance of Pipe Materials Based on Equivalent Roughness and Energy Losses in a High-Flow Penstock System. *Buletin Profesi Insinyur* 9(2) 050-057

This is an open access article under the CC BY-NC-SA license

assessing turbulent pipe friction, with both Reynolds number and relative roughness controlling the resulting friction factor. More specifically for hydropower applications, Tchawe et al. (2024) evaluated friction coefficients in a hydroelectric penstock using Swamee–Jain and Haaland formulations and highlighted the sensitivity of penstock hydraulic calculations to the selected friction-factor approach. These findings indicate that reliable representation of internal roughness is important not only for predicting frictional head loss but also for evaluating hydraulic performance at the system level.

Nevertheless, many analyses of pipe roughness focus primarily on the relationship between equivalent roughness, friction factor, and major head loss. Such an approach does not fully quantify how roughness-induced friction losses propagate through the overall energy-conversion process of a high-flow penstock. In an actual penstock system, distributed losses occur simultaneously with local losses caused by pipeline geometry and hydraulic components. Their combined effect determines the effective head available to the turbine and consequently the potential power output. Therefore, evaluating pipe roughness within the complete hydraulic configuration provides a more informative assessment than considering friction loss independently.

This study addresses this issue by evaluating eight representative pipe-material roughness scenarios under identical operating conditions in an existing high-flow penstock system. The analysis sequentially quantifies the effect of equivalent roughness on the friction factor, major head loss, total hydraulic loss, effective head, hydraulic efficiency, and turbine power. Unlike a simple material-ranking approach based solely on roughness or friction loss, the present study also incorporates local losses associated with the existing penstock configuration. This enables the hydraulic benefit obtained from reducing pipe roughness to be distinguished from losses imposed by pipeline geometry and fittings. The study therefore aims to quantify the extent to which material-dependent equivalent roughness influences energy transmission and power availability and to provide a hydraulic basis for evaluating pipe-material alternatives in high-flow penstock systems.

Methodology

Research Framework

This study employed a quantitative comparative approach to evaluate the influence of material-dependent equivalent roughness on the hydraulic performance of a high-flow penstock system. Eight representative pipe-material roughness scenarios were evaluated under identical hydraulic and geometric conditions. The analysis linked pipe equivalent roughness to the Darcy friction factor, major head loss, total hydraulic loss, effective head, hydraulic efficiency, and turbine power.

The hydraulic analysis was conducted sequentially through: (1) determination of average flow velocity and Reynolds number, (2) calculation of relative roughness for each material, (3) estimation of the Darcy friction factor using the Swamee–Jain equation, (4) calculation of major head loss using the Darcy–Weisbach equation, (5) calculation of minor losses associated with bends, expansion joints, and couplings, (6) determination of total head loss and effective head, and (7) calculation of hydraulic efficiency and turbine power. All material alternatives were evaluated under the same discharge, pipe diameter, pipe length, gross head, and water properties.

Case Study and Hydraulic Parameters

The analysis was based on a high-flow penstock system of an existing mini-hydropower installation in West Java. The same operating conditions and geometric parameters were applied to all pipe-material scenarios to provide a consistent hydraulic comparison.

Table 1 Hydraulic and Geometric Parameters of the Penstock

Parameter	Symbol	Value	Unit
Flow rate	Q	8.26	m^3/s
Pipe diameter	D	1.9	m
Penstock length	L	1870.403	m
Gross head	Hg	138.077	m
Water density	ρ	1000	kg/m^3
Dynamic viscosity	μ	0.00089	Pa·s
Gravitational acceleration	g	9.81	m/s^2
Turbine efficiency	ηt	0.84	–

The average flow velocity was calculated using the continuity relationship (Equation 1).

$$V = \frac{Q}{A} = \frac{4Q}{\pi D^2} \quad (1)$$

where V is average flow velocity (m/s), Q is flow rate (m^3/s), A is cross-sectional area of the pipe (m^2), and D is internal pipe diameter (m). For the specified operating condition:

$$V = \frac{4(8.26)}{\pi\,(1.9)^2} = 2.913\ {}^{m}/_{s}$$

Pipe Equivalent Roughness

The evaluated materials represent a range of internal pipe-surface conditions from relatively rough to hydraulically smooth surfaces. Equivalent roughness values were obtained from established fluid-mechanics references and expressed consistently in meters.

