Power Waterway Design - Introduction

Workshop on

Penstocks, pressure shafts & pressure tunnels

European ICOLD and ITCOLD

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Content

1. Vertical and horizontal layout
2. Loading acting in operation
3. Design and applicability of different lining methods
   - Unlined and shotcrete lined systems
   - Concrete and reinforced lining
   - Concrete lining with seal
   - Steel penstock
4. Conclusions

Power Waterway

Transfer of power water from reservoir to powerhouse and into the downstream reservoir/river

Main parts of power waterway (upstream of the PH):

- Intake structure with trash rack
- Gates (shaft, cavern, intake building, etc.)
- Headrace tunnel
- Surge tank
- Penstock
- Auxiliary parts (sand trap, manifold, adits, inspection and safety equipment)

Main parts of power waterway (downstream of the PH):

- Turbine outlet gates
- Open channel or outlet tunnel
- Auxiliary parts (outlet gates, manifold, etc.)

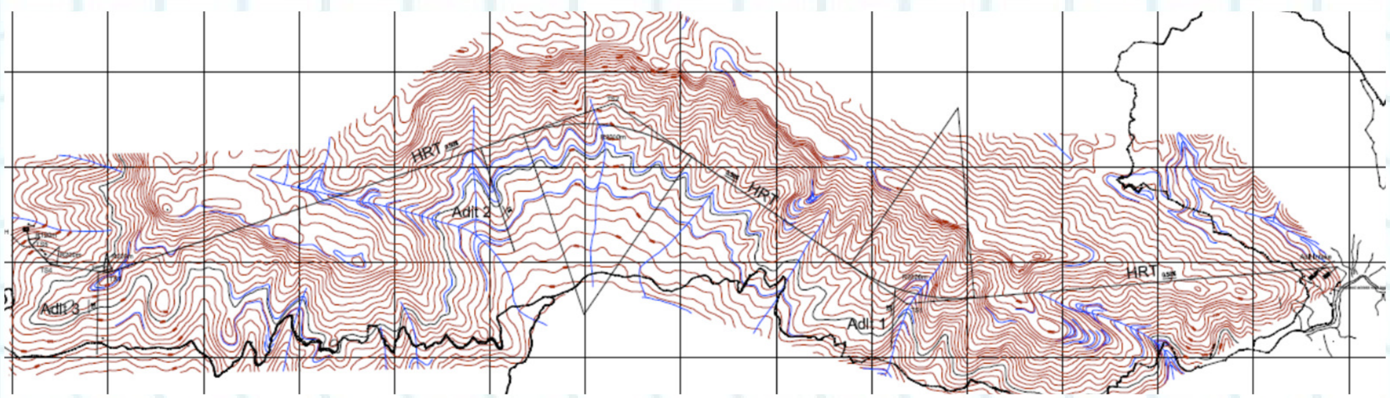
Power Waterway – Layout

Horizontal alignment:

- Topography
- Geology
- Hydrogeology
- Constraint points (intake, powerhouse, adit, etc.)
- Power waterway size
- Construction method (TBM, NATM, etc,)

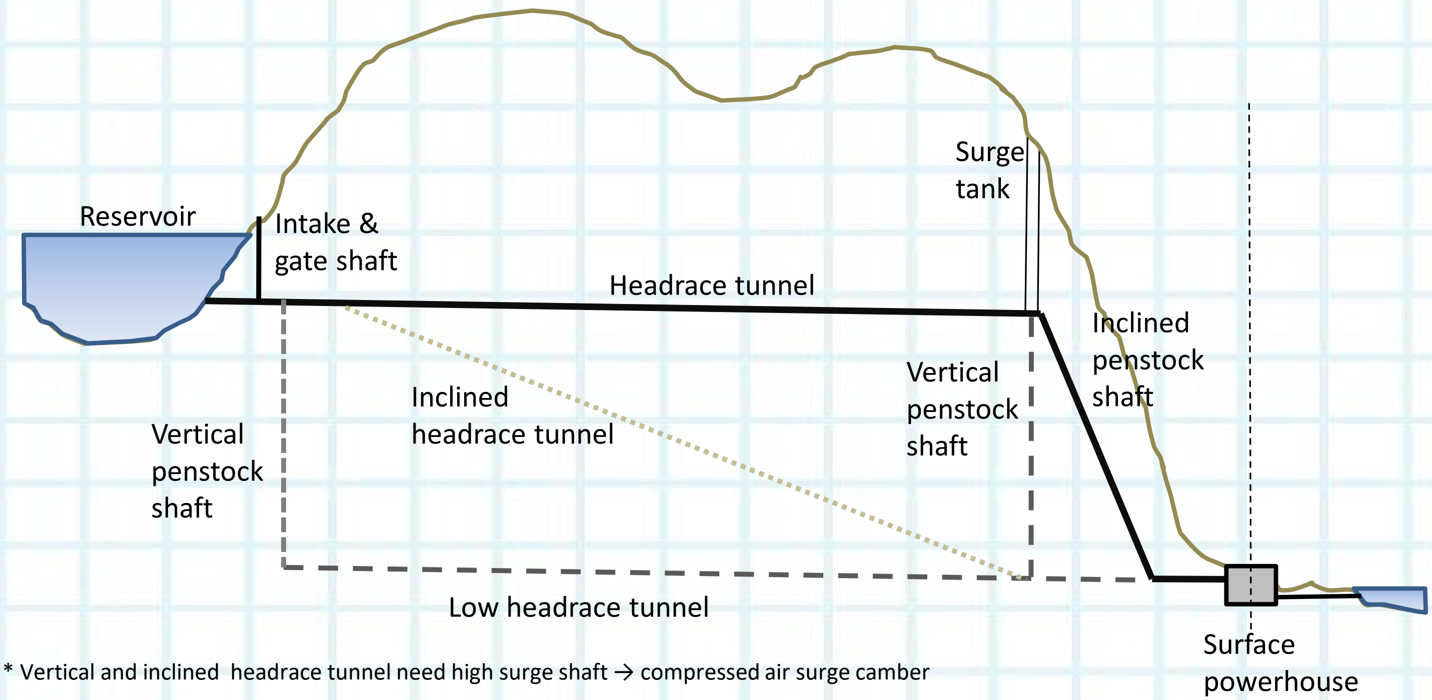
Vertical alignment:

- Inclination for the traffic in the tunnel (rails, rubber vehicles, etc)
- Drainage during construction
- Drainage of power water for inspection/maintenance
- Aeration and de-aeration during empting and filling



Power Waterway – Schemes

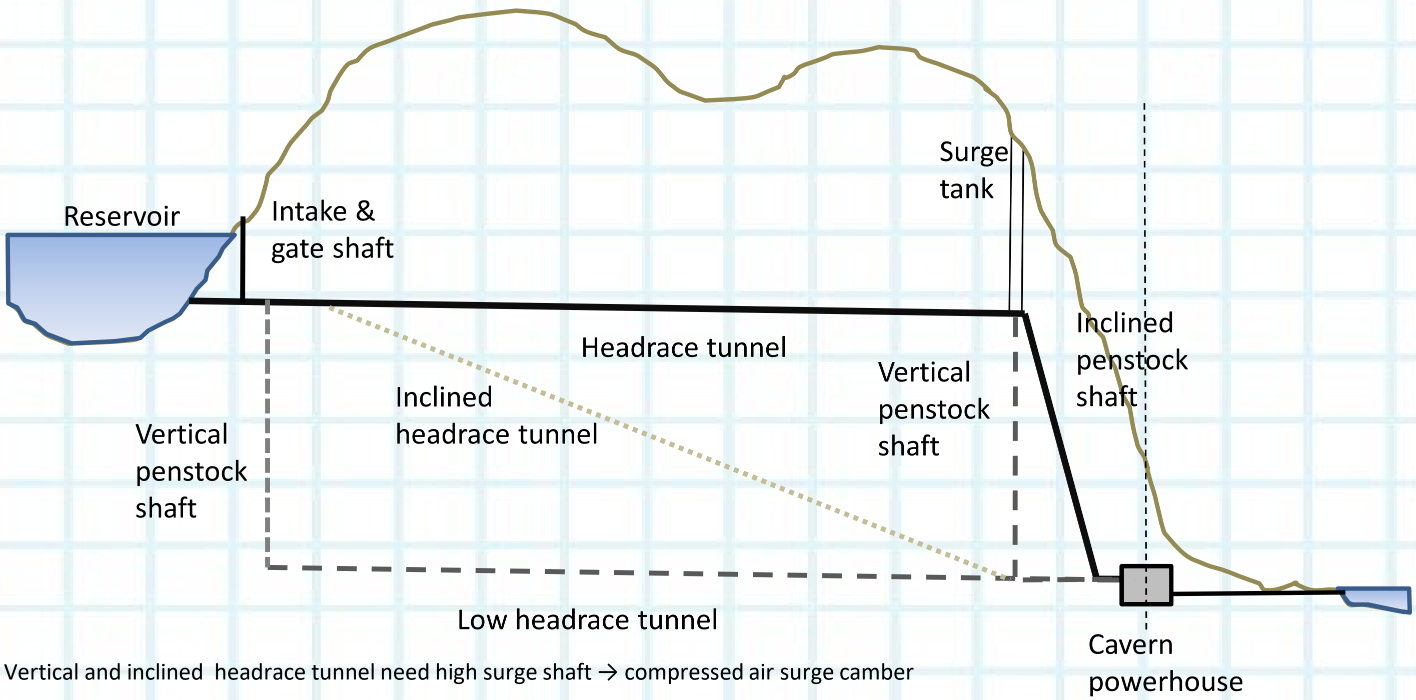
Main scheme types (downstream PH situated on surface)



* Vertical and inclined headrace tunnel need high surge shaft → compressed air surge camber

