Pressure Tunnel/Shafts – Rick of Oversimplifications or Overdesigning

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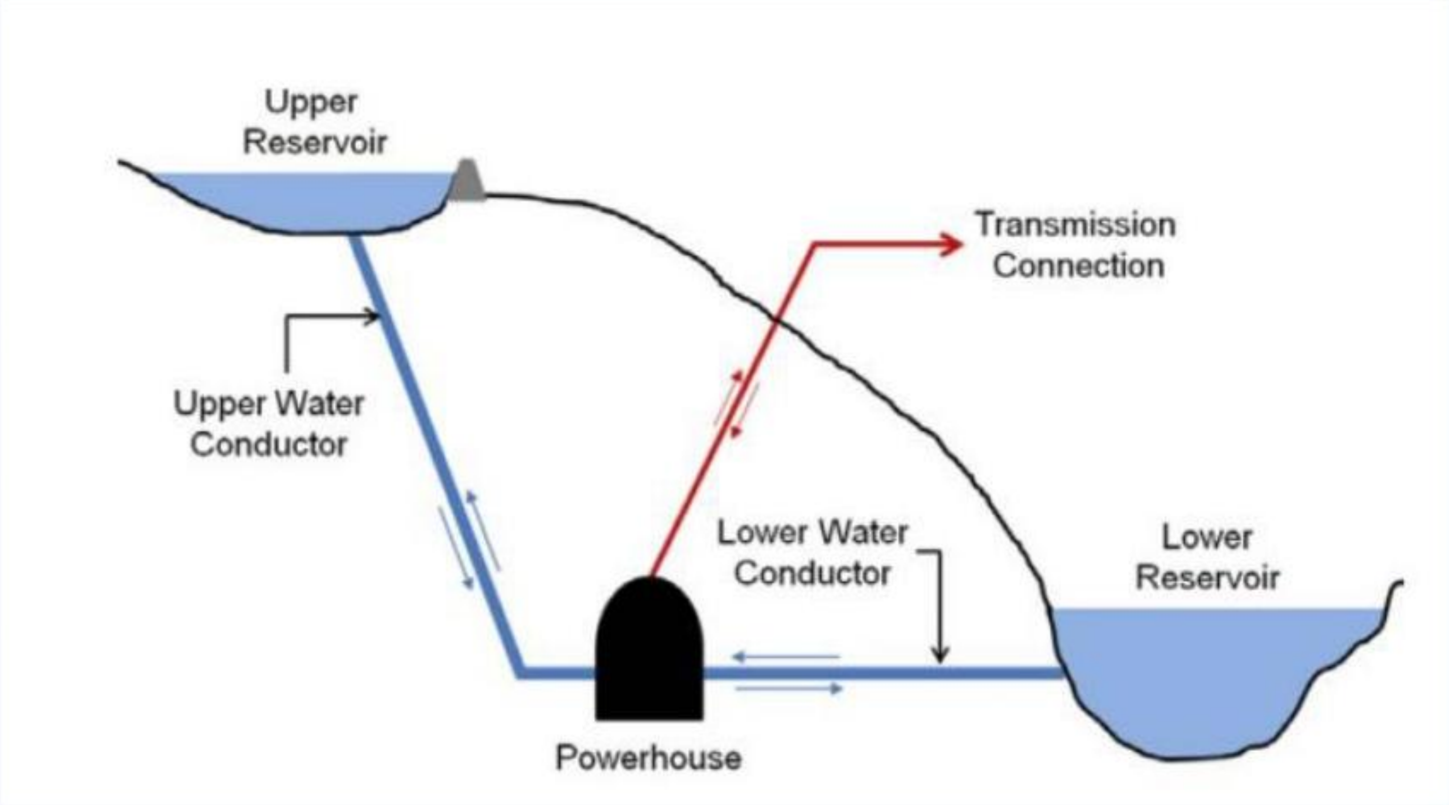
Disclaimer

This presentation was developed using only publicly available data on pumped hydro projects. No information from projects currently under construction or under study in Australia was used.

Pumped Storage Hydropower

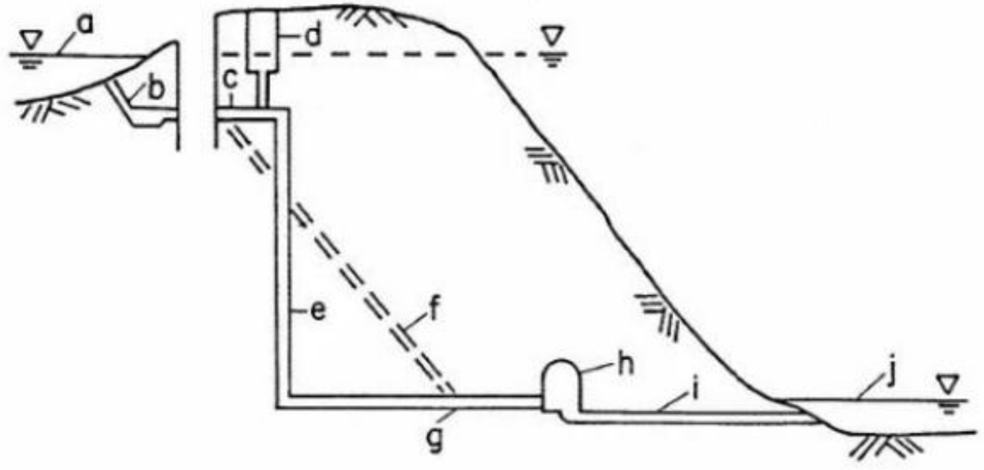
Pumped hydro projects are a highly relevant sources of renewable energy and play a crucial role in the provision of sustainable energy supply and storage.



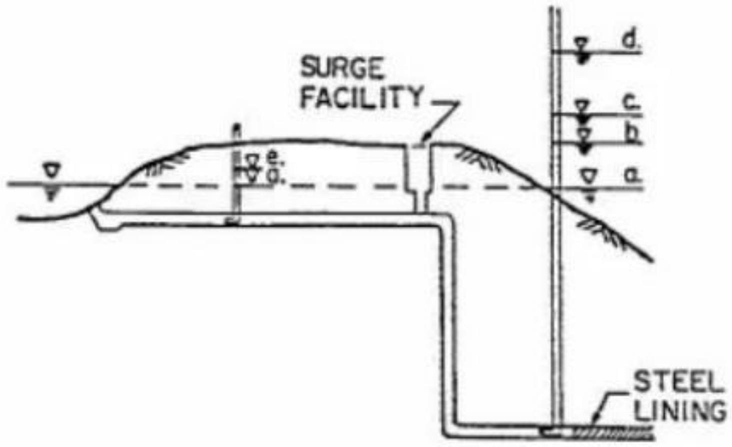
Koritarov et al. (2022)

Pressure Tunnel/Shafts

Pressure tunnels transfer pressurised water (caused by differential elevation or imposed by pump) from on reservoir to another reservoir (pumped hydro) or to turbine



a = UPPER RESERVOIR
b = INTAKE
c = LOW PRESSURE (HEADRACE) TUNNEL
d = SURGE CHAMBER
e = VERTICAL PRESSURE SHAFT
f = INCLINED PRESSURE SHAFT
g = HIGH PRESSURE (PENSTOCK) TUNNEL
h = UNDERGROUND POWERHOUSE
i = TAILRACE TUNNEL
j = LOWER RESERVOIR



a. = STATIC WATER LEVEL
b. to c. = NORMAL SURGE WATER LEVEL FOR IMPULSE TURBINES; = (1.15 TO 1.25) x STATIC HEAD
c. to d. = NORMAL SURGE WATER LEVEL FOR REACTION TURBINES; = (1.25 TO 1.50) x STATIC HEAD
e. = NORMAL SURGE WATER LEVEL, FOR IMPULSE AND REACTION TURBINES, UPSTREAM OF SURGE FACILITIES

Figure S-1. Static and Dynamic Heads

Brekke & Ripley (1987)

Unrealistic Simplification

Pressure Tunnel/Shafts – Main Simplification

- Tunnel is not just a line on the map.

