

Design of a reservoir hydropower scheme

Arthur Guillot - Le Goff

Autumn semester 2021-2022 | Hydroelectric power

Design of a reservoir hydropower scheme

Task 1: Determine the design of a gravity dam, height H to satisfy safety factors against sliding and overturning.

Finding measurement

Stability analysis

Load Combination

Checking safety factors

Annex: calculation code

Task 2: Determine the design of spillway section to safely evacuate flood with a 100-year return period downstream

Spilway equations

Technical drawing at scale

Task 3: Design the intake structure for the powerhouse, route water to the powerhouse and further to the stilling basin downstream of the dam

Hydraulic losses in the pressure tunnel

Task 1: Determine the design of a gravity dam, height H to satisfy safety factors against sliding and overturning.

Finding measurement

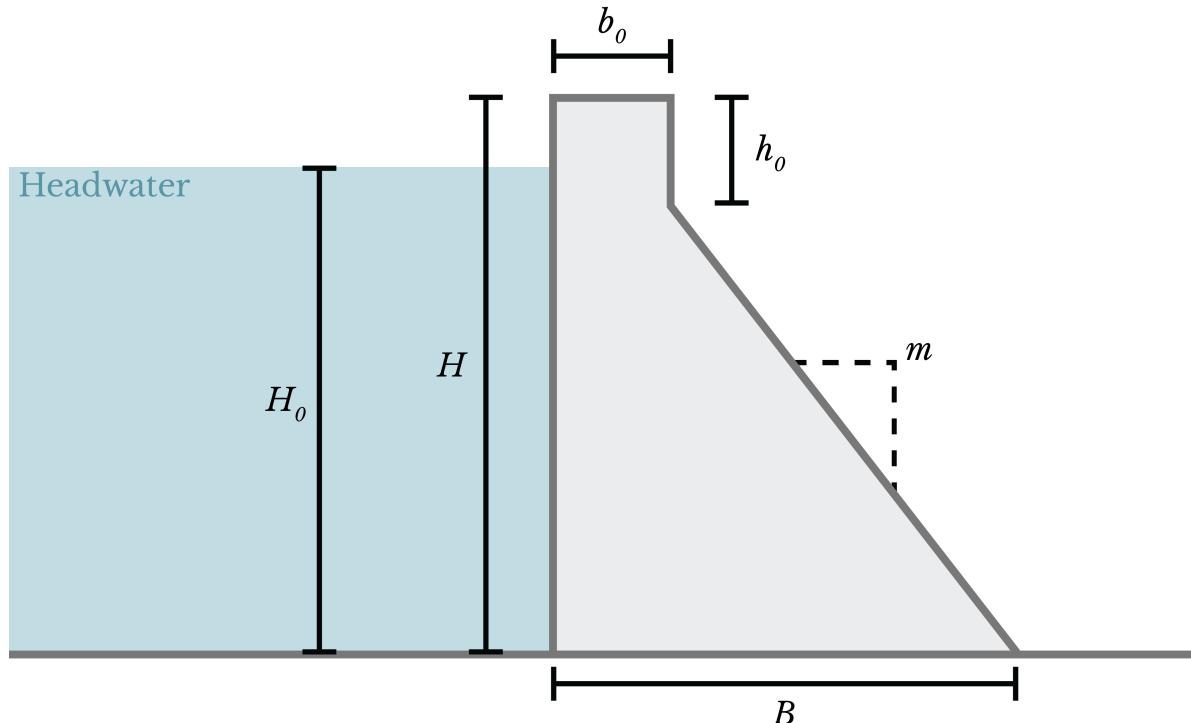


Figure 1 : Introduction to notations for the gravity dam measurements

According to the Bureau of Reclamation of the USA department of the interior "Design of gravity dams" paper we can calculate the missing dimensions according to the current standards.