Power Waterway – Schemes

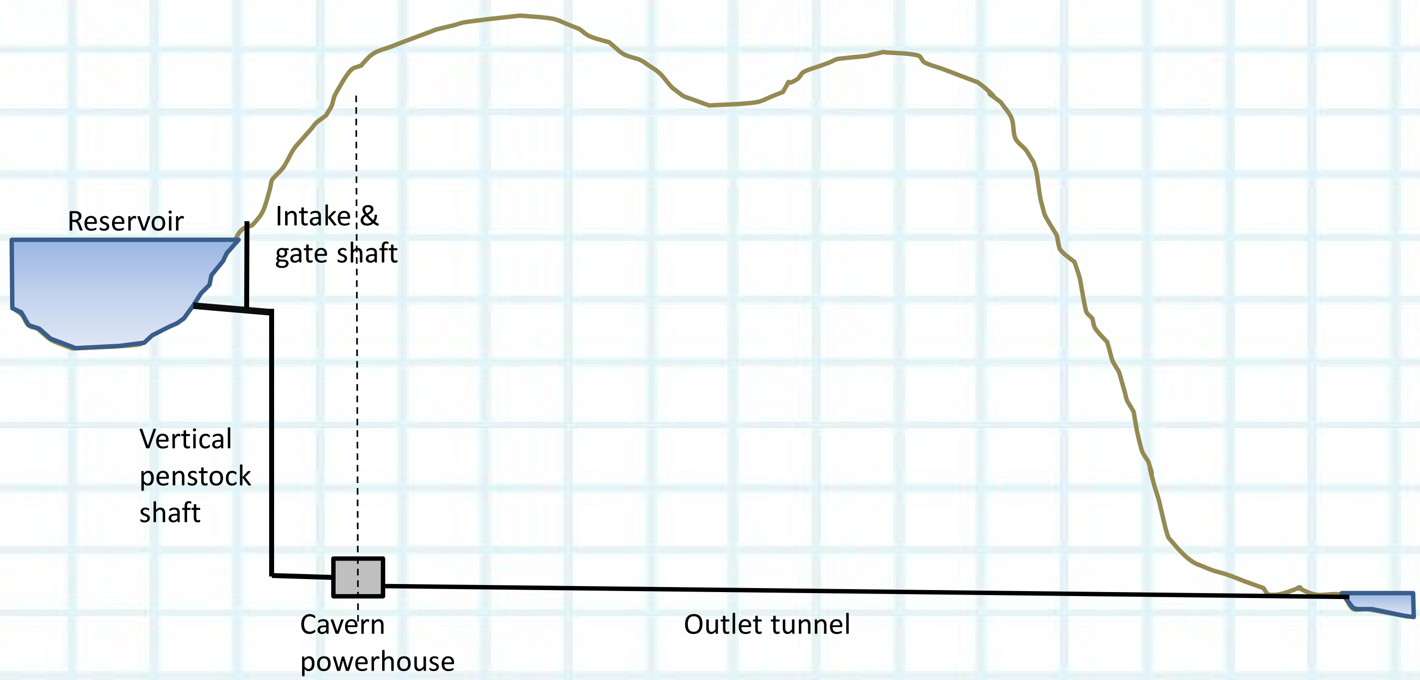
Main scheme types (downstream PH situated in cavern)



* Vertical and inclined headrace tunnel need high surge shaft → compressed air surge camber

Power Waterway – Schemes

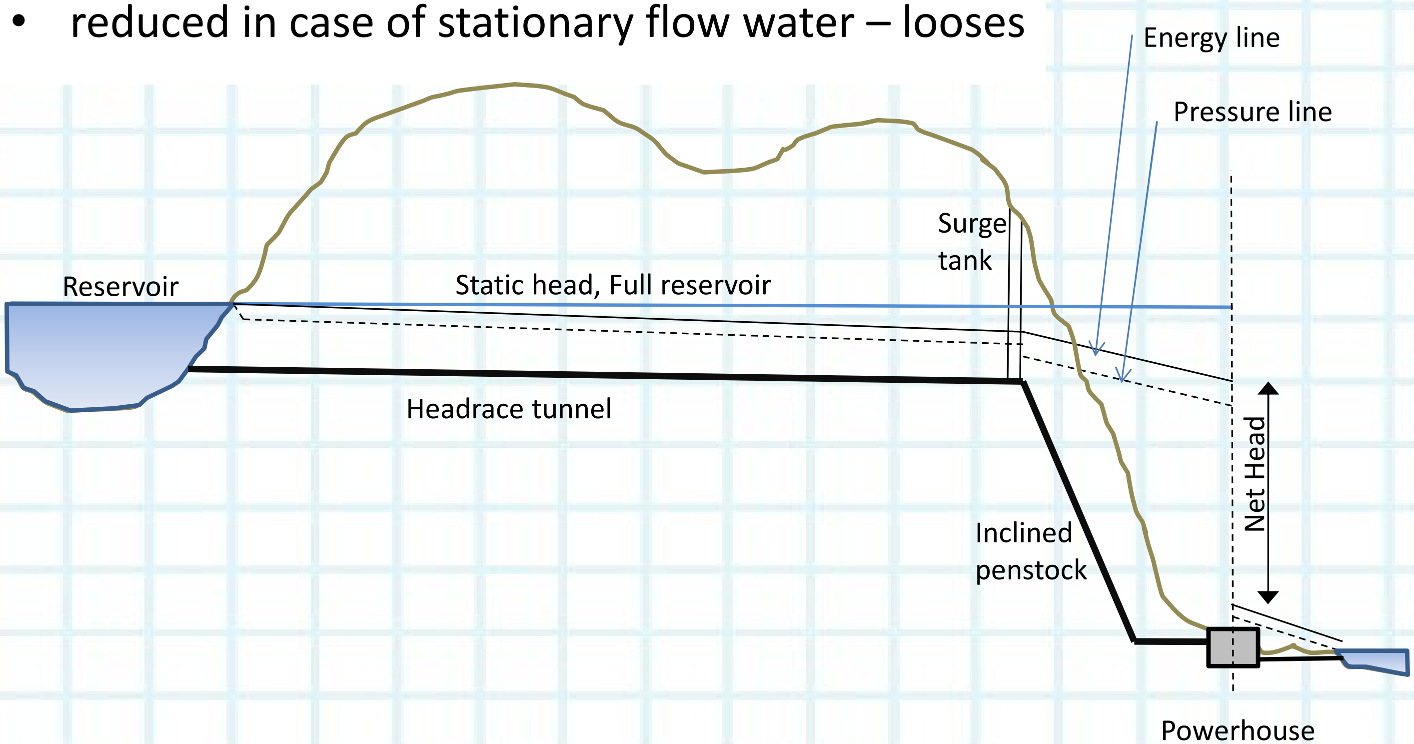
Main scheme types (upstream cavern powerhouse)



Power Waterway – Loading

Static water pressure

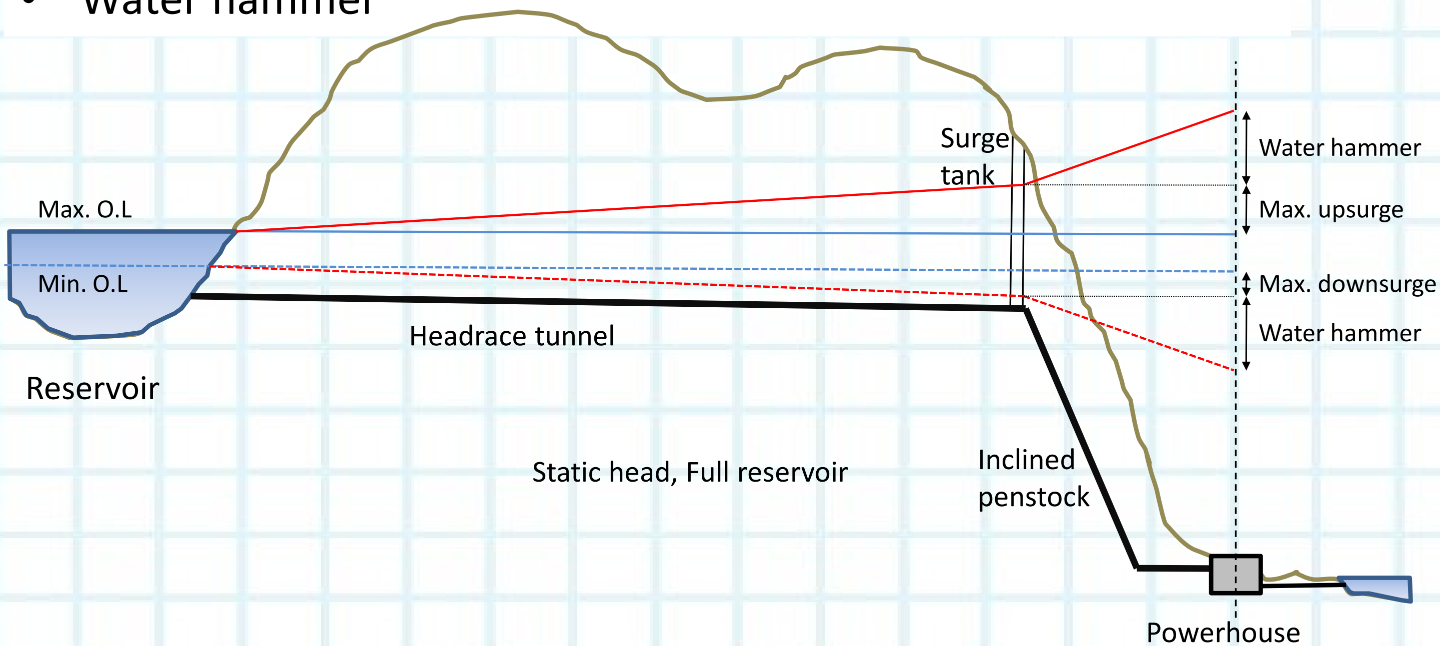
- defined by reservoir level by still stand
- reduced in case of stationary flow water – looses



Power Waterway – Loading

Dynamic water pressure – caused by changing of the flow condition (opening or closing the turbine valves

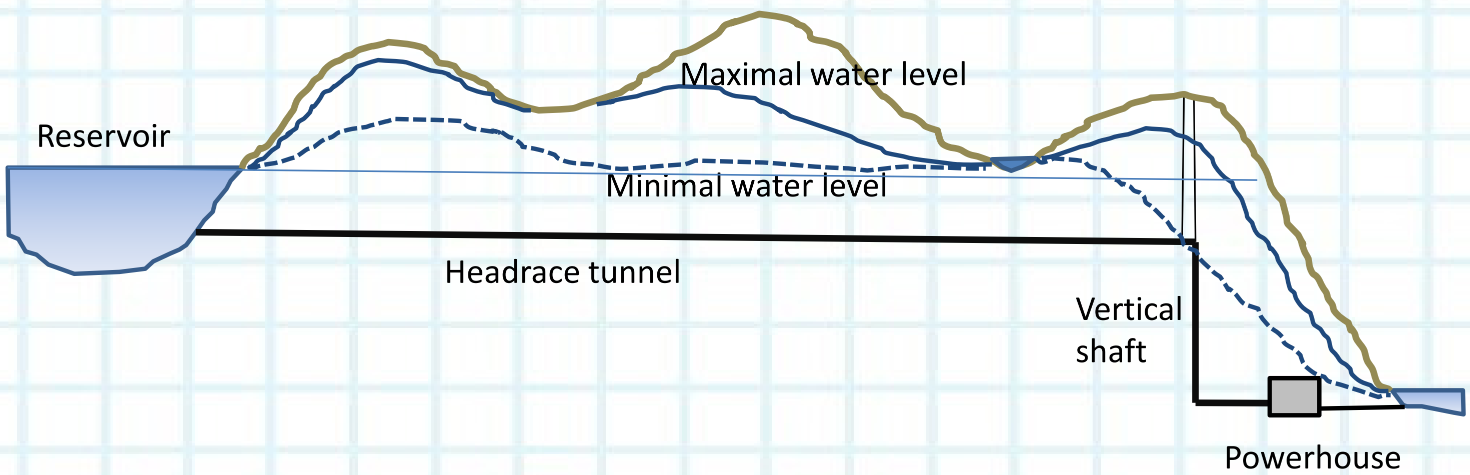
- Surge tank oscillations
- Water hammer



