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UNLINED HIGH PRESSURE TUNNELS AND AIR CUSHION SURGE CHAMBERS

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GEOLOGY OF NORWAY

Two thirds: Precambrian rocks. Gneiss dominating (granites, gabbros and quartzite).

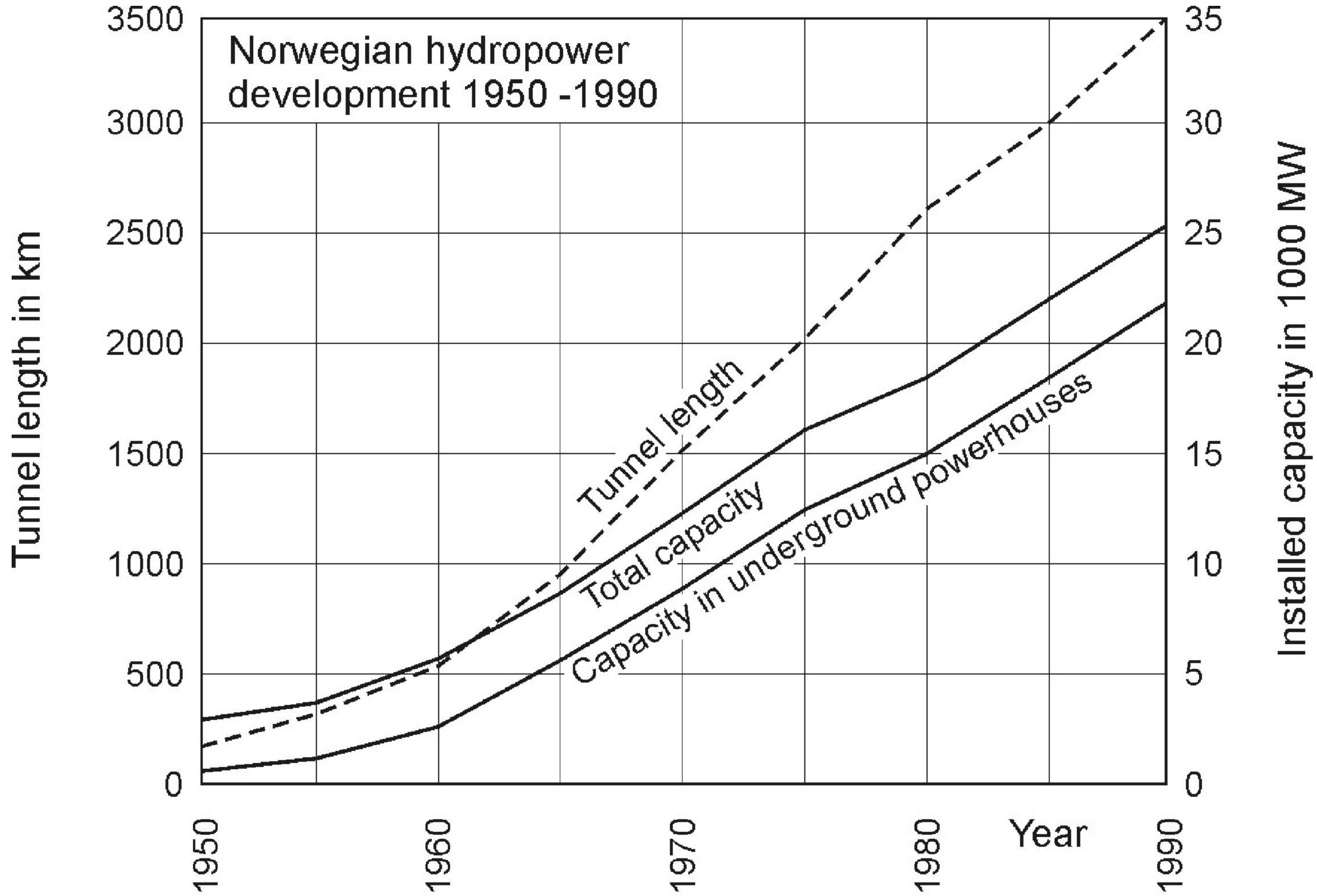
One third: Paleozoic rocks. Gneisses, mica-schists and greenstones + sandstones, shales, limestones. .

Typical hard rock province.

