Hydro power plants
Hydro power plants

- Tail water
- Penstock
- Air inlet
- Inlet gate
- Surge shaft
- Tunnel
- Sand trap
- Trash rack
- Self closing valve
- Main valve
- Turbine
- Draft tube
- Draft tube gate
The principle the water conduits of a traditional high head power plant
Ulla- Førre

Original figur ved Statkraft Vestlandsverkene
Typical Power House with Francis Turbine

- Intake gate
- Intake trashrack
- Tunnel Inlet
- Tunnel Inlet trashrack
- Headrace tunnel
- Anchor block
- Surge tank
- Penstock inlet Valve
- Tunnel Inlet
- Anchor block
- Desilting basin
- Shaddle
- Anchor block
- Exp. joint
- Power house
- DT end gate
- Tailrace
- IV -inlet valve
- R -turbine runner
- SC -spiral case
- G -generator
Arrangement of a small hydropower plant

1. Intake dam
2. Gate
3. Trash rack
4. Emptying gate
5. Ice gate
6. Intake cone
7. Expansion stuffing box
8. Fundament
9. Turbine shaft
10. Turbine
11. Draft tube
12. Closing valve
13. Tail race canal

A. Water intake
B. Penstock
C. Turbine
Ligga Power Plant, Norrbotten, Sweden

H = 39 m
Q = 513 m$^3$/s
P = 182 MW
$D_{runner} = 7.5$ m
Borcha Power Plant, Turkey

H = 87.5 m
P = 150 MW
D_{runner} = 5.5 m
Water intake

- Dam
- Coarse trash rack
- Intake gate
- Sediment settling basement
Dams

- Rockfill dams
- Pilar og platedammer
- Hvelvdammer
Rock-fill dams

1. Core: Moraine, crushed soft rock, concrete, asphalt
2. Filter zone: Sandy gravel
3. Transition zone: Fine blasted rock
4. Supporting shell: Blasted rock
Slab concrete dam
Arc dam
Gates in Hydro Power Plants
Types of Gates

- Radial Gates
- Wheel Gates
- Slide Gates
- Flap Gates
- Rubber Gates
Radial Gates at Älvkarleby, Sweden
Radial Gate

The forces acting on the arc will be transferred to the bearing.
Flap Gate
Rubber gate

- Reinforced rubber
  - Open position
- Flow disturbance
- Bracket
- Reinforced rubber
  - Closed position
- Air inlet
Circular gate

End cover

Ribs
Pipe

Hinge
Manhole

Bolt

Fastening element

Seal
Frame

Ladder
Circular gate

Jhimruk Power Plant, Nepal
Trash Racks

Panauti Power Plant, Nepal
Theun Hinboun Power Plant
Laos
Gravfoss
Power Plant
Norway

Trash Rack size:
Width: 12 meter
Height: 13 meter

Stainless Steel
CompRack
Trash Rack delivered by VA-Tech
Cleaning the trash rack
Pipes

- Materials
- Calculation of the change of length due to the change of the temperature
- Calculation of the head loss
- Calculation of maximum pressure
  - Static pressure
  - Water hammer
- Calculation of the pipe thickness
- Calculation of the economical correct diameter
- Calculation of the forces acting on the anchors
Materials

• Steel
• Polyethylene, PE
• Glass-fibre reinforced Unsaturated Polyesterplastic, GUP
• Wood
• Concrete
## Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Max. Diameter</th>
<th>Max. Pressure</th>
<th>Max. Stresses</th>
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<tbody>
<tr>
<td></td>
<td>[m]</td>
<td>[m]</td>
<td>[MPa]</td>
</tr>
<tr>
<td>Steel, St.37</td>
<td></td>
<td></td>
<td>150</td>
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<tr>
<td>Steel, St.42</td>
<td></td>
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<td>190</td>
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<td>Steel, St.52</td>
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<td></td>
<td>206</td>
</tr>
<tr>
<td>PE</td>
<td>~1,0</td>
<td>160</td>
<td>5</td>
</tr>
<tr>
<td>GUP</td>
<td>2,4</td>
<td>320</td>
<td></td>
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<tr>
<td></td>
<td>Max. p = 160 m.</td>
<td></td>
<td>Max. D: 1,4 m.</td>
</tr>
<tr>
<td>Wood</td>
<td>~5</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>~5</td>
<td>~400</td>
<td></td>
</tr>
</tbody>
</table>
Steel pipes in penstock
Nore Power Plant, Norway
GUP-Pipe
Raubergfossen Power Plant, Norway
Wood Pipes

Breivikbotn Power Plant, Norway

Øvre Porsa Power Plant, Norway
Calculation of the change of length due to the change of the temperature

\[ \Delta L = \alpha \cdot \Delta T \cdot L \]