Table 2 Equivalent Roughness Values Used in the Analysis Adapted from Munson et al. (2009).

Material	Equivalent Roughness, ε (m)
Riveted steel	0.009
Concrete	0.003
Wood stave	0.0009
Cast iron	0.00026
Galvanized iron	0.00015
Commercial steel or wrought iron	0.000045
Drawn tubing	1.5E-06
Plastic/Glass	0

The equivalent roughness values were used as hydraulic scenarios and do not represent a comprehensive assessment of the structural suitability of each material for high-pressure penstock applications.

Relative roughness was calculated as:

$$\text{Relative roughness} = \varepsilon/D \quad (2)$$

where ε represents the equivalent roughness of the pipe surface (m), and D is the internal pipe diameter (m).

Reynolds Number and Flow Regime

The Reynolds number was calculated to determine the flow regime:

$$Re = \frac{\rho V D}{\mu} \quad (3)$$

where Re is the Reynolds number, ρ is water density (kg/m³), V is the average flow velocity (m/s), D is the pipe diameter (m), and μ is the dynamic viscosity (Pa·s).

Using the hydraulic parameters, Re = [1000 × 2.913 × 1.90]/0.00089. Re ≈ 6.22×10^6

The Reynolds number is considerably greater than 4000, indicating that the flow is fully turbulent. Because the discharge, pipe diameter, and water properties were kept constant, the Reynolds number was identical for all evaluated material scenarios.

Friction Factor

For turbulent flow, the Darcy friction factor was determined using the Swamee–Jain equation:

$$Friction\ Factor\ (f) = \frac{0.25}{\left[log\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^2} \quad (4)$$

where f is Darcy friction factor, ε is equivalent roughness (m), D is pipe diameter (m), and Re is Reynolds number.

The Swamee–Jain equation was selected because it explicitly accounts for Reynolds number and relative roughness and provides the friction factor without requiring the iterative solution needed by the Colebrook–White equation.

The calculated friction factors were subsequently compared with the expected turbulent-flow behaviour represented by the Colebrook–White/Moody framework. This comparison was treated as a theoretical consistency check rather than experimental validation because independent friction-factor measurements were not available.

Major Head Loss

Major head loss caused by friction along the pipe wall was calculated using the Darcy–Weisbach equation:

$$h_f = f\frac{LV^2}{D2g} \quad (5)$$

where h_f is major head loss (m), f is Darcy friction factor, L is pipe length (m), D is pipe diameter (m), V is average flow velocity (m/s), and g is gravitational acceleration (m/s²).

Because the penstock consists of several sections separated by anchor blocks, the major head loss of each section can be calculated as:

$$h_{f,i} = f\frac{L_i V^2}{D2g} \quad (6)$$

The total major head loss is:

$$h_{f,total} = \Sigma h_{f,i} \quad (7)$$

where L_i is length of penstock section i (m), $h_{f,i}$ is major head loss in section i (m)

This section-wise analysis allows the contribution of individual penstock segments to the total distributed hydraulic loss to be identified.

Minor Head Loss

Minor head loss occurs due to local disturbances such as bends, expansion joints, couplings, valves, and changes in flow direction. The minor head loss was calculated using:

$$h_m = \sum K_i \frac{V^2}{2g} \quad (8)$$

where h_m is total minor head loss (m), K_i is local loss coefficient of component i, V is average flow velocity (m/s), and g is gravitational acceleration (m/s²).

For bends located at the anchor blocks, the loss coefficient was determined based on the pipe diameter, bend radius, and change in flow direction. Expansion joints and sleeve couplings were evaluated using their corresponding local loss coefficients.

Because the pipe geometry, fittings, discharge, and flow velocity were unchanged among material scenarios, the minor head loss was maintained constant for all evaluated materials.

The total hydraulic head loss was calculated as:

$$h_L = h_f + h_m \quad (9)$$

 ISSN 2654-5926

where h_L is total head loss (m), h_f is major head loss (m), and h_m is minor head loss (m).

Effective Head

The effective head available to the turbine was obtained by subtracting total hydraulic losses from the gross head:

$$H_{eff} = H_g - h_L \quad (10)$$

where H_{eff} is effective head (m), H_g is gross head (m), and h_L is total head loss (m).

