Table of Contents

Purpose:

This Python model is a Darcy–Weisbach–based pipeline screening tool used to compare pipe materials, working fluids, roughness growth over time, cavitation risk, and cost under turbulent flow conditions. The project was developed to translate core engineering equations into a working computational model and was completed during the winter break.

Governing equations:

the equations used here are the

- Reynolds
- Swamee–Jain
- Darcy–Weisbach
- Cavitation head

Model Architecture Summary

The model is driven directly by the user's inputs. The user selects the fluid, pipe material, length, diameter, and flow velocity. From these values, the model first and foremost calculates the Reynolds number to determine the flow regime and confirm turbulent flow conditions, which the model assumes.

Once the material is chosen, its properties are pulled from a material database, including the initial roughness, roughness growth rate, and cost coefficients. These properties are then used to compute the friction factor using the Swamee–Jain equation. The Darcy–Weisbach equation is applied to calculate head loss.

Pipe roughness increases over time using a linear roughness model. At each simulated year, the roughness is updated and the friction factor and head loss are recalculated. This produces a time history of how hydraulic performance degrades as the pipe ages. Plots are provided for each output.

Cavitation is evaluated by calculating the maximum allowable head loss from atmospheric pressure, vapor pressure of the fluid, and the factor of safety of 2.5 . The model compares the actual Darcy Weisbach head loss to this limit. If the limit is exceeded at any point, the system is flagged as failing and the user is instructed to redesign the pipe. This is modeled as hl>h allow

Costs are computed at the same time. Pipe material cost scales non-linearly with diameter and linearly with length, while labor cost is proportional to pipe length. These values are combined to give the total system cost.

Assumptions: The following assumptions define the scope and physical validity of the model. This list is not exhaustive.

Pipe & Geometry Assumptions:

The following assumptions define the physical geometry of the pipeline modeled:

• The pipe is circular in cross-section
• The pipe diameter is constant along its length

• The pipe material is uniform
• The pipe is straight and horizontal with no elevation change
• Minor losses from fittings, bends, and valves are neglected

Flow & Fluid Assumptions

These assumptions define the physical behavior of the working fluid:

• The fluid is incompressible and Newtonian
• Flow is fully developed and turbulent ($Re > 4000$ enforced)
• The mean flow velocity is constant
• The flow is single-phase (no gas or vapor bubbles)

Cavitation & Pressure Assumptions

These assumptions define how pressure and cavitation are evaluated in the model:

• The pipe inlet is connected to a free surface at atmospheric pressure
• The pipe is horizontal, resulting in no static elevation head
• No pump is applied
• Cavitation is evaluated using the fluid vapor pressure
• A safety factor of 2.5 is applied to the cavitation threshold

Roughness & Aging Assumptions

These assumptions define how pipe surface roughness evolves over time:

• Initial roughness values are taken from standard material tables
• Pipe roughness increases linearly with time
•Other Effects such as corrosion, heat and any biodegradation effects are neglected

Cost Modeling Assumptions

These assumptions define how project costs are estimated costs are not representative of industry values:

• Cost per meter depends on pipe material
• Pipe material cost scales with diameter raised to the 1.75 power
• Labor cost is constant per unit length
• Costs associated with excavation, permitting, and installation complexity are neglected

Hand Validation:

For our validation case, we analyze water at 20 °C flowing through a standard steel pipe with a length of 1000 m, a diameter of 0.5 m, and a velocity of 2 m/s. We compute the Reynolds number, the friction factor using the Swamee–Jain equation, the resulting Darcy–Weisbach head loss, and the maximum allowable head loss before cavitation occurs, a FOS of 2.5 will be used for this. The initial roughness is 4.5x10^-5.

Reynolds Number calculation:

$$RE = \frac{\rho v D}{\mu} = \frac{998.1 * 2 * 0.5}{1.002 * 10^{-3}} = \approx 9.96 \times 10^{5} (turbulent)$$

Friction factor calculation (Swamee–Jain**):**

$$\boldsymbol{f} = \frac{0.25}{\left(\log\left(\frac{\epsilon}{3.7D} + \frac{5.74}{RE^{0.9}}\right)\right)^2} = \frac{0.25}{\left(\log\left(\frac{4.5*10^{-5}}{3.7(0.5)} + \frac{5.74}{9.96\times10^{5\,0.9}}\right)\right)^2} = \mathbf{0.01336}$$

Darcy–Weisbach head Loss calculation:

$$HL = \frac{f * L * V^2}{D * 2g} = \frac{0.01336 * 1000 * 2^2}{0.5 * 2(9.81)} = 5.448m$$