Power Waterway – Loading

Groundwater level – hydrogeology

- Minimal water level – if known – reduces design internal pressure
- Maximal water level – crucial for empty power waterway

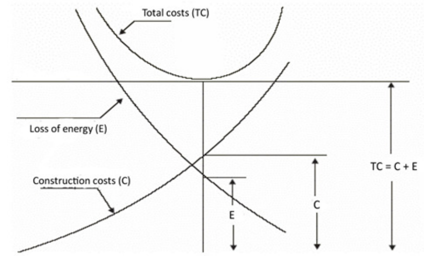


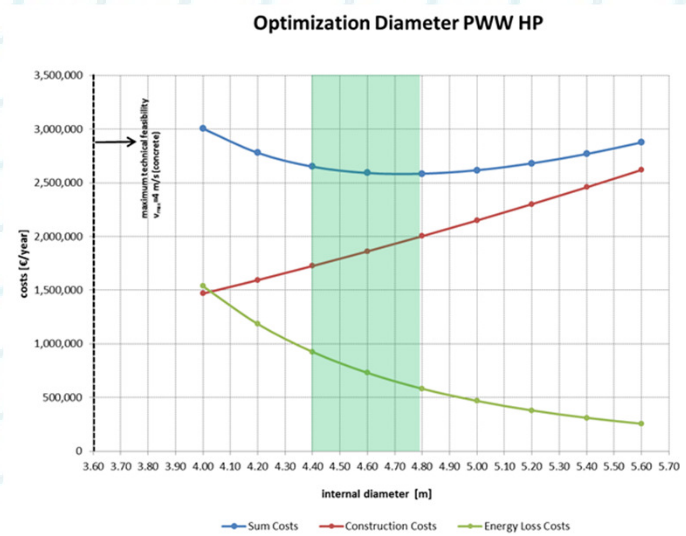
Design – Optimal size

Costs
- Investment (construction, contingencies, interests…)
- Maintenance

Hydraulic Losses
- Power
- Energy

Minimizing





Practical velocities in PWW:

Concrete lined tunnels:	3-4 m/s (max. 6 m/s)
Concrete shafts:	5-6 m/s (max. 6 m/s)
Steel lined tunnels:	5-6 m/s (max. 10 m/s)
Steel lined shafts:	6-7 m/s (max. 10 m/s)
Tailwater tunnels:	1-3 m/s (max. 5 m/s)
Bottom outlet tunnels :	max. 10 m/s
Diversion tunnels:	10 m/s (max. 20 m/s)
Valves and entrance to turbines:	15-20 m/s

Hydraulic design – Head losses

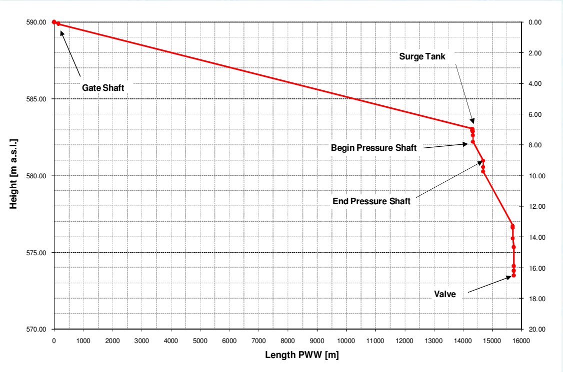
Head loses in the PWW:

- Local losses: trash rack, shape and size change, gates, curves, bifurcations

$$h_v = \xi \frac{v^2}{2g}$$

- Continuous losses – linear along constant geometry of PWW section
- Total losses

$$\sum h_v = \alpha Q^2$$

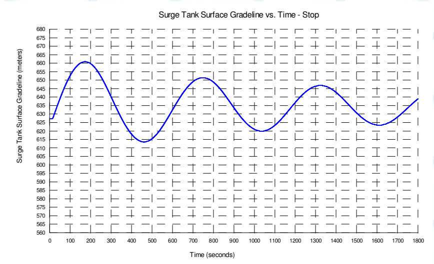


Transient flow:

Transient flow is a fluid flow where the velocity and pressure changes over time. Transient flow usually occurs during:

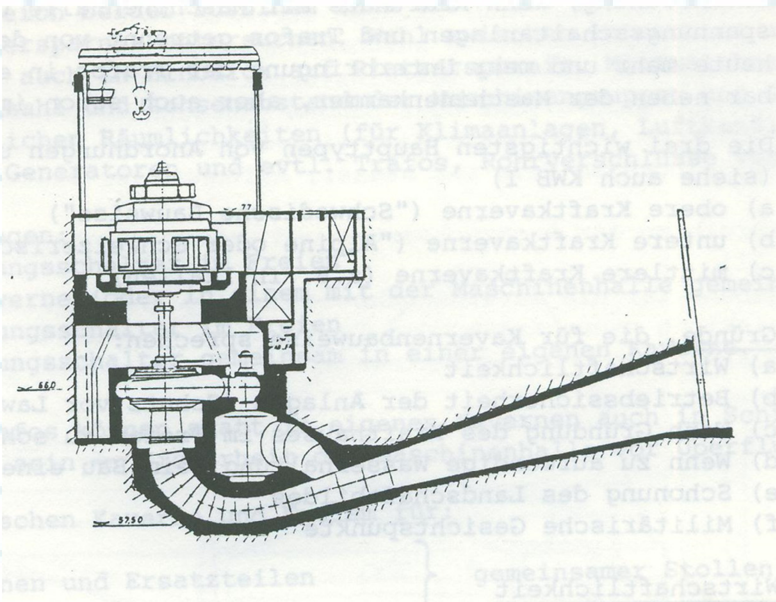
- starting or stopping of a pump or turbine,
- changing in discharge during operation
- opening or closing of a tank, or
- simple changes in tank levels.

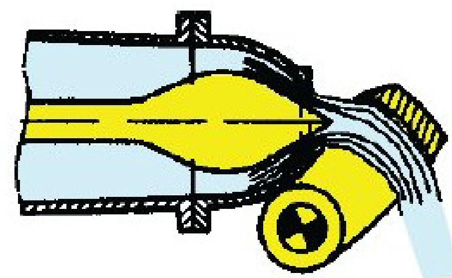
Transient flow usually refers to **surge** or **water hammer**.



Reduction of surge effect

The surge effect **can be reduced** if requirements for opening/closing (start/stop) of machine are decreased. In case when such decrease is not possible (operation) the by-pass valve (Francis turbine) or deflector system (Pelton turbine) can be installed.





Water jet fully deflected

Tunnel flow problems – Presence of air in PWW

Presence of air in tunnel under pressure can be source for grave nuisance. **Air may enter and accumulate in the tunnel** by following aspects:

- **During filling** air may be trapped along the crown at highest points or at changes in cross-sectional size or shape
- Air may be **entered at intake** either by vortex action or by means of hydraulic jump associated with a partial gate opening
- Air dissolved in the flowing water may come out of solution as a result of decreasing in pressure along the **tunnel - cavitation**

Prevention measures:

- Shallow intakes are likely to induce air being sucked in. **Vortices** should be avoided, if avoiding is impossible they should be suppressed by floating baffles, hoods or similar devices
- The **water velocity** along tunnel should either remain constant or increase towards the outlet end.
- No point along the tunnel alignment with **negative pressure** should develop
- **Partial gate openings** that can result in hydraulic jumps should be avoided
- **Traps or pockets** along the crown have to be avoided

Tunnel flow problems – High water pressures

Internal water pressure:

Problem: Fast opening and closing of the valve causes high dynamic pressures in the system

Run-off the Francis turbine with sudden flow clogging

Solution: Design of a surge tank in the power waterway system

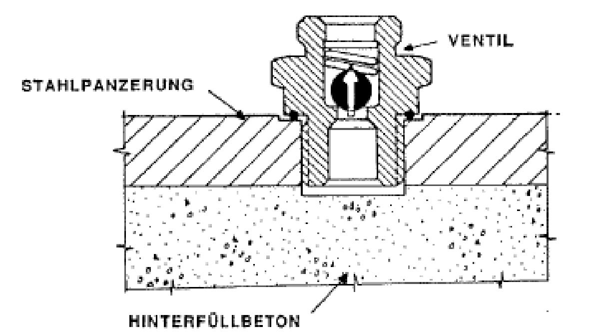
Longer opening and closing time of the valves

By-pass valve before turbine

Groundwater (external) pressure:

Problem: By empty power waterway external water (groundwater) pressure can destroy the lining (buckling of steel penstock, but also failure of concrete lining)

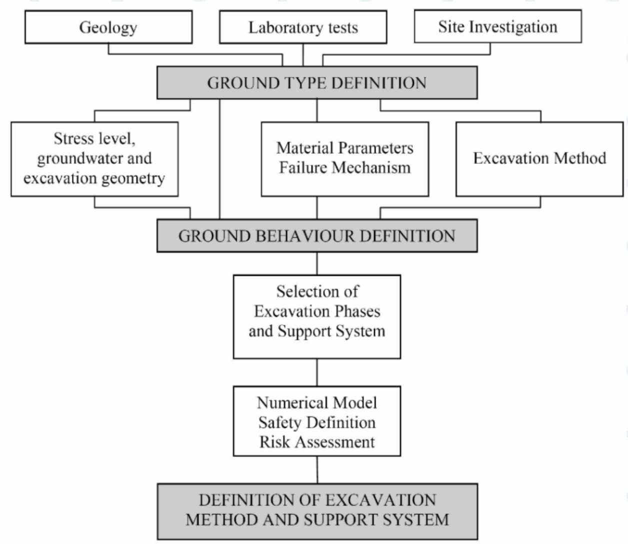
Solution: Installation of the pressure relive valves in the lining. The valves open by certain external pressure and allow water flow in the tunnel releasing the pressure behind the lining