$$m = \frac{B}{H} = \frac{b_0}{h_0} \simeq 0,8$$

$$b_0 = \frac{H}{10} \geq 8m$$

We can therefore calculate :

- $B = m \cdot H = 0,8 \times 71 = 56,8m$
- $b_0 = \frac{H}{10} = \frac{71}{10} = 7,1m \leq 8$, so we choose $b_0 = 8m$
- $h_0 = \frac{b_0}{m} = \frac{8}{0,8} = 10m$

Stability analysis

Now we have to figure out the weakpoints and the critical failure modes. We can identify three of them:

- **Sliding** : too much pressure causes the dam to move in the horizontal plane. The following safety factor is then considered: $n_{SL} = \frac{\sum V}{\sum H}$. Where $\sum V$ represent the sum of the vertical efforts and $\sum H$ for the horizontal ones. To meet the safety requirements $n_{SL} > 3$ for the usual load case.
- **Overturning** : the dam rotates around a fixed point. In our case and as shown in the diagram the lower end on the right. The safety factor is described as, $n_{OV} = \frac{M_{stab}}{M_{dest}} > 2$.
- **Crushing** : in this case we are looking at compression and tension failure.

Load Combination

For this example we have chosen to consider the usual load case. It is then a question of determining the set of forces which have a reasonable probability of simultaneous occurrence. The calculations could have been made in an even less favourable scenario (unusual or extreme flood case, dynamic cases by considering waves, wind, earthquakes). The problem will be solved with the following assumptions :

- The reservoir is at his operational level (H_0),
- we are considering the dead load of the dam,
- the uplift pressure is at his full drainage capacity,
- there is a presence of silt that affect the dam.

We can report on the following efforts :

