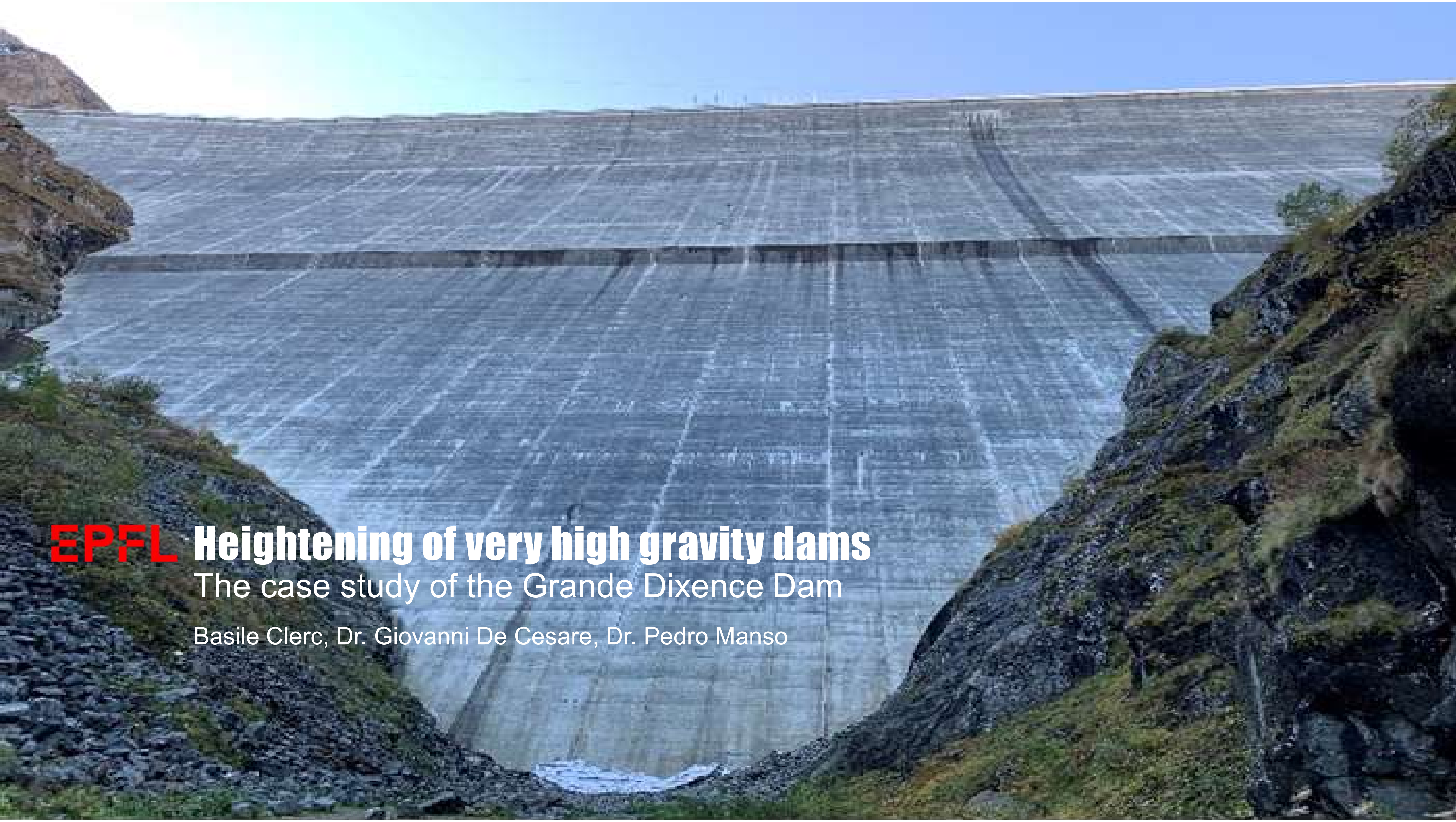


Heightening of very high gravity dams

The case study of the Grande Dixence Dam

Basile Clerc, Dr. Giovanni De Cesare, Dr. Pedro Manso

Introduction

Context:

- Energy Transition in Switzerland
- Mitigation of the effects of climate change

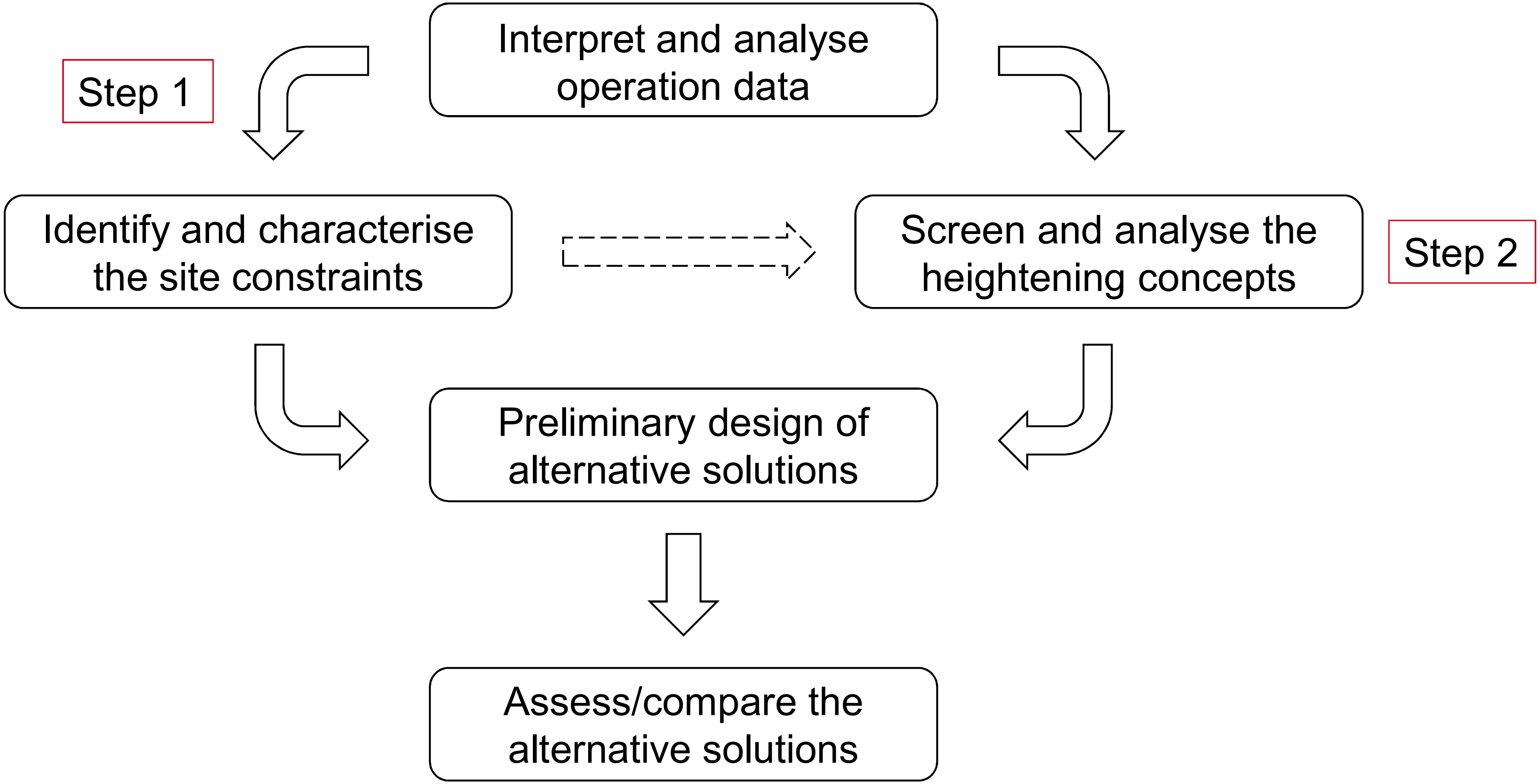
Motivation:

- Large incremental positive impacts on storage with low negative impacts
- Very high gravity dams are well studied and documented
  - ➢ Availability of monitoring data and safety assessment tools

Objective:

- Establishment of a general approach to identify and develop solutions for the heightening of very high gravity dams
  - ➢ Application to the case study of the Grande Dixence Dam