Where:
- \( \Delta L \) = Change of length [m]
- \( L \) = Length [m]
- \( \alpha \) = Coefficient of thermal expansion [m/°C m]
- \( \Delta T \) = Change of temperature [°C]
Calculation of the head loss

\[ h_f = f \cdot \frac{L}{D} \cdot \frac{c^2}{2 \cdot g} \]

Where:

- \( h_f \) = Head loss [m]
- \( f \) = Friction factor [-]
- \( L \) = Length of pipe [m]
- \( D \) = Diameter of the pipe [m]
- \( c \) = Water velocity [m/s]
- \( g \) = Gravity [m/s^2]
Example
Calculation of the head loss

Power Plant data:
\[ H = 100 \text{ m} \quad \text{Head} \]
\[ Q = 10 \text{ m}^3/\text{s} \quad \text{Flow Rate} \]
\[ L = 1000 \text{ m} \quad \text{Length of pipe} \]
\[ D = 2.0 \text{ m} \quad \text{Diameter of the pipe} \]
The pipe material is steel

\[ h_f = f \cdot \frac{L \cdot c^2}{D \cdot 2 \cdot g} \]

\[ \text{Re} = \frac{c \cdot D}{\nu} \]

Where:
\[ c = 3.2 \text{ m/s} \quad \text{Water velocity} \]
\[ \nu = 1.308 \cdot 10^{-6} \text{ m}^2/\text{s} \quad \text{Kinetic viscosity} \]
\[ \text{Re} = 4.9 \cdot 10^6 \quad \text{Reynolds number} \]
Where:

\[
\text{Re} = 4,9 \cdot 10^6 \quad \text{Reynolds number}
\]
\[
\varepsilon = 0,045 \text{ mm} \quad \text{Roughness}
\]
\[
D = 2,0 \text{ m} \quad \text{Diameter of the pipe}
\]
\[
\varepsilon/D = 2,25 \cdot 10^{-5} \quad \text{Relative roughness}
\]
\[
f = 0,013 \quad \text{Friction factor}
\]

The pipe material is steel
Example
Calculation of the head loss

Power Plant data:

- **H** = 100 m  Head
- **Q** = 10 m$^3$/s  Flow Rate
- **L** = 1000 m  Length of pipe
- **D** = 2,0 m  Diameter of the pipe

The pipe material is steel

\[
h_f = f \cdot \frac{L}{D} \cdot \frac{c^2}{2 \cdot g} = 0,013 \cdot \frac{1000}{2} \cdot \frac{3,2^2}{2 \cdot 9,82} = 3,4 \text{ m}
\]

Where:

- **f** = 0,013  Friction factor
- **c** = 3,2 m/s  Water velocity
- **g** = 9,82 m/s$^2$  Gravity
Calculation of maximum pressure

- Static head, $H_{gr}$ (Gross Head)
- Water hammer, $\Delta h_{wh}$
- Deflection between pipe supports
- Friction in the axial direction
Maximum pressure rise due to the Water Hammer

\[ \Delta h_{wh} = \frac{a \cdot c_{\text{max}}}{g} \quad \text{IF} \quad T_c << \frac{2 \cdot L}{a} \quad \text{Jowkowsky} \]

- \( \Delta h_{wh} \) = Pressure rise due to water hammer [mWC]
- \( a \) = Speed of sound in the penstock [m/s]
- \( c_{\text{max}} \) = maximum velocity [m/s]
- \( g \) = gravity [m/s²]
Example

Jowkowsky

\[ a = 1000 \text{ [m/s]} \]
\[ c_{\text{max}} = 10 \text{ [m/s]} \]
\[ g = 9.81 \text{ [m/s}^2\text{]} \]

\[ T_c \ll \frac{2 \cdot L}{a} \]

\[ \Delta h_{\text{wh}} = \frac{a \cdot c_{\text{max}}}{g} = 1020 \text{ m} \]
Maximum pressure rise due to the Water Hammer

\[ \Delta h_{wh} = \frac{a \cdot c_{\text{max}}}{g} \cdot \frac{2 \cdot L}{T_c} = \frac{c_{\text{max}} \cdot 2 \cdot L}{g \cdot T_c} \]

IF \[ T_c \geq \frac{2 \cdot L}{a} \]

Where:
- \( \Delta h_{wh} \) = Pressure rise due to water hammer \([\text{mWC}]\)
- \( a \) = Speed of sound in the penstock \([\text{m/s}]\)
- \( c_{\text{max}} \) = maximum velocity \([\text{m/s}]\)
- \( g \) = gravity \([\text{m/s}^2]\)
- \( L \) = Length \([\text{m}]\)
- \( T_c \) = Time to close the main valve or guide vanes \([\text{s}]\)
Example

\[ L = 300 \, [m] \]
\[ T_C = 10 \, [s] \]
\[ c_{\text{max}} = 10 \, [m/s] \]
\[ g = 9.81 \, [m/s^2] \]

\[ \Delta h_{\text{wh}} = \frac{c_{\text{max}} \cdot 2 \cdot L}{g \cdot T_C} = 61 \, m \]
Calculation of the pipe thickness

\[ L \cdot D_i \cdot p \cdot C_s = 2 \cdot \sigma_t \cdot L \cdot t \]
\[ \Downarrow \]
\[ \sigma_t = \frac{p \cdot r_i \cdot C_s}{t} \]

\[ p = \rho \cdot g \cdot (H_{gr} + h_{wh}) \]

