Lombardi

Lining of pressure tunnels

Philippe Lazaro

Kolloquium «Untertagbau für Wasserkraftanlagen»
ETH Zürich, Professur für Untertagbau

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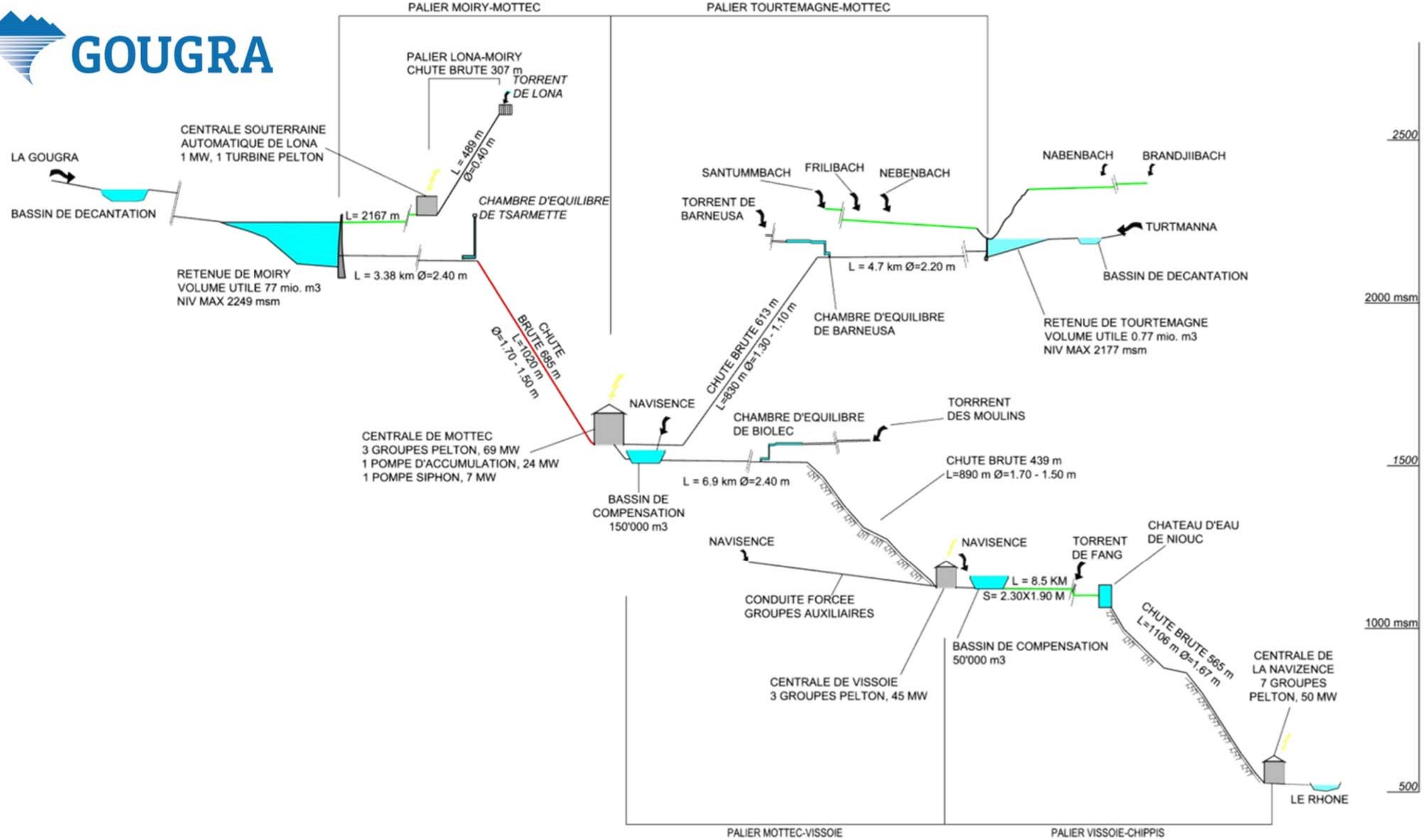
Lining of pressure tunnels

Contents of presentation

1. Introduction



2. Types of linings

- No lining (permeable)
- Reinforced shotcrete lining (semi-permeable)
- Unreinforced concrete lining (semi-permeable)
- Reinforced concrete lining (slightly permeable)
- Pre-stressed concrete lining (slightly permeable)
- Steel lining (impermeable)
- Composite membrane lining (impermeable)

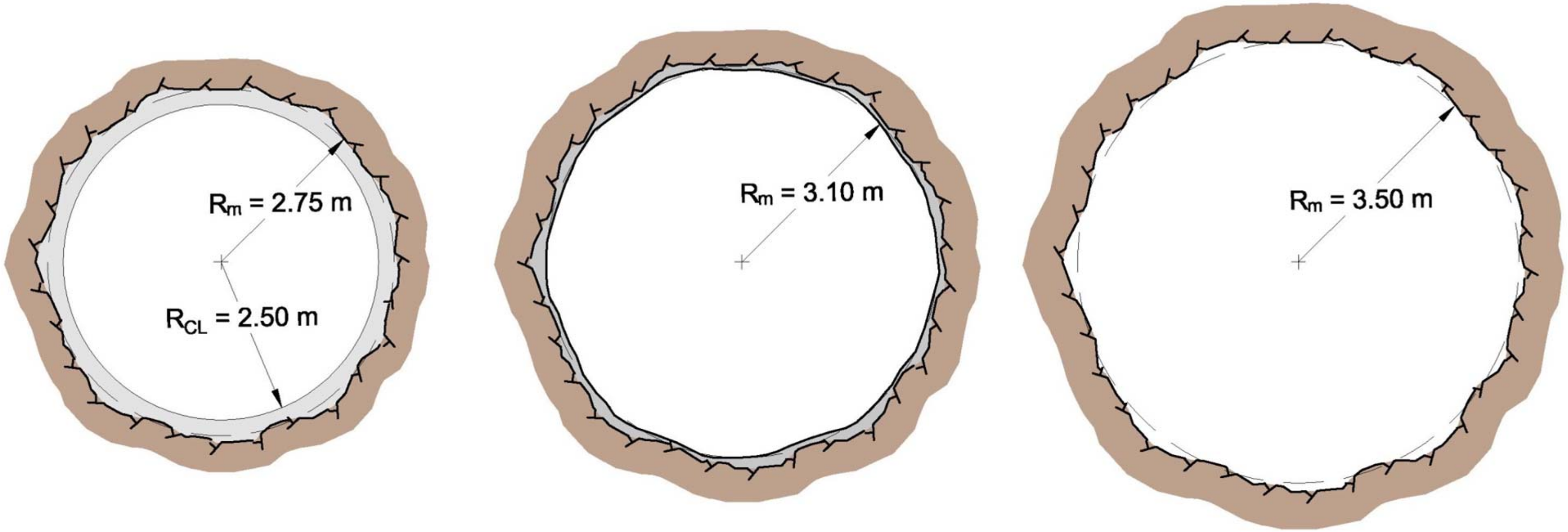
2. Role of the lining of a pressure tunnel

Design considerations about final lining

- Water losses reduction
- Head losses reduction
- Groundwater table sustainability
- Guarantee rock chemical and mechanical integrity
- Guarantee long term tunnel operation
- Minimisation of maintenance works

2. Role of the lining: hydraulic requirements

LINING		
Concrete lining (CL)	Shotcrete lining (SL)	No lining (NL)

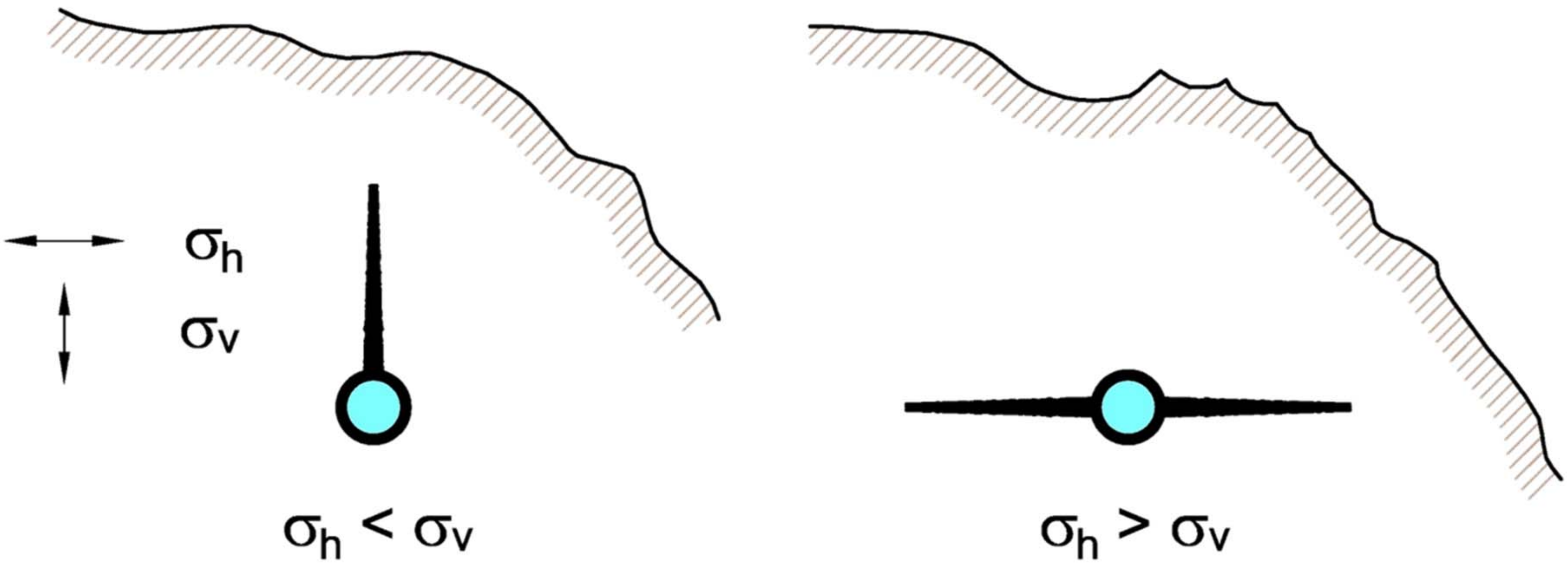


k_s = 0.6 mm	k_s = 50 mm	k_s = 300 mm
v = 3.5 m/s	v = 2.3 m/s	v = 1.8 m/s
F_{CL}	F_{SL}/F_{CL} = 1.5	F_{NL}/F_{CL} = 2.0

3. Unlined tunnel

The problem of Hydrofracturing

"Hydraulic jacking"