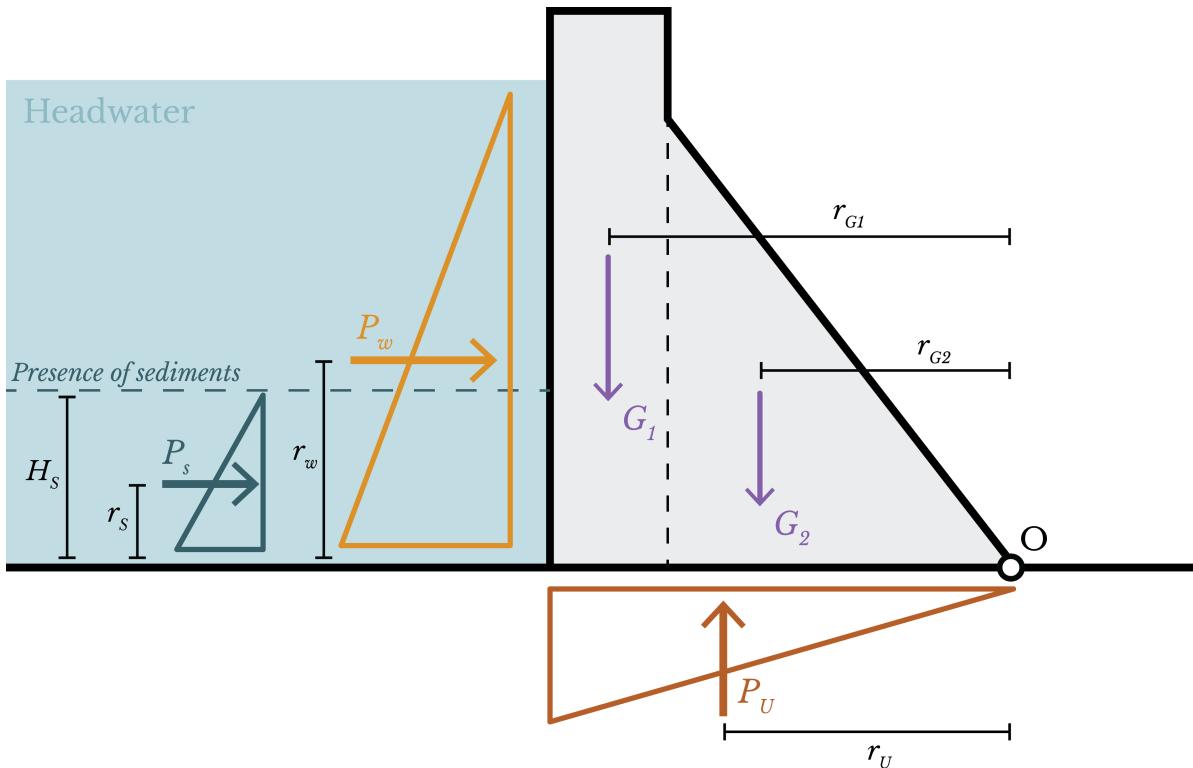


Figure 2 : Efforts on the dam

Where :

- G_1 and G_2 represent the **dead load** of the dam. The following formulas describing the effort are then considered :
 - $\gamma_{conc} = 24 \text{ kN/m}^3$
 - $G_1 = b_0 \cdot H \cdot \gamma_{conc} \cdot e = 13632 \text{ kN}$
where e is the thickness of the study section ($e = 1 \text{ m}$), so we won't consider it in the next equations
 - $G_2 = \frac{1}{2}(B - b_0)(H - H_0)\gamma_{conc} = 35721 \text{ kN}$
 - $r_{G1} = B - \frac{b_0}{2} = 52,8 \text{ m}$
 - $r_{G2} = \frac{2}{3}(B - b_0) = 32,5 \text{ m}$
- P_w the **hydrostatic pressure** on the dam :
 - $\gamma_w = 10 \text{ kN/m}^3$
 - $P_w = \gamma_w \cdot \frac{H_0^2}{2} = 21125 \text{ kN}$
 - $r_w = \frac{1}{3} \cdot H_0 = 21,7 \text{ m}$
- P_u the **uplift pressure** on the dam :

- To reduce the effect of uplift, drainage to the ground are installed in the dam. This reduction is associated with the coefficient $\lambda = 0,85$
- $P_u = \lambda \cdot H_0 \cdot \gamma_w \cdot \frac{B}{2} = 15691 \text{ kN}$
- $r_u = \frac{2}{3} \cdot B = 37,8 \text{ m}$
- P_s the silt pressure on the dam :
 - $\gamma_S = 18 \text{ kN/m}^3$
 - $H_S = \frac{H_0}{3} = 21,6 \text{ m}$
 - $P_S = \gamma_S \cdot \frac{H_S^2}{2} = 4225 \text{ kN}$
 - $r_S = \frac{H_S}{3} = 7,2 \text{ m}$

Checking safety factors

We can therefore calculate our safety factors.

$$n_{SL} = \frac{G_1 + G_2 - P_u}{P_w - P_S} = 1,99$$

$$n_{OV} = \frac{G_1 \cdot r_{G1} + G_2 \cdot r_{G2}}{P_w \cdot r_w + P_S \cdot r_S + P_u \cdot r_u} = 1,74$$

We can now conclude that the current design of the dam does not satisfy the safety criteria because $n_{SL} < 3$ and $n_{OV} < 2$.

Annex: calculation code

```

'''Finding measurement'''
H=71
m=0.8
B=m*H
b0=H/10
if b0<=8:
    b0=8
h0=b0/m

'''Load combination'''
#dead load
gconc=24
H0=H-6
G1=b0*H*gconc
G2=0.5*(B-b0)*(H-h0)*gconc
rG1=B-(b0/2)
rG2=(2/3)*(B-b0)
#hydrostatic pressure
gw=10
Pw=gw*0.5*H0*H0
rw=(1/3)*H0
#uplift pressure
lamb=0.85
Pu=lamb*H0*gw*B/2
ru=(2/3)*B
#silt pressure
gs=18
Hs=H0/3
Ps=gs*0.5*Hs*Hs
rs=Hs/3

'''security factors check'''
nsl=(G1+G2-Pu)/(Pw-Ps)
nov=(G1*rG1+G2*rG2)/(Pw*rw+Ps*rs+Pu*ru)

