DESIGN OF PENSTOCKS

BY

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Introduction

- From the forbay tank down to the turbine water is conveyed through the penstock.

Major components

- Forbay
- Penstock value
- Vent pipe
- Support pier
Components

- Anchors
- Drain valve
- Air bleed value
- Bends
- Thrust block
Major components (joint types)

- flanged
- Socket
- Sleeve type
Components of penstock

Forebay

Vent pipe

Joint

Air bleed valve (placed at peaks)

Penstock valve (gate or butterfly valve)

Support pier

Drain valve (placed where the penstock rises)

Anchor

Bend
Material used for construction...

- Mild steel
- uPVC (unplastizied polyvinyl chloride)
- HDPE (high density polyethylene)
- Ductile iron
- Prestressed concrete
- GRP (glass reinforced plastic)
Important factors to be considered when selecting material

- Design Pressure
- Surface Roughness
- Weight of material
- Ease of transportation
- Method of jointing
- Cost of material etc
Constraints in deciding diameter

- Price
- Head loss

Compromise: Minimum cost (smallest diameter)
or Minimum head loss? (acceptable head loss)
Major contributions to head loss, $h_f$

* Friction (due to surface roughness)

$$h_f = \frac{1}{2} \cdot \frac{V^2 \cdot L \cdot f}{g \cdot D}$$

Darcy’s equation

V – flow velocity
L – penstock length
D – diameter
f -- friction constant

from moody chart
Major contributions to head loss, $h_f$

- **Turbulence** (caused by due to bends, inlet, valves, reductions etc)

$$h_f = \sum K_i \cdot V_i^2 / 2.g$$

$K_i = \text{turbulence loss coefficient}$
Calculation of head loss & diameter

- **CASE STUDY:** A steel penstock, 500 m long, has a design flow of 0.42 m³/s and a gross head of 220 m. Calculate the diameter and wall thickness where the head loss is less than 2% of the gross head.

- **Select** diameter as \( D = 300 \text{ mm} \)
- **Flow velocity** \( V = \frac{4Q}{\pi D^2} \)
  - \( = 5.9 \text{ m/s} \)
- **Renolds no** \( = VD \times 10^6 \)
  - \( = 1.8 \times 10^6 \)
Surface roughness of mild steel is,  \( f = 0.3 \)

So,  \( \frac{K}{D} = \frac{0.3}{300} = 1 \times 10^{-3} \)

from Moody chart  \( f = 0.005 \),

From Darcy’s eqn,

\[
h_f = \frac{1}{2} \times 5.9^2 \times 500 \times 0.0046 / 9.81 \times 0.25
\]

= 15.0 m
in our case gross head = 220 m

\[ H_f = \left( \frac{15}{220} \right) \times 100 = 6.8\% \]

**Calculation of diameter is an iterative process**,

increase \( D \) by 10 mm,

now \( V = 5.5 \text{ m/s} \)

\[ K/D = \frac{0.3}{310} = 9.6 \times 10^{-4} \]

\[ \text{Re} = V \times D = 5.5 \times 0.310 = 1.7 \times 10^6 \]

corresponding \( f = 0.005 \)

\[ h_f = 12.7 \text{ m} \]

\[ h_f = 5.77\% \]
## Results of 15 iterations

<table>
<thead>
<tr>
<th>iterations</th>
<th>Diameter (mm)</th>
<th>hf / (m)</th>
<th>V / (m/s)</th>
<th>%hf</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>15</td>
<td>5.9</td>
<td>6.82</td>
</tr>
<tr>
<td>2</td>
<td>310</td>
<td>12.7</td>
<td>5.5</td>
<td>5.77</td>
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<tr>
<td>3</td>
<td>315</td>
<td>11.8</td>
<td>5.3</td>
<td>5.36</td>
</tr>
<tr>
<td>4</td>
<td>320</td>
<td>10.8</td>
<td>5.22</td>
<td>4.91</td>
</tr>
<tr>
<td>5</td>
<td>325</td>
<td>10</td>
<td>5</td>
<td>4.55</td>
</tr>
<tr>
<td>6</td>
<td>330</td>
<td>9.3</td>
<td>4.9</td>
<td>4.23</td>
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<tr>
<td>7</td>
<td>335</td>
<td>8.2</td>
<td>4.7</td>
<td>3.73</td>
</tr>
<tr>
<td>8</td>
<td>340</td>
<td>7.7</td>
<td>4.6</td>
<td>3.50</td>
</tr>
<tr>
<td>9</td>
<td>350</td>
<td>6.6</td>
<td>4.3</td>
<td>3.00</td>
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<tr>
<td>10</td>
<td>355</td>
<td>6.2</td>
<td>4.2</td>
<td>2.82</td>
</tr>
<tr>
<td>11</td>
<td>360</td>
<td>5.7</td>
<td>4.1</td>
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<tr>
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<td>4</td>
<td>2.45</td>
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<td>13</td>
<td>370</td>
<td>5</td>
<td>3.9</td>
<td>2.27</td>
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<td>14</td>
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<td>4.7</td>
<td>3.8</td>
<td>2.14</td>
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<tr>
<td>15</td>
<td>380</td>
<td>4.3</td>
<td>3.7</td>
<td>1.95</td>
</tr>
</tbody>
</table>
Constraints in deciding wall thickness