Hydraulic Efficiency

The hydraulic efficiency of the penstock system was calculated as:

$$\eta_h = (H_{eff}/H_g) \times 100\% \quad (11)$$

where η_h is hydraulic efficiency (%), H_{eff} is effective head (m), and H_g is gross head (m).

The hydraulic efficiency represents the proportion of the gross hydraulic head remaining after major and minor hydraulic losses.

Turbine Output Power

The turbine output power was calculated as:

$$P = \rho \times g \times Q \times H_{eff} \times \eta_t \quad (12)$$

where P is turbine output power (W), ρ is water density (kg/m³), g is gravitational acceleration (m/s²), Q is flowing rate (m³/s), $H_{eff,}$ is effective head (m), and η_t is turbine efficiency.

A constant turbine efficiency of 0.84 was applied to all material scenarios. Therefore, differences in calculated turbine power were attributed to differences in hydraulic losses rather than variations in turbine performance. For reporting purposes, turbine power was converted from watts to megawatts using:

$$P(MW) = P(W)/10^6 \quad (13)$$

Comparative Performance and Roughness Sensitivity

Commercial steel or wrought iron was used as the reference steel scenario to quantify the hydraulic benefit associated with smoother or rougher pipe surfaces.

The change in turbine power relative to the reference condition was calculated as:

$$\Delta P_i = P_i - P_{ref} \quad (14)$$

where ΔP_i is change in turbine power for material i, Pi is turbine power for material i, and P_{ref} is turbine power for the reference steel scenario.

The percentage change in power was calculated as:

$$\text{Power Gain (\%)} = [(P_i - P_{ref})/P_{ref}] \times 100\% \quad (15)$$

This parameter was used to quantify the practical magnitude of the hydraulic benefit resulting from changes in equivalent roughness rather than relying solely on a ranking of materials.

Graphical Analysis of Roughness Effects

The calculated hydraulic parameters for the eight equivalent-roughness scenarios were subsequently presented graphically to illustrate the relationship between pipe roughness and hydraulic performance. Equivalent roughness was used as the independent variable, while the friction factor, major head loss, and turbine power were used as the response variables. The resulting plots were combined into a single multi-panel figure consisting of: (a) equivalent roughness versus friction factor, (b) equivalent roughness versus major head loss, and (c) equivalent roughness versus turbine power. The graphical comparison was used to visualize the cascading effect of increasing surface roughness on flow resistance, energy loss, and available power.

LINGO-Based Hydraulic Selection Model

LINGO was employed as an auxiliary decision-support model to identify the pipe-roughness scenario that maximized turbine power under identical hydraulic operating conditions. The hydraulic parameters calculated analytically, including equivalent roughness, friction factor, major head loss, effective head, and turbine power, were incorporated into the optimization model. Each pipe-material scenario was represented by a binary decision variable, where Y = 1 indicated the selected material and Y = 0 represented the remaining alternatives.

The objective function was defined as:

$$\text{Maximize } Z = \Sigma(P_i Y_i) \quad (16)$$

subject to:

$$\Sigma Y_i = 1 \quad (17)$$

and:

$$Y_i = 0 \text{ or } 1 \quad (18)$$

where: Z = objective-function value, Pi = calculated turbine power for material i, and Y_i = binary decision variable for material i.

The constraint ΣYi = 1 ensures that only one material scenario is selected. Because structural strength, transient pressure, durability, material cost, and constructability were not included as optimization constraints, the LINGO analysis was interpreted specifically as a hydraulic performance selection model, rather than as a comprehensive engineering-material optimization model. The result obtained from LINGO was compared with the analytical ranking to confirm consistency between the hydraulic calculations and the decision model.

ISSN 2654-5926

Results and Discussion

Hydraulic Characteristics of the Penstock

The hydraulic analysis was performed using the operating conditions of an existing mini-hydropower penstock system in West Java. The penstock has an internal diameter of 1.90 m and a total length of 1,870.403 m, with a discharge of 8.26 m^3/s. Based on these conditions, the average flow velocity was calculated as 2.913 m/s. The corresponding velocity head was approximately 0.433 m, while the gross head obtained from the difference between inlet and outlet elevations was 138.077 m.