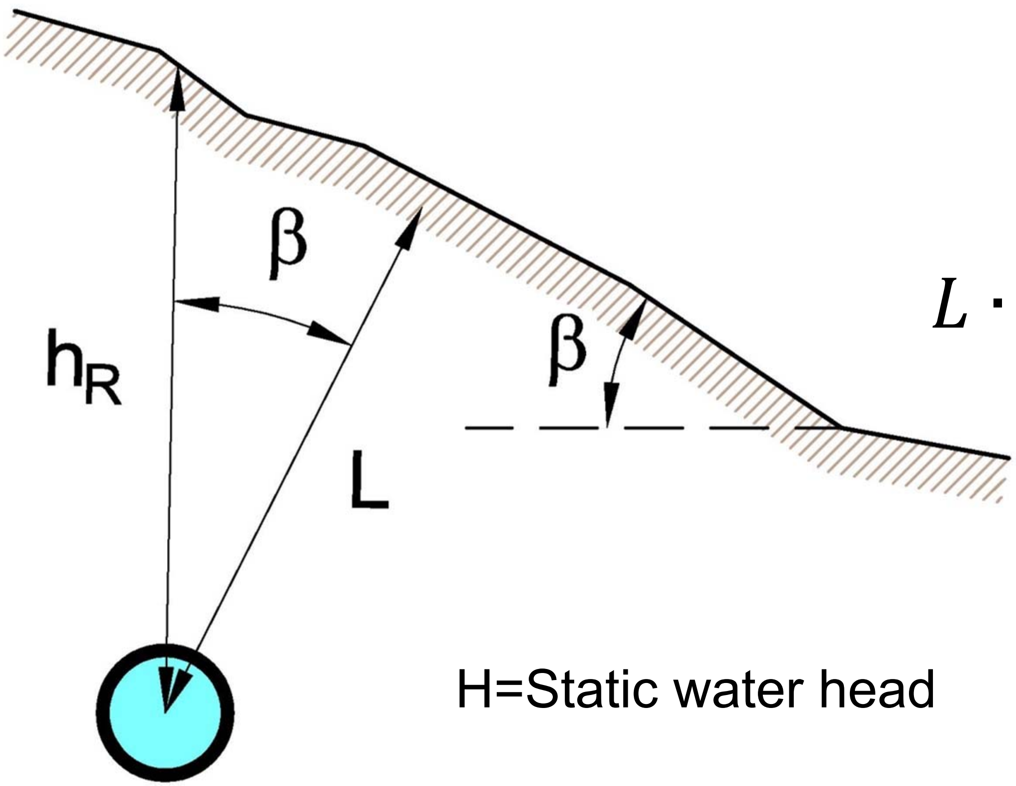


$$\sigma_h = \lambda \cdot \sigma_V$$

Alpin region $\lambda = 0.4 \div 1.0$

3. Pervious pressure tunnel

The Norwegian rule (Bergh – Christensen, 1974)
"rule of thumb"



$$L > \frac{H \cdot \gamma_e}{\cos\beta \cdot \gamma_R}$$

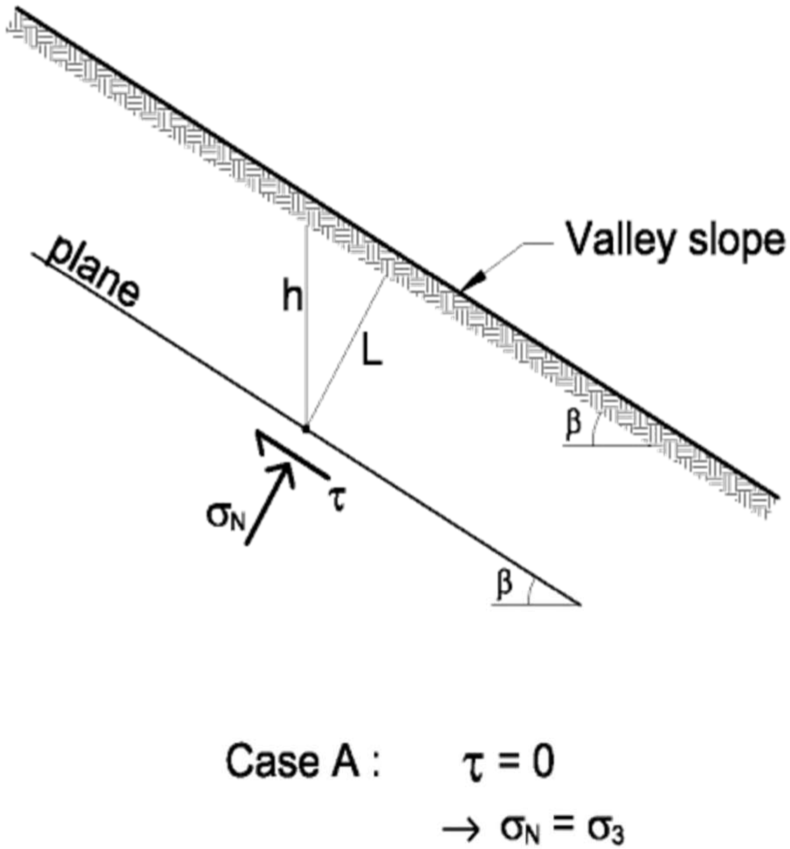
$$L \cdot \cos\beta \cdot \gamma_R > H \cdot \gamma_e$$

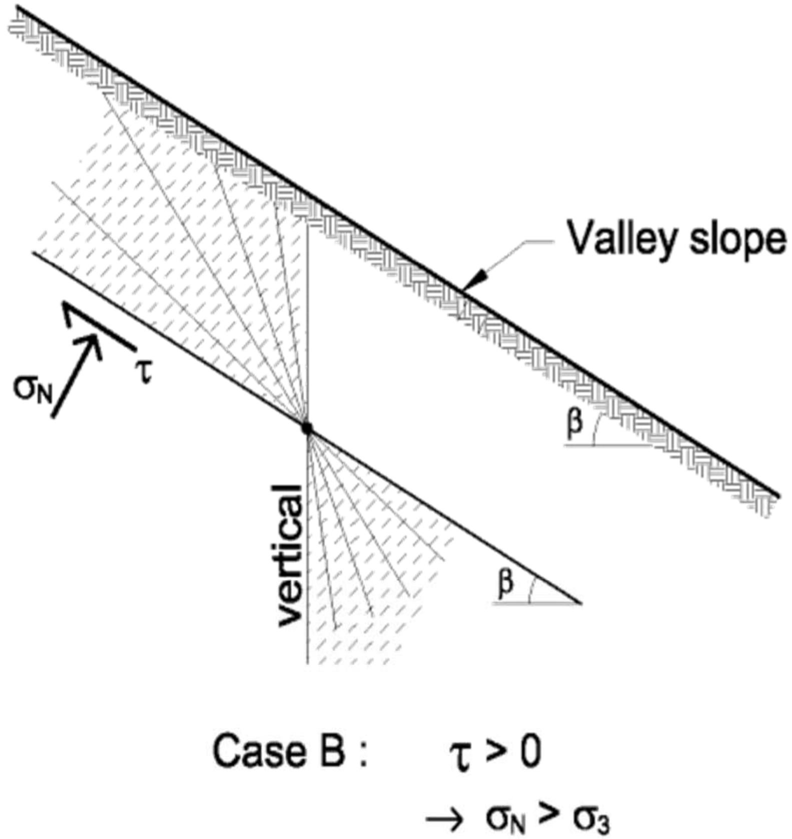
$$\sigma_N > P_i$$

H=Static water head

3. Pervious pressure tunnel

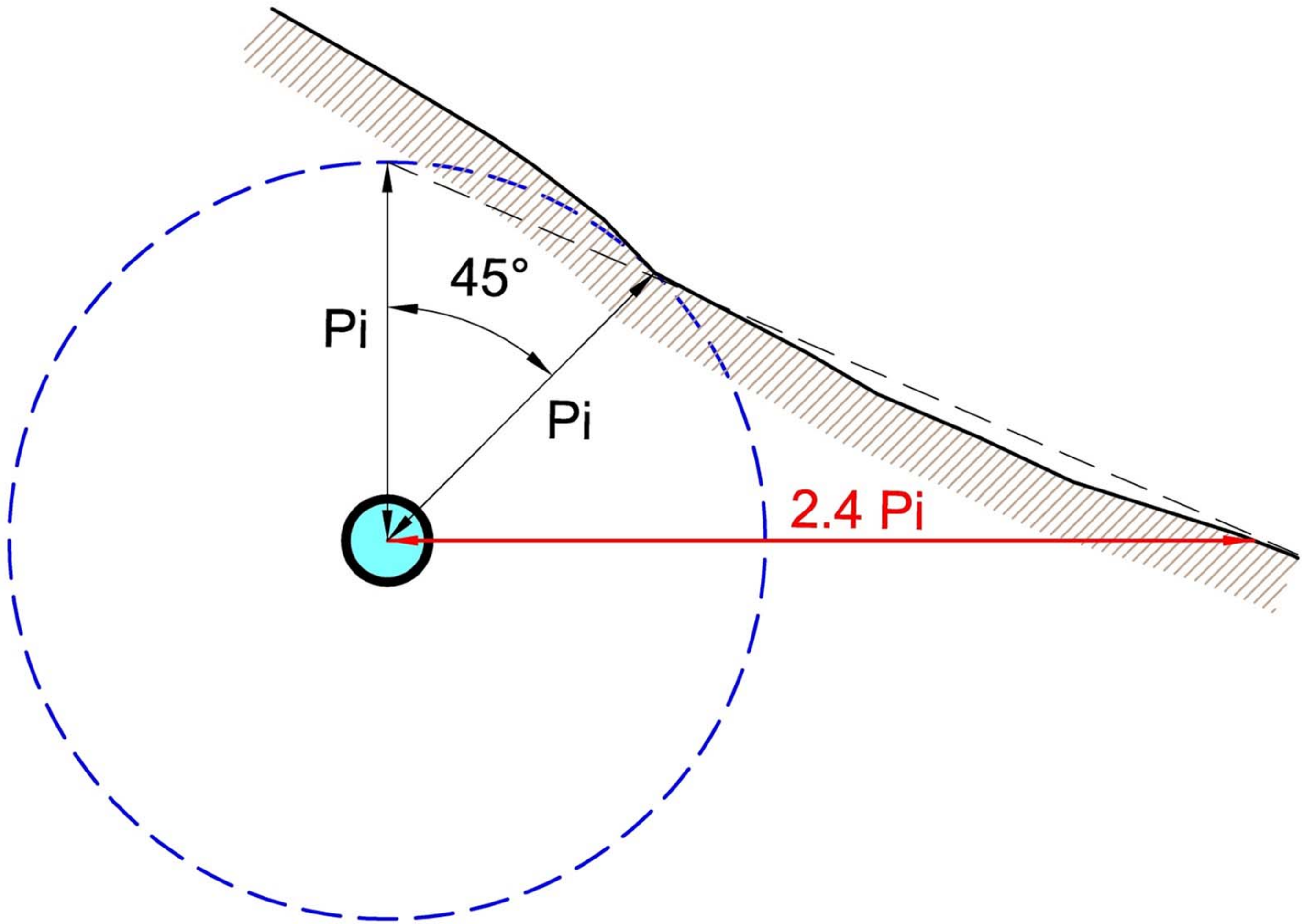
The Norwegian rule (Bergh – Christensen, 1974)