Maximum allowable head loss before cavitation also using a FOS of 2.5:

$$Hfmax = \frac{(patm - pvap)}{\rho g} = \frac{101325 - 2340}{998.1 * 9.81} = 10.109\, m$$

Final value after using the FOS of 2.5: 4.036 m

Model results:

If we enter the same inputs, these are the results as follows:

Model Inputs:

- Fluid: Water @ 20 °C
- Material: Steel
- Pipe Length = 1000 m
- Diameter = 0.5 m
- Velocity = 2 m/s
- Initial Roughness = 4.5×10^{-5} m

Reynolds Number:
Re = 9.96×10^5

Friction Factor Evolution (Swamee–Jain):

- Year 0: f = **0.013362**
- Year 1: f = 0.01419
- Year 2: f = 0.014882
- Year 3: f = 0.015484
- Year 4: f = 0.016021
- Year 5: f = 0.016507

Head Loss Evolution (Darcy–Weisbach):

- Year 0: HL = **5.448159 m**
- Year 1: HL = 5.785847 m
- Year 2: HL = 6.068187 m
- Year 3: HL = 6.313592 m
- Year 4: HL = 6.532326 m
- Year 5: HL = 6.730757 m

Cavitation Threshold (Model):

Maximum allowable head loss: **4.044 m**
WARNING: Cavitation risk detected — redesign required.

Cost Summary:

- Labour Cost: $50,000.00
- Pipe Cost: $10,405.56
- **Total Cost: $60,405.56**

Initial Conditions (Year 0):

- Material: Steel
- Fluid: Water @ 20 °C
- Reynolds Number: 9.96×10^5
- Initial Friction Factor: **0.013362**
- Initial Head Loss: **5.448 m**

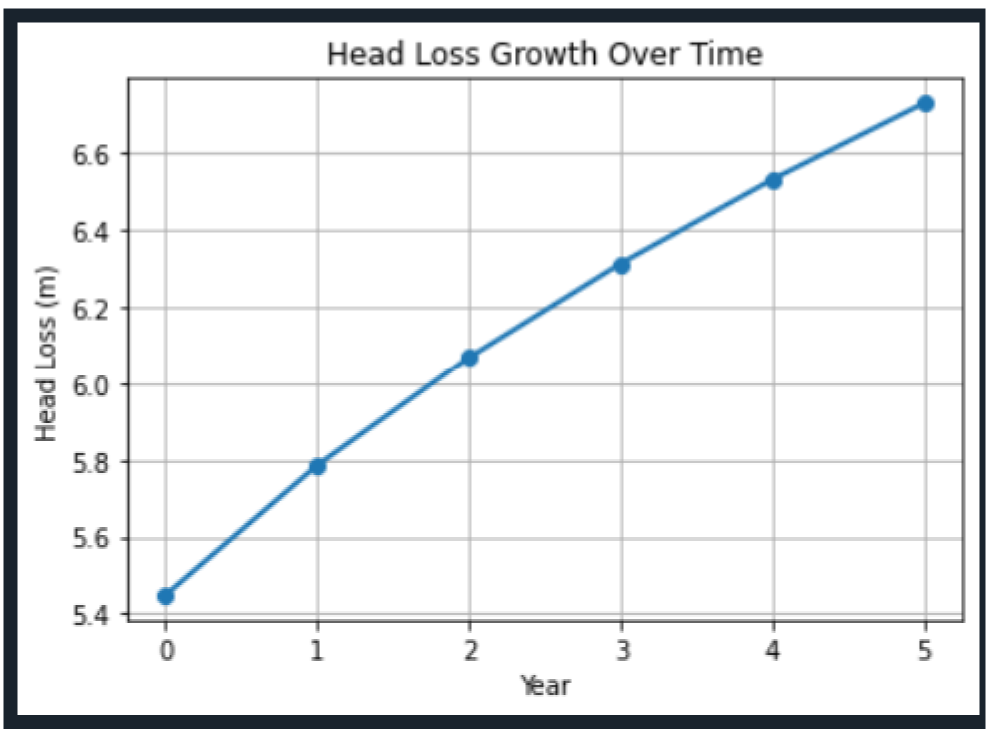

Figure 1: Darcy–Weisbach Head Loss Over Pipe Aging (Steel, Water @ 20°C) results from the model