The Reynolds number was approximately $\mathbf{6.22 \times 10^6}$, confirming that the water flow was fully turbulent. This condition justifies the use of a roughness-dependent turbulent friction-factor formulation. Tchawe et al. (2024) similarly demonstrated that friction-factor estimation is particularly important in hydroelectric penstocks and reported that the Swamee–Jain formulation provides results close to the Colebrook–White relationship. This supports its application in the present comparative analysis.

Because discharge, diameter, and water properties were kept constant for all material scenarios, the Reynolds number remained unchanged. Consequently, differences in friction factor among the evaluated scenarios were predominantly associated with differences in relative roughness.

Friction Factor and Major Head Loss

The calculated friction factor for the reference commercial steel/wrought iron scenario was approximately 0.010. Using the Darcy–Weisbach equation, the total major head loss along the 1,870.403 m penstock was approximately 4.315 m. The distribution of major head loss among the 14 penstock sections is presented in Table 4.

Table 4 Major Head Loss along Penstock Sections

Section	Length, ΔL (m)	Major Head Loss (m)
1	28.656	0.066
2	91.008	0.21
3	97	0.224
4	55.995	0.129
5	300.004	0.692
6	143.27	0.33
7	73.531	0.17
8	266.925	0.616
9	65.713	0.152
10	339.55	0.783
11	108.75	0.251
12	127.802	0.295
13	122.199	0.282
14	50	0.115
Total	1,870.40	4.315

Section 10 produced the largest major head loss, approximately 0.783 m, because it had the greatest pipe length. In contrast, Section 1 generated the smallest loss. This distribution is consistent with the Darcy–Weisbach relationship because, when diameter, velocity, and friction factor remain constant, frictional head loss varies linearly with pipe length.

The result also confirms that penstock geometry cannot be ignored when interpreting material roughness. Although roughness determines the friction factor, the actual magnitude of distributed loss depends on the interaction among friction factor, pipe length, diameter, and flow velocity. Similar hydraulic studies on hydropower systems have used the Darcy–Weisbach framework to quantify frictional losses and subsequently determine net head and power output (Muteba et al., 2023).

Minor Head Loss

Minor losses were evaluated for expansion joints, sleeve couplings, and changes in flow direction at the anchor blocks. At the calculated flow velocity of 2.913 m/s, the velocity head was approximately 0.433 m.

The 14 expansion joints, each represented by a loss coefficient of 0.10, contributed approximately one-third of the total local losses. Three sleeve couplings contributed only a small proportion, whereas bends associated with the anchor-block alignment represented approximately 63% of the total minor loss. The total minor head loss was approximately 1.78 m.

The dominance of bend losses indicates that local hydraulic performance is influenced more strongly by pipeline alignment than by sleeve couplings or individual expansion joints. This finding is important because improvements in pipe-surface roughness primarily reduce distributed friction losses, whereas local losses remain controlled by geometry. Therefore, material improvement alone cannot eliminate a substantial portion of hydraulic losses if the pipeline contains numerous directional changes.

This observation agrees with previous hydropower analyses in which both friction losses and fitting-related losses were incorporated when estimating usable net head. Muteba et al. (2023), for example, evaluated friction losses in the penstock together with losses associated with valves and other components when determining micro-hydropower performance. More recent model-based studies have also emphasized that accurate estimation of head losses under actual operating conditions is important for hydropower performance assessment (Alonso et al., 2024).

Total Head Loss, Effective Head, and Hydraulic Efficiency

For the commercial steel/wrought iron reference scenario, the major head loss was approximately 4.315 m and the minor loss was approximately 1.78 m. Therefore, the total hydraulic loss was approximately:

 ISSN 2654-5926

$h_L = 4.315 + 1.78 \approx 6.10$ m

The resulting effective head was approximately:

$H_{eff} = 138.077 - 6.10 \approx 131.98$ m

This corresponds to a hydraulic efficiency of approximately:

$\eta h \approx 95.58\%$

Thus, approximately 95.6% of the available gross head remained after hydraulic losses in the reference steel condition. The magnitude is comparable with efficient penstock systems reported in previous studies, although direct numerical comparison must be interpreted cautiously because pipe diameter, discharge, length, roughness, and system geometry differ among hydropower installations.

The results further demonstrate that even when the percentage loss relative to gross head is modest, the hydraulic consequence can become important in a high-flow system because power is directly proportional to effective head. This relationship between hydraulic losses, net head, and generated power has also been observed in previous hydropower-system analyses.