- Unlike transport and utility tunnels, pressure tunnels and shafts carry pressurised water, which creates extra interaction between the lining and the rock mass and can lead to erosion problems over time.

- At the concept design stage, hydraulic and hydropower engineers often treat pressure tunnels, shafts, headrace, and tailrace tunnels as simple lines connecting two reservoirs to deliver the required head, overlooking the potential excavation challenges that may arise during construction. Along with a lower head-to-distance separation ratio, construction challenges can also greatly increase construction costs.

- Head-to-distance separation ratio>10% is favorable (Blakers et al., 2025).

Pressure Tunnel/shaft – Historical Failures

Brekke & Ripley (1987) found from 54 incidents in pressure tunnels/shafts:

- **59% were related to leakage due to HJ, deformable rock mass or geological feature with high conductivity.**
- **22% were related to deterioration of rock mass leading to instabilities.**
- **13% were buckling of steel lining induced by groundwater pressure or excessive grouting pressure.**

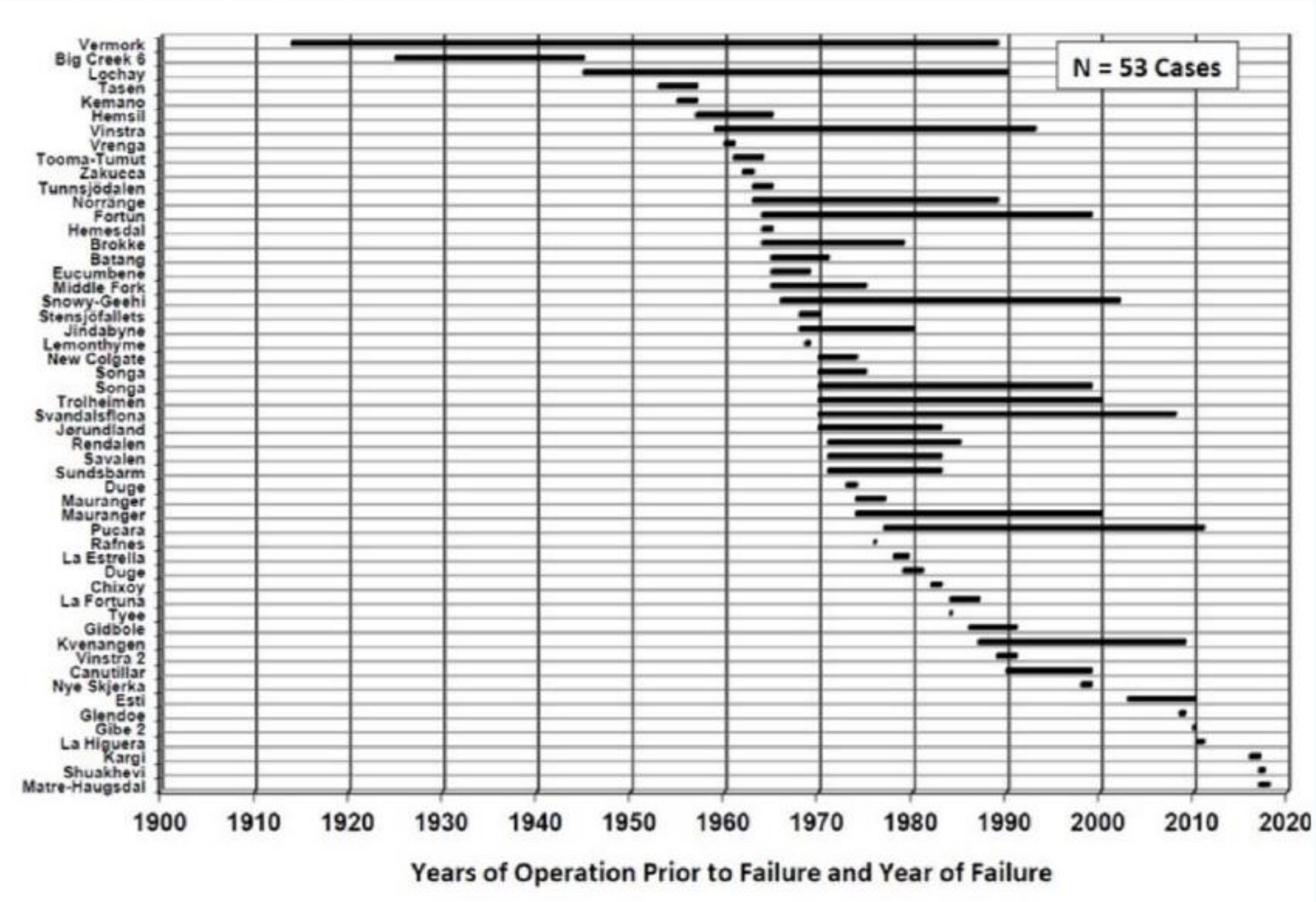


Figure 1. Hydropower tunnel collapses.

There are several failed cases from recent projects such as

Pressure Tunnel/shaft – Historical Failures

There are several failed cases from recent projects such as (unlined or shotcrete lining):