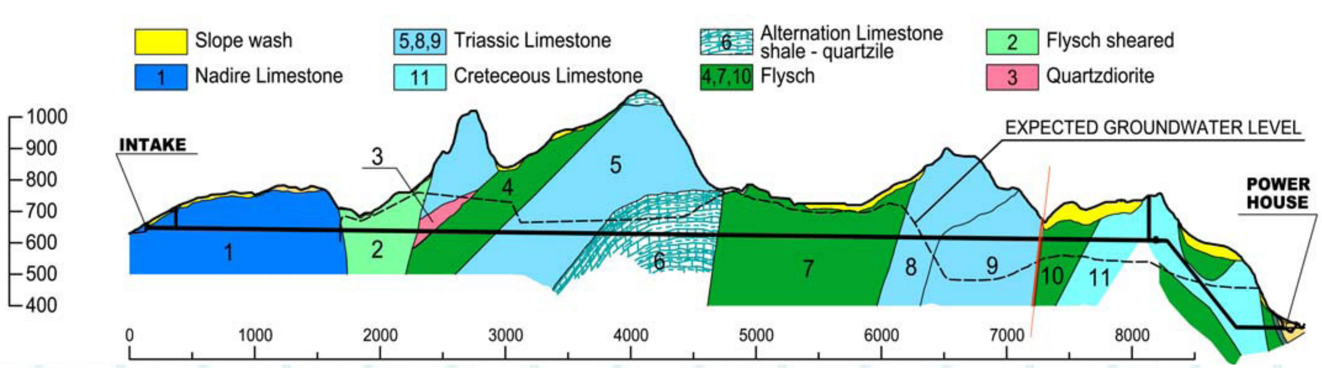


Geology

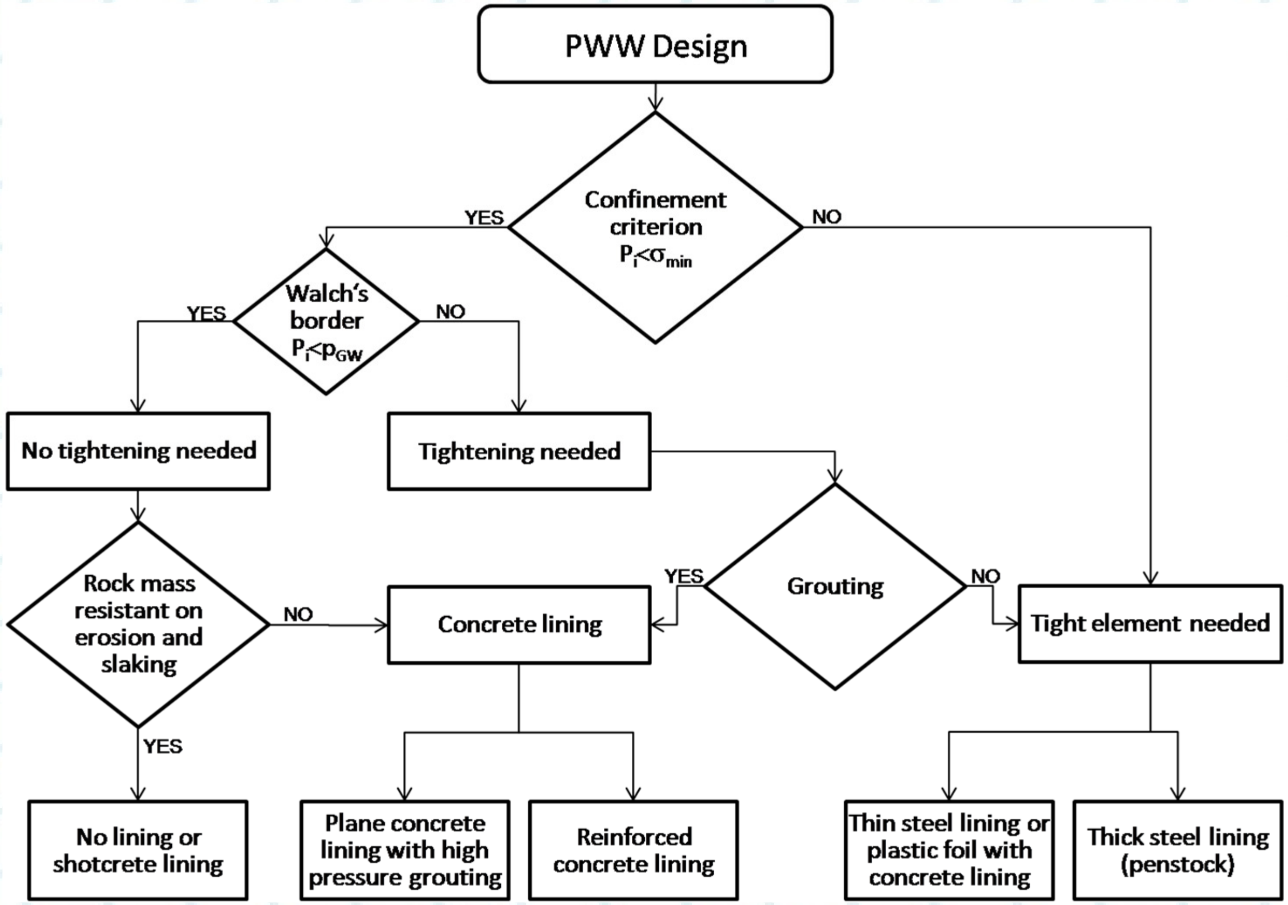
Excavation and support:
- Rock mass strength
- Joint systems
- Water inflow

Final lining design:
- Rock mass stiffness
- Permeability
- Min. and max. groundwater level
- Minimal primary stress





Final lining design – decision flow chart



Structural design – Confinement criterion

Water leaked out of tunnel can cause opening of the existing joints in the surrounding rock mass, especially in case of low normal stress on the joints. Result: more leakage and possible instabilities of the rock mass caused my leaked water and pore pressures on joint

Different criteria

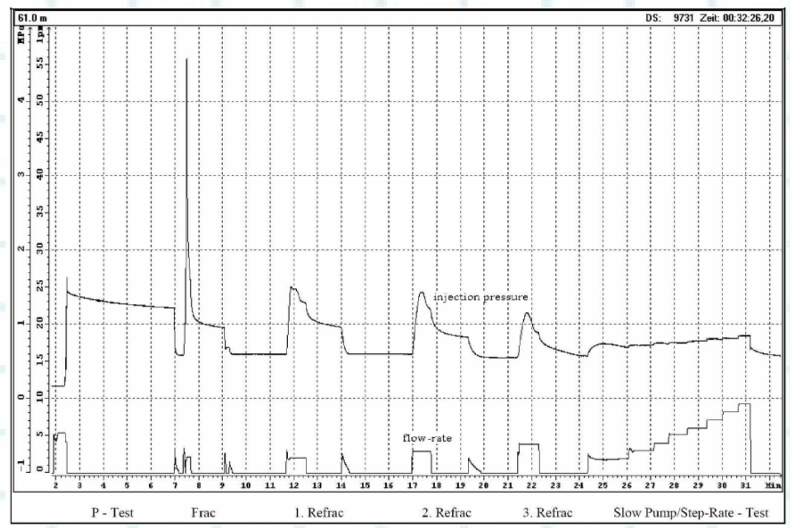
- Vertical criterion, Snowy Mountain, Norwegian, Schleiss …
- Assumptions and limits
- Suggested criterion

$$SF = \frac{\sigma_{\min,rock}}{\sigma_{\max}(p_i)} = $$

$$= \frac{\gamma_r h_r k_0}{\gamma_w h_w} \xrightarrow[k_0=0.5,\gamma_r=26kN/m^3]{} \frac{1.3h_r}{h_w}$$

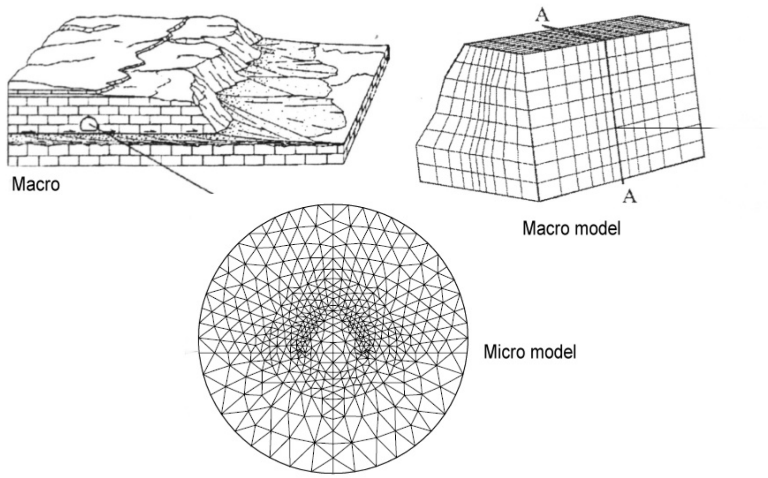
Primary stress determination

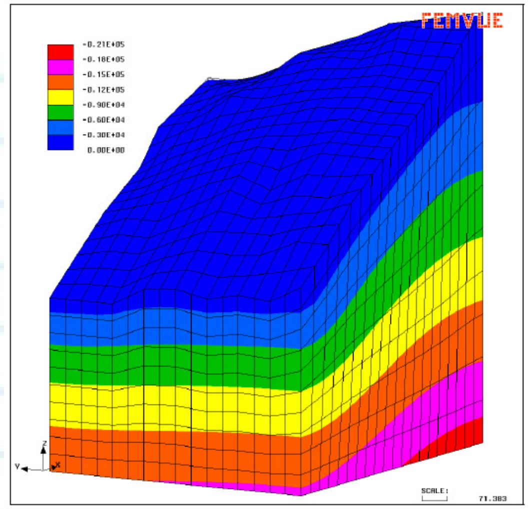
- Flat jack, over-coring methods
- Hydro-fracturing/hydro-jacking



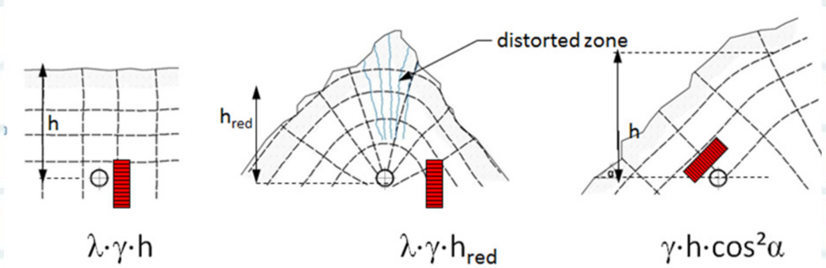
Structural design – Confinement criterion