```

Task 2: Determine the design of spillway section to safely evacuate flood with a 100-year return period downstream

Our spillway design must be designed to propagate $Q_{100} = 400 \text{ m}^3/\text{s}$ while one of the four overspilling sections is blocked. The spillway is constructed with a Creager shape and the overspilling section are 6 m wide.

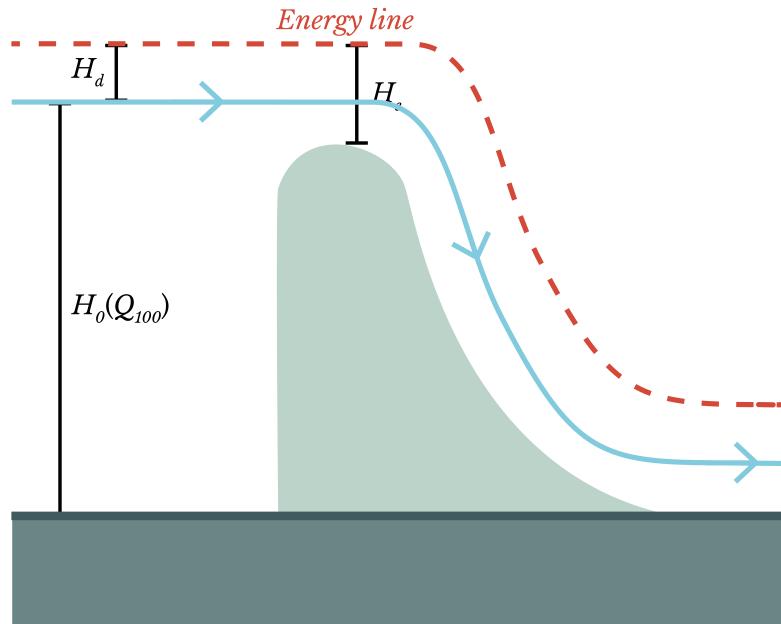


Figure 3 : Sideview of Creager spillway

Where :

- H_d is overspilling height of the water,
- H_e is the energy height.

Spillway equations

$$Q = m \cdot b \cdot \sqrt{2g} \cdot H_e^{3/2}$$

Where :

- $m = m_0 \left(\frac{H_e}{H_d} \right)^{0,16}$, the spillway coefficient for a Creager spillway ($m_0 = 0,4956$),
- $b = 6\text{m}$ the width of the spillway,
- $H_e = H_d + \frac{v_0^2}{2}$, with two cases : $\begin{cases} \frac{H_0}{H_d} > 1,33 \Rightarrow v_0 = 0 \\ \frac{H_0}{H_d} \leq 1,33 \Rightarrow v_0 \neq 0 \end{cases}$

For our design: $H_0 \gg H_d$ so $v_0 = 0$, then $H_e = H_d$ and $m = m_0$.

We can rewrite the spillway equation as $Q_p = m_0 \cdot b \cdot \sqrt{2g} \cdot H_d^{3/2}$