Folding, faulting and high tectonic stresses influence the stability in tunnels and underground caverns

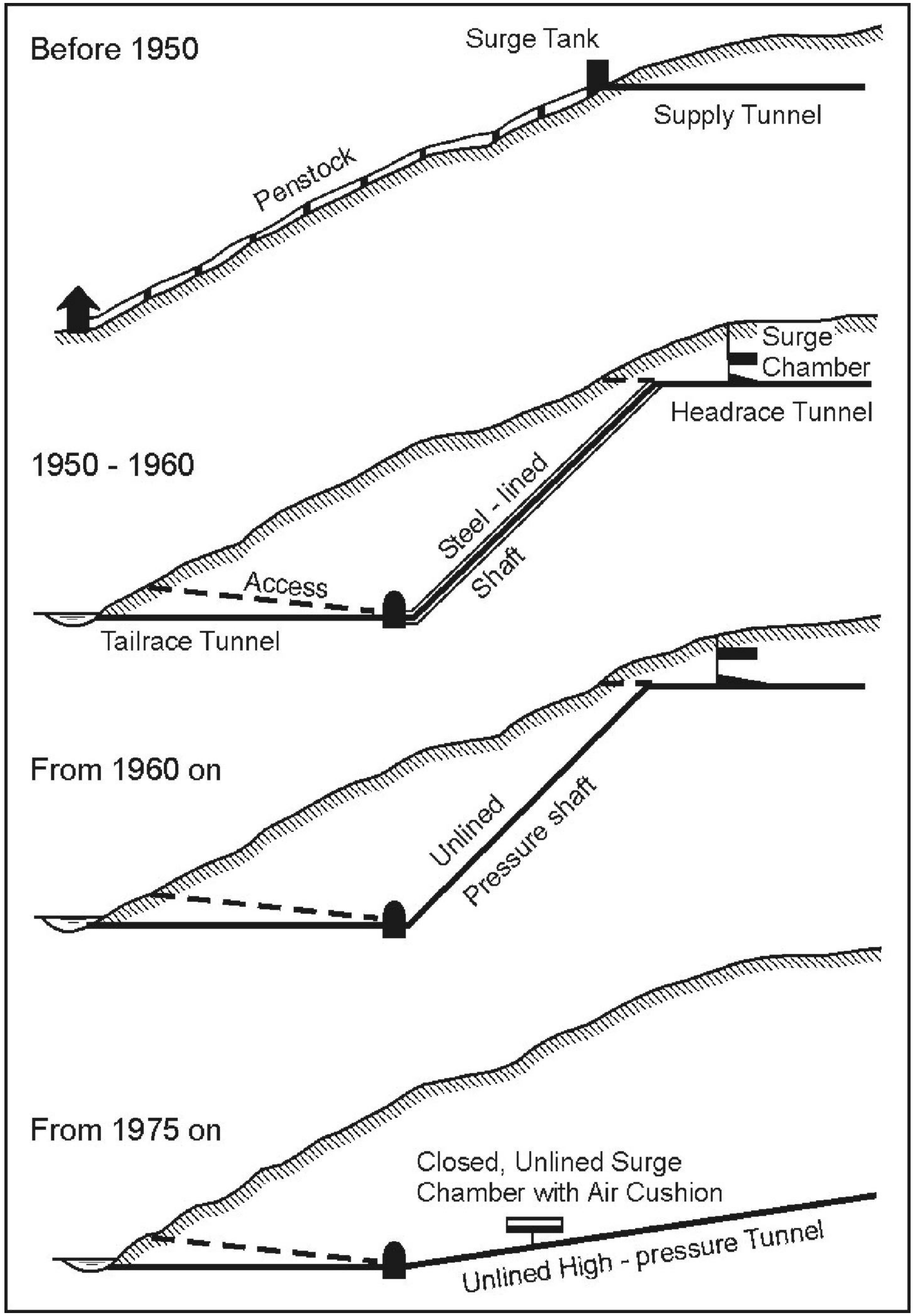
- Topographical and geological conditions in Norway are favourable for the development of hydroelectric energy.
- Rocks are of Pre-cambrian and Paleozoic age and highly metamorphic rocks predominate.
- They may in general be classified as typical hard rocks.