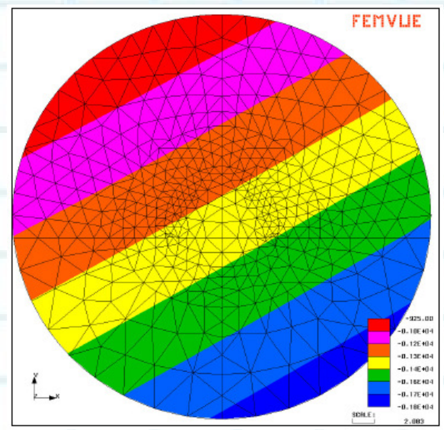
Stress mapping method





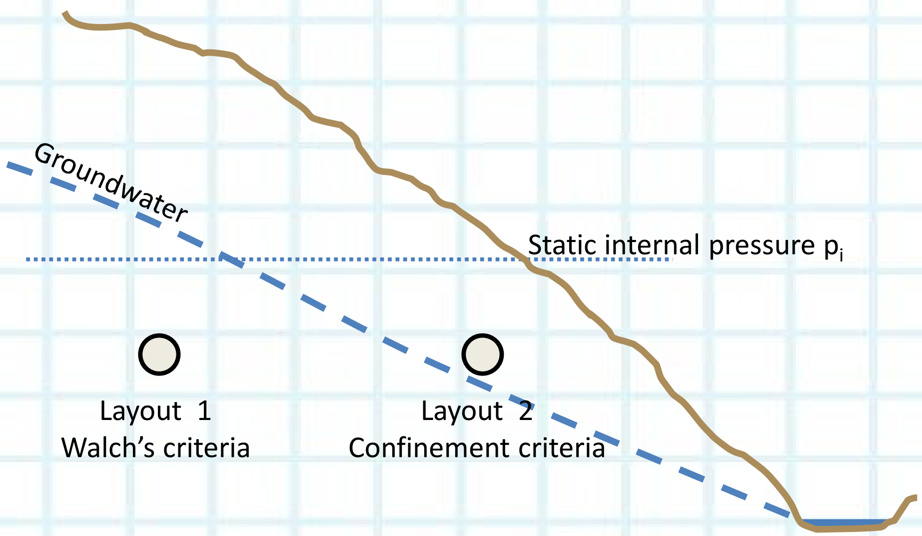
Influences on minimal primary stress





Structural design – Walch's border

Walch's criteria: $p_{GW} > p_i$ tight tunnel lining is not necessary, no loosing of power water by leaking out in operation



PWW layout deeper in the mountain with higher groundwater level can be more economical (regardless possible longer alignment and adit an more problems by excavation) because no or less intense grouting around the tunnel is needed

Rock mass resistance – Erosion and slaking

Surrounding rock mass has to be resistant on erosion, slaking and washing out of the rock joints.

Erosion a mechanical process of destroying the rock surface by linear or areal removal of the surface rock particles.

Slaking is the process in which earth materials disintegrate and crumble when exposed to moisture.

In case of joints and discontinuities filled with claylike or sandy material these can be washed out.

ASTM D 4644

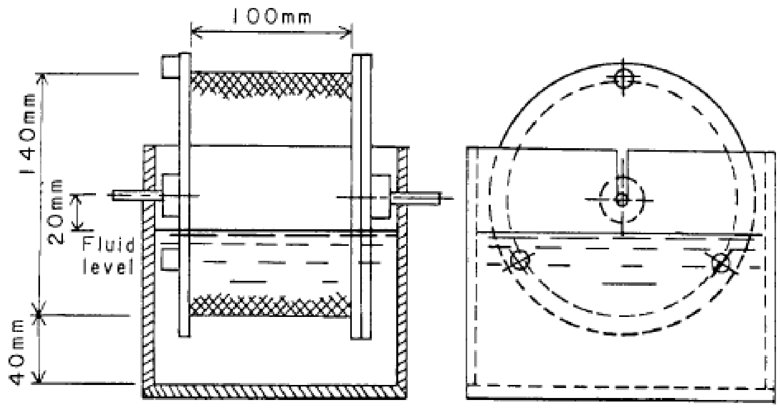


FIG. 1 Critical Dimensions of Slake Durability Equipment

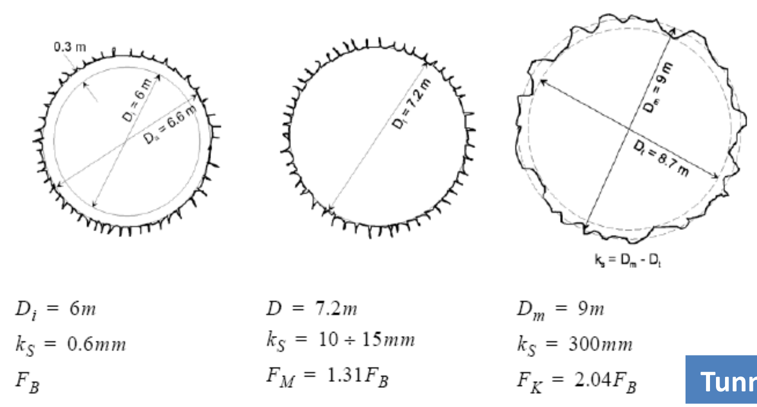
Virtually unchanged sample after test

Exclusively small fragments retained

Unlined and shotcrete lined tunnels

- Rock mass must be resistant on slaking and erosion, no joint filling that can be washed out
- Lining is not tight – water can leak in and out of tunnel
- Rough tunnel surface – need bigger tunnel size

Concrete lined tunnel | TBM excavated unlined tunnel | Conventional excavated unlined tunnel



Minor: Wasserbau, Leitungen, 2004

$$A_1 / A_2 = (M_2 / M_1)^{0.75}$$

A tunnel area

M Manning's number

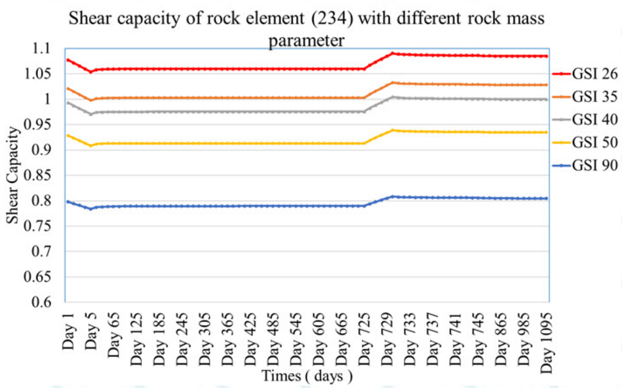
$$\Delta h = \frac{Q^2}{M^2 A^2 R^{4/3}}$$

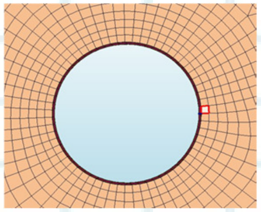
Tunnel surface	Manning's number
Unlined rock (drill and blast)	25-40
Shotcrete lining	45-55
Concrete lining	62-83
Steel lining	71-100

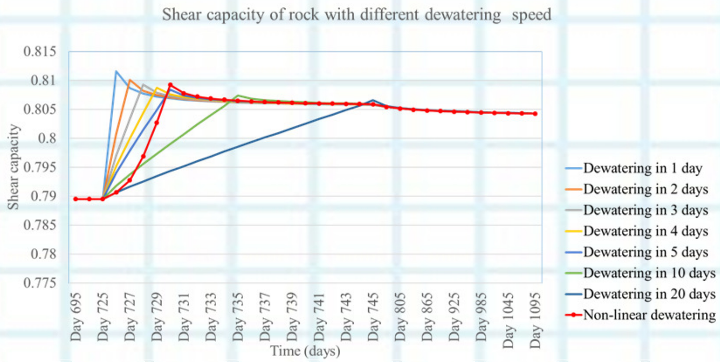
Unlined and shotcrete lined tunnels – Fast dewatering

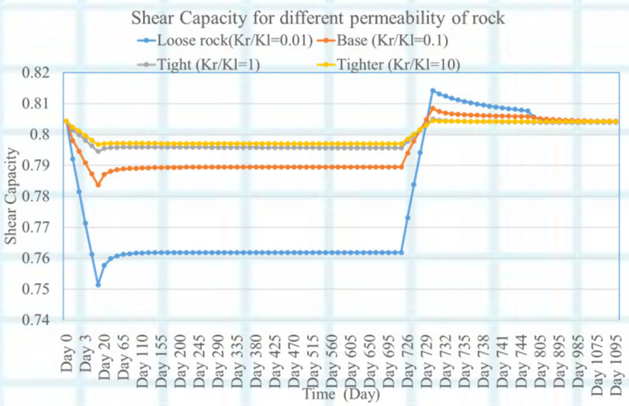
Unlined and shotcrete lined tunnels – Numerical modelling

Coupled stress – transient seepage analysis, Software DIANA FEA

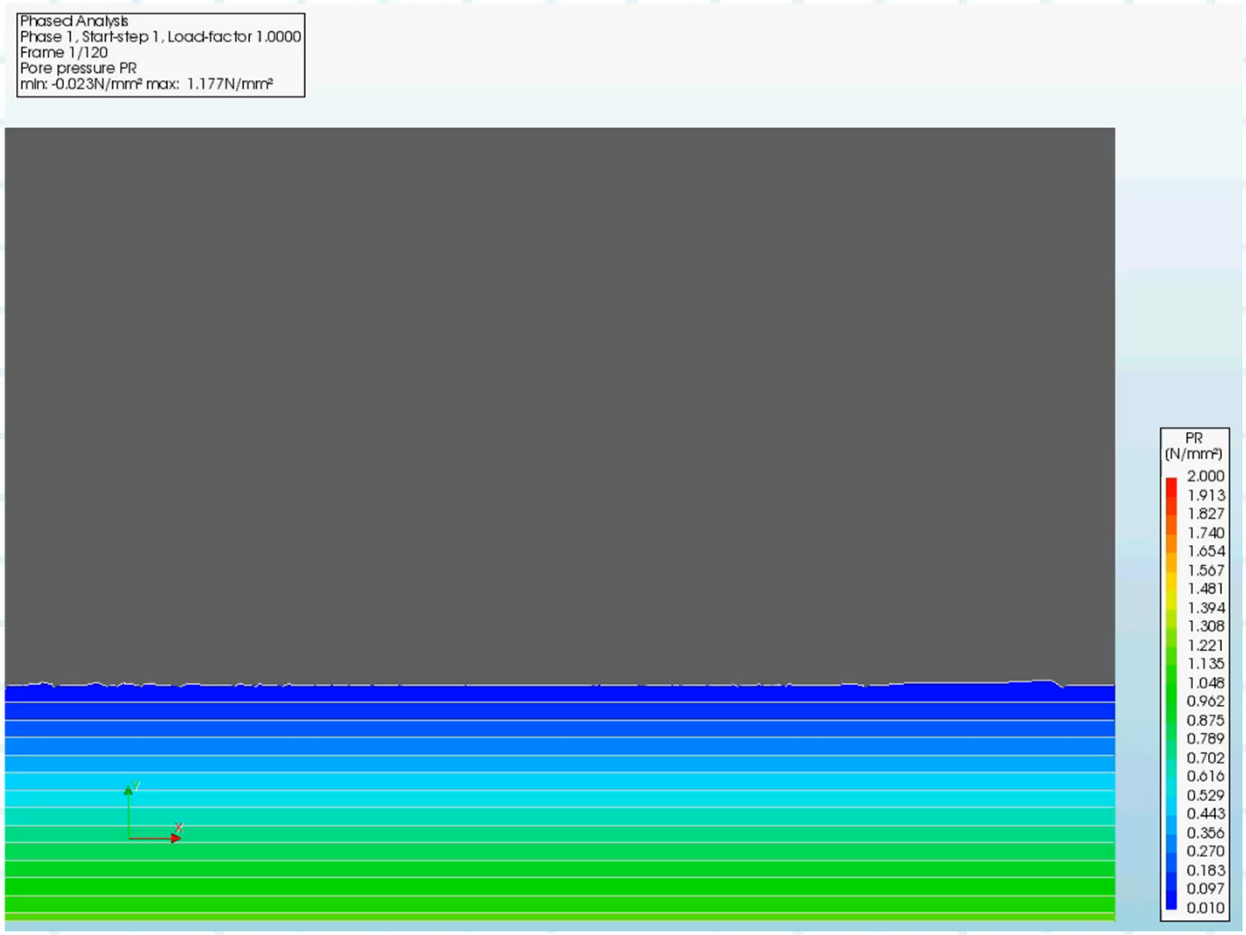








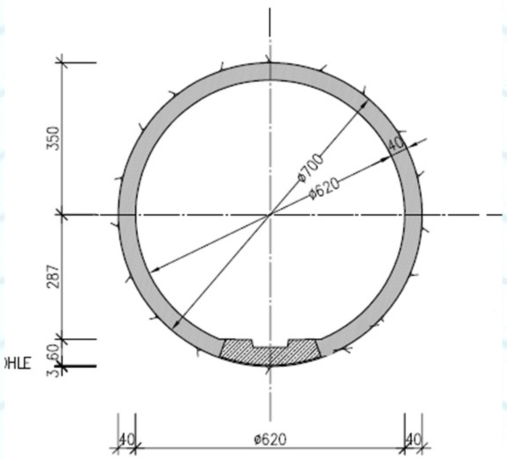
Unlined and shotcrete lined tunnels – Numerical modelling