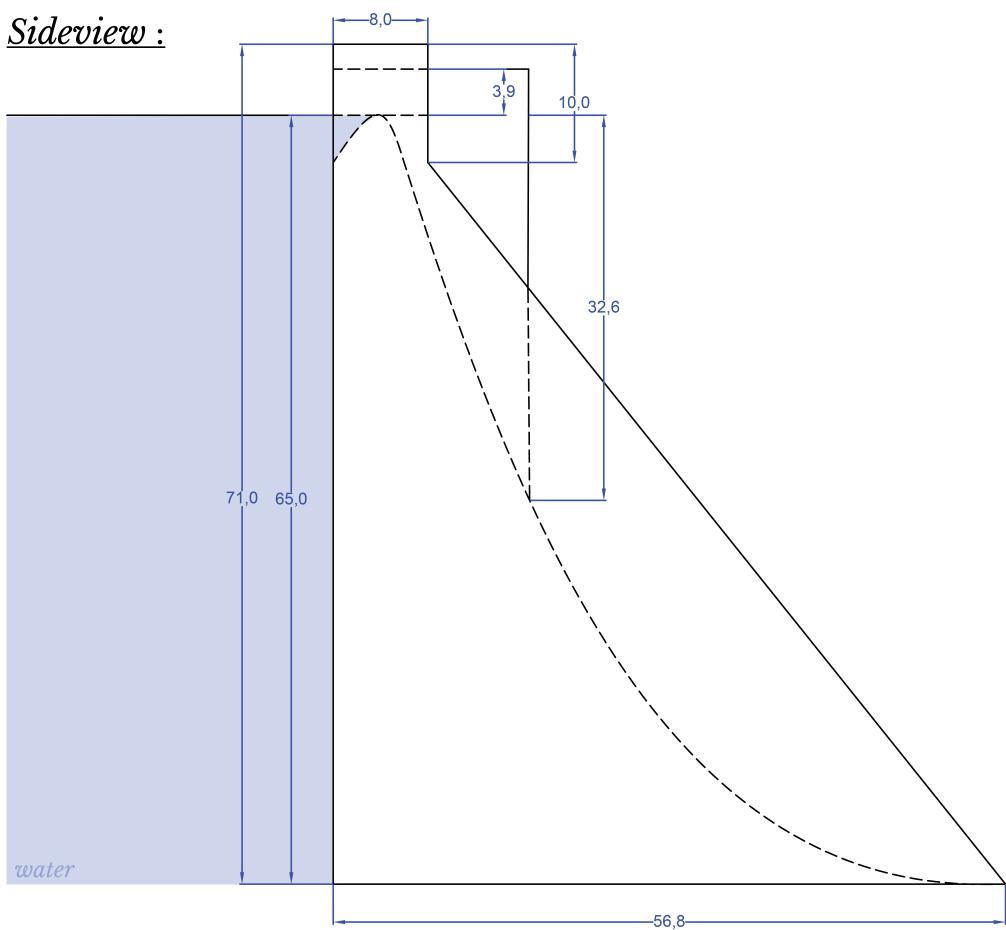
$$H_d = \left(\frac{Q_p}{m_0 \cdot b \cdot \sqrt{2g}} \right)^{2/3} = \left(\frac{400/3}{0,4956 \cdot 6 \cdot \sqrt{2 \cdot 9,81}} \right)^{2/3} = 4,68 \text{ m}$$

As we want $H_d \leq 4 \text{ m}$, we can calculate $b_{min} = \frac{Q_p}{m_0 \cdot \sqrt{2g} \cdot H_d^{3/2}} = 7,6 \text{ m}$, and we round it up at $b_{min} = 8 \text{ m}$.