Effect of Equivalent Roughness on Hydraulic Performance

The same hydraulic calculations were subsequently applied to eight representative equivalent-roughness scenarios. The resulting friction factors, major head losses, and turbine powers are summarized in Table 5.

Table 5 Effect of Equivalent Roughness on Hydraulic Performance

Material Scenario	ε (m)	Friction Factor	Major Head Loss (m)	Turbine Power (MW)
Riveted steel	0.009	0.03	12.729	8.41
Concrete	0.003	0.022	9.395	8.64
Wood stave	0.0009	0.017	7.075	8.79
Cast iron	0.00026	0.013	5.539	8.9
Galvanized iron	0.00015	0.012	5.052	8.93
Commercial steel/wrought iron	0.000045	0.01	4.315	8.98
Drawn tubing	1.5E-06	0.009	3.739	9.02
Plastic/Glass	0	0.009	3.71	9.02

A clear monotonic relationship was observed between equivalent roughness and hydraulic performance. Increasing equivalent roughness increased the Darcy friction factor and consequently increased major head loss. Riveted steel represented the roughest scenario and generated approximately 12.73 m of major head loss, whereas the hydraulically smooth Plastic/Glass scenario produced approximately 3.71 m. The difference of approximately 9.0 m represents a reduction of about 71% in major friction loss between the roughest and smoothest scenarios.

This result is physically consistent with the turbulent-flow relationships represented by the Moody and Colebrook–White frameworks, in which increased relative roughness produces greater friction resistance. The recent penstock study by Tchawe et al. (2024) likewise confirmed the importance of turbulent friction-factor representation for predicting penstock hydraulic behavior.

However, the influence of roughness on turbine power was considerably less dramatic than the difference in major head loss. Power increased from approximately 8.41 MW for riveted steel to approximately 9.02 MW for the smoothest scenarios, corresponding to an increase of about 0.61 MW or 7.3%. This difference demonstrates that substantial changes in friction loss do not translate proportionally into power gains because the gross head remains much larger than the friction loss.

More importantly, compared with the commercial steel/wrought iron reference scenario, the theoretical power gain achieved by switching to the smoothest roughness condition was only approximately 0.04 MW, or about 0.4–0.5%. Thus, the results provide a more nuanced interpretation than simply identifying the smoothest material as optimal. Lower roughness clearly improves hydraulic transmission, but once the pipe surface approaches the hydraulically smooth regime, further reductions in roughness yield diminishing gains in power output.

The difference between drawn tubing and Plastic/Glass illustrates this behavior. Although their assumed roughness values differ, both produced friction factors close to 0.009, major head losses of approximately 3.74 and 3.71 m, respectively, and virtually identical turbine powers of approximately 9.02 MW. As shown in Figure 1, the hydraulic benefit becomes progressively smaller as the pipe surface approaches the hydraulically smooth regime. Therefore, selecting between very smooth materials solely on the basis of equivalent roughness may have limited practical value unless structural, economic, durability, and installation considerations are also incorporated.

Hydraulic Interpretation and Engineering Implications

The results indicate that equivalent roughness is important primarily through its effect on distributed friction losses. However, the benefit of reducing roughness becomes progressively smaller as the hydraulic surface approaches the smooth-pipe condition. Therefore, the use of the lowest possible roughness does not necessarily imply the best overall engineering solution.

 ISSN 2654-5926

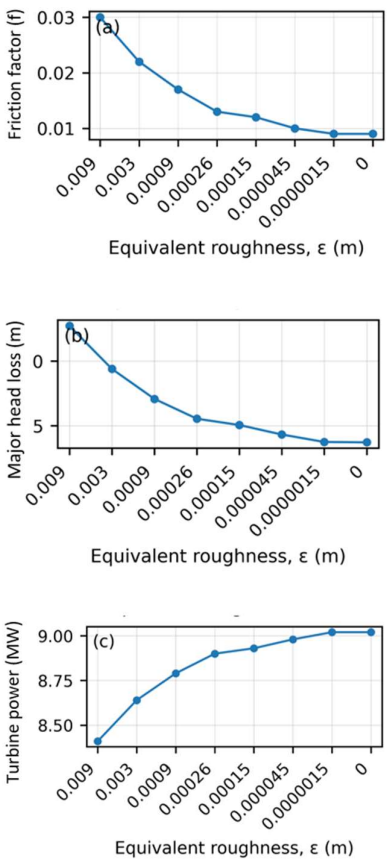

Figure 1 Effect of equivalent roughness on (a) friction factor, (b) major head loss, and (c) turbine power.