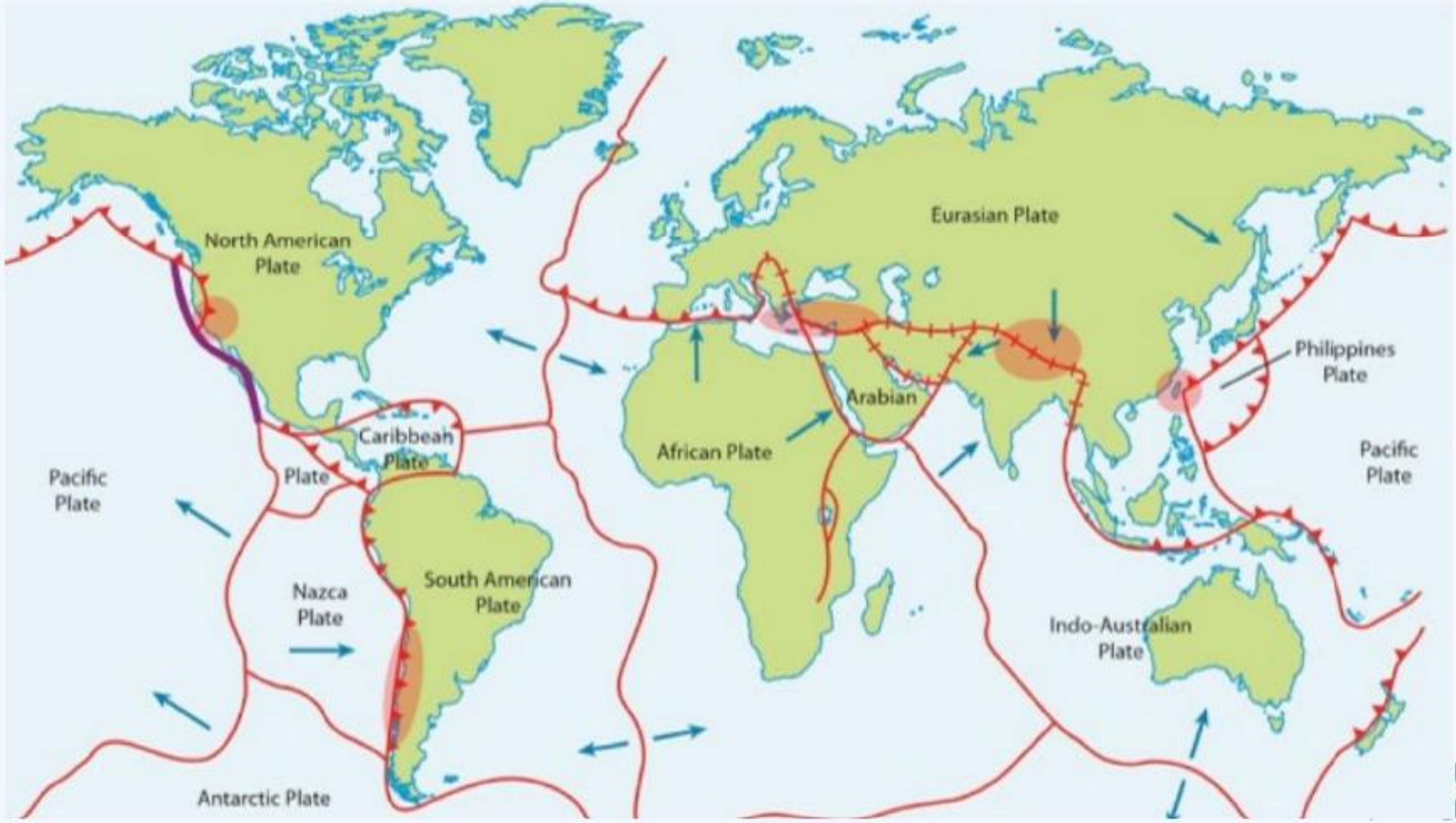
Table I. Hydroelectric tunnel collapses

Project	Year	Size, m	Length, km	Collapse time after start, years
Glendoe	2009	5	8	0.5
Rio Esti	2010	10	5	7
La Higuera	2011	6	16	0.8
Kargi	2016	9	12	1
Shuakhevi	2017	5	18	0.5
Ituango	2018	16	2.5	During construction

Brox (2022)

Pressure Tunnel/Shafts – Main Simplification

- Tunnel is not just a line on the map.
- Water tunnels located in young and active geological environments such as Andes, Himalayas, Chile, Georgia, Greece, Turkey and Taiwan are considered high risk.
- Karstic rock mass



Brox (2022)

Pressure Tunnel/Shafts – Main Simplification

- **Tunnel is not just a line on the map.**

Joint power plant Inn (Austria-Switzerland)

- 22 Km headrace tunnel with 6.5 m diameter.
- Asbestos fibres were found in a significant part of the tunnelling sections.
- Tunnelling work in 2017 and 2018 was delayed by five major interruptions, mostly caused by the shield skin becoming trapped (through sheared and altered rocks).
- Backfill, contact, and consolidation grouting were necessary.

Pressure Tunnel/Shafts – Main Simplification

- **Tunnel is not just a line on the map.**

Lesotho Highlands water scheme

- **Two long tunnels one with 36 Km and other with 30 Km length.**
- **Main rock type is basalt.**
- **Degradation of basalt due to presence of specific minerals (Laumonite) that experience shrinkage cracking due to lose of water when exposed to atmosphere during construction (chemical weathering).**
- **The original plan was for a partially lined tunnel, but due to durability concerns, the tunnels were fully lined instead.**

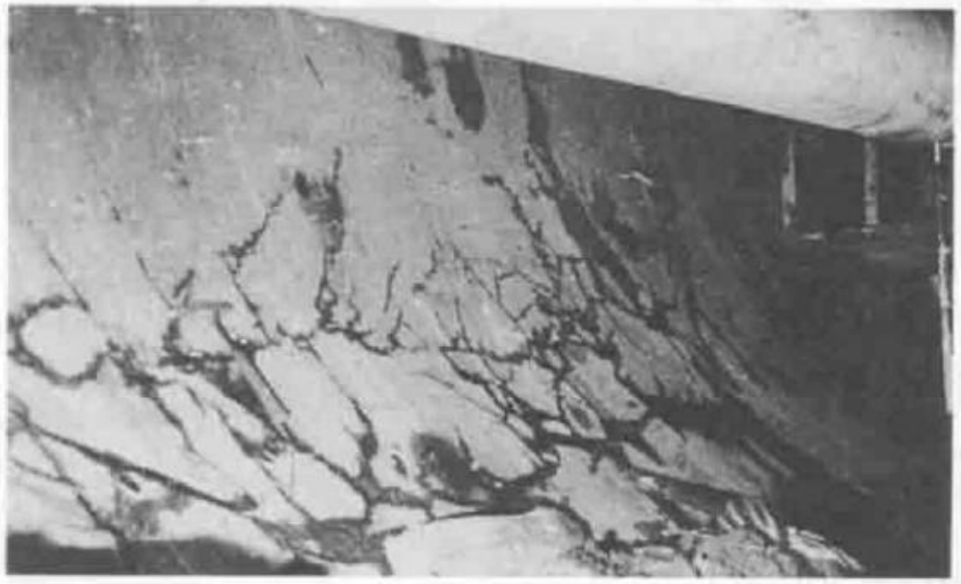


Fig. 9. Crazing in basalt of the Transfer Tunnel.

Bell & Haskins (1997)

Overdesigning

Pressure Tunnel/Shafts – Overdesigning

Much Higher Factor of Safety for Hydraulic Fracturing and Hydraulic Jacking

When the internal water pressure induces effective stress greater than that acting on the pre-existing fracture, the fracture's aperture can undergo irreversible enlargement (HJ), resulting in excessive leakage, landslides, and loss of bearing capacity.