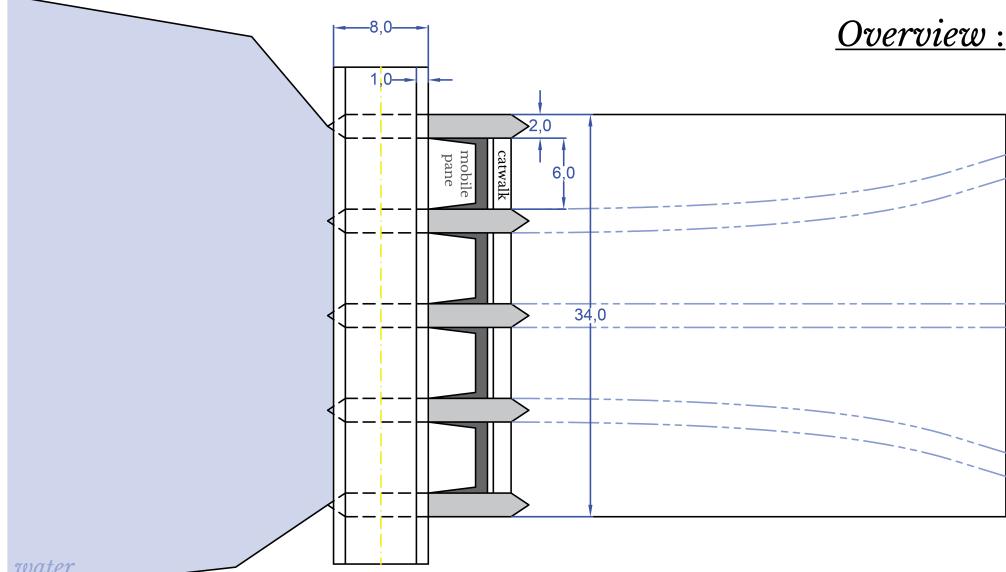
Using the same formula, we obtain : $H_d(b_{min}) = 3,9 \text{ m}$.

Technical drawing at scale

Sideview :



Overview :



0m 5m 15m

Task 3: Design the intake structure for the powerhouse, route water to the powerhouse and further to the stilling basin downstream of the dam

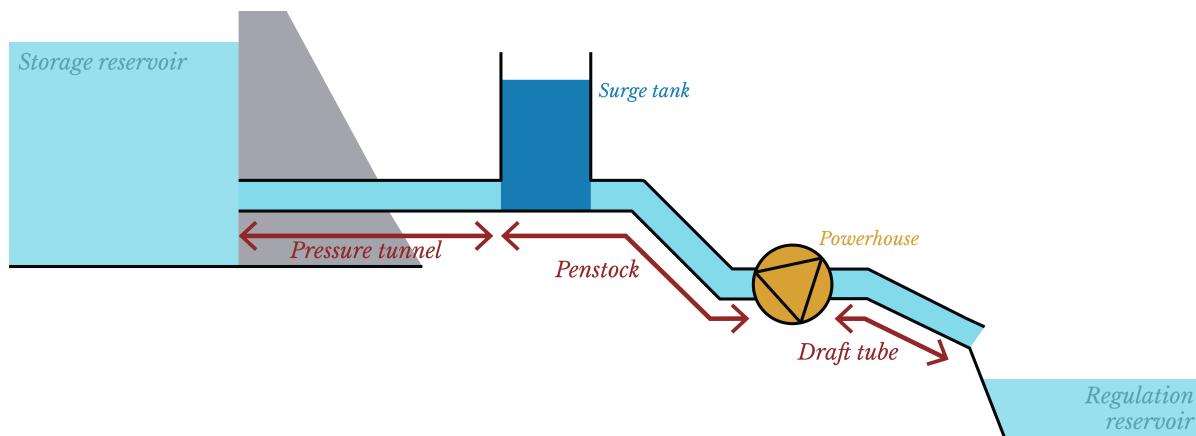


Figure 4 : Design of the waterway to the powerhouse

We are now going to calculate all of the losses from the pressure tunnel entrance to the regulation basin. As shown in the previous figure we separate the calculations into three parts:

- Δh_1 : head loss in the pressure tunnel,
- Δh_2 : penstock losses,
- Δh_3 : draft tube ones.

These losses are defined as lengths corresponding to the dissipation of the mechanical energy of a moving fluid.

$$\Delta h_i = \xi_i \frac{v_i^2}{2g} = \xi_i \frac{Q_i^2}{F_i^2 \cdot 2g} = K_i \cdot Q_i^2$$

We are then interested in two types of losses: local losses and frictional losses.