Norwegian hydroelectric power capacity and accumulated length of tunnels excavated for the period 1950 – 1990



NORWEGIAN HYDROPOWER

- 99% of a total annual production of 140 TWh of electric energy is generated from hydropower
- Of the world's 600 - 700 underground powerhouses 200 are located in Norway
- More than 4000 km of hydropower tunnels.
- 2 – 4 % of the tunnels are lined with concrete or shotcrete



Development of the general lay-out of hydroelectric plants in Norway.

EARLY REASONS FOR GOING UNDERGROUND

- Traditional design was to bring the water to the powerhouse through a steel penstock
- Both the penstock and the powerhouse were above ground structures.
- After the First World War there was a shortage of steel.
- Four Norwegian hydropower stations with unlined pressure shafts were put into operation during the years 1919-21.
- Water heads varied from 72 to 152 m.

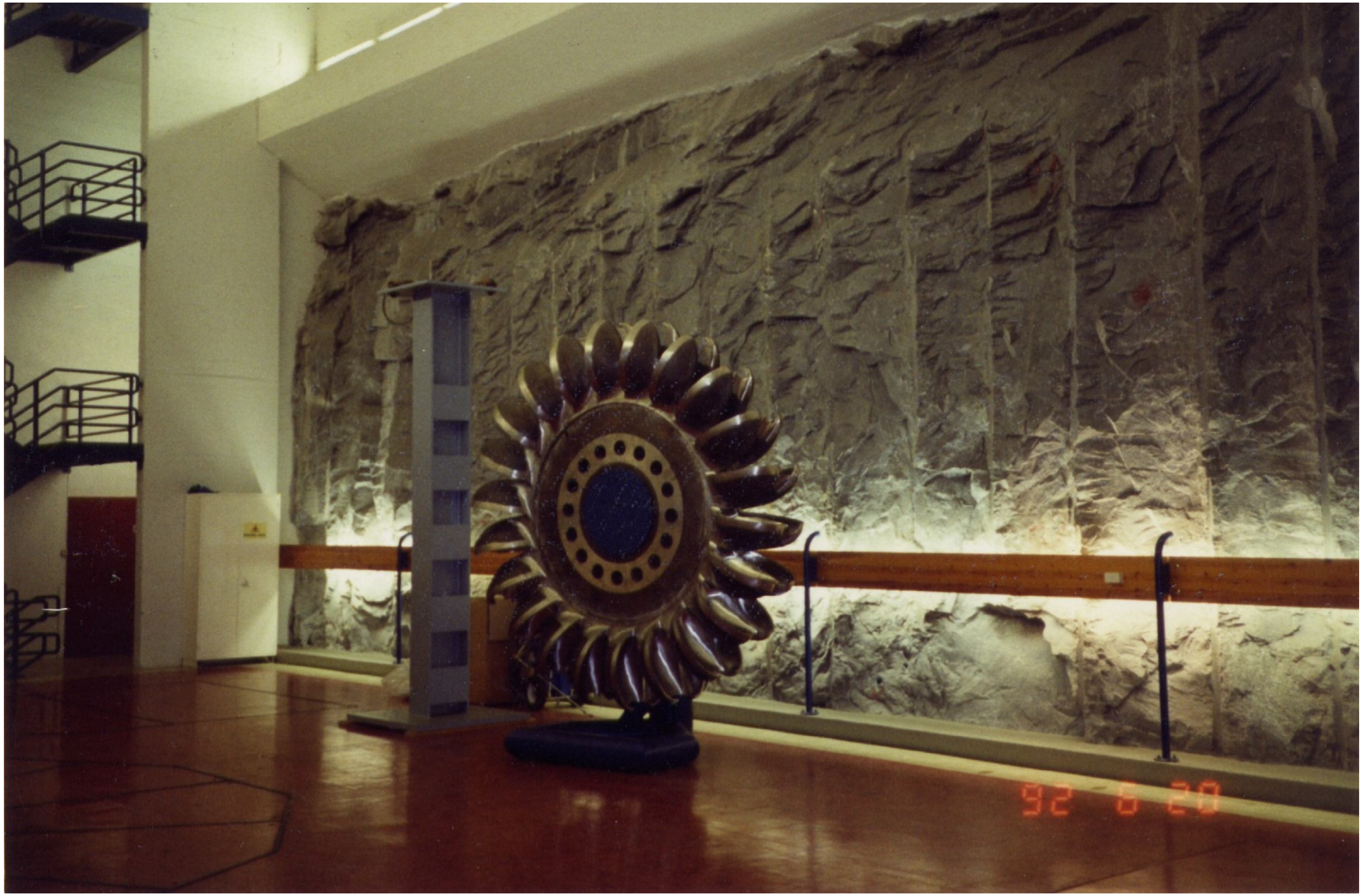
DEVELOPMENT AFTER 1945

- After the Second World War, underground location of powerhouses was given preference based on safety considerations
- Rapid advances in rock excavation methods soon showed that this was the most economic solution.
- Underground solutions also gave freedom of layout independent of the surface topography.
- Underground location of the powerhouse is now chosen whenever sufficient rock cover is available.

Aura underground hydropower station, commissioned in 1953

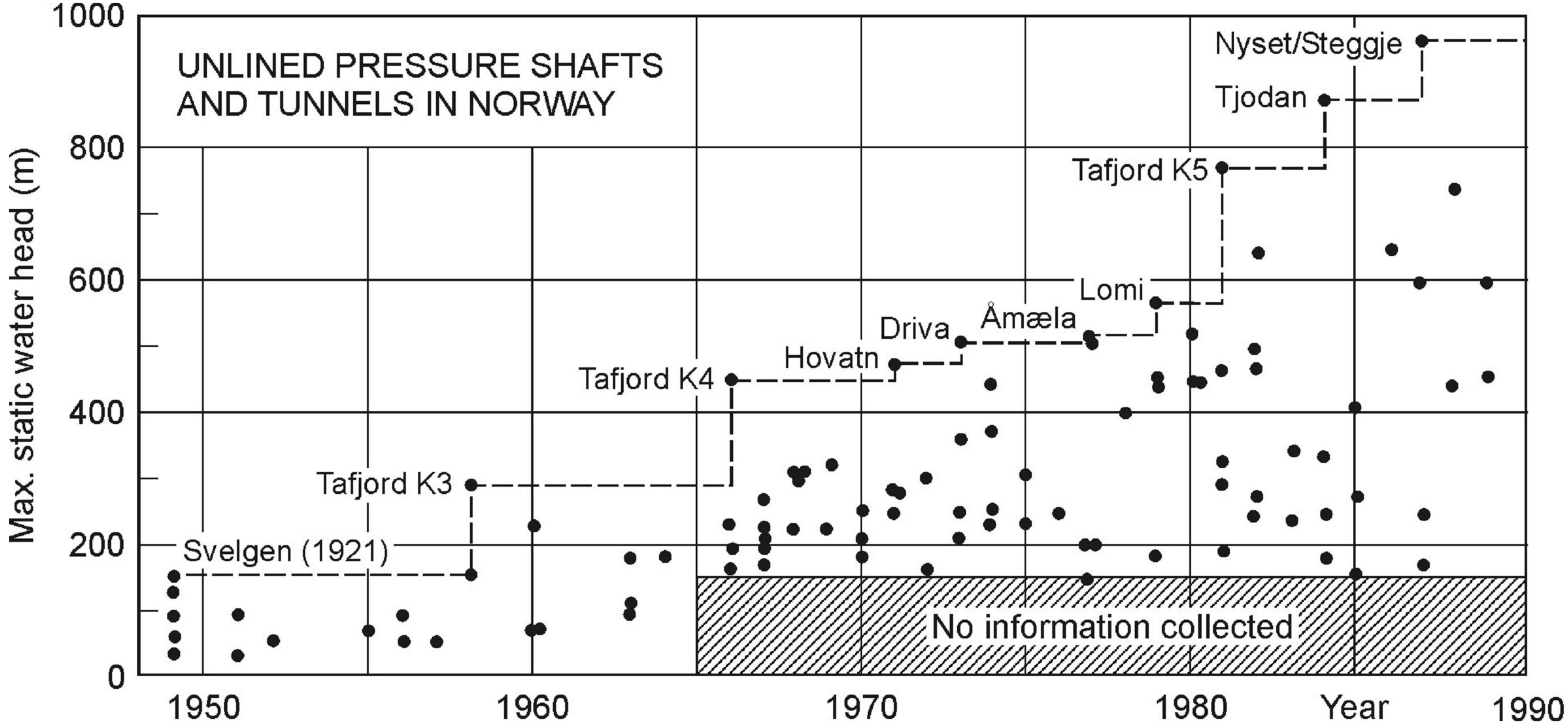
Modern underground hydropower stations, - exposing the rock walls