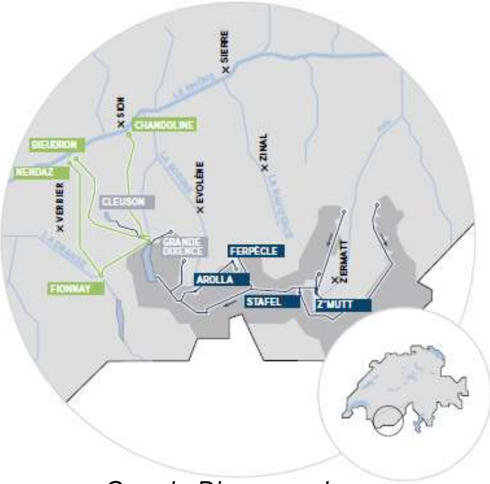
Methods


Interpret and analyse operation data
Step 1
Identify and characterise the site constraints
Screen and analyse the heightening concepts
Step 2
Preliminary design of alternative solutions
Assess/compare the alternative solutions

Case study: The Grande Dixence Dam

The scheme

- 420 km^2 watershed
- 100 km of galleries
- 5 pumping stations
- 3 power plants

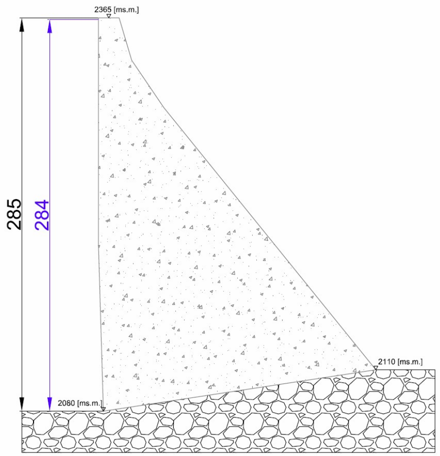


Grande Dixence scheme

The dam

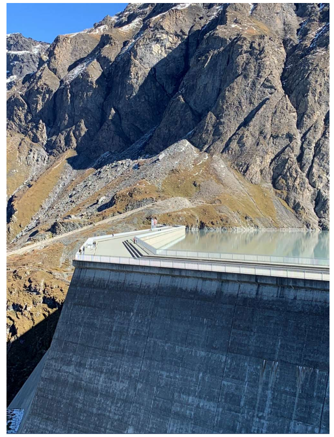
- World highest gravity dam
- Creates a reservoir of 400 hm^3

Characteristics	
Height	285 m
Base width	200 m
Dam crest width	15 m
Dam crest developed length	700 m



Dam central cross-section

Dam's downstream view



Dam's crest

Results: Additional water supply and available storage

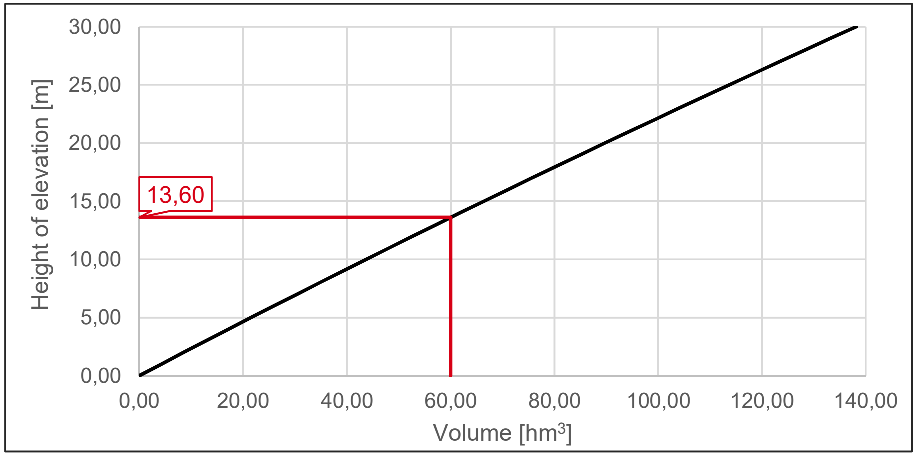
- Actual water supply and future estimations

Year	Accumulated volume [hm^3]
2011	504
2012	540
2013	481
2014	451
2015	548
2016	478
2017	525
Average	**504**

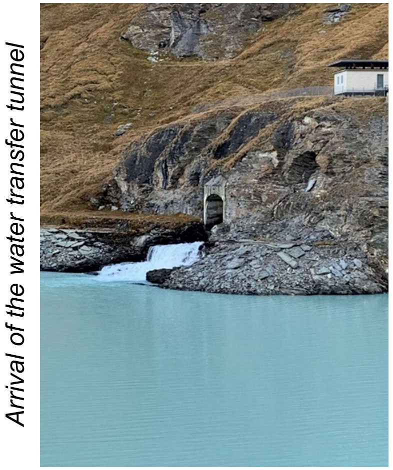
- Average additional volume of 100 hm^3
- Future estimations show a water supply decrease