3. Pervious pressure tunnel

The Talobre rule

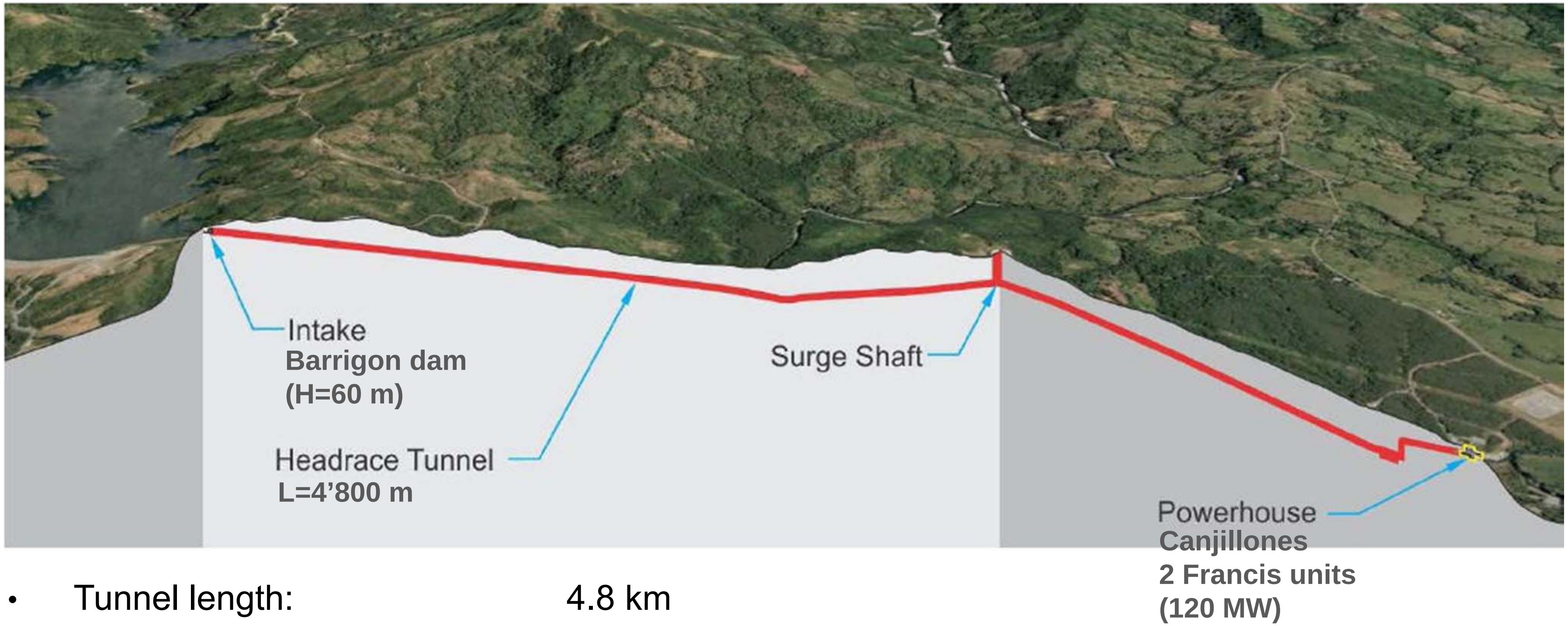


4. Case studies

Rehabilitation of Estí pressure tunnel (Panamá)

4.1 Estí pressure tunnel (Panamá)

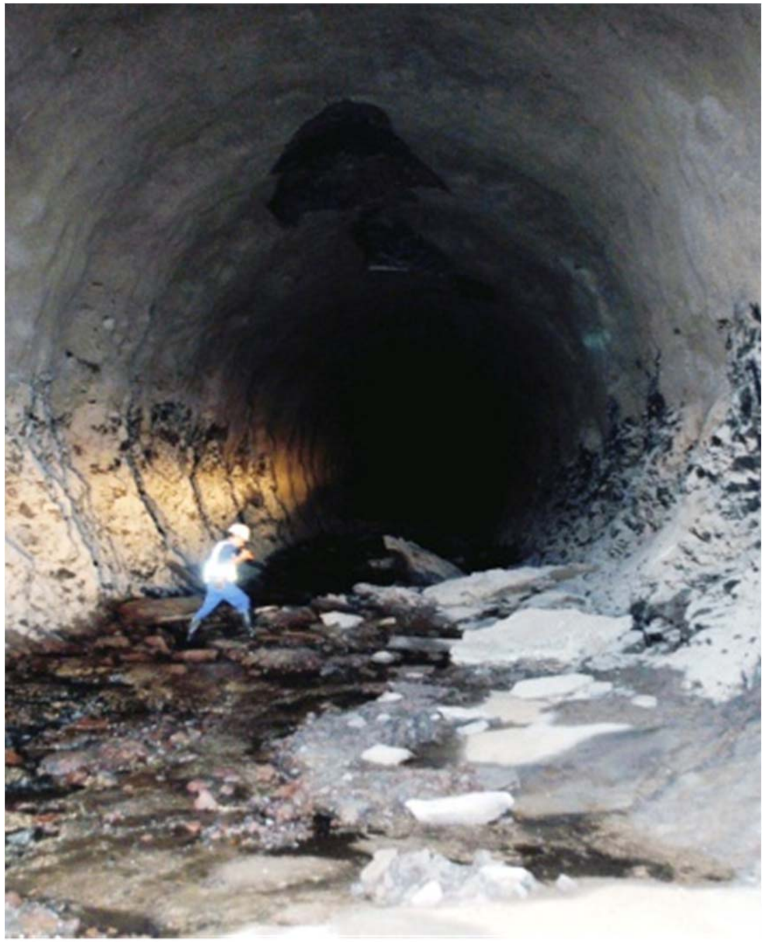
General layout of Estí HPP



• Tunnel length:	4.8 km
• Construction period:	2001-2002
• Year of collapse:	2010
• Period of repair works:	2011-2012
• Rehabilitation costs:	~60 Mio. USD

4.1 Estí pressure tunnel (Panamá)

Typical cross section

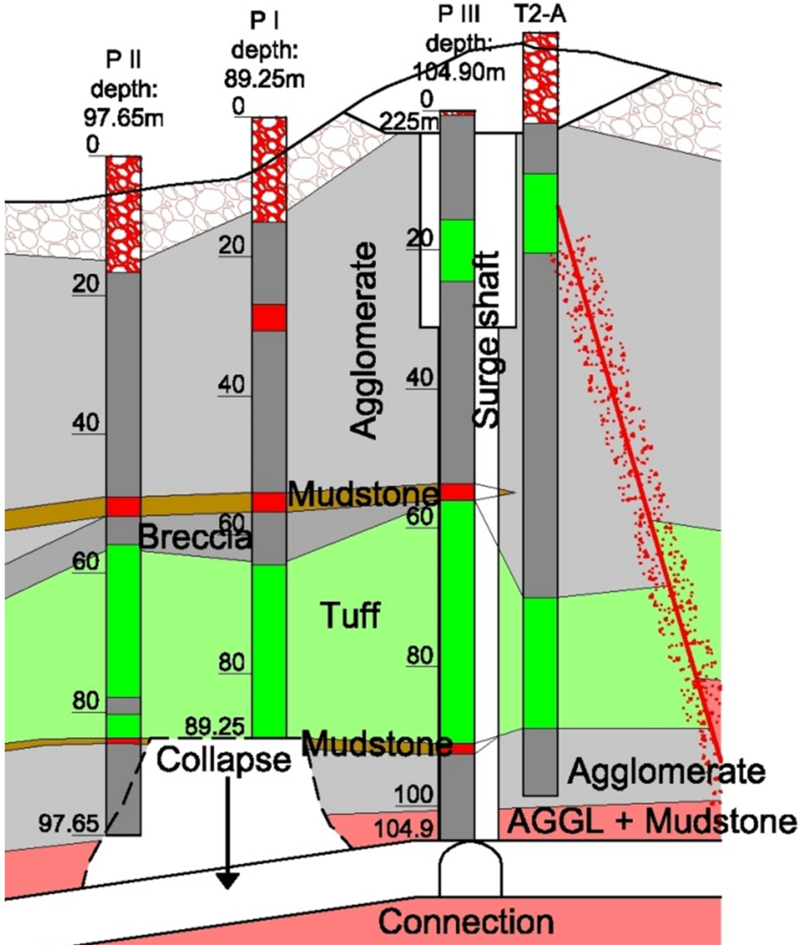


- Horseshoe cross section
- Area: ~67 m^2
- Internal diameter: 8.80 m
- Lining type: shotcrete and grouted bolts

- Design flow: 180 m^3/s
- Max. head: 180 m

4.1 Estí Power Tunnel (Panamá)

Geological setting in the main collapse zone



Main collapse probably due to a combination of:

- sub-vertical faults and
- horizontal water-sensitive rock layers

Main collapse estimated dimensions:

Length: ≥ 40 m

Width: 23 m

Height: ≥ 15 m

4.1 Estí Power Tunnel (Panamá)

Main tunnel collapse in 2010 (after 7 years of regular operation)

Huge rock blocks in the main collapse zone

4.1 Estí Power Tunnel (Panamá)

Minor tunnel collapses in 2010

Collapses in tunnel roof controlled by rock-mass stratification. Sub-horizontal rock layers were separated by water-sensitive mudstone layers. Maximum collapses height: 5 m.

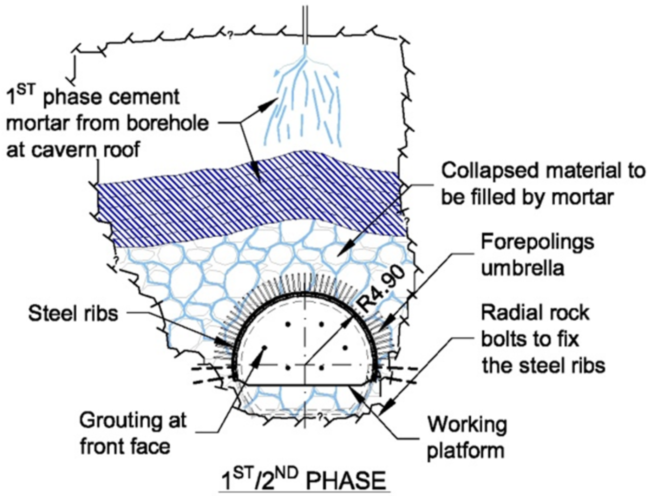
Collapses at tunnel walls probably occurred in the dewatering operation consequent to the main collapse.