Exposing and illuminating the gneissic rock wall at Tafjord K5 hydropower station

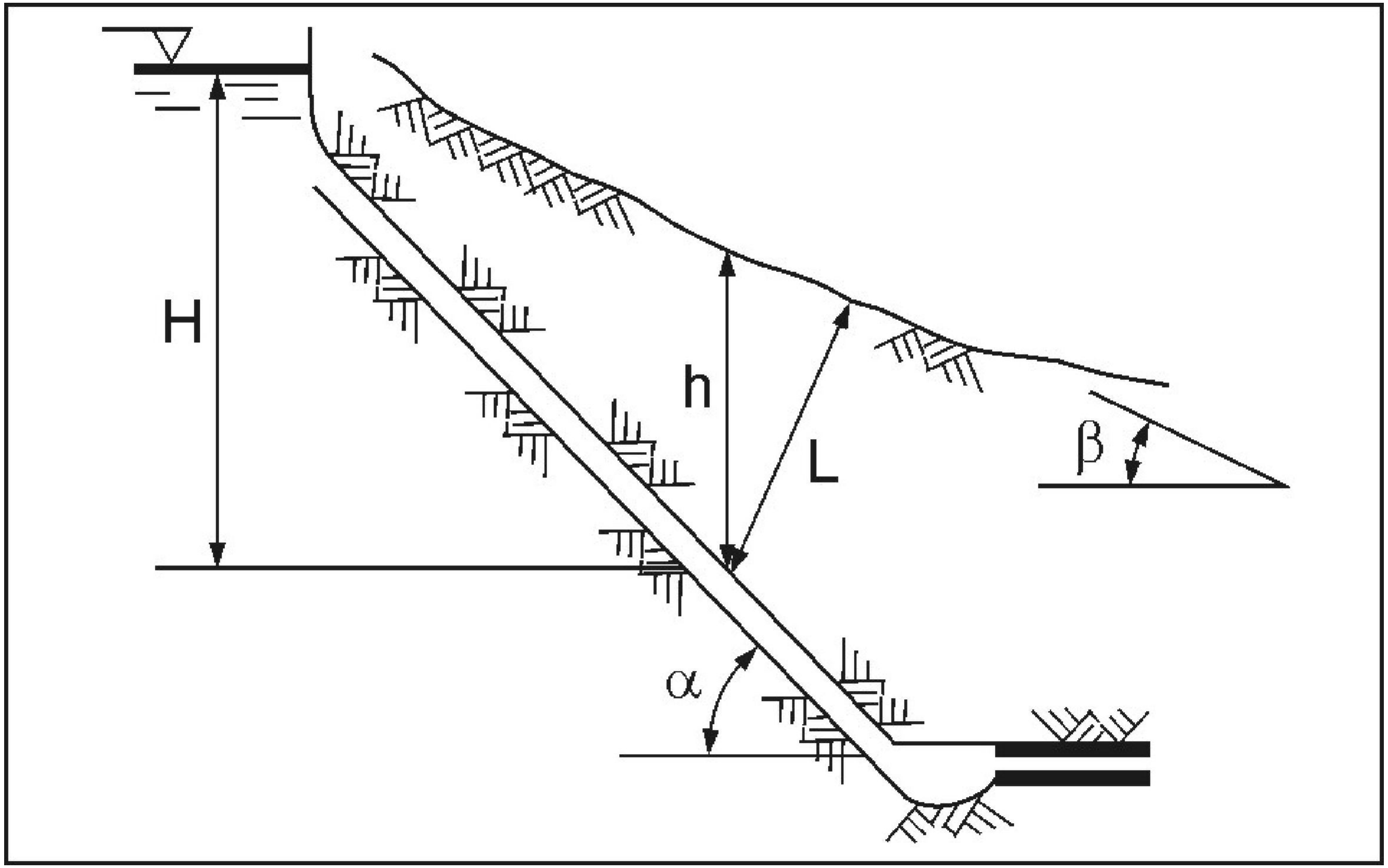


Extension of the Nedre Vinstra hydropower station

The development of unlined pressure