Where:
- \( L \) = Length of the pipe [m]
- \( D_i \) = Inner diameter of the pipe [m]
- \( p \) = Pressure inside the pipe [Pa]
- \( \sigma_t \) = Stresses in the pipe material [Pa]
- \( t \) = Thickness of the pipe [m]
- \( C_s \) = Coefficient of safety [-]
- \( \rho \) = Density of the water [kg/m\(^3\)]
- \( H_{gr} \) = Gross Head [m]
- \( \Delta h_{wh} \) = Pressure rise due to water hammer [m]

Based on:
- Material properties
- Pressure from:
  - Water hammer
  - Static head
Example
Calculation of the pipe thickness

\[ L \cdot D_i \cdot p \cdot C_s = 2 \cdot \sigma_t \cdot L \cdot t \]

\[ t = \frac{p \cdot r_i \cdot C_s}{\sigma_t} = 0,009 \text{ m} \]

\[ p = \rho \cdot g \cdot (H_{gr} + h_{wh}) = 1,57 \text{ MPa} \]

Where:
- \( L = 0,001 \text{ m} \) Length of the pipe
- \( D_i = 2,0 \text{ m} \) Inner diameter of the pipe
- \( \sigma_t = 206 \text{ MPa} \) Stresses in the pipe material
- \( \rho = 1000 \text{ kg/m}^3 \) Density of the water
- \( C_s = 1,2 \) Coefficient of safety
- \( H_{gr} = 100 \text{ m} \) Gross Head
- \( \Delta h_{wh} = 61 \text{ m} \) Pressure rise due to water hammer

Based on:
- Material properties
- Pressure from:
  - Water hammer
  - Static head
Calculation of the economical correct diameter of the pipe

\[ \frac{dK_{\text{tot}}}{dD} = \frac{d(K_f + K_t)}{dD} = 0 \]
Example
Calculation of the economical correct diameter of the pipe

Hydraulic Losses

Where:

\[ P_{\text{Loss}} = \rho \cdot g \cdot Q \cdot h_f = \rho \cdot g \cdot Q \cdot f \frac{L}{2 \cdot r} \frac{Q^2}{2 \cdot g \cdot \pi^2 \cdot r^4} = \frac{C_2}{r^5} \]

- \( P_{\text{Loss}} \) = Loss of power due to the head loss [W]
- \( \rho \) = Density of the water [kg/m³]
- \( g \) = gravity [m/s²]
- \( Q \) = Flow rate [m³/s]
- \( h_f \) = Head loss [m]
- \( f \) = Friction factor [-]
- \( L \) = Length of pipe [m]
- \( r \) = Radius of the pipe [m]
- \( C_2 \) = Calculation coefficient
Example
Calculation of the economical correct diameter of the pipe
Cost of the Hydraulic Losses per year

\[ K_f = P_{\text{Loss}} \cdot T \cdot \text{kWh}_{\text{price}} = \frac{C_2}{r^5} \cdot T \cdot \text{kWh}_{\text{price}} \]

Where:
- \( K_f \) = Cost for the hydraulic losses [€]
- \( P_{\text{Loss}} \) = Loss of power due to the head loss [W]
- \( T \) = Energy production time [h/year]
- \( \text{kWh}_{\text{price}} \) = Energy price [€/kWh]
- \( r \) = Radius of the pipe [m]
- \( C_2 \) = Calculation coefficient
Example
Calculation of the economical correct diameter of the pipe
Present value of the Hydraulic Losses per year

\[ K_f = \frac{C_2}{r^5} \cdot T \cdot kWh_{\text{price}} \]

Where:
- \(K_f\) = Cost for the hydraulic losses \([\text{€}]\)
- \(T\) = Energy production time \([\text{h/year}]\)
- \(kWh_{\text{price}}\) = Energy price \([\text{€/kWh}]\)
- \(r\) = Radius of the pipe \([\text{m}]\)
- \(C_2\) = Calculation coefficient

Present value for 20 year of operation:

\[ K_{f_{pv}} = \sum_{i=1}^{n} \frac{K_f}{(1+I)^i} \]