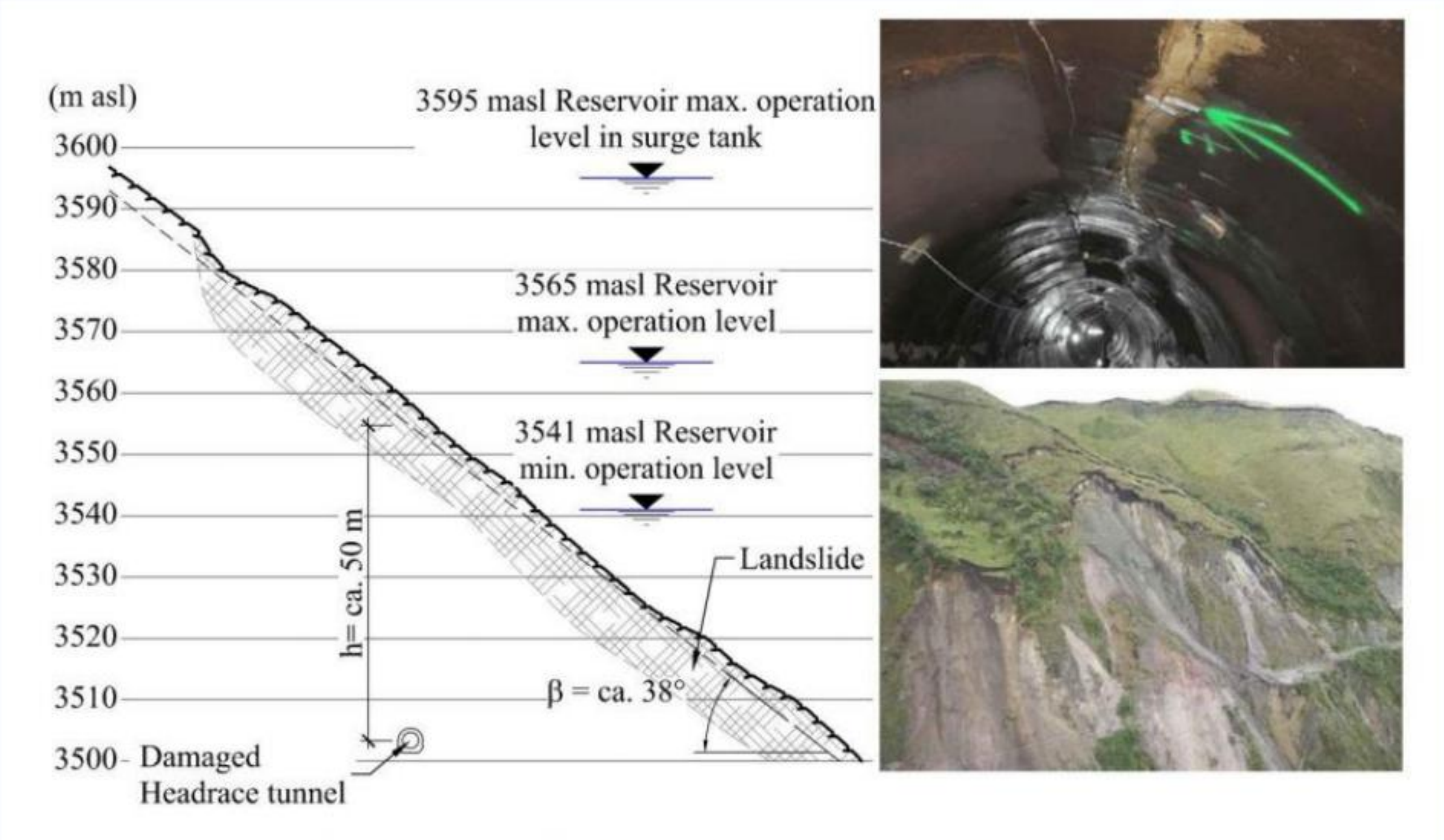


Fig. 10. Left: Situation of the Pisayambo headrace tunnel in the damaged stretch.
Right: Image of the crack inside the tunnel and of the main landslide.

Amberg & Vietti (2015)

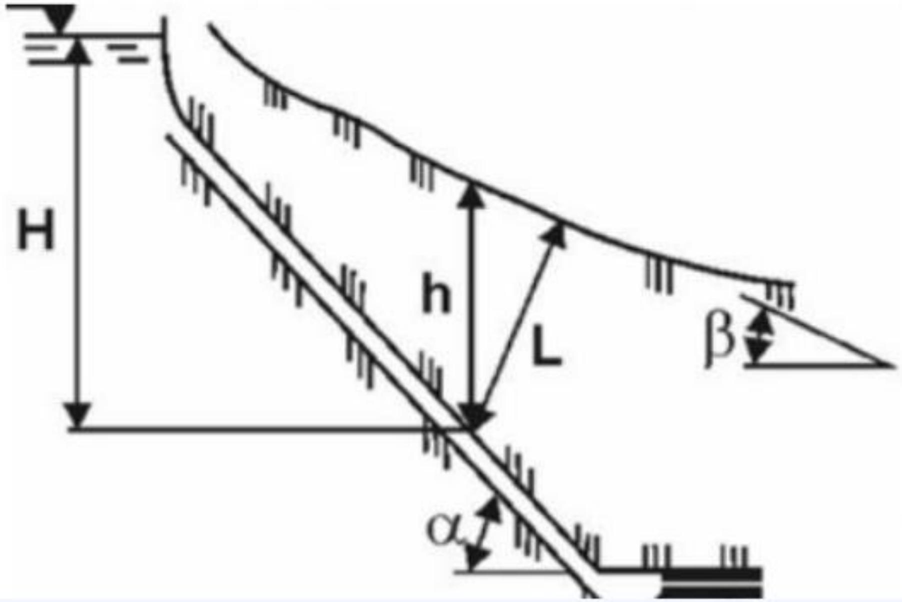
Pressure Tunnel/Shafts – Overdesigning

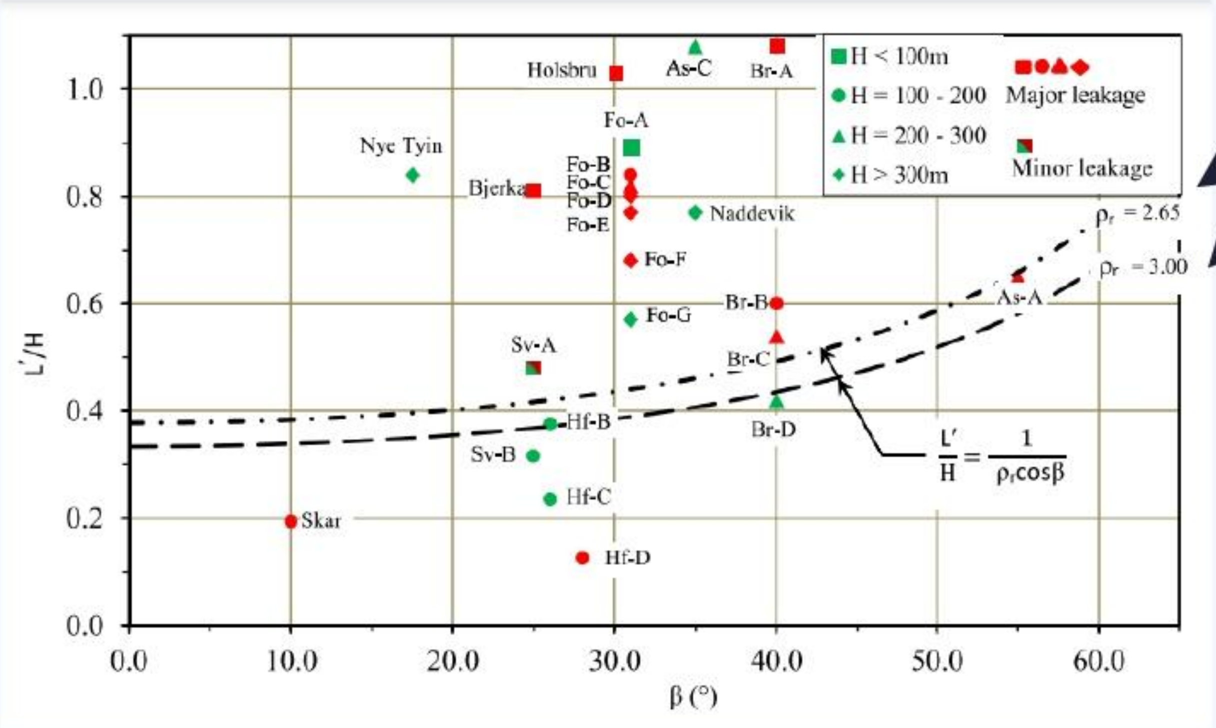
Much Higher Factor of Safety for Hydraulic Fracturing and Hydraulic Jacking

Norwegian Rule of Thumb

$$h > \frac{H \times \gamma_w}{\gamma_r \times \cos\alpha} \quad \text{------------- (1)}$$

$$L > \frac{\gamma_w \times H}{\gamma_r \times \cos\beta} \quad \text{------------- (2)}$$





Colluvial, loose sediments and irregular topographies must be excluded from the effective rock cover

Pressure Tunnel/Shafts – Overdesigning

Much Higher Factor of Safety for Hydraulic Fracturing and Hydraulic Jacking

Norwegian Rule of Thumb

- Norway rule of thumb was developed based on data from tunnels excavated in hard and massive rocks with moderate stress with little open or partially filled joints parallel to slope.