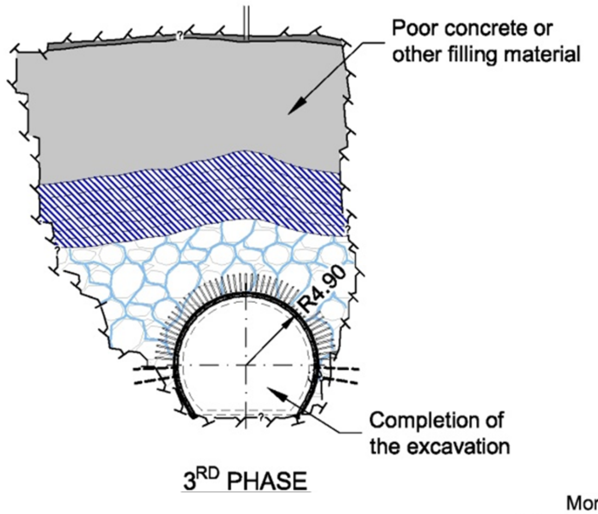
Lining (shotcrete) detachments probably occurred in the dewatering phase

Complete obstruction of the tunnel section due to a collapse

4.1 Estí Power Tunnel (Panamá)

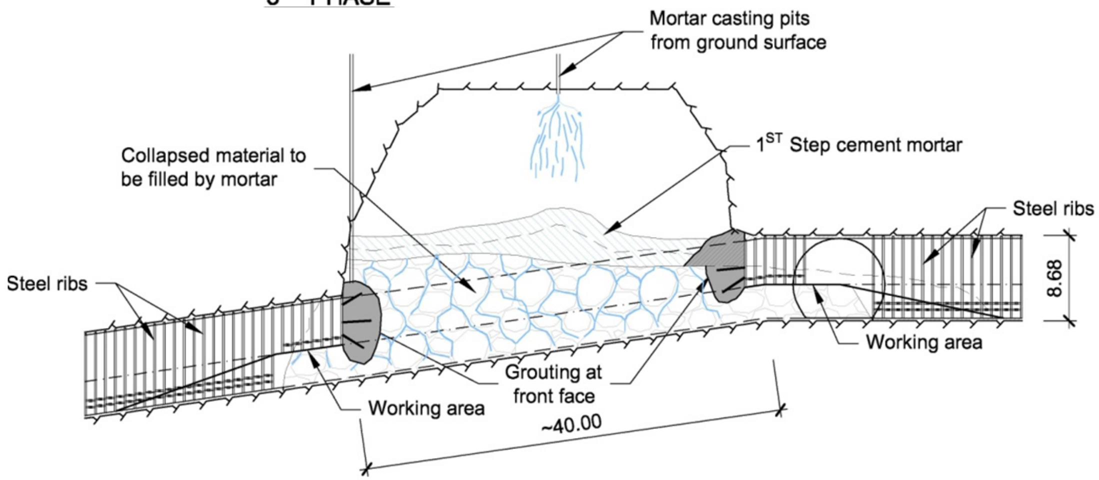
Repair solutions – Main collapse





Operation sequence:

1. Partial void filling using boreholes from the surface with cement mortar;
2. Formation of a concrete “cap” over the collapsed material;
3. Systematic injection of the collapsed material with cement mortar;
4. Realization of forepolings and front face consolidations;
5. Excavation of the collapsed material with advance techniques typical for soils of very weak rocks.



4.1 Estí Power Tunnel (Panamá)

Repair solutions – Main collapse

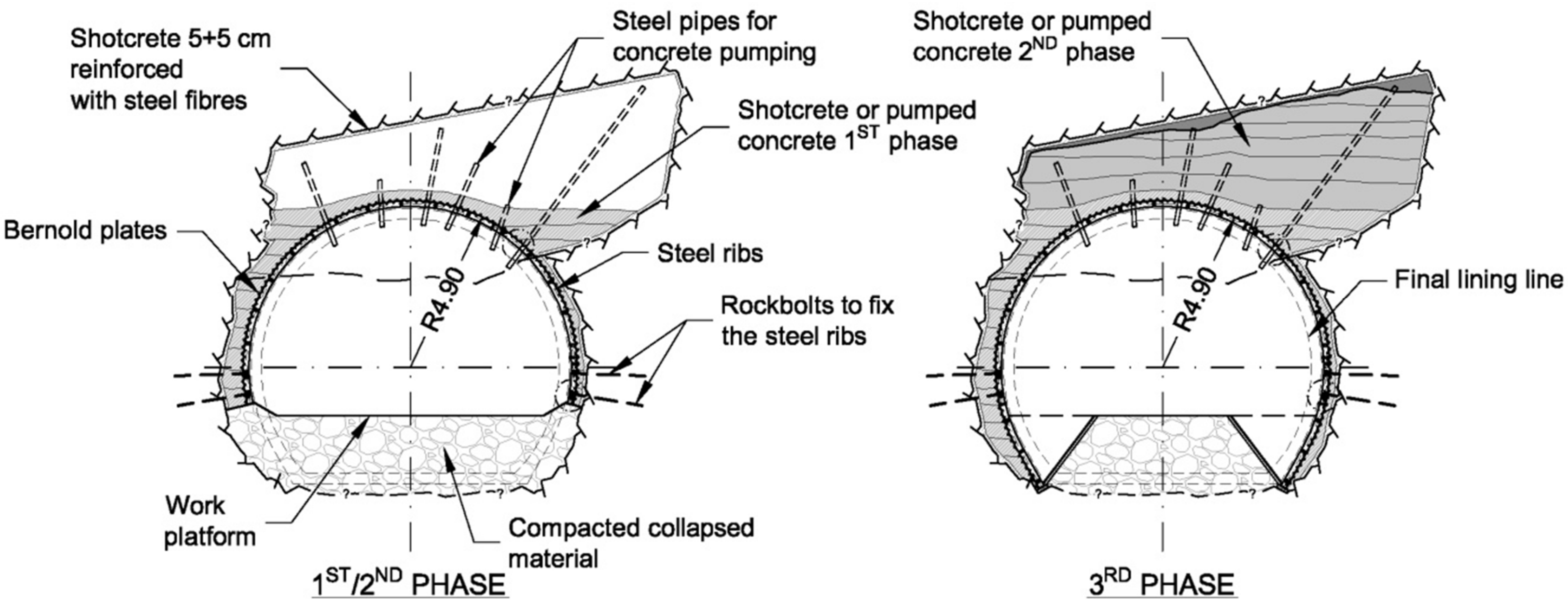
Cement mortar pumping from the surface to partially fill the void.

Main collapse crossing works.

Main collapse crossing works. Is possible to see the installation of the forepoling umbrellas.

4.1 Estí Power Tunnel (Panamá)

Repair solutions – Minor collapses



Operation sequence:

- Installation of steel ribs (HEB140 – spacing 0.75 -1.00 m) and Bernold plates to form a shield for workers and a formwork for the void filling;
- Partial filling of the voids with pumped concrete in order to form a “cap” of concrete over the ribs;
- Completion of the void filling;
- Realization of contact grouting in order to assure the contact between the filling material and the rock-mass.

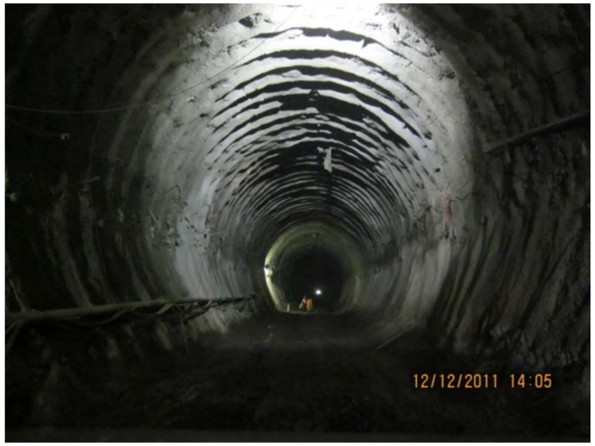
4.1 Estí Power Tunnel (Panamá)

Repair solutions – Minor collapses

Steel ribs installation phase

Steel ribs completion phase

Preparation of the void filling phase with pumped concrete



Final result of the repair process

4.1 Estí Power Tunnel (Panamá)

Final lining to imrpove HRT efficiency, safety and durability

Realization of the final lining with cast in place concrete.
Minimum thickness = 30 cm
Reinforced with steel ribs (minimum dosage 35 kg/m^3)

Realization of a flat invert. Minimum thickness = 30 cm.

4 Case studies

Rehabilitation of Pucará pressure tunnel (Ecuador)

- Owner: Corporación Eléctrica del Ecuador (CELEC EP)
- Plant located about 160 km South East of Quito, in the province of Tungurahua
- Construction: 1972-1977
- First main plant of Ecuador’s power supply system
- Installed capacity: 75 MW
- Average annual energy production: 230 GWh

4.2 Rehabilitation of Pucará headrace tunnel

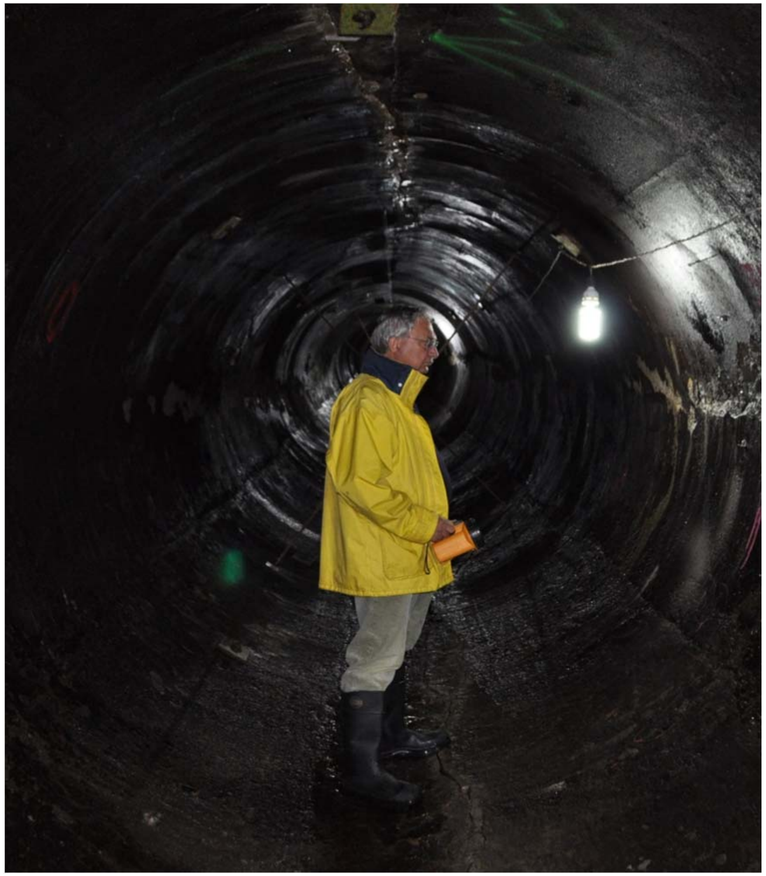
General layout of Pisayambo HPP

Pisayambo reservoir (2012)

- Rockfill dam: H=41.20 m
- Crest elevation: 3’569.20 m asl
- Storage volume: 90 Mio. m^3
- Embedded intake structure
- Headrace tunnel: L=5.5 km, D=2.60 m with concrete lining
- Surge shaft: H=117 m, D=5.00 m
- Pressure shaft with steel lining: L=685 m, D=2.20-1.90 m
- Underground powerhouse at 3’086 m asl 2 Pelton units, gross head: 479 m, installed capacity: 75 MW
- Tailrace tunnel and channel between powerhouse and Yanayacu river

4.2 Rehabilitation of Pucará headrace tunnel

General layout of Pucará headrace tunnel



Pucará headrace tunnel in the damaged zone (2011)

- Tunnel length: 5’475 m
- Internal diameter: 2.60 m
- Concrete lining with reinforcement at final part (higher pressures and lower coverage)
- Design discharge: 18.6 m^3/s
- Max. head: 65 m (at surge tank)

4.2 Rehabilitation of Pucará headrace tunnel

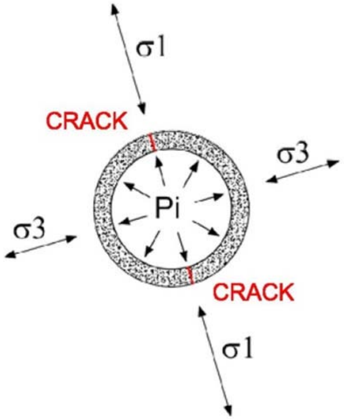
Landslide and damages of concrete lining occurred in 2011