Where:
- \(K_{f_{pv}}\) = Present value of the hydraulic losses \([\text{€}]\)
- \(n\) = Lifetime, (Number of year ) \([-]\)
- \(I\) = Interest rate \([-]\)
Example
Calculation of the economical correct diameter of the pipe
Cost for the Pipe Material

\[ m = \rho_m \cdot V = \rho_m \cdot 2 \cdot \pi \cdot r \cdot t \cdot L = \rho_m \cdot 2 \cdot \pi \cdot r \cdot \frac{p \cdot r}{\sigma} \cdot L = C_1 \cdot r^2 \]

\[ K_t = M \cdot m = M \cdot C_1 \cdot r^2 \]

Where:
- \( m \) = Mass of the pipe [kg]
- \( \rho_m \) = Density of the material [kg/m³]
- \( V \) = Volume of material [m³]
- \( r \) = Radius of pipe [m]
- \( L \) = Length of pipe [m]
- \( p \) = Pressure in the pipe [MPa]
- \( \sigma \) = Maximum stress [MPa]
- \( C_1 \) = Calculation coefficient
- \( K_t \) = Installation costs [€]
- \( M \) = Cost for the material [€/kg]

NB:
This is a simplification because no other component then the pipe is calculated
Example

Calculation of the economical correct diameter of the pipe

• Installation Costs:
  – Pipes
  – Maintenance
  – Interests
  – Etc.
Example
Calculation of the economical correct diameter of the pipe

\[
K_{f_{p}} = \sum_{i=1}^{n} \frac{C_2 \cdot T \cdot kWh_{\text{price}}}{r^5 \left(1+I\right)^i}
\]

\[
K_t = M \cdot C_1 \cdot r^2
\]

\[
\frac{d(K_t + K_f)}{dr} = 2 \cdot M \cdot C \cdot r - \frac{5}{r^6} \cdot \sum_{i=1}^{n} \frac{C_2 \cdot T \cdot kWh_{\text{price}}}{\left(1+I\right)^i} = 0
\]

Where:
- \(K_f\) = Cost for the hydraulic losses [€]
- \(K_t\) = Installation costs [€]
- \(T\) = Energy production time [h/year]
- \(kWh_{\text{price}}\) = Energy price [€/kWh]
- \(r\) = Radius of the pipe [m]
- \(C_i\) = Calculation coefficient
- \(M\) = Cost for the material [€/kg]
- \(n\) = Lifetime, (Number of year ) [-]
- \(I\) = Interest rate [-]
Example
Calculation of the economical correct diameter of the pipe

\[
\frac{d(K_t + K_f)}{dr} = 2 \cdot M \cdot C \cdot r - \frac{5}{r^6} \cdot \sum_{i=1}^{n} \frac{C_2 \cdot T \cdot kWh_{\text{price}}}{(1+I)^i} = 0
\]

\[
\downarrow
\]

\[
r = \sqrt[7]{\sqrt{\frac{5}{2} \cdot \sum_{i=1}^{n} \frac{C_2 \cdot T \cdot kWh_{\text{price}}}{M \cdot C \cdot (1+I)^i}}}
\]
Calculation of the forces acting on the anchors
Calculation of the forces acting on the anchors

\[ F_1 = \text{Force due to the water pressure} \quad [\text{N}] \]
\[ F_2 = \text{Force due to the water pressure} \quad [\text{N}] \]
\[ F_3 = \text{Friction force due to the pillars upstream the anchor} \quad [\text{N}] \]
\[ F_4 = \text{Friction force due to the expansion joint upstream the anchor} \quad [\text{N}] \]
\[ F_5 = \text{Friction force due to the expansion joint downstream the anchor} \quad [\text{N}] \]
Calculation of the forces acting on the anchors
Valves
Principle drawings of valves

Open position
Closed position

Spherical valve
Gate valve
Hollow-jet valve
Butterfly valve
Spherical valve
Bypass system
Butterfly valve
Butterfly valve
Butterfly valve disk types
Pelton turbines

- Large heads (from 100 meter to 1800 meter)
- Relatively small flow rate
- Maximum of 6 nozzles
- Good efficiency over a wide range
Jostedal, Norway

*Q = 28,5 m$^3$/s
*H = 1130 m
*P = 288 MW
Francis turbines

- Heads between 15 and 700 meter
- Medium Flow Rates
- Good efficiency $\eta = 0.96$ for modern machines
SVARTISEN

\begin{align*}
P & = 350 \text{ MW} \\
H & = 543 \text{ m} \\
Q^* & = 71.5 \text{ m}^3/\text{S} \\
D_0 & = 4.86 \text{ m} \\
D_1 & = 4.31 \text{ m} \\
D_2 & = 2.35 \text{ m} \\
B_0 & = 0.28 \text{ m} \\
n & = 333 \text{ rpm}
\end{align*}
Kaplan turbines

- Low head (from 70 meter and down to 5 meter)
- Large flow rates
- The runner vanes can be governed
- Good efficiency over a wide range