- High pressure grouting of all potential leakage zones with pressure slightly above the internal hydrostatic pressure has been suggested in Norwegian method.

- All clay filled weak zones should be sealed with a concrete lining and grouted.

- Risk of HJ is increased in areas of steep, irregular topography where erosion and associated lateral strain relief have reduce the in-situ horizontal stress, weathering proceeded along the joints. Measuring minimum principal stress will be best assurance.

Pressure Tunnel/Shafts – Overdesigning

Much Higher Factor of Safety for Hydraulic Fracturing and Hydraulic Jacking

Other Rules/Methods

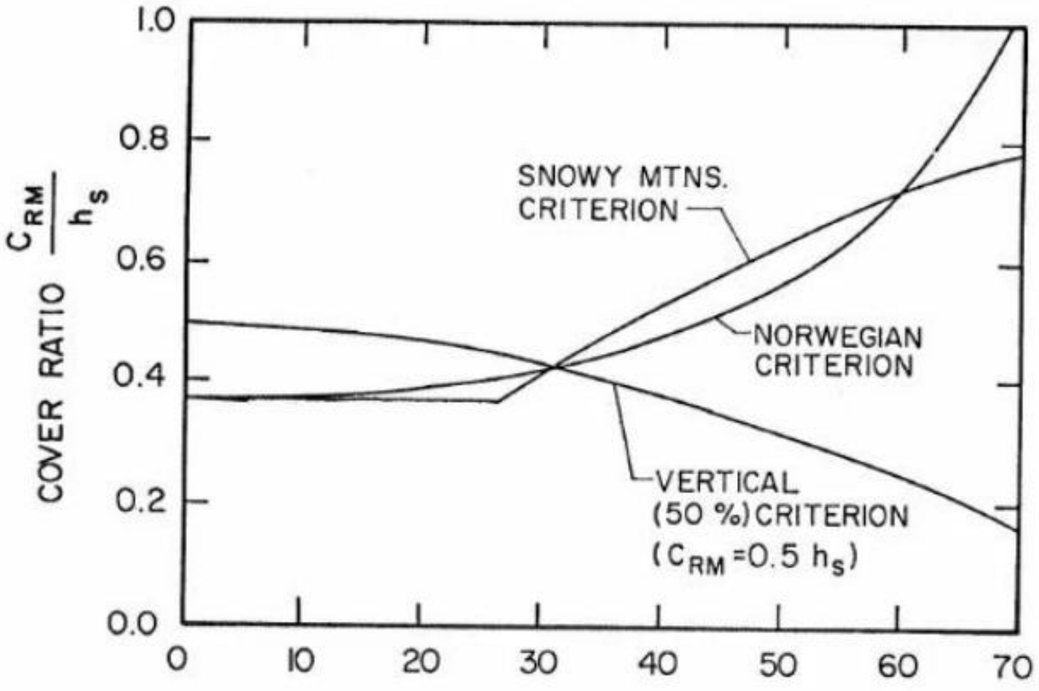
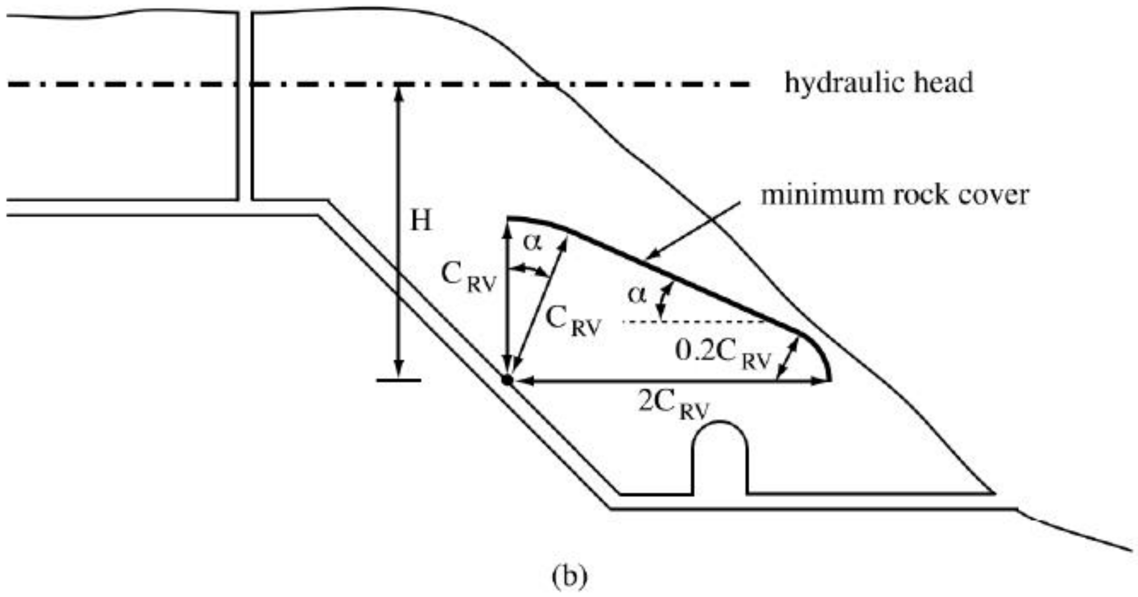


Figure 3-8. Comparison of vertical, Snowy Mountains, and Norwegian criteria for sloping topography.

Brekke & Ripley (1987)



Snowy Hydro (Dann et al., 1964)

$$C_{RV} > \frac{\gamma_w H}{\gamma_r}$$

Pressure Tunnel/Shafts – Overdesigning

Much Higher Factor of Safety for Hydraulic Fracturing and Hydraulic Jacking

With FoS=1.3

$$H_r = \frac{1.3\,H_w - H_s\,\gamma_s}{\gamma_r}$$

H_r = height of the rock above the tunnel (m);
γ_r = density of rock (t/m³);
H_s = height of soil above the tunnel (m);
γ_s = density of soil (t/m³); and
H_w = maximum static head (m).

Other Rules/Methods

$h > 0.5P$ former soviet union (P is internal water pressure)

$$h > 0.8 \cdot H$$
$$d > 2.0 \cdot H$$

Don Deere rule

Deere (1983)

H = hydraulic head
h = vertical overburden
d = horizontal overburden

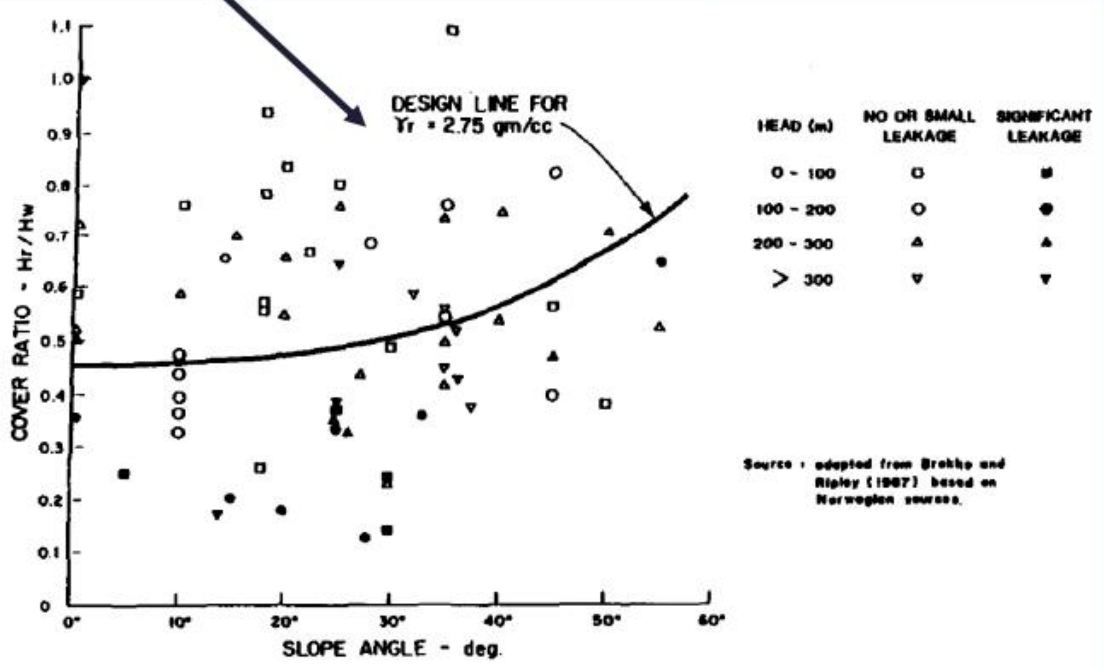


Figure 4. Recommended design line to prevent hydraulic jacking.