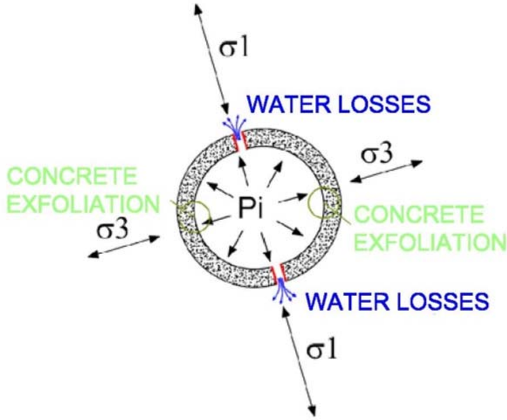
Landslide occurred in September 2011

- After 34 years of operation a landslide occurred in 2011 at the final part of headrace tunnel
- Very complex geology contest with many faults, discontinuities an open fissures
- Zone with high seismic activity called "Pisayambo Seismic Nest"
- After tunnel dewatering and inspection damages in the concrete lining were observed

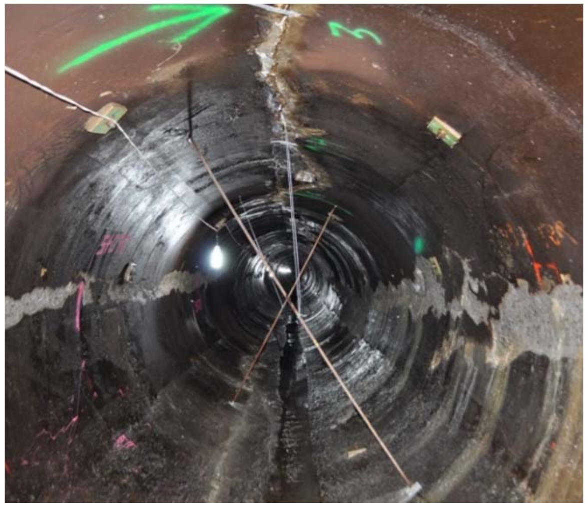
4.2 Rehabilitation of Pucará headrace tunnel

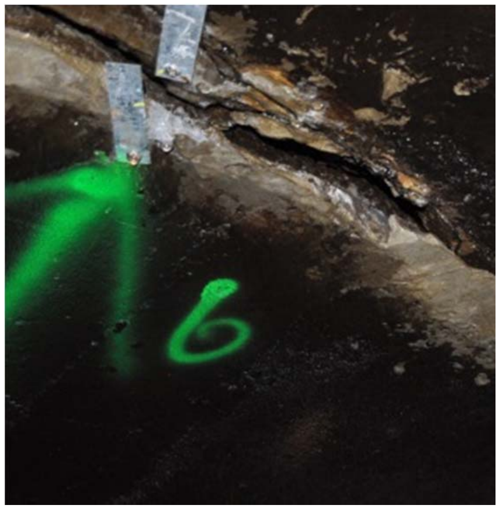
Collapse of concrete lining in 2011





- Location and shape of the fissures indicate tensile stresses caused by internal water pressure



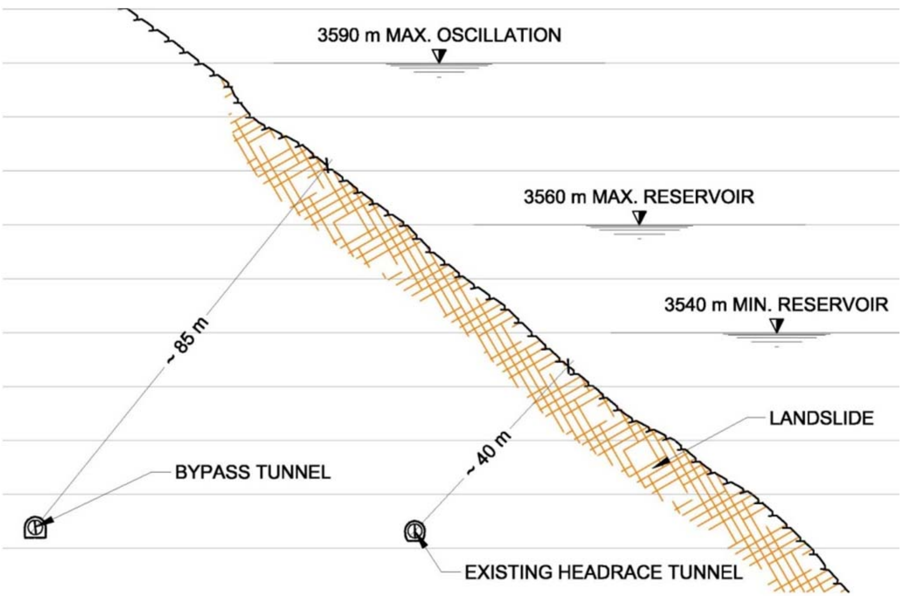


- Fissure propagation destroyed/affected arch effect in the concrete lining
- Compression of semi-circumferential concrete parts
- Rock spalling at the tunnel roof

4.2 Rehabilitation of Pucará headrace tunnel

Lateral and vertical rock coverage

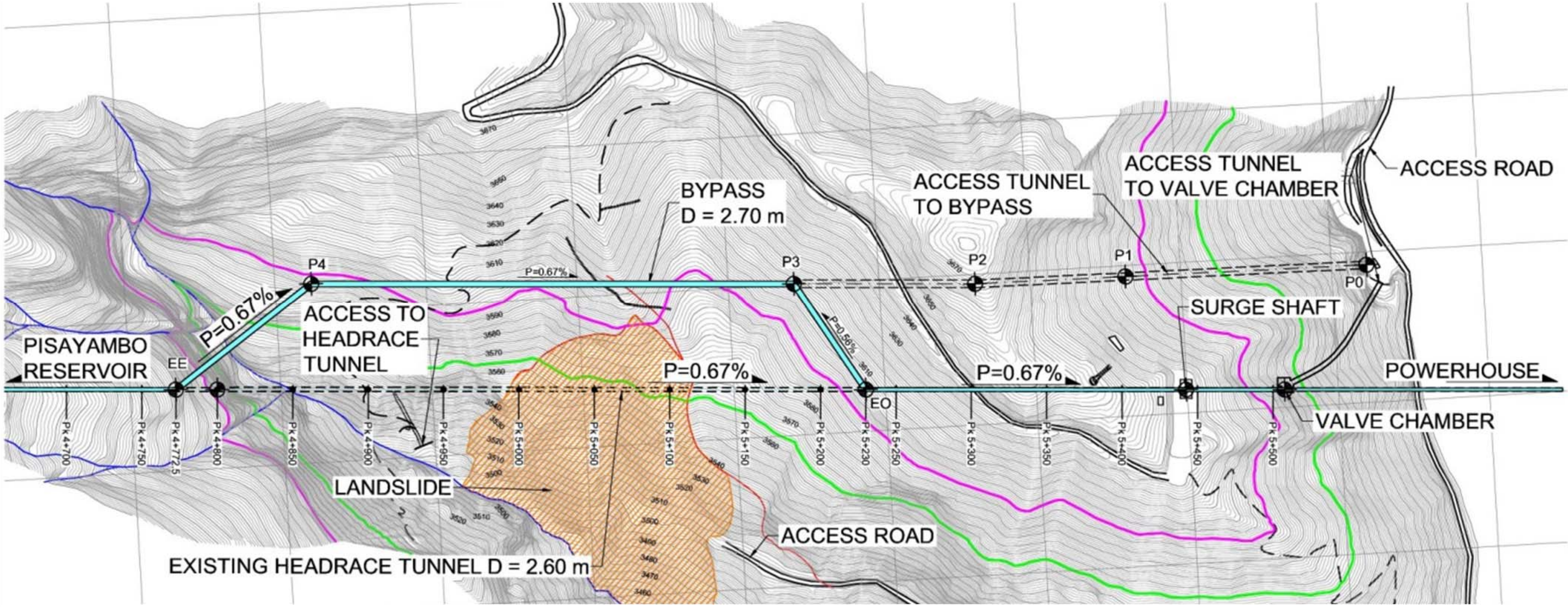
- Position of the affected headrace tunnel not adequate with respect to the distance to slope surface
- Lateral and vertical rock thickness not sufficient to ensure long term stability
- Rock mass characteristics progressively reduced due to water circulation



→ Construction of a bypass tunnel to the damaged section

4.2 Rehabilitation of Pucará headrace tunnel

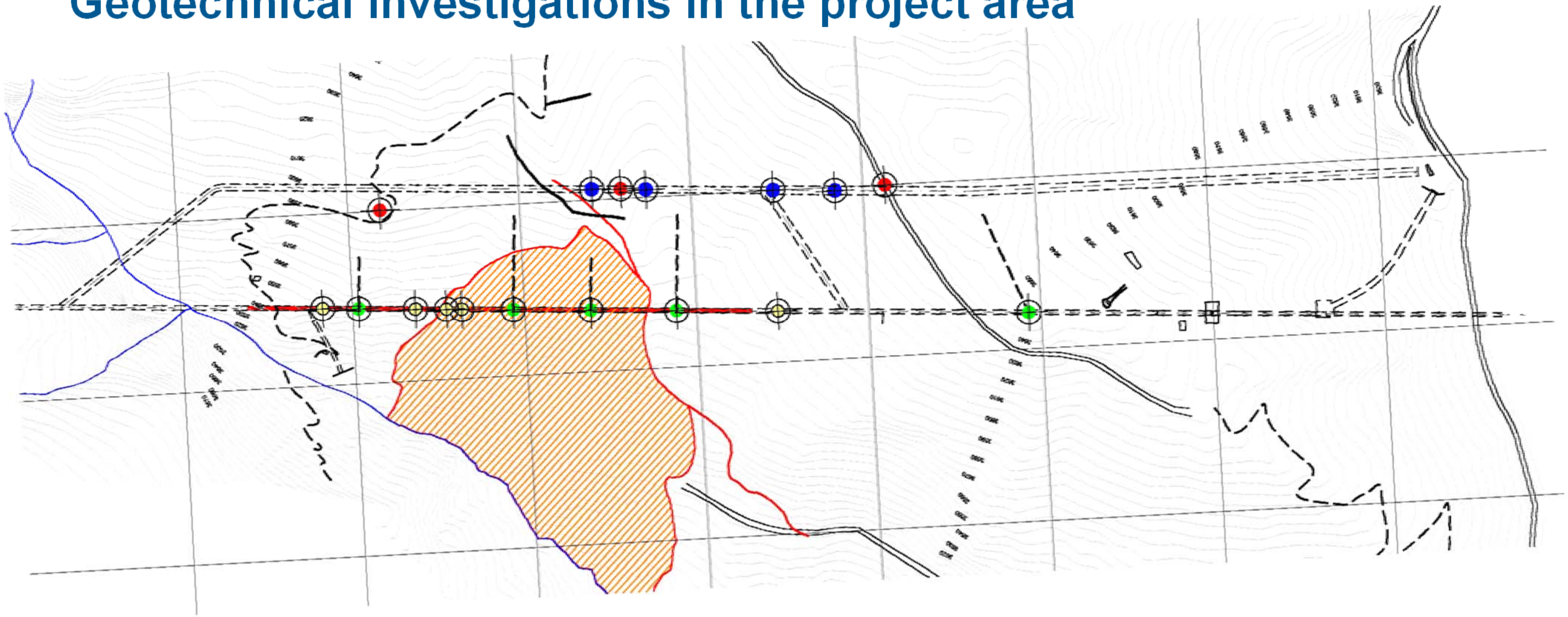
New bypass tunnel



- Bypass tunnel displaced some 70 m into the mountain (L=519 m, D=2.70 m)
- Access tunnel (380 m) to allow safe bypass excavation
- Drainage holes from the existing tunnel to drain the nearby rock slope