shafts and tunnels in Norway



Definition of ”rule of thumbs” for unlined high-pressure tunnels and shafts



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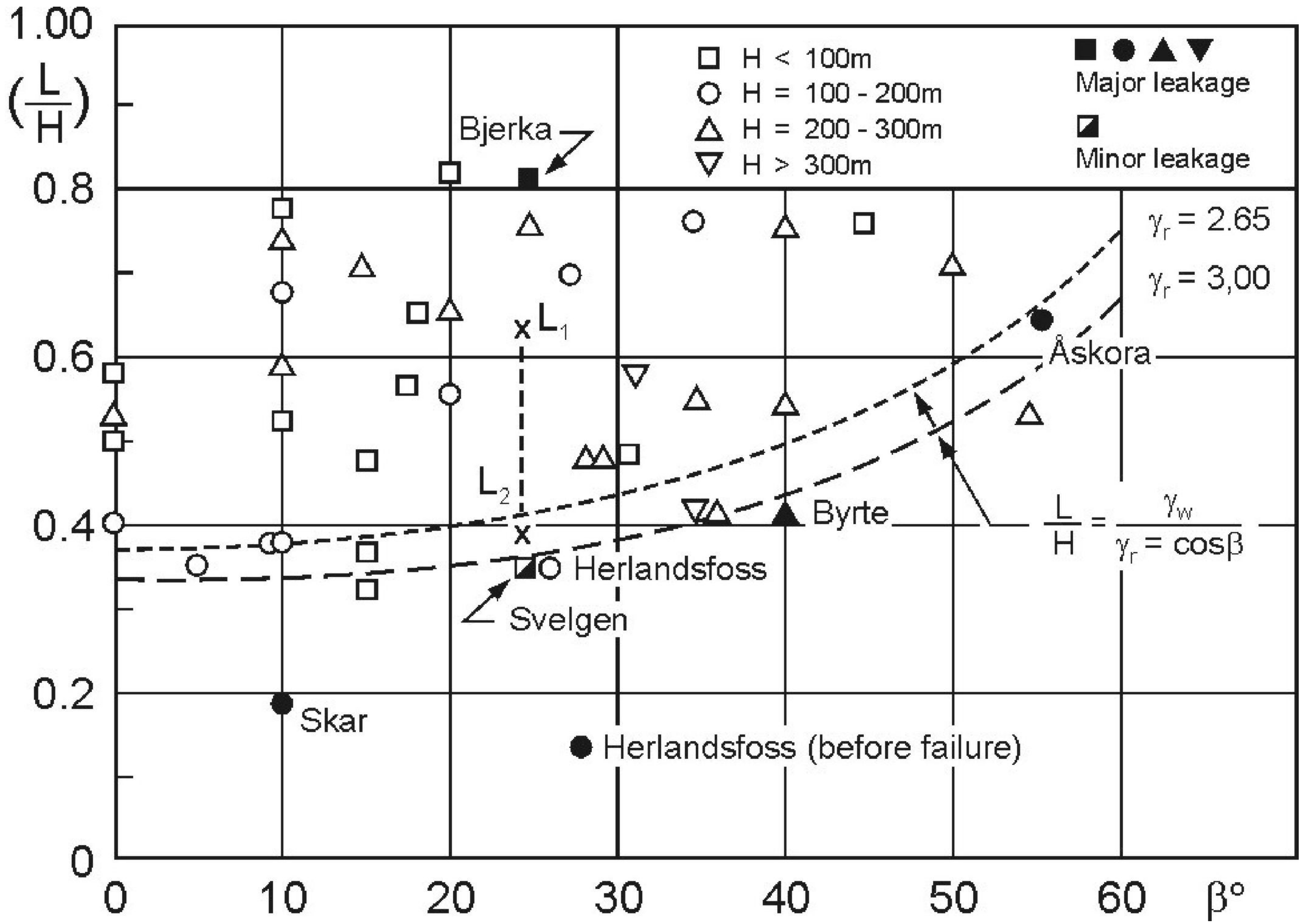