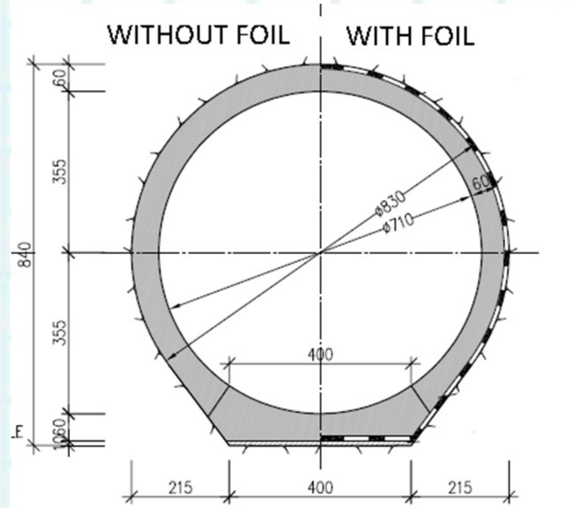
Concrete lined tunnels

Less head loss – smooth lining (steel formwork)
Technically tight – water leaking out = lost energy
– practical criteria: 1-2 l/s/km/bar (Schleiss, Laufer)
Lining thickness – approximately 5% of internal diameter (minimal 25 cm)

Pressure tunnel shape:



TBM - tunnel



NATM (drill & blast) - tunnel

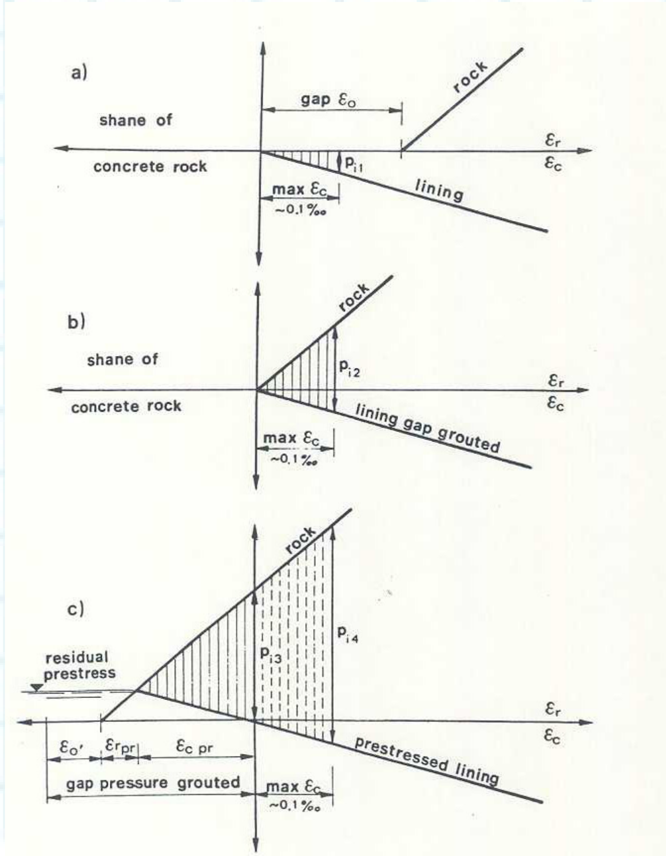
Plane concrete lined tunnels

Bearing capacity of concrete lining

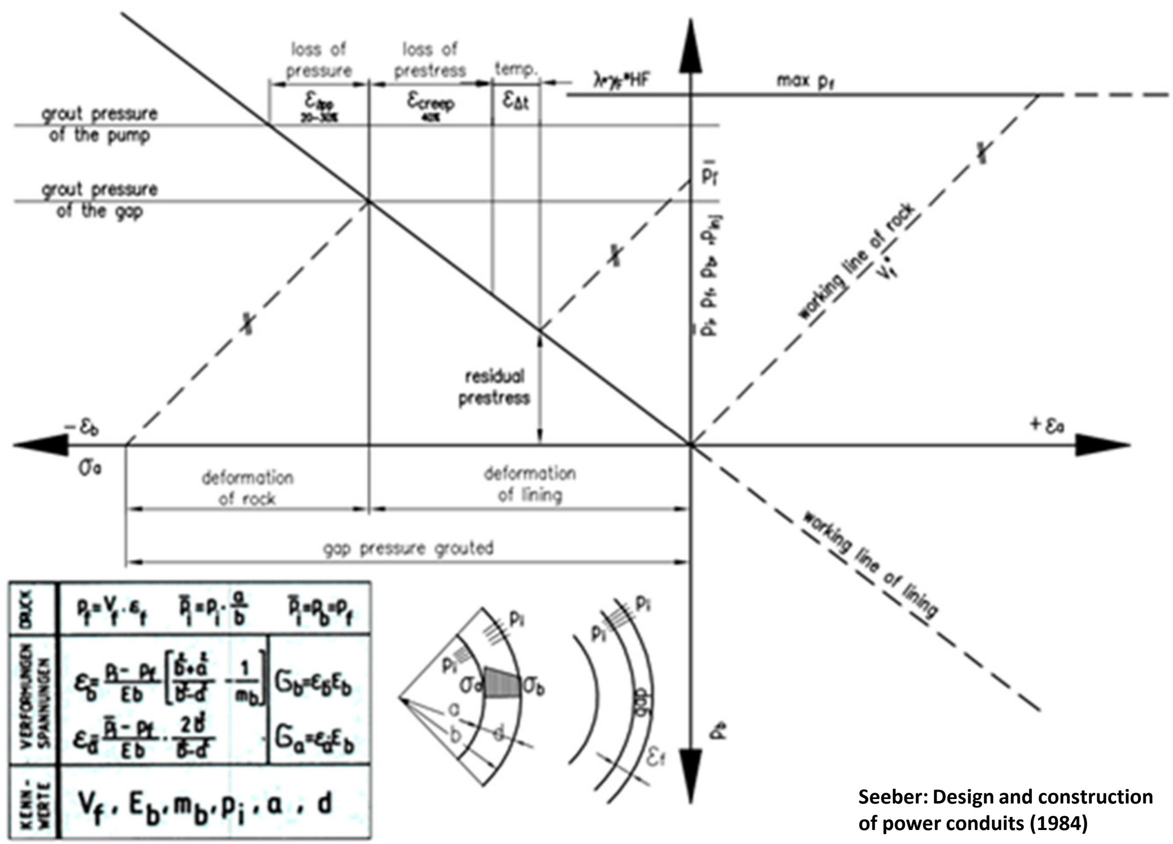
- After concreting shrinkage occurs causing gap opening between lining and surrounding rock mass - contact grouting reduce this gap
- During first filling lining will be cooled and temperature change caused additional shrinkage and gap development again
- System (a) with limited bearing capacity (tensile strength of concrete) is a result

Possible solutions:

- Not allow a gap to develop (b)
- Not allow tensile stress to develop (c)
- Reinforced concrete lining
- Combination of above



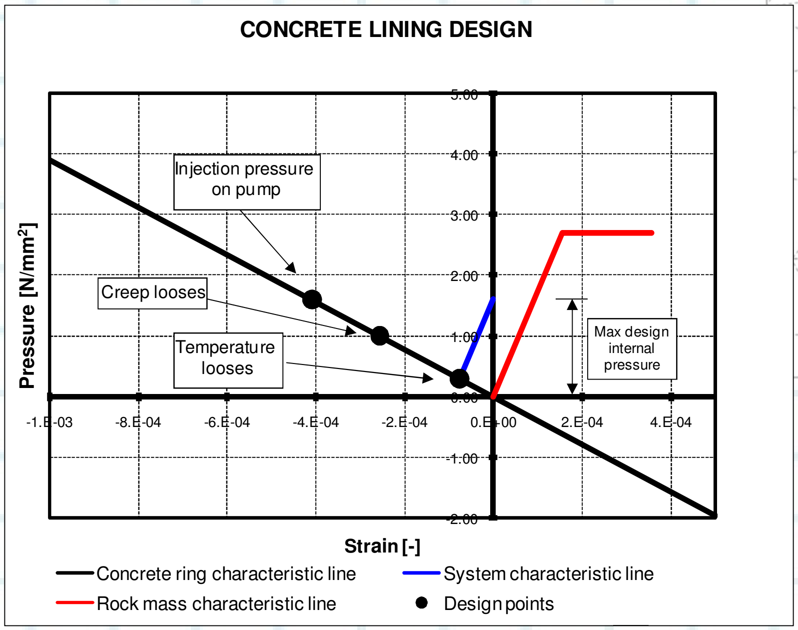
Plane concrete lining – Analytical solution (Seeber)

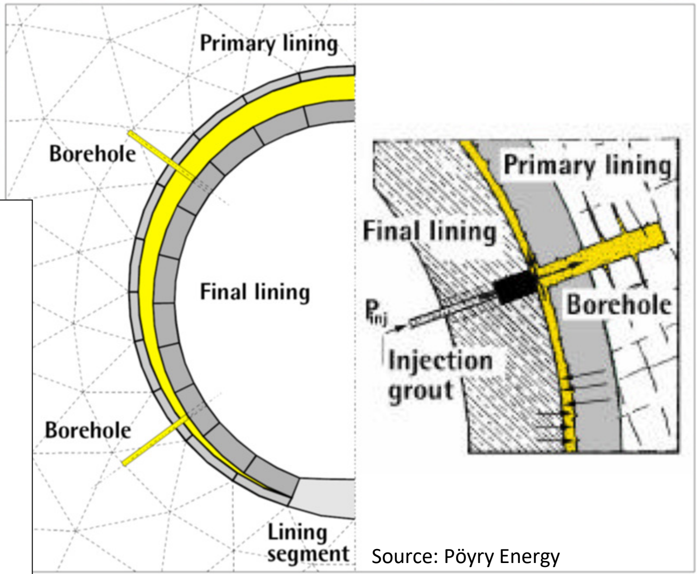


Seeber: Design and construction of power conduits (1984)