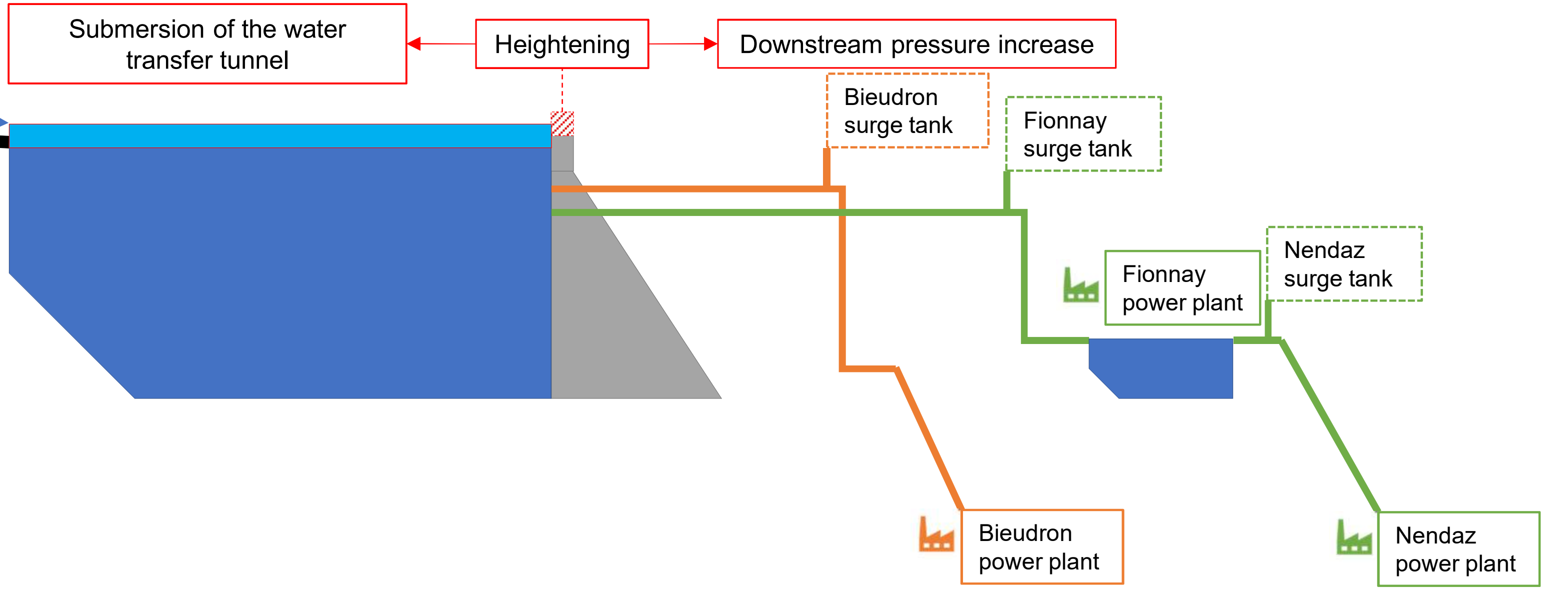
- Indicative additional volume and corresponding height

- Smaller indicative additional volume of 60 hm^3
- More viable and profitable on the long-term



Results: Site constraints





Grande Dixence simplified scheme (not to scale)

Submersion of the water transfer tunnel

- Backwater effects modifying pumping
- Aerations issues farther upstream

Downstream pressure increase

- Impact on downstream surge tanks
- Fionnay surge tank requires adaptation measures

Results: Screening of heightening concepts

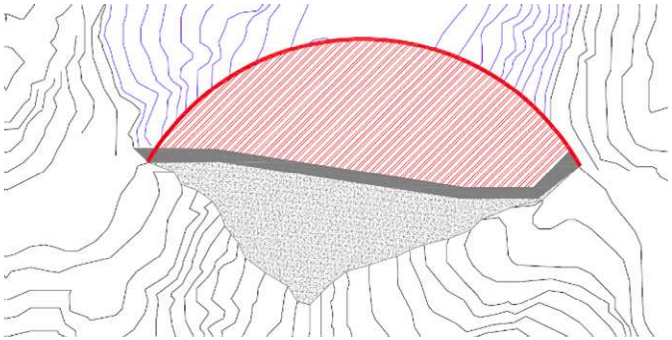
Several heightening solutions were considered:

- Gravity dam
- Arch dam
- Multiple-arch dam
  - Use of post-stressed anchors
  - Build artificial abutments

Top view of Grande Dixence dam

Constraints:

- Valley and dam shape
- Dam joints every 16 m
- Dam height
- Prohibitive conflicts with hydropower must-run operation



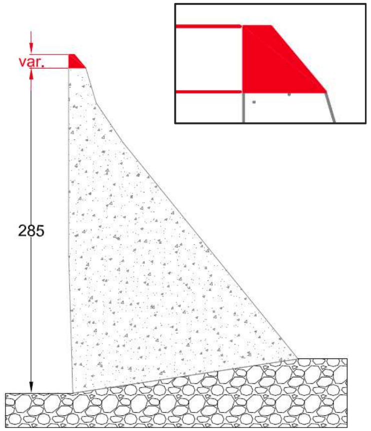
Implementations of dam heightening

➢ Gravity dam heightening was retained for preliminary design

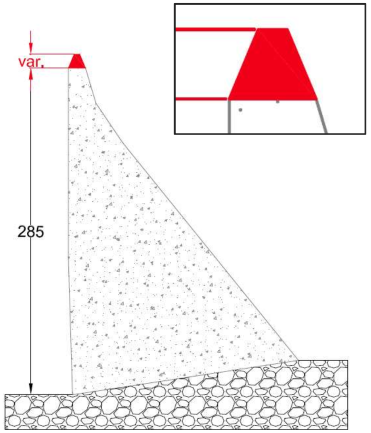
Results: Heightening options

New crest width of 5 m for all solutions

Variant 1
«Standard»

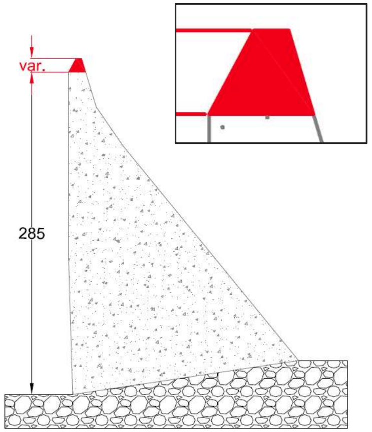


Variant 2
«Symmetrical»



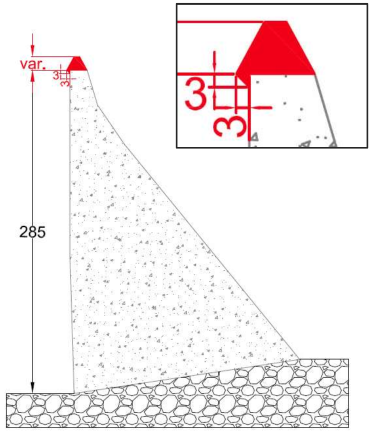
- Favourable hydrostatic pressure
- Better weight balance

Variant 3
«Asymetrical»



- Increased favourable hydrostatic pressure
- Heightening weight farther downstream

Variant 4
«Offset»



- Favourable hydrostatic pressure
- Creation of a cantilever
- Greater load upstream

Results: Stability and structural analysis

Verifications:

- Sliding stability
- Overturning stability
- Ultimate resistance

Verified elevation heights:

- 6, 9, 12 and 15 m

All calculations were made considering a normal load case and a full lake.

Using two models:

- Analytical
- Computational

Design criteria:

- Based on the recommendations of “Directive on the Safety of Water Retaining Facilities” established by Swiss Federal Office of Energy
- Higher tensile resistance criterion of 1 MPa

Results: Analytical model

- Sliding stability

$$S_G = \frac{\left[\frac{(tg\varphi \sum N)}{\gamma_{m\varphi}}\right] + \left[\frac{(cA)}{\gamma_{mc}}\right]}{\sum T} \geq 1.0$$