A second important finding is that local losses account for a non-negligible portion of the hydraulic losses and are dominated by bends in the present penstock configuration. This suggests that improving pipeline alignment may provide an additional route for reducing energy loss. The combined consideration of roughness-dependent friction losses and geometry-dependent local losses therefore provides a more complete basis for penstock hydraulic assessment than considering either component independently.

This system-level interpretation is consistent with previous studies that estimate hydropower potential by subtracting both distributed and local losses from gross head before calculating usable power. Studies of run-of-river and micro-hydropower systems have similarly applied Darcy–Weisbach-based head-loss estimation in determining net head and energy output.

LINGO-Based Hydraulic Selection

LINGO was used as an auxiliary hydraulic-selection model to determine which of the eight roughness scenarios maximized turbine power under identical operating conditions. The binary decision model selected one material scenario while maximizing the calculated power output.

After correction of all hydraulic inputs to match the analytical model, the expected optimal solution corresponds to the Plastic/Glass roughness scenario, because it produces the lowest friction factor and major head loss. However, the difference between Plastic/Glass and drawn tubing is marginal. Therefore, the LINGO result should be interpreted as a mathematical hydraulic optimum rather than as proof that Plastic/Glass is the most suitable engineering material for the actual penstock.

The optimization result should be summarized in the main text as shown in Table 6 rather than through multiple software screenshots.

Table 6 LINGO Hydraulic Selection Result

Parameter	Optimal Result
Selected roughness scenario	Plastic/Glass
Equivalent roughness	0 m
Friction factor	≈ 0.009
Major head loss	≈ 3.71 m
Turbine power	≈ 9.02 MW
Decision variable	Y = 1

Conclusion

The results demonstrate that material-dependent equivalent roughness influences the hydraulic performance of the high-flow penstock through its effect on the friction factor and distributed head loss. Under identical operating conditions, rougher pipe scenarios produced greater frictional resistance and higher major head losses, while smoother scenarios preserved a larger effective head and consequently higher turbine power.

Among the eight evaluated roughness scenarios, Plastic/Glass produced the lowest major head loss, approximately 3.71 m, and the highest calculated turbine power, approximately 9.02 MW. However, its hydraulic performance was nearly identical to that of drawn tubing, indicating diminishing gains as the pipe surface approaches the hydraulically smooth regime. In contrast, riveted steel generated the highest major head loss, approximately 12.73 m, and the lowest turbine power, approximately 8.41 MW.

The analysis also shows that local losses remain an important component of the total hydraulic loss, particularly those associated with bends in the penstock alignment. Therefore, improving pipe-surface roughness alone cannot fully optimize system performance; pipeline geometry and local hydraulic disturbances should also be considered.

The LINGO-based selection model identified the Plastic/Glass roughness scenario as the hydraulic optimum under the specified conditions, consistent with the analytical ranking. Nevertheless, this result represents a hydraulic-performance optimum rather than a comprehensive material-selection

recommendation because structural strength, durability, transient pressure effects, constructability, and lifecycle cost were not included in the model. Overall, the study highlights the importance of evaluating equivalent roughness together with distributed and local losses when assessing penstock hydraulic performance and potential power output.

Declaration of Generative AI Use

Generative artificial intelligence was used solely to assist with English-language editing, translation, and manuscript organization. The authors independently reviewed and approved the final text. The authors take full responsibility for the accuracy and integrity of the manuscript.

References

Abdulameer, L. S., Dzhumagulova, N., Algretawee, H., Zhuravleva, L., & Alshammari, M. H. (2022). Comparison between Hazen-Williams and Darcy-Weisbach equations to calculate head loss through conveyancing treated wastewater in Kerbala City, Iraq. *Eastern-European Journal of Enterprise Technologies, 1*(1–115), 36–43. DOI: 10.15587/1729-4061.2022.251385.

Animashaun, L. A., Rabiu, T. O., Sogunro, O., & Lamidi, S. B. (2022). Determination of energy losses in fluid flow through pipes and bends. *International Journal of Sciences, Engineering & Environmental Technology, 7*(13), 117–124.