Plane concrete lined tunnels

Analytical solution - Seeber

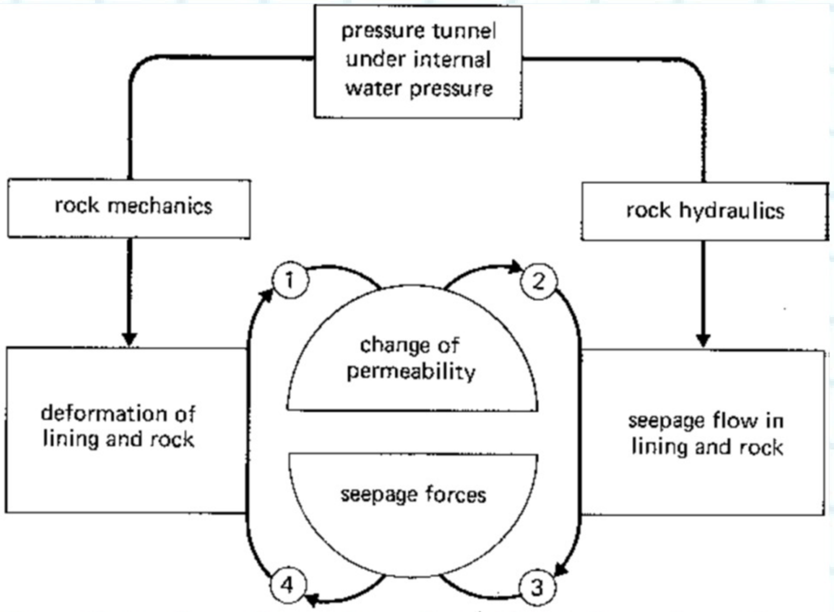


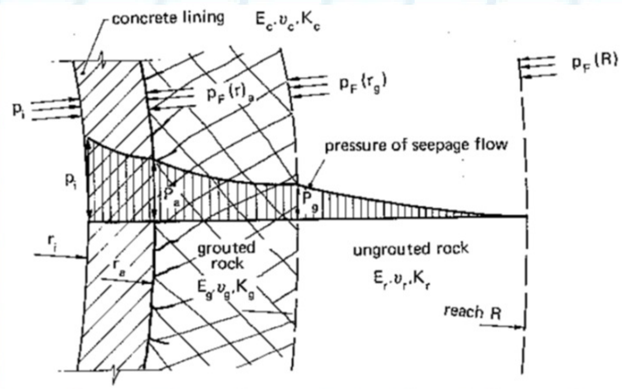


Source: Pöyry Energy

Reinforced concrete lined tunnels

Analytical solution - Schleiss





Assumption: full contact between surrounding rock mass and lining concrete after shrinkage and temperature change by first filling with cold water

Concrete lining with seal

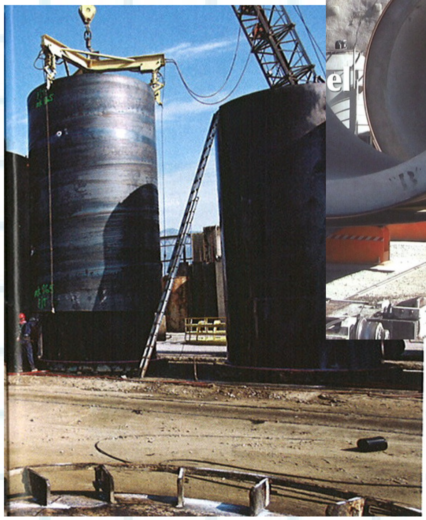
In case where the tightness of the concrete lining cannot be achieved by high pressure injections or reinforcement a tightening element has to be installed. The tightening element is normally (thick lined) steel penstock. As a transition between concrete lining and steel penstock a concrete lining with seal element is used. As a seal element:

- thin steel lining,
- plastic foil, or
- Fiberglas pipe is used.

These solutions are often called “sandwich” linings, because of their composition. Tightening element is not stiff enough to take external loadings and a concrete ring inside the sealing element gives additional necessary stiffness.

Concrete lined tunnels with seal – thin steel lining

Tightening is achieved by thin (5 – 10 mm thick) steel lining. Steel seal is designed to takes et least a part of internal water pressure.
Such thin steel pipe is often not stabile during transport and assembling. Additionally, thin steel has very limited buckling stiffness against external water pressure. Therefore during fabrication a thin (10-15 cm) concrete lining is cast in the pipe. The concrete lining takes external water pressure and protect steel against buckling. After putting on place and welding the connection part inside the pipe and backfilling with concrete is necessary.
After installation through prepared grouting holes consolidation grouting (with pre-stressing effect) is performed.



Concrete lined tunnels with seal – plastic foil

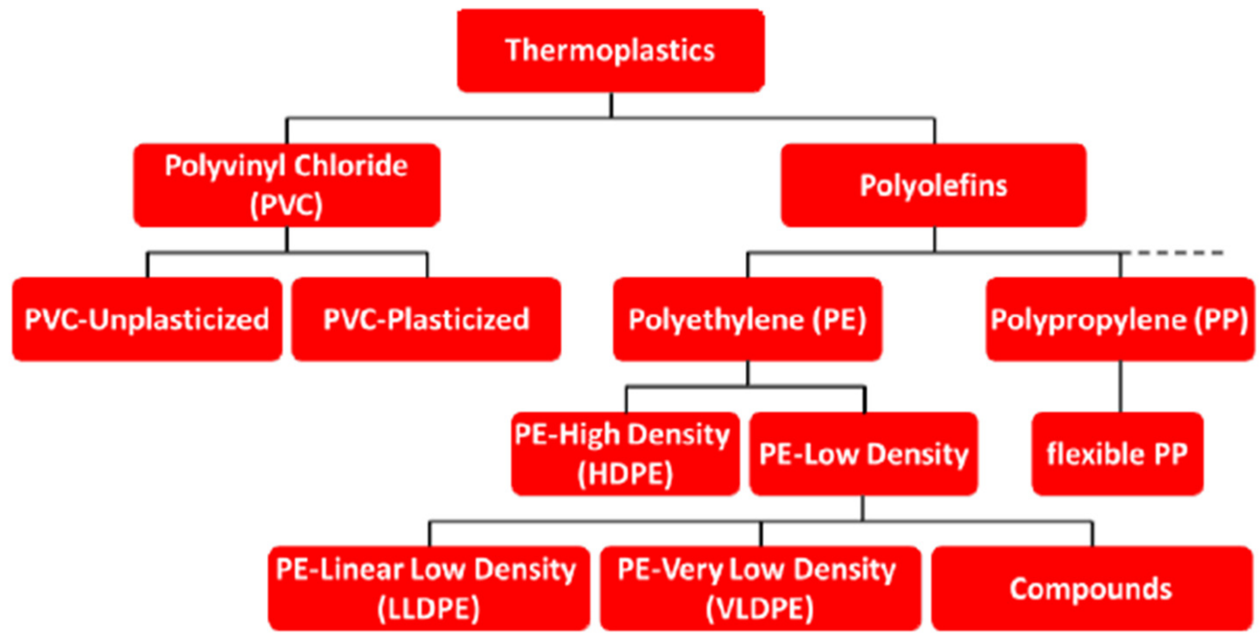
An alternative to thin steel lining. The foil is thin (2-3 mm) plastic (PE, LPO) membrane that is very flexible. (PVC foil because its environmental impact and changing characteristics during time – getting brittle, not suitable). The foil can be installed (fixed) directly on the primary support by TBM tunnels or an fine shotcrete layer is spread, smoothening the underground. Usually, the foil have on rock side a fleece (500-1000 g/m²). Fleece protects the foil from irregularities in the shotcrete lining. Fleece is often protected with thin plastic foil that mechanically protects it, but also during grouting protects fleece from the grout penetration. Instead of fleece also plastic grid could be installed.

The foil can take a part of internal water pressure, but is not resistant on external water pressure. Therefore, final lining is installed.

Consolidation grouting (with pre-stressing effect) through prepared grouting holes (steel pipes glued with the foil) is necessary to achieve force transfer.

Design is performed similar as for thin steel lining that for internal pressure the concrete inner ring could get cracked and is not taking internal forces. External water pressure is taken by the inner concrete ring.

Concrete lined tunnels with seal – plastic foil



Concrete lined tunnels with seal – plastic foil

During loading by internal water pressure the foil must also be able to over bridge the tensile cracks that can occur in the rock mass behind the foil.

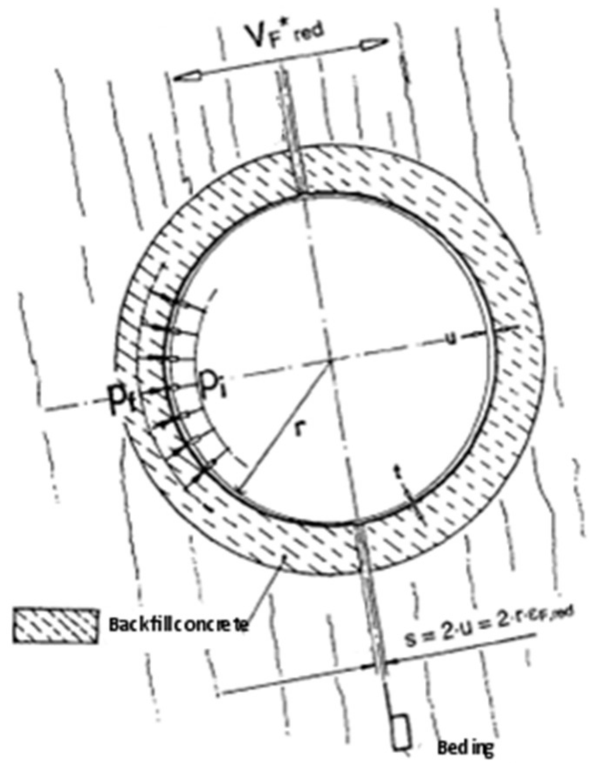
"Rule-of thumb" proven by the test: the foil thickness "*s*" must be bigger than double crack width "*2u*". Under assumption that only 2 diametrical cracks will occur perpendicular to the weakest rock plane the crack width yields to:

$$s = 2u = \frac{2r(1-\nu)\,p_i}{V}$$

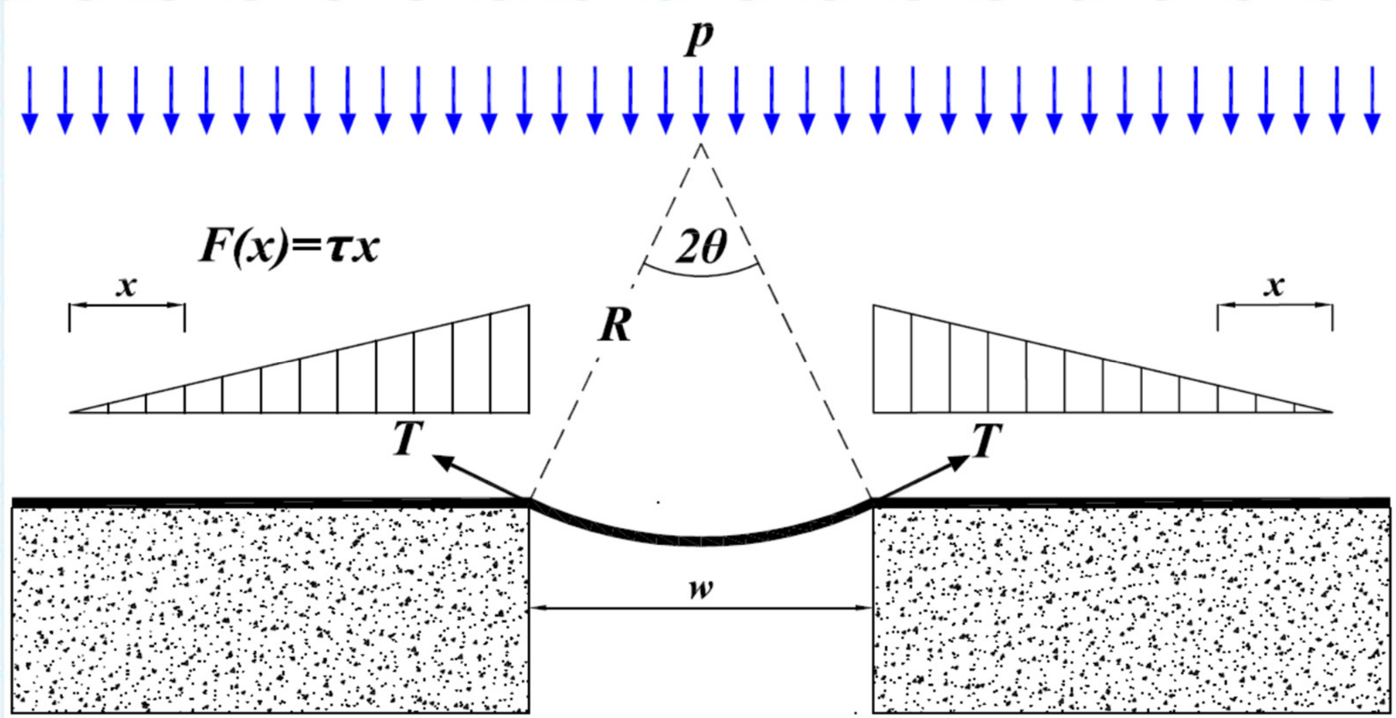
where:

V, ν deformation modulus and Poisson number of surrounding rock

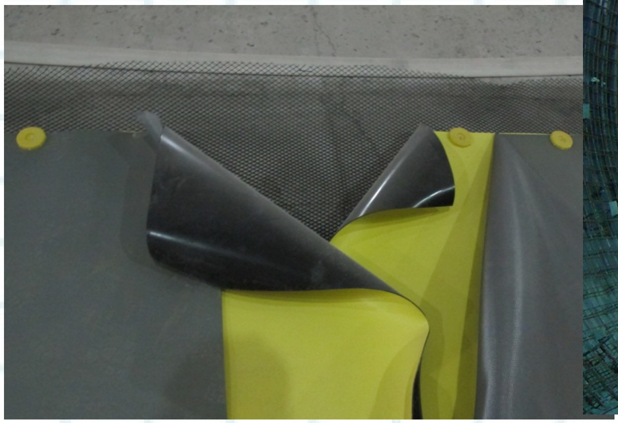
p_i internal pressure



Concrete lined tunnels with seal – plastic foil



Concrete lined tunnels with seal – plastic foil



Concrete lined tunnels with seal – Fiberglas plastic pipe

During last years Fiberglas plastic pipes becomes accepted, especially in the range of the relatively low internal pressure (up to 30 bar). Production is not limited by diameter or by the pipe thickness. The pipes up to 3.0 m diameter are produced in the factories and transported in 6m lengths directly on site. Bigger diameters (>3.0 m) have to be fabricated on site. Fabrication needs a production hall on site with constant temperature and humidity. Pipes are connected by muffs.

Bending, changing of diameter and manifolds needs a lot of hand work by production and are mostly omitted by using steel parts (simpler connection).

Pipe diameters less than 3.0 m, relatively low internal pressure (30 bar), cheap material (~3.000 US$/m) , and simple assembling makes the Fiberglas very interesting specially for small hydro.

Concrete lined tunnels with seal – Fiberglas plastic pipe

Steel lined tunnels (penstocks)

Steel lined penstocks cannot mostly be avoid if:

- internal pressure is to high
- by poor rock mass quality or to shallow overburden
- the lining must be absolutely tight

Design:

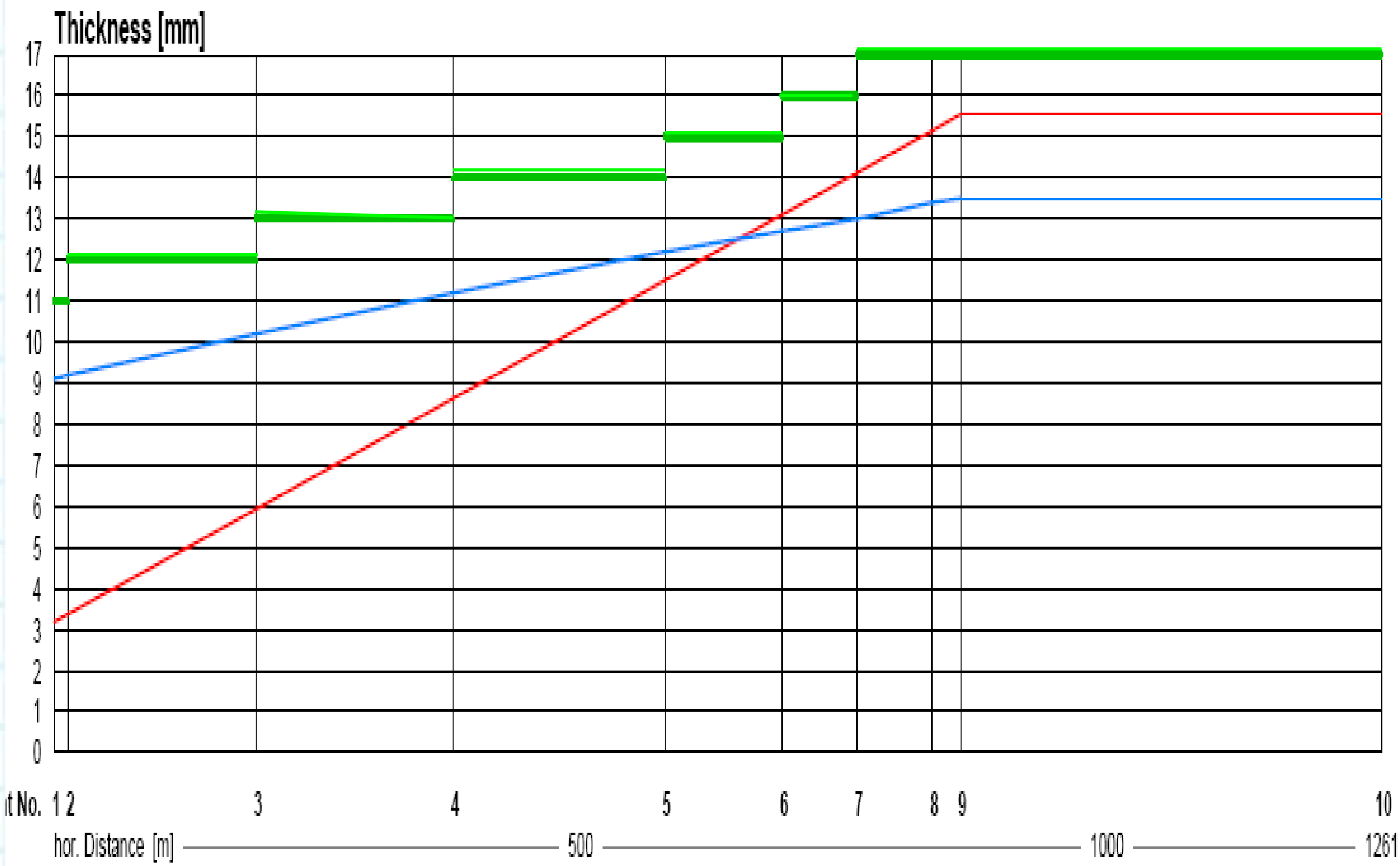
Internal pressure:

- Full internal pressure is taken by the steel – simple calculation by pipe formula – pipe must be fully imbedded in the surrounding rock mass or fully free
- Internal pressure is taken by steel and surrounding rock mass – based on their stiffness – full safety (1.67) to the composed system and additionally reduced safety for the steel lining alone (1.10)

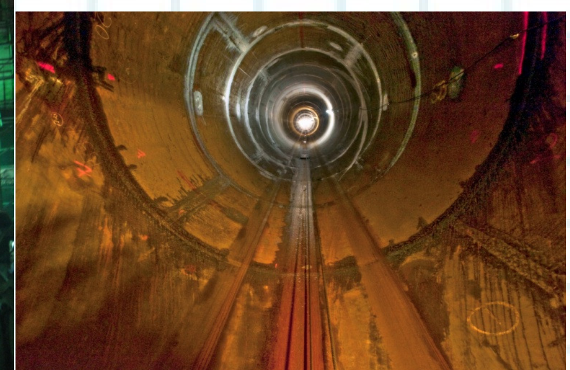
External pressure:

- Pipe can buckle if external pressure too high. Buckling pressure function of the pipe geometry and the gap between steel lining and backfill concrete (temperature, shrinkage, irregularities, etc)

Steel penstock - design



Steel lined tunnels (penstocks)



Power waterway – lining types

Unlined

- Unlined tunnels
- Shotcrete lined tunnels

Concrete lining

- Plane concrete lining
- Plane concrete lining with high pressure consolidation grouting
- Reinforced concrete lining

Concrete with seal

- Concrete with thin steel lining
- Concrete with plastic seal
- Concrete with GFP

Steel lining

- Open penstocks
- Burred penstocks
- Penstock pipes in tunnels
- Penstocks in tunnels embedded in concrete lining