- Overturning stability

$$0.33 < X = \frac{R_x}{B_B} < 0.66$$

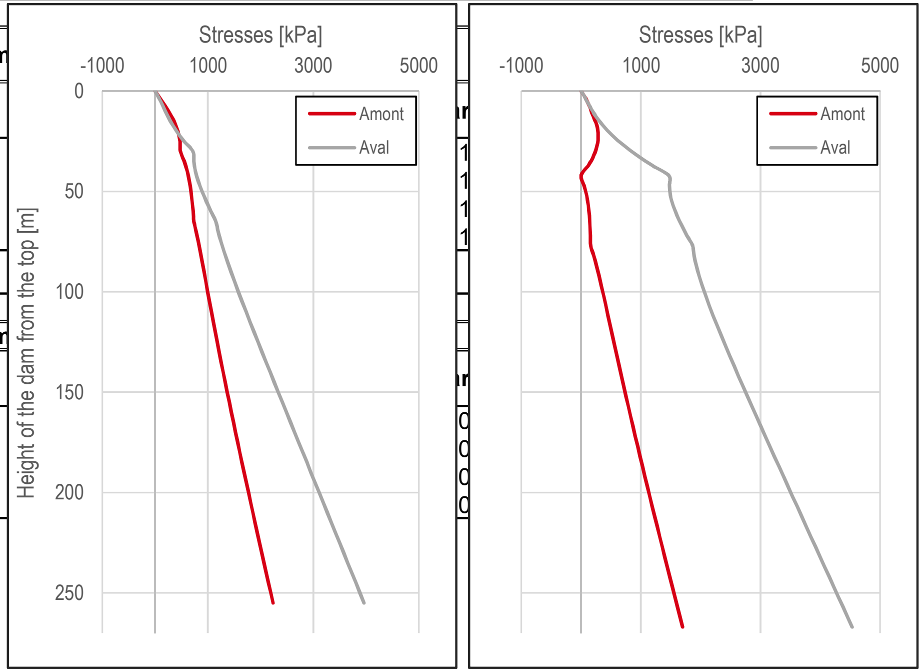
- Ultimate resistance

$$-1\ MPa \leq \sigma_{z,up} = \frac{6}{b^2}\left[G\left(\frac{2}{3}b - x_G\right) - W\frac{z_W}{3}\right] \leq 8\ MPa$$

$$-1\ MPa \leq \sigma_{z,dw} = \frac{6}{b^2}\left[G\left(x_G - \frac{b}{3}\right) + W\frac{z_W}{3}\right] \leq 8\ MPa$$

Existing dam
Height m
6
9
12
15

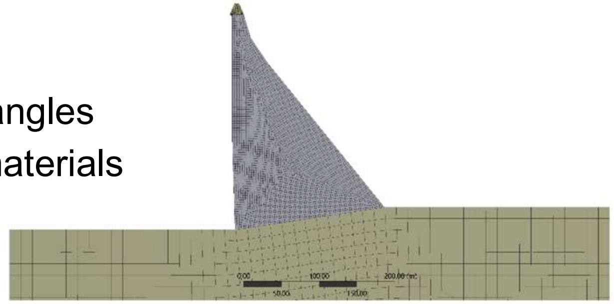
Existing dam
Height m
6
9
12
15



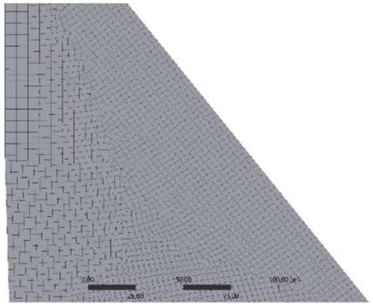
Existing dam *Variants 2 & 3*

Results: Computational model

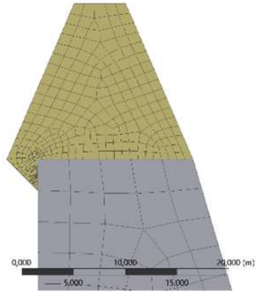
- Using *ANSYS Workbench* (2017) in 2D
  - Three main elements
  - Different mesh size
  - Quadrilaterals and triangles
  - Standard values for materials
  - Two friction surfaces