Arumugam, A., Kibrom, H., Gebreamlak, M., Teame, M., & Mengstu, M. (2022). Comparative analysis and validation of selected explicit equation models for determination of Darcy friction factor to estimate major head loss for a pressurized flow system. *Science & Technology Asia, 27*(3), 216–235. DOI: 10.14456/scitechasia.2022.57.

de Souza Mendes, P. R. (2024). A note on the Moody diagram. *Fluids, 9*(4), 98. DOI: 10.3390/fluids9040098.

Ferreri, G. B. (2024). A new approach for explicit approximation of the Colebrook–White formula for pipe flows. *Journal of Hydroinformatics, 26*(7), 1558–1571. DOI: 10.2166/hydro.2024.280.

Fiorillo, F., Esposito, L., Ginolfi, M., & Leone, G. (2024). New insights into turbulent and laminar flow relationships using Darcy–Weisbach and Poiseuille laws. *Water, 16*(10), 1452. DOI: 10.3390/w16101452.

Firdaus, A., Hartono, B., & Kindi, A. (2023). Analisa pressure drop pada prototype instalasi pipa industri. *Jurnal ALMIKANIKA, 5*(1).

Haktanir, T., & Ardıçlıoğlu, M. (2004). Numerical modeling of Darcy-Weisbach friction factor and branching pipes problem. *Advances in Engineering Software, 35*(12), 773–779. DOI: 10.1016/j.advengsoft.2004.07.005.

Herwig, H., Gloss, D., & Wenterodt, T. (2008). A new approach to understanding and modelling the influence of wall roughness on friction factors for pipe and channel flows. *Journal of Fluid Mechanics, 613*, 35–53. DOI: 10.1017/S0022112008003534.

Islam, A. K. (2024). Hydropower coupled with hydrogen production from wastewater: Integration of micro-hydropower plant (MHP) and microbial electrolysis cell (MEC). *International Journal of Hydrogen Energy, 49*, 1–14. DOI: 10.1016/j.ijhydene.2023.06.179.

Madeira, A. A. (2020). Major and minor head losses in a hydraulic flow circuit: Experimental measurements and a Moody's diagram application. *Eclética Química, 45*(3), 47–56. DOI: 10.26850/1678-4618eqj.v45.3.2020.p47-56.

Munson, B. R., Young, D. F., Okiishi, T. H., & Huebsch, W. W. (2009). *Fundamentals of fluid mechanics* (6th ed.). John Wiley & Sons.

Muteba, M. C., Foster, S. N., Raheem, D., & Agwu, A. E. (2023). Micro-hydropower systems for smallholder farmers in rural communities of Taraba State, Nigeria: Feasibility study, system analysis, design and performance evaluation (Part II). *Energy Nexus, 11*, 100228. DOI: 10.1016/j.nexus.2023.100228.

Pizzo, H. S., Dantas, C. A. S., & Ribeiro, C. B. M. (2022). Fitting Hazen-Williams roughness coefficient to the head loss obtained by Darcy-Weisbach equation in PVC pipes. *Advance Researches in Civil Engineering, 4*(1), 1–13. DOI: 10.30469/arce.2022.150292.

Sammartano, V., Aricò, C., Sinagra, M., & Tucciarelli, T. (2015). Cross-flow turbine design for energy production and discharge regulation. *Journal of Hydraulic Engineering, 141*(3), 04014083. DOI: 10.1061/(ASCE)HY.1943-7900.0000977.

Tan, K., Mahajan, D., & Venkatesh, T. A. (2024). Computational fluid dynamic modeling of methane-hydrogen mixture transportation in pipelines: Understanding the effects of pipe roughness, pipe diameter and pipe bends. *International Journal of Hydrogen Energy, 49*, 1028–1042. DOI: 10.1016/j.ijhydene.2023.06.195.

Tchawe Moukam, T. T., Nkontchou Ngongang, F., Tientcheu Nsiewe, M.-W., Djiako, T., Tcheukam-Toko, D., & Kenmeugne, B. (2024). Determination of the coefficient of friction in the penstock of a hydro-electric dam: Application of two approaches. *Hydrology Research, 55*(10), 1030–1042. DOI: 10.2166/nh.2024.054.