4.2 Rehabilitation of Pucará headrace tunnel

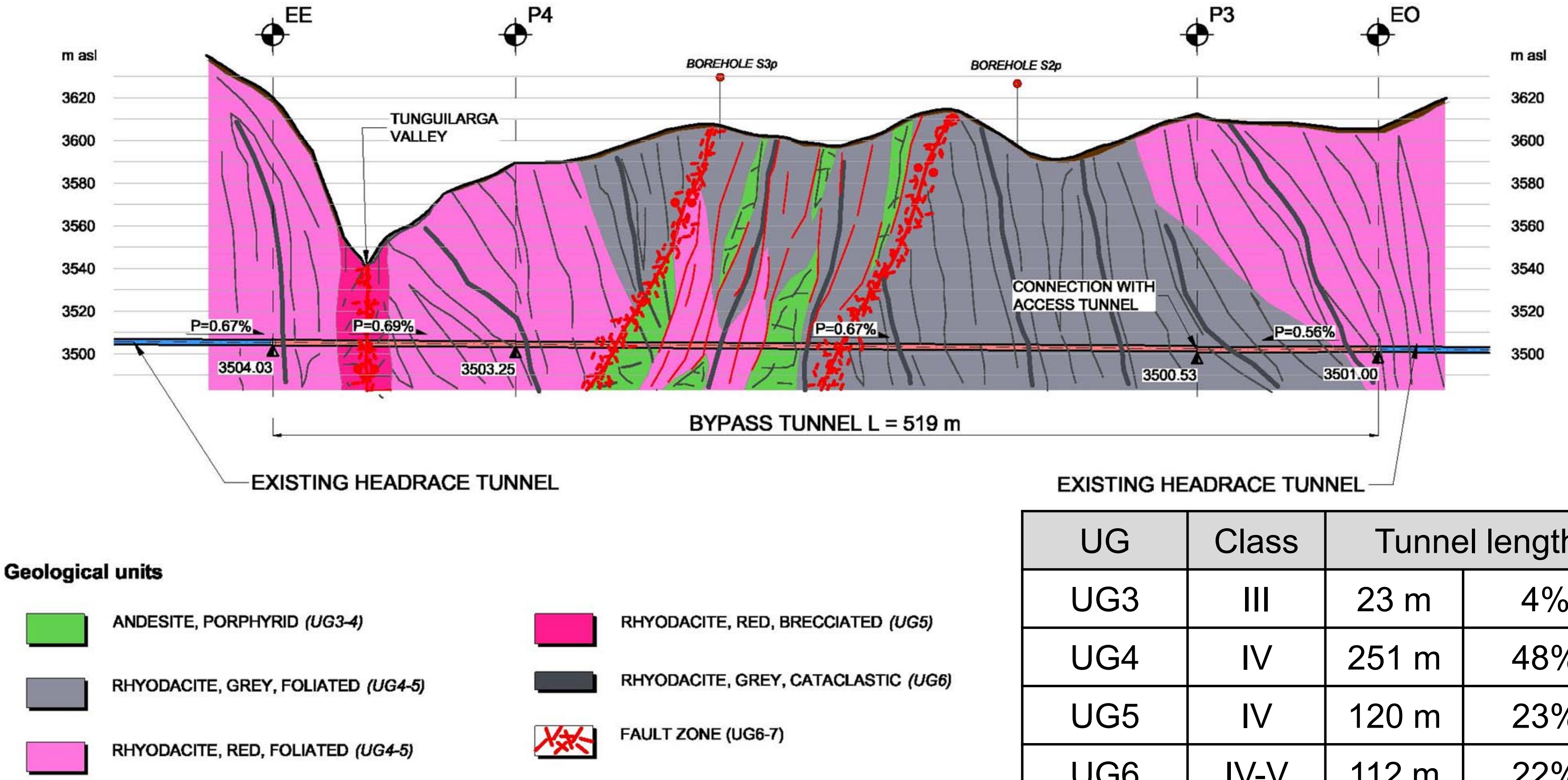
Geotechnical investigations in the project area



- vertical boreholes from the surface (70-100 m)
- sub-horizontal (10°) boreholes from the existing tunnel (15, 30, 55, 60 m)
- sub-vertical (30°) boreholes from the existing tunnel (12 m)
- boreholes from the bypass during construction

4.2 Rehabilitation of Pucará headrace tunnel

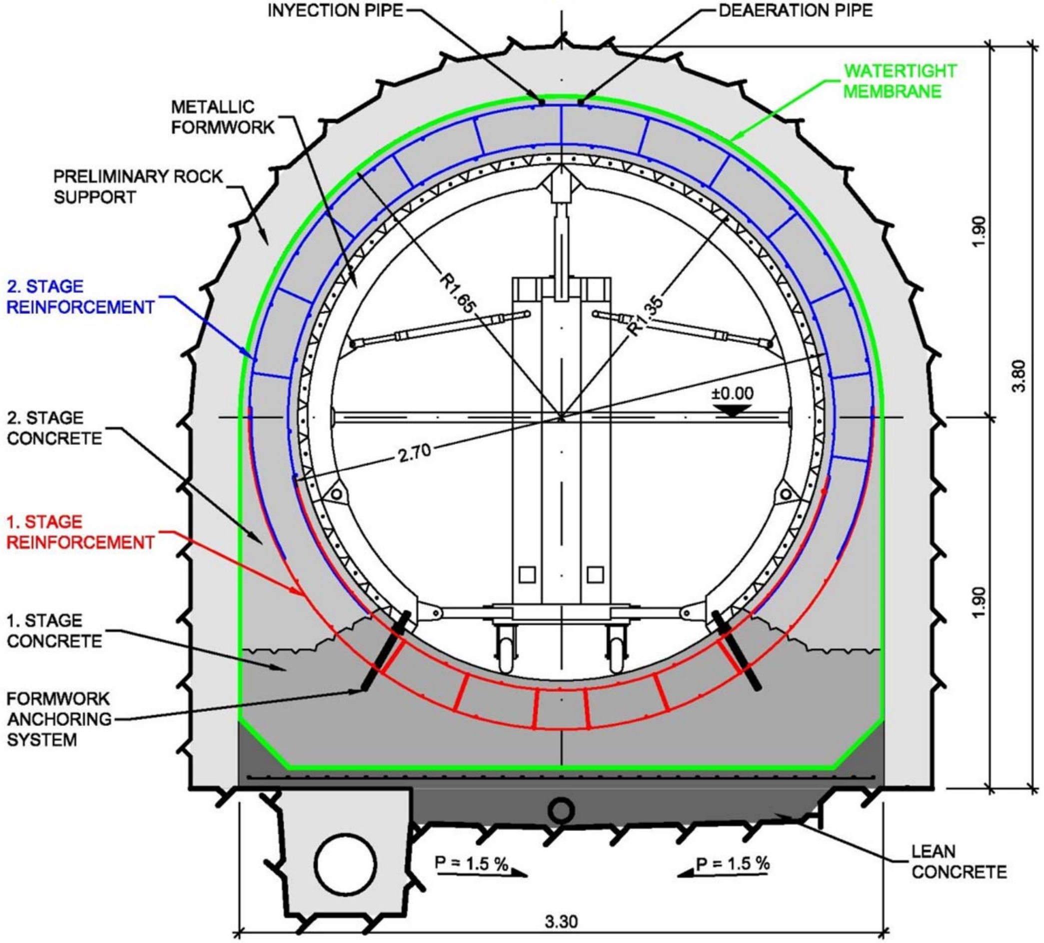
Geotechnical characterisation of the project area



UG	Class	Tunnel length	
UG3	III	23 m	4%
UG4	IV	251 m	48%
UG5	IV	120 m	23%
UG6	IV-V	112 m	22%
UG7	V-VI	14 m	3%

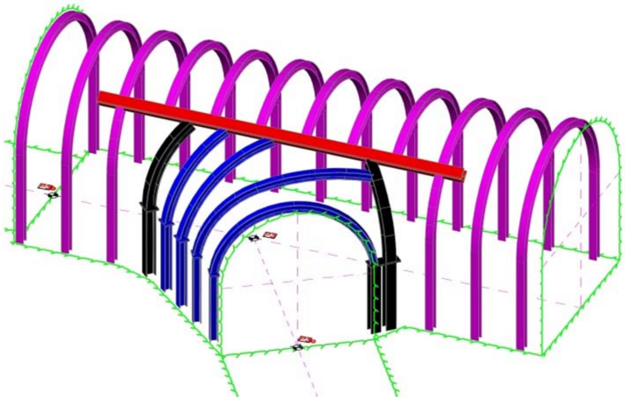
4.2 Rehabilitation of Pucará headrace tunnel

Typical cross section of the new bypass tunnel



4.2 Rehabilitation of Pucará headrace tunnel

Construction works



4.2 Rehabilitation of Pucará headrace tunnel

Temporary service of the existing tunnel during

GRP pipe DN1600 in the existing headrace tunnel (D=2.40 m)

- Duration of repair works (plant shutdown): 2011-2013
- Rehabilitation costs: 22 Mio USD
- Support measures of the most strongly damaged tunnel section (70 m) with circumferential steel ribs and 15 cm of shotcrete with steel mesh reinforcement
- Installation of a GRP pipe DN1600 in the existing tunnel
- Operation 24 h/day of one unit (36.5 MW, 9.3 m^3/s) for 8 months, during bypass construction

4 Case studies

Rehabilitation of the Navizence headrace tunnel (Switzerland)