Benson (1987)

Pressure Tunnel/Shafts – Overdesigning

Much Higher Factor of Safety for Hydraulic Fracturing and Hydraulic Jacking

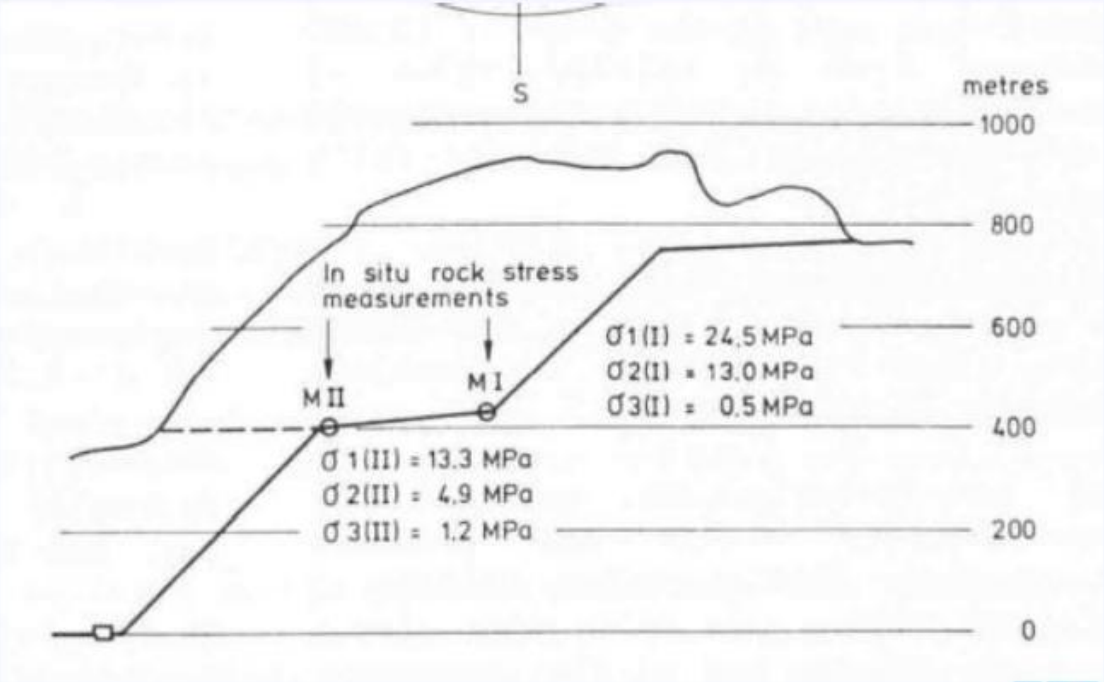
Hydraulic Jacking (HJ):

Other Rules/Methods **Internal water pressure must be less than minimum principal Stress**

- **The magnitude of the minimum principal stress may vary significantly from the stress acting on the pre-existing joints.**

Stress relief due to topography and major structures can significantly affect the prediction of the Norwegian rule. Measuring minimum principal stress will be best assurance.

Mauranger power plant (Norway) with hydrostatic pressure of 450 m



(Bregh-Christensen, 1982)

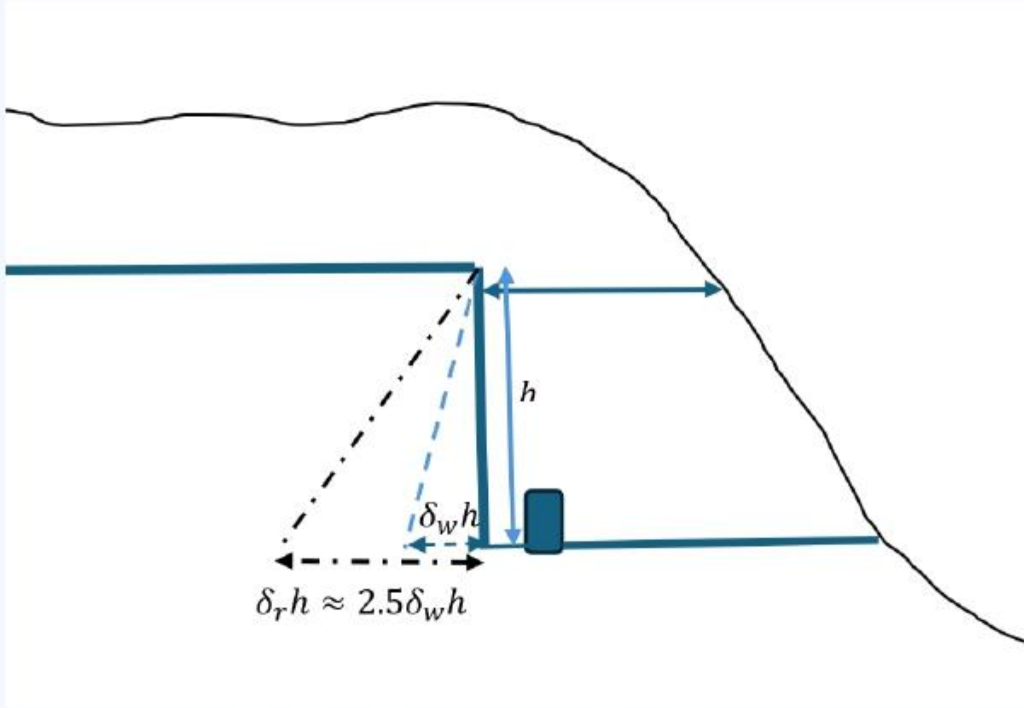
Reliability of measured stress???

Pressure Tunnel/Shafts – Overdesigning

Much Higher Factor of Safety for Hydraulic Fracturing and Hydraulic Jacking

Hydraulic Jacking (HJ): Vertical Shafts

- Reinforced concrete lining is generally the most optimised solution for pressure shafts. Exceptions apply at the upper and lower bends of vertical shafts, where highly turbulent water flow occurs and steel lining would be preferred.
- Steel lining is only required in vertical shafts when either:
    - Horizontal rock cover is inadequate due to varying topography (low confinement), or
    - Rock mass hydraulic conductivity is sufficiently high that leakage exceeds acceptable criteria.



Overburden stress gradient is approximately 2.5 time of internal water pressure gradient minimizing the likelihood of hydraulic jacking at sub-horizontal rock defects

Based Schleiss (2013), vertical shaft is an optimised design (particularly when raise boring is being used to excavate the shaft) for hydropower and pumped storage project to avoid excessive use of steel lining in the high-pressure zones.