Hydraulic losses in the pressure tunnel



Figure 5 :Scheme of the intake structure of the pressure tunnel

With :

- (1) : the intake,
- (2) : the trash-racks,

- (3) : a transition from the quadratic intake profile to gate profile,
- (4) : main hydraulic gates,
- (5) : transition from gate profile to tunnel profile,
- (6) : the pressure tunnel.

(1) The intake

$$\xi_{Vt} = 0,5$$

$$K_{Vt} = \frac{\xi_{Vt}}{F_{Vt}^2 \cdot 2g} = \frac{0,5}{71^2 \cdot 2,981} = 5,05e - 06, \text{ avec } F_{Vt} = A_p$$

(2) The trash-racks

Some notations :

- $\alpha = 70^\circ$, the inclination of the trash-racks
- $\chi = 1$, the flow coefficient ($= 1$ because of the horizontal flow)
- $s = 10$ mm, width of individual trash-rack bar
- $l = 50$ mm, distance between each bars
- $\beta = 2,42$, the trash-rack bar geometry coefficient

$$\xi_{res} = \chi \cdot \beta \left(\frac{s}{l} \right)^{\frac{4}{3}} \cdot \sin(\alpha) = 0,219$$

$$K_{res} = \frac{\xi_{res}}{F_{res}^2 \cdot 2g} = 2,21e - 06$$

(3) Narrowing of the tunnel

To estimate ξ_{zoz} :

F_2/F_1	0,01	0,1	0,2	0,4	0,6	0,8
ξ_{zoz}	0,5	0,45	0,4	0,3	0,2	0,1

With a linear interpolation we get : $\xi_{zoz} = 0,34$

$$K_{zoz} = \frac{\xi_{zoz}}{F_{res}^2 \cdot 2g} \left(\frac{F_{res}^2}{F_{zap}^2} - 1 \right) = 2,92e - 05$$

(4) Main hydraulic gates

$$\xi_{zap} = 0,1$$

$$K_{zap} = \frac{\xi_{zap}}{F_{zap}^2 \cdot 2g} = 9,62e - 06$$

(5) Changing of geomtry

With a linear interpolation we get : $\xi_{tran} = 0,11$

$$K_{tran} = \frac{\xi_{tran}}{F_{zap}^2 \cdot 2g} \left(\frac{F_{zap}^2}{F_k^2} - 1 \right) = 6,57e - 06$$

Curvature of the tunnel axis

We have four turn in the tunnel, described as :

Angle of the turn	Radius of the tunnel axis
$\alpha_1 = 90^\circ$	$R_1 = 70$ m
$\alpha_2 = 47^\circ$	$R_2 = 110$ m
$\alpha_3 = 16^\circ$	$R_3 = 150$ m
$\alpha_4 = 24^\circ$	$R_4 = 150$ m

$$\text{and : } \xi_{lom,i} = (0, 13 + 1, 85 \left(\frac{r}{R_i} \right)^{3,5}) \frac{\alpha_i}{90}$$

$$K_{lom} = \sum_{i=1}^{n=4} \frac{\xi_{lom,i}}{F_k^2 \cdot 2g} = 4,01e - 05$$

Surge tank

$$\xi_{st} = 0, 1$$

$$K_{st} = \frac{\xi_{st}}{F_k^2 \cdot 2g} = 1, 56e - 05$$

Friction losses

Some notations :

- $\lambda = 0,012$, Dracy-Weisbach coefficient
- $L_K = 2600 \text{ m}$

$$K_{lin} = \frac{\lambda \cdot L_k}{D} \frac{1}{F_k^2} \frac{1}{2g} = 0,0010$$

Summation of the hydraulic losses in the pressure tunnel :

$$\Delta h_1 = Q^2 (K_{Vt} + K_{res} + K_{zoz} + K_{zap} + K_{lom} + K_{st} + K_{lin})$$

We have for hydraulic losses in the tunnel $\Delta h_1 = 5,83 \text{ m}$