4.3 Navizence Headrace tunnel

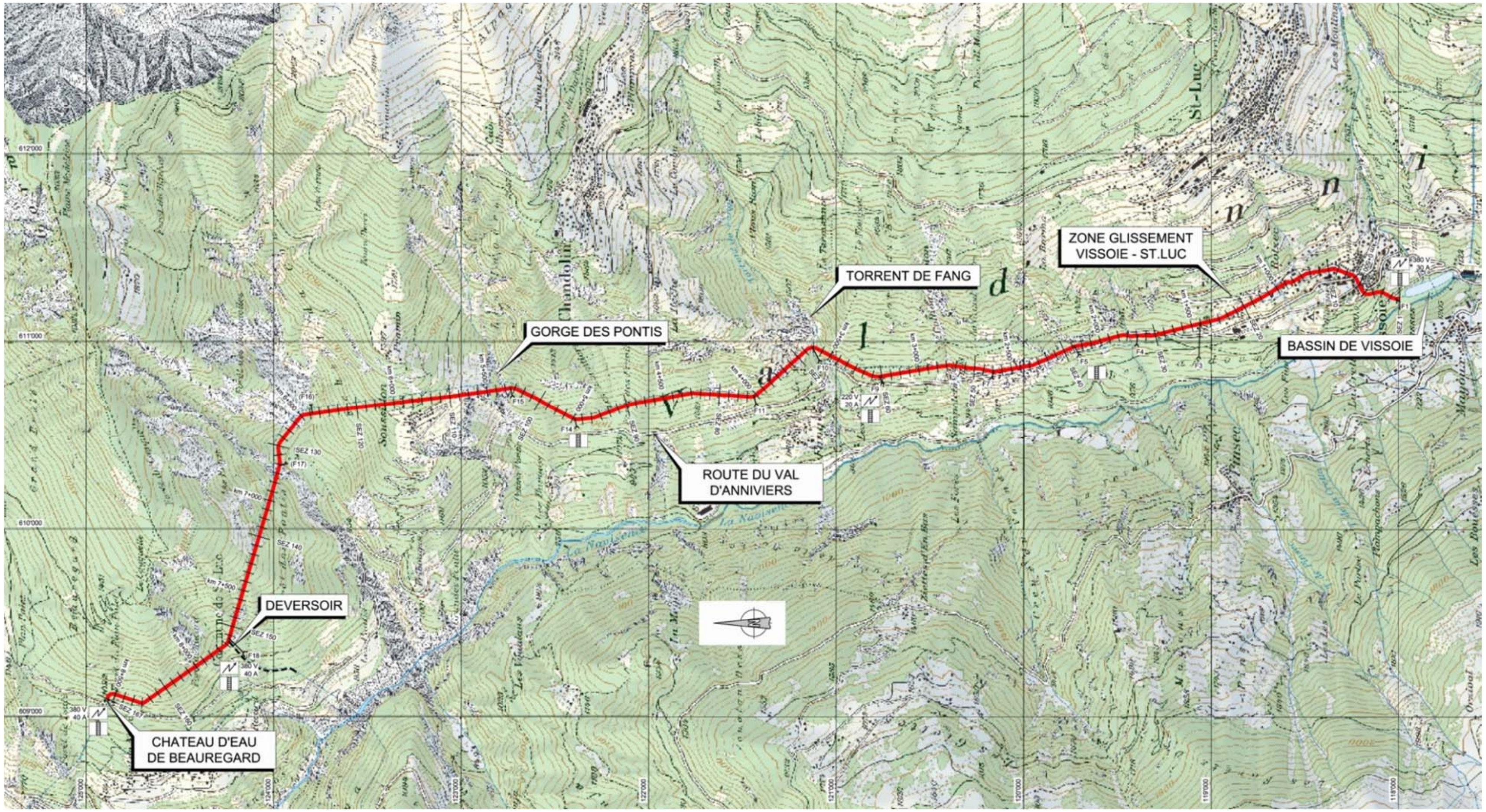
Characteristics of the Navizence HPP

- Inauguration: 1908
- Rehabilitation: 1950

- Capacity: 50 MW
- Generation: 290 GWh/y
- Net Head: 540 m
- Discharge: 10.5 m^3/s
- Nb of units 7
- Unit type: horizontal Pelton

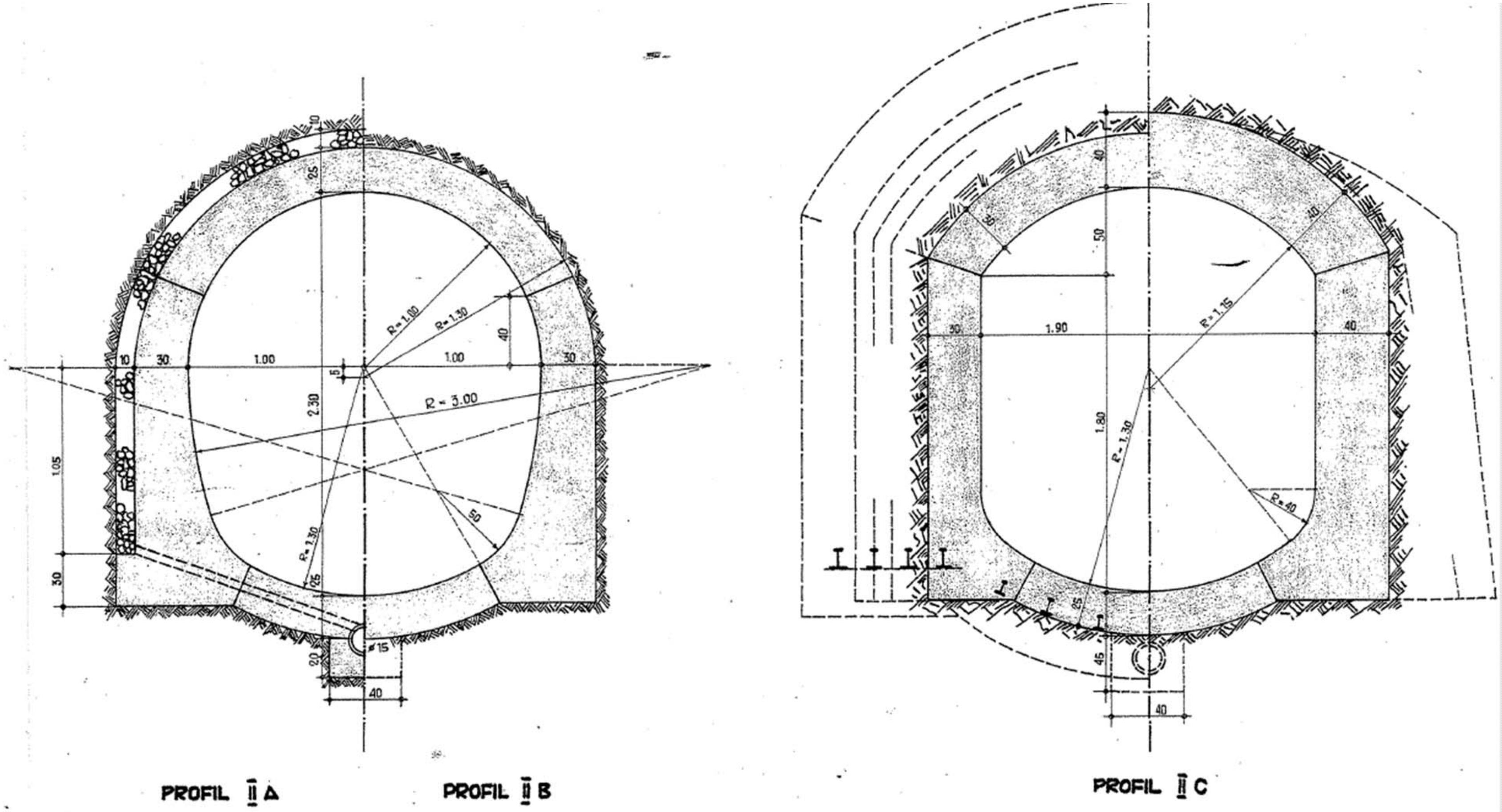
4.3 Navizence headrace tunnel

Layout of the free flow headrace tunnel (L=8.3 km)