Pressure Tunnel/Shafts – Overdesigning

Transient Hydraulic Loading

- Every start, stop and load change in hydropower plants generate flow and pressure transients in the waterway.
- As an example, the emergency shutdown at Roskrepp power plant, the turbines close rapidly within 10 s and result in a rapid decrease of the water flow. The resulting deceleration of the water in the waterway causes a pressure increase on the upstream side of the turbine, and a pressure decrease on the downstream side. (Neupane et al., 2020)
- Water is barely elastic and requires a large pressure increase to cause a small compression, resulting in the maximum compression being reached in a short time, which leads to a fast-traveling water hammer. The water hammer starts from turbine and progresses towards the nearest free water surface where the water hammer is reflected back towards the turbine with the opposite pressure, a positive pressure becoming a negative one.

Helwig (1987) presented a theoretical study to estimate the depth to which significant pressure transients are transferred into the rock mass. It concludes that the effect of water hammer is limited to a relatively shallow depth around the tunnel walls because of the short time period. It also concludes that pressure penetration into the rock mass could be considerably larger during pressure transients with a longer time period, i.e. mass oscillations.

Pressure Tunnel/Shafts – Overdesigning

Transient Hydraulic Loading

- The real measurements from an unlined tunnel (Neupane et al, 2020) showed that, water hammer can only travel deep into the rock mass at presence of open joint (ungrouted), however, the amplitude is greatly reduced.

- This study also showed that even slow-acting mass oscillations do not travel into the rock mass if the joints in the rock mass are very tight.

Pressure Tunnel/Shafts – Overdesigning

Factor of Safety for Hydraulic Fracturing and Hydraulic Jacking

Factor of Safety

1. FoS=1.1 ASCE (1989)
2. FoS=1.15 Palmstrom & Berdal (1987)
3. FoS=1.2 Broch (1982)

- Normal operating surge (mass oscillation) for HJ is not recommended by Norwegian rule of other commonly used methods such as Merritt (1999).
- Normal surge can be 15% to 20 % of static internal pressure (caused by operation of hydraulic machinery under controlled conditions).

Design condition	Normal operating: Static	Normal operating: Surge	Water hammer
Lifting of rock above horizontal unlined or concrete lined tunnel.	1.3*	1.1	N/A
Along sloping portion near valleys, and at end of steel liner, with proper allowance for slope, topography, and possible landslides removing soil cover.	1.3	1.1	N/A

* May be reduced to 1.2 if geological conditions are well-known.

Benson (1987)

Pressure Tunnel/Shafts – Overdesigning

Factor of Safety for Hydraulic Fracturing and Hydraulic Jacking

Factor of Safety

$$FS = Fa * Fb * Fc$$

Parameter	Description	Factor of Safety
A. Rock Mass Characteristics		**Fa**
Soft, low modulus (E_{rm}<5GPa) Highly anisotropic	Sedimentary Metamorphic Horizontal lying	1.3
Medium modulus (5 – 20GPa) Anisotropic	Sedimentary Metamorphics Volcanics	1.2
Hard, high modulus (>20GPa) Isotropic, with slight foliation	Gneiss	1.1
	Massive	1.0
B. Cover to tunnel diameter ratio	**C/D_T**	**Fb**
	< 5	Not recommended
	5 – 10	1.2
	10 – 20	1.15
	> 20	1.1
C. Presence of Structures		**Fc**
Within 2 D_T of distance Consider semi-lined section	Yes	1.1
	Perpendicular to surface	1.2
	No	1.0

Note: This approach was developed only based on numerical modelling

Rancourt (2010)

Pressure Tunnel/Shafts – Overdesigning

Transient Hydraulic Loading – overdesigning of Lining (reinforced concrete lining)

- Schleiss (1986 & 1997) and Fernandez (1994) did not consider the transient loading for designing of the reinforced concrete lining.

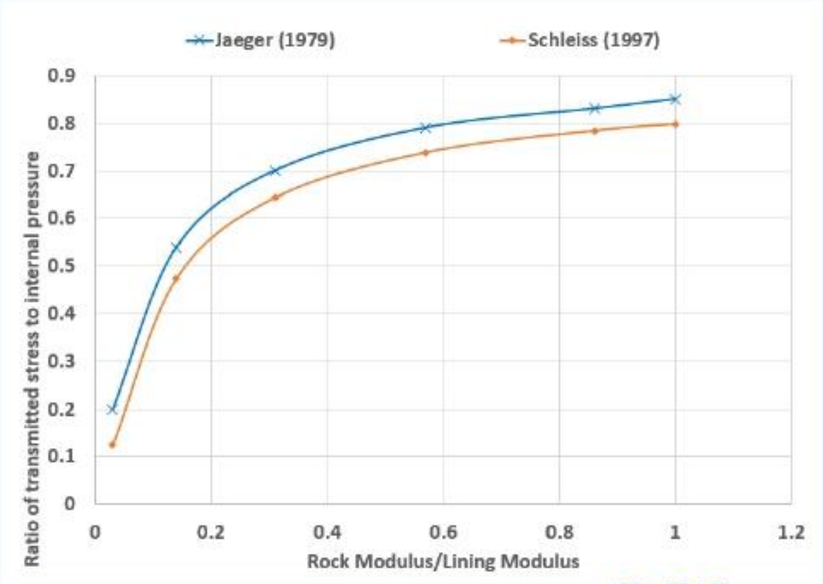
- The operation surges are more important for the steel lining. It can be also part of concrete lining design and unlined tunnel stability assessment if the surges are very frequent (which is the case in new pumped hydro projects) but not for HJ assessment.

- The elastic modulus of rock mass (as supporting element for the reinforced concrete) increases with the loading rate. If transient loading is considered for lining design, don't use conservative elastic modulus for the rock mass.

$$\sigma_t = \frac{(p_a - p_i)(2 - v_c)}{3(1 - v_c)}\left[\frac{1 + \frac{r_a^2}{r_i^2}}{\frac{r_a^2}{r_i^2} - 1} + \frac{1 - \frac{r_i(1 + v_c)}{r_a(2 - v_c)}}{1 - \frac{r_i}{r_a}}\right] + \frac{2P_{fa}}{1 - \frac{r_i^2}{r_a^2}}$$