Foundation mesh: Elements of 15 m

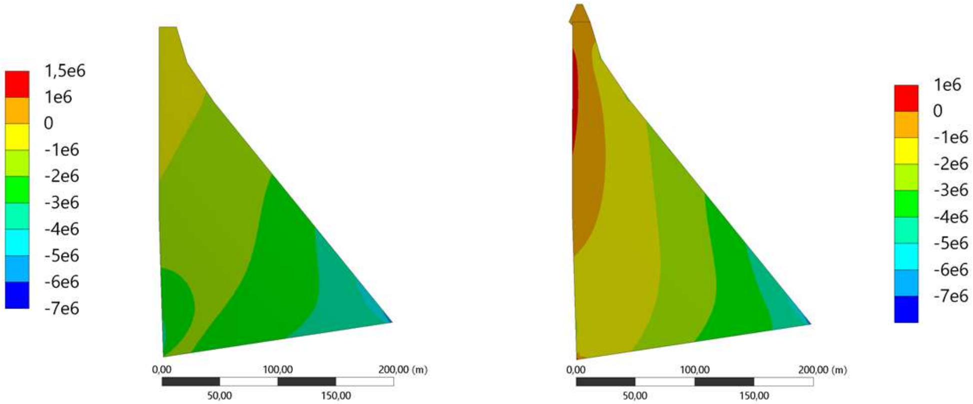


Existing dam mesh: Elements of 3 m



Heightening mesh: Elements of 1 m

- Ultimate resistance



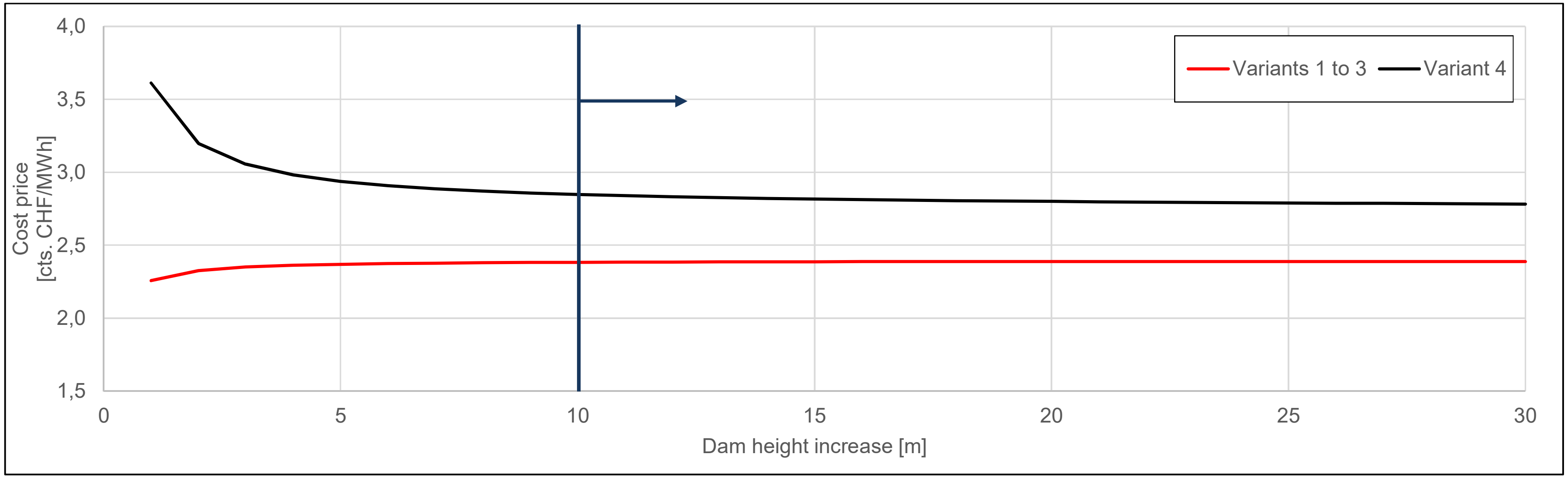
Normal stresses of existing (left) and variant 4, 15 m (right)

Results: Economic analysis

- Levelelized Cost of Electricity (LCOE)

Height of elevation m	Cost price cts. CHF/MWh Variants 1 to 3	Variant 4
1	2.2578	3.6124
5	2.3691	2.9377
10	2.3827	2.8474
15	2.3866	2.8162
20	2.3879	2.7999
25	2.3883	2.7896

Little variation from 10 m



Conclusion

Establishment of a general approach ✓

Application to the case study of the Grande Dixence dam

- Determination of major constraints ✓
- Selection of a single heightening concept ✓
- Generation of four variants ✓
- Study of the overall behaviour of the heightened dam with two different models ✓
  - ➢ Satisfactory results for all variants
- Preliminary economic analysis ✓
  - ➢ Extremely low LCOE in comparison with other potential hydropower projects
  - ➢ **Height increase within 10 to 15 m is likely optimal**

Further investigations

- Adaptation of the water transfer tunnel, pressurized waterways and surge tanks


Thank you for your attention!