- Cost
- Strength (withstanding pressure)

*Compromise:* Minimum cost or Minimum strength?
Calculation of wall thickness

- Wall should be thick enough to withstand the maximum water pressure

- Maximum pressure = static + surge

- Surge pressure: worst possible case (instantaneous closure of valve)
Surge pressure, $h_{\text{surge}}$

- $h_{\text{surge}} = C \cdot V / g$
  - $V$ – flow velocity
  - $C$ – velocity of pressure wave

- $C = \frac{1}{\sqrt{\rho \left(\frac{1}{k} + \frac{D}{E \cdot t}\right)}}$
  - $D$ – diameter
  - $t$ – Wall thickness
  - $E$- Young’s modulus of elasticity
  - $K$ – Bulk modulus of water
  - $\rho$ – density of water
Thickness,
\[ t_{\text{min}} = \rho \cdot g \cdot h_{\text{max}} \cdot D / (2 \cdot \sigma_T / S) \]

- \( \sigma_T \) – ultimate tensile strength
- \( S \) - safety factor typically 3

Procedure: this is an iterative process

1. Estimate \( t \)
2. Calculate \( C, h_{\text{max}}, t_{\text{min}} \)
3. Compare \( t \) with \( t_{\text{min}} \)
4. If \( t < t_{\text{min}} \) increase \( t \)
5. If \( t > t_{\text{min}} \) reduce \( t \) close to \( t_{\text{min}} \)
6. Repeat 2 and 3
Calculation of penstock wall Thickness

Let us select $t$ as 5 mm, $D = 380$ mm

- Iteration 1
- Iteration 2
- Iteration 3
- Iteration 4
References:

- Micro hydro power – Adam Harvey, Andrew Brown, Rod Edward, VAris Bokalders
Thank You!
Figure 6.8  Moody's chart for finding the friction factor $f$ of pipes
select D

Calculate $V$, $Re$, $No$, $k/D$

Get friction from moody chart

calculate head loss

head loss acceptable

change D

no

yes

stop
Results of iterations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Thickness, $t = \quad$</td>
<td>5.00 mm</td>
</tr>
<tr>
<td>Diameter, $D = \quad$</td>
<td>380 mm</td>
</tr>
<tr>
<td>Velocity, $V = \quad$</td>
<td>3.70 m/s</td>
</tr>
<tr>
<td>Surge wave velocity, $C = \quad$</td>
<td>1088.93 m/s</td>
</tr>
<tr>
<td>$h$ surge = \quad$</td>
<td>410.71 m</td>
</tr>
<tr>
<td>$P_{max} = h_{static} + h_{serge}$</td>
<td>626.41 m</td>
</tr>
<tr>
<td>$t_{min}$</td>
<td>7.30 mm</td>
</tr>
</tbody>
</table>
Wall Thickness $t = 7.30$ mm
Diameter $D = 380$ mm
Velocity $V = 3.70$ m/s
Surge wave velocity $C = 1172.29$ m/s
$h_{serge} = 442.15$ m
$P_{max} = h_{static} + h_{serge} = 657.85$ m
$t_{min} = 7.66$ mm
3

Wall Thickness $t = 7.66$ mm
Diameter $D = 380$ mm
Velocity $V = 3.70$ m/s
Surge wave velocity $C = 1181.93$ m/s
$h_{serge} = 445.78$ m
$P_{max} = h_{static} + h_{serge} = 661.48$ m
$t_{min} = 7.71$ mm
Wall Thickness $t = 7.71 \text{ mm}$
Diameter $D = 380 \text{ mm}$
Velocity $V = 3.70 \text{ m/s}$
Surge wave velocity $C = 1183.21 \text{ m/s}$
h surge $= 446.27 \text{ m}$
P max $= h_{\text{static}} + h_{\text{serge}} = 661.97 \text{ m}$
t min $= 7.71 \text{ mm}$