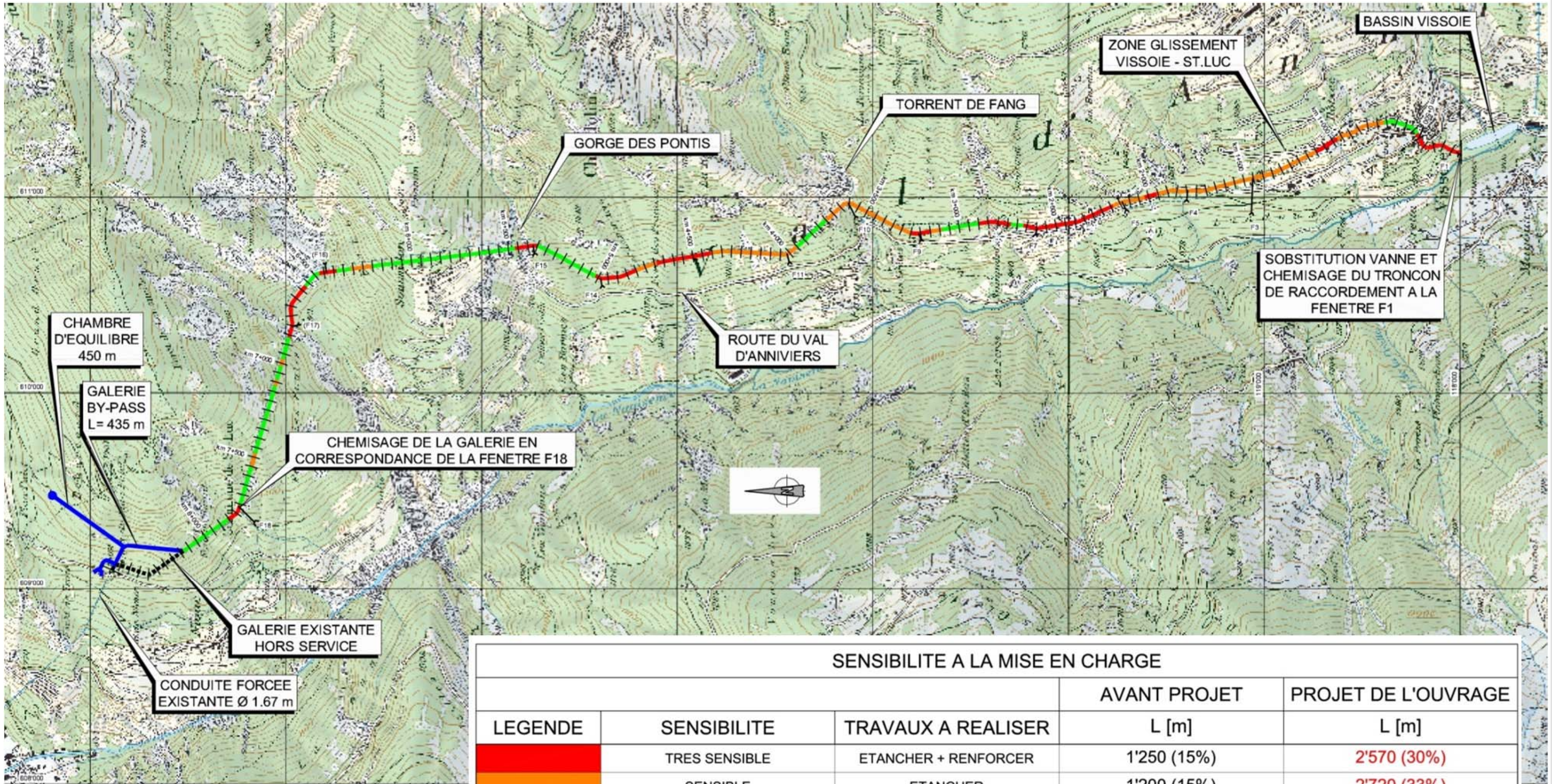
4.3 Navizence headrace tunnel

Typical cross sections



4.3 Navizence headrace tunnel

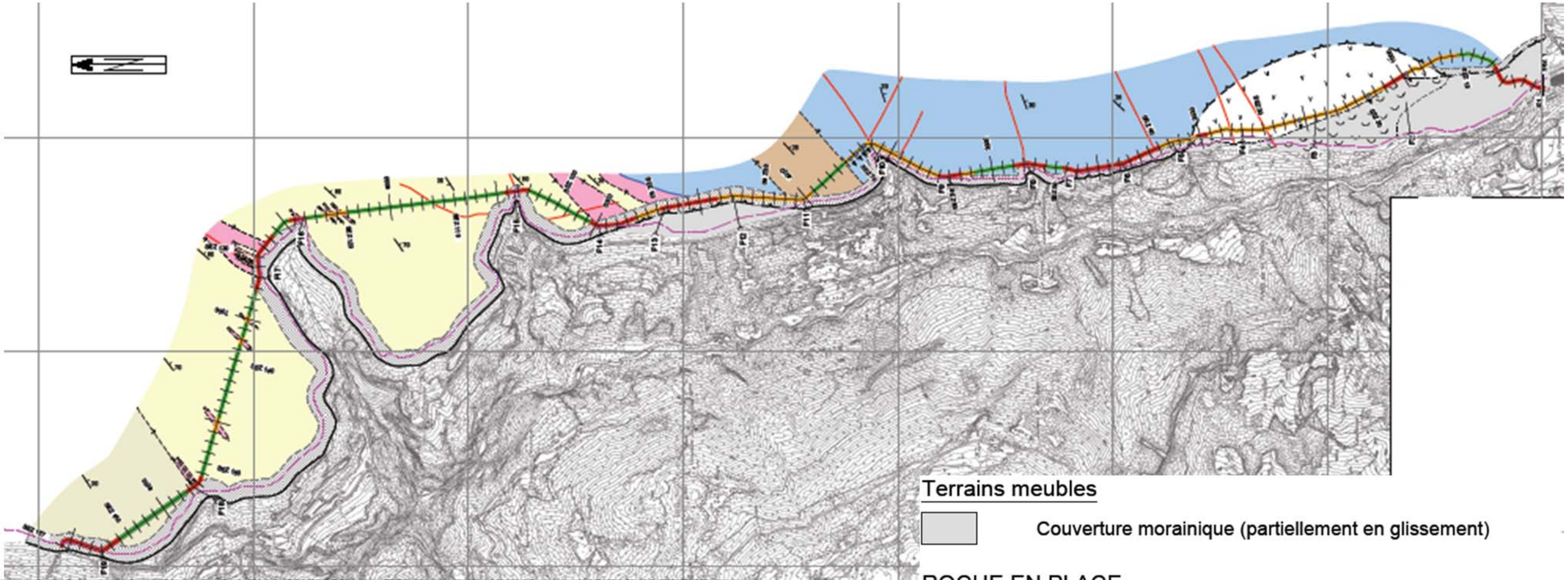
Rehabilitation works: pressure tunnel



SENSIBILITE A LA MISE EN CHARGE				
			AVANT PROJET	PROJET DE L'OUVRAGE
LEGENDE	SENSIBILITE	TRAVAUX A REALISER	L [m]	L [m]
(red)	TRES SENSIBLE	ETANCHER + RENFORCER	1'250 (15%)	2'570 (30%)
(orange)	SENSIBLE	ETANCHER	1'200 (15%)	2'720 (33%)
(green)	PEU SENSIBLE	RIEN A FAIRE	5'850 (70%)	3'010 (37%)
			8300 (100%)	8'300 (100%)

4.3 Navizence headrace tunnel

Horizontal section: qualitative analysis (geology, overburden and lateral extension



SENSIBILITE A LA MISE EN CHARGE			
LEGENDE	DEGRE	TRAVAUX A REALISER	L [m]
(red)	Très sensible	Etancher + renforcer	2'570
(orange)	Sensible	Etancher	2'720
(green)	Peu sensible	Rien à faire	3'025

Terrains meubles

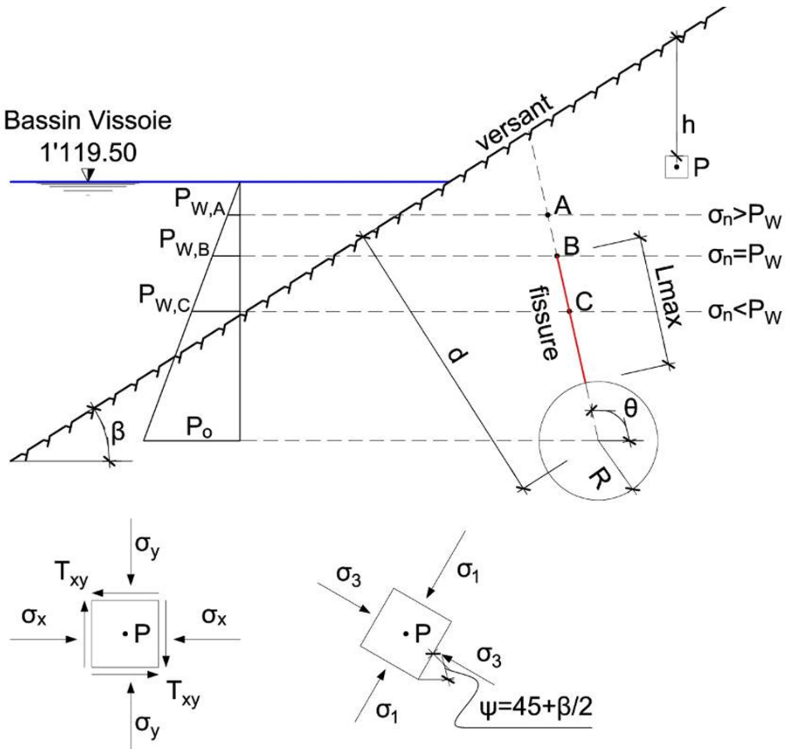
- Couverture morainique (partiellement en glissement)

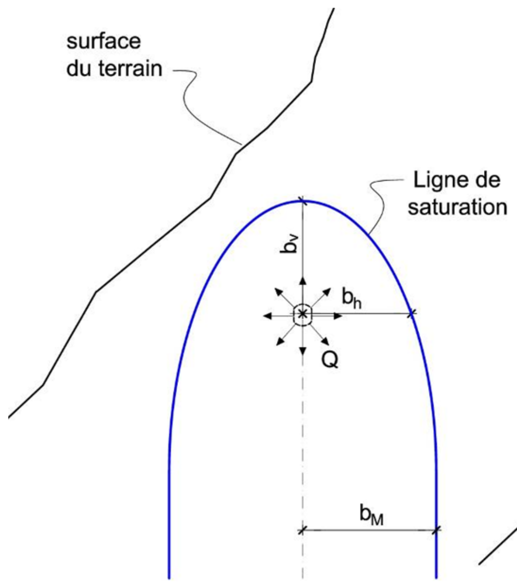
ROCHE EN PLACE

- Cornieule
- Quartzites massifs localement feuilletés ou saccharoïdes
- Micaschistes et schistes bruns quartzeux
- Calcaires marmorisés et dolomitiques
- Micaschistes et paragneiss quartzeux

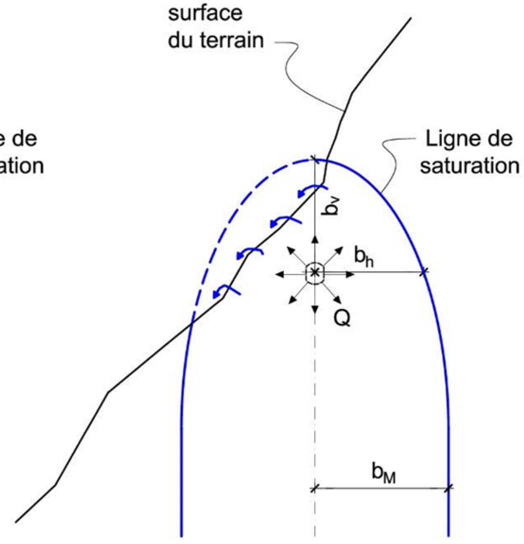
4.3 Navizence headrace tunnel

Structural & hydraulic analyses





Ligne de saturation
confinée au terrain



Résurgence

4.3 Navizence headrace tunnel

Study of alternatives: GFRP Inliner

4.3 Navizence headrace tunnel

Study of alternatives : carbon fiber tissue and resin
In situ tests (Sika Travaux et Freyssinet CH)

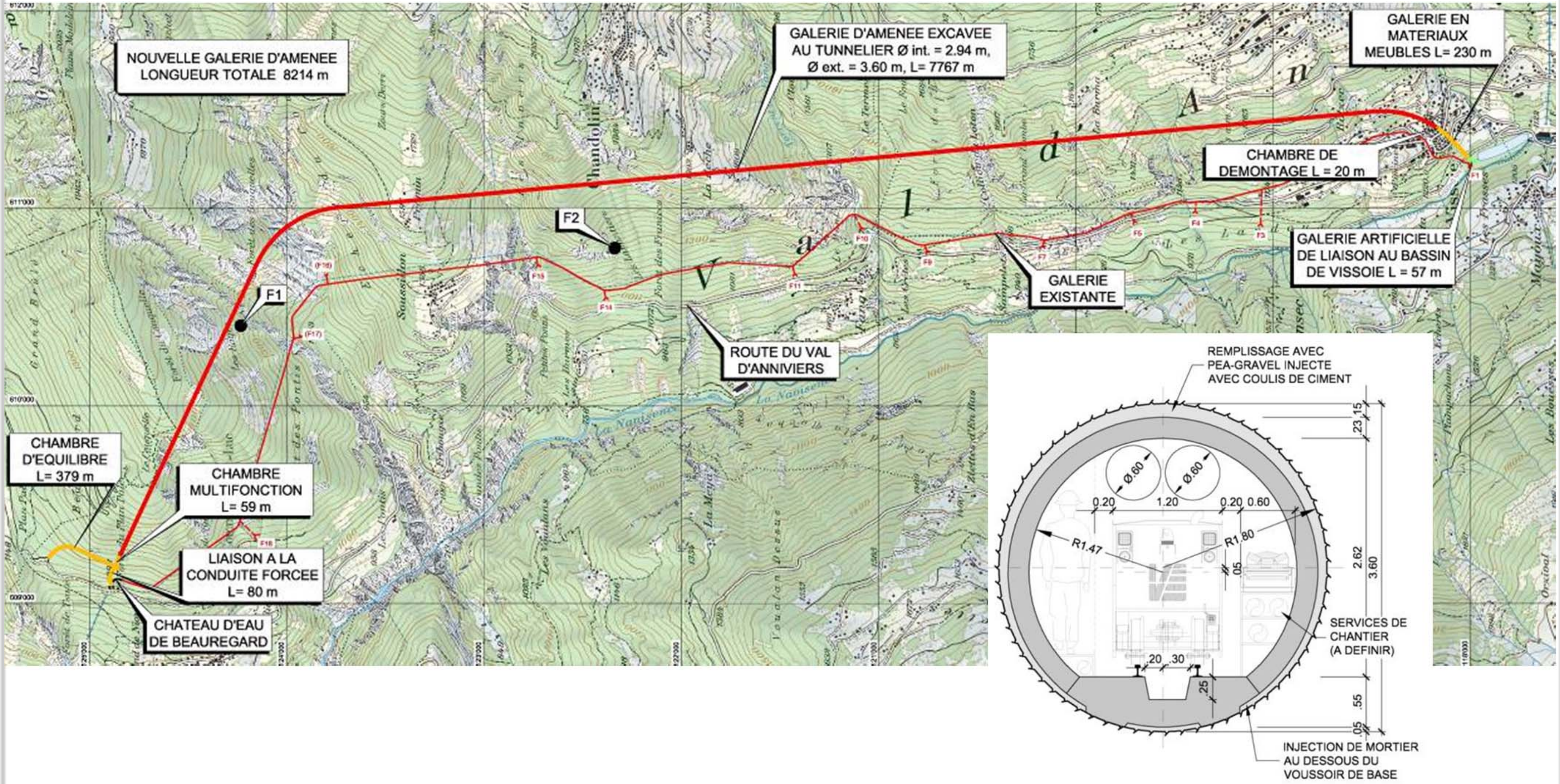
Application 1ère couche

Marouflage du tissu

Passage de la spatule

4.3 Navizence headrace tunnel

Final proposal: New headrace excavated by TBM



THANK YOU FOR YOUR ATTENTION

Philippe Lazaro