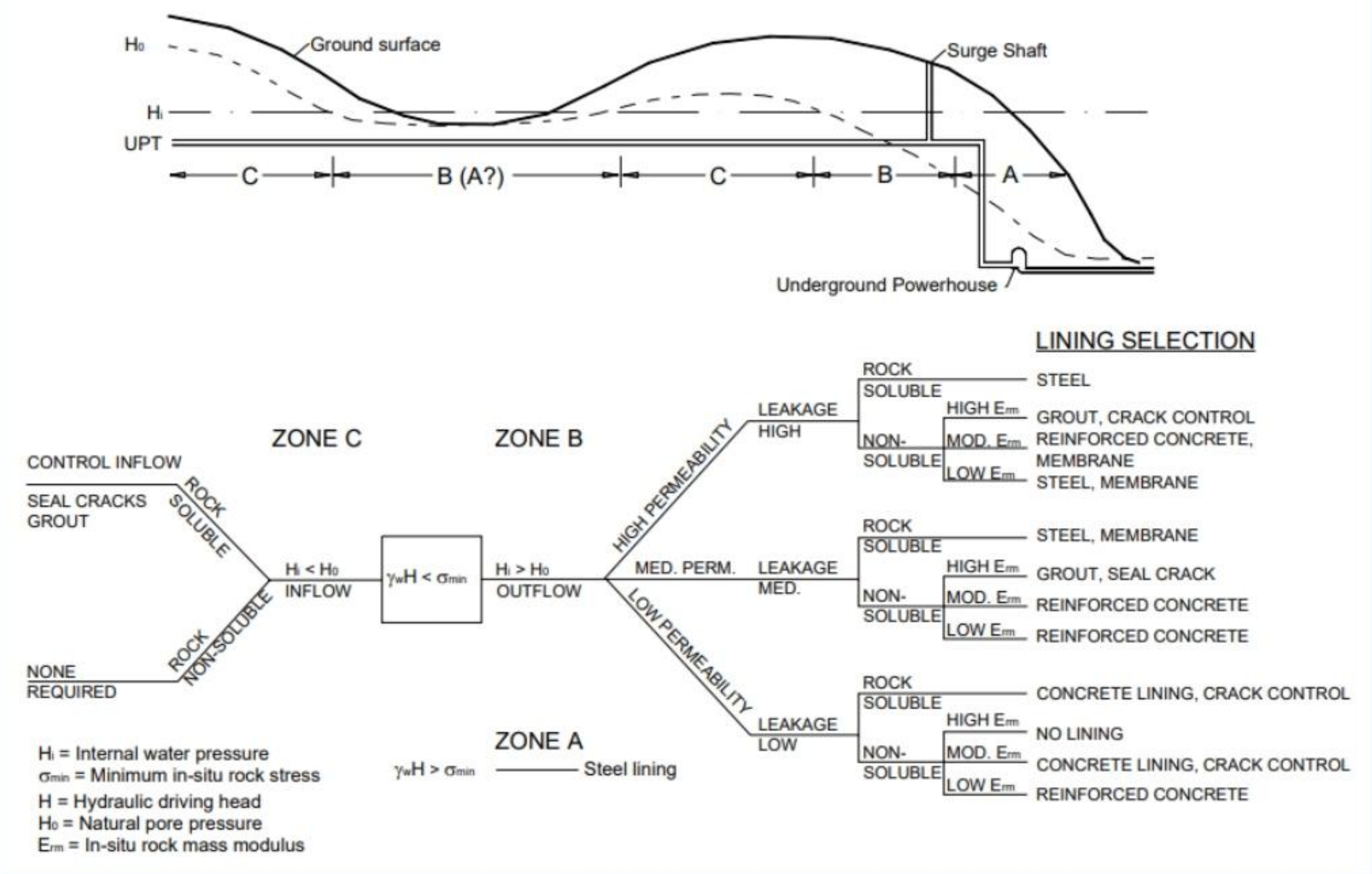
Schleiss (1986 & 1997)

stiffer rock masses will absorb a larger portion of the differential water pressure, reducing the likelihood of lining cracks



Pressure Tunnel/Shafts

Lining – Type? When?

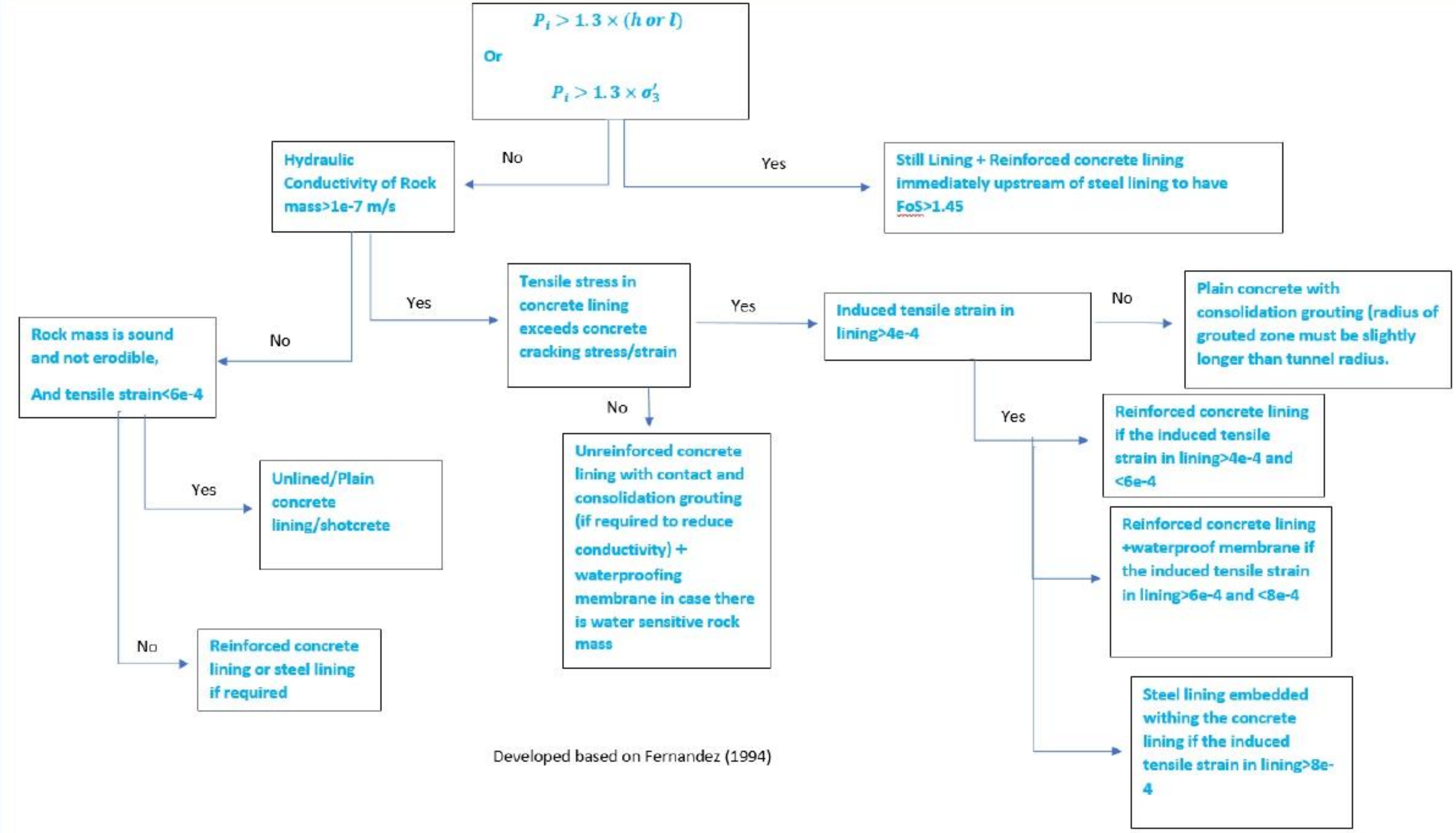


Merritt (1999)

Soluble rocks terms include erodible rock too

Pressure Tunnel/Shafts

Lining – Type? When?



Zoorabadi (2023)

Conclusions:

- Pressure tunnels/shafts are main parts of hydropower and pumped hydro projects.

- The longer the length of wet-tunnels including pressure tunnel/shaft, the greater the risk of unexpected challenges, delays, and cost overruns.

- Hydrostatic pressure is the main source of potential HJ/HF in rock mass. Grouting to close the open joints in few meters of tunnel surface significantly reduces the penetration of the mass oscillations.

- A factor of safety between 1.3 to 1.5 is considered sufficient for hydraulic jacking (HJ) or hydraulic fracturing (HF) under hydrostatic loading. For mass oscillation loading, a factor of safety of 1.1 is deemed adequate.

- Stiffer rock masses tend to absorb more of the differential water pressure, which helps reduce the risk of cracking in the lining. When accounting for transient loading in the lining design, avoid using overly conservative values for the rock mass elastic modulus (static modules).

THANK YOU

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