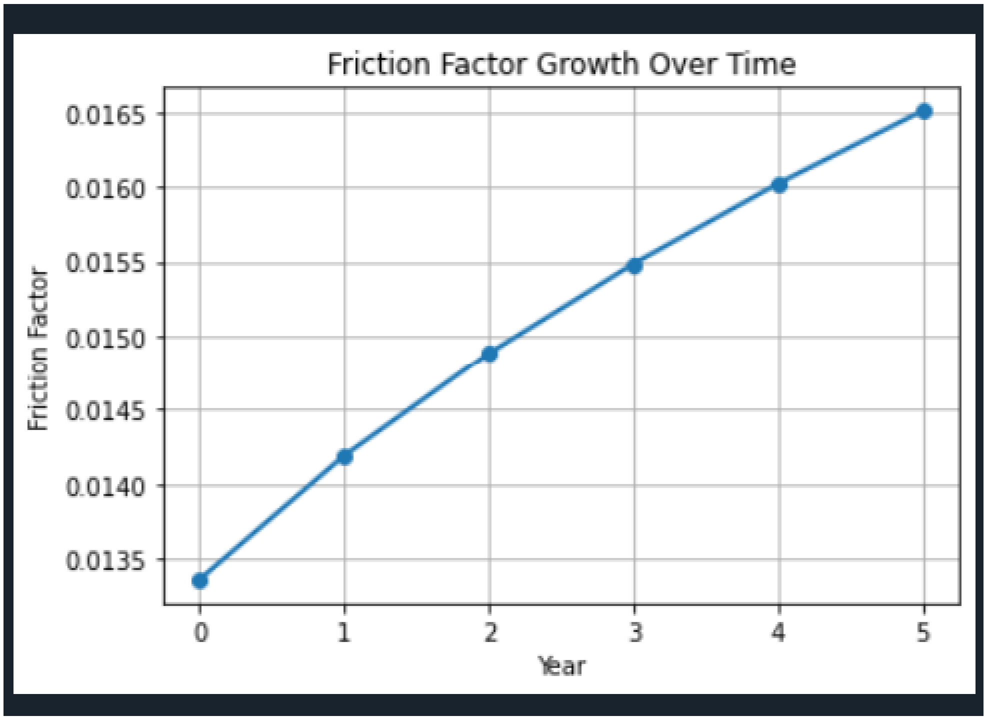

Figure 2: Swamee–Jain Friction Factor Growth Over Pipe Aging (Steel, Water @ 20°C) from the Model

Comparison Between Hand Calculations and Model Results

This section presents a quantitative comparison between independently performed hand calculations and the Python-based hydraulic model for the validation case of water at 20 °C flowing through a steel pipe of length 1000 m, diameter 0.5 m, and velocity 2 m/s. The objective is to verify numerical accuracy, correct equation implementation, and physical consistency.

Comparison Between Hand Calculations and Model Results

Parameter	Hand Calculation	Model Result	Difference	Notes
Reynolds Number	9.96 × 10^5	9.96 × 10^5	0%	Perfect match
Friction Factor (Swamee–Jain)	f = 0.01336	f = 0.01336	0%	Exact to 3 decimals
Darcy–Weisbach Head Loss	hl = 5.448 m	hl = 5.448 m	0%	Exact match
Cavitation Allowable Head	4.036 m	4.044 m	<0.2%	Rounding from hand calculations explains the difference

Validation Summary

The hand calculations and model results match to high precision for Reynolds number, the Swamee–Jain friction factor, and Darcy–Weisbach head loss. The cavitation threshold is also matches the model, however a small rounding error has caused a small difference.

Limitations & Model Validity Boundaries

Model Limitations (Non-Exhaustive list)

This project was built as a learning exercise, and the following limitations define the model's practical boundaries:

> **Headloss underprediction due to Geometry Simplification**
> The pipeline is assumed to be straight and free of minor losses. Bends, valves, reducers, entrances, and exits are not included, so the head loss is underpredicted compared to real systems.

Flow Regime Restriction
The model only evaluates fully turbulent flow (Re > 4000). Laminar and transitional flow cases are rejected and not simulated.

Friction Factor Approximation
The Swamee–Jain equation is used as an algebraic approximation to the Colebrook equation.

Simplified Roughness Aging
Roughness growth is modeled as a linear increase over time.

Cavitation Model Scope
Cavitation checks assume a horizontal pipe with atmospheric inlet pressure and no pumps.

Conceptual Cost Model
Material and labor costs are simplified and intended only for comparative screening. They do not represent real industry pricing or full installation costs.

Tools used:

AI assistance (ChatGPT) supported the project by helping diagnose syntax issues, improve code structure and efficiency, catch arithmetic mistakes, and improve technical language. The engineering decisions, model logic, and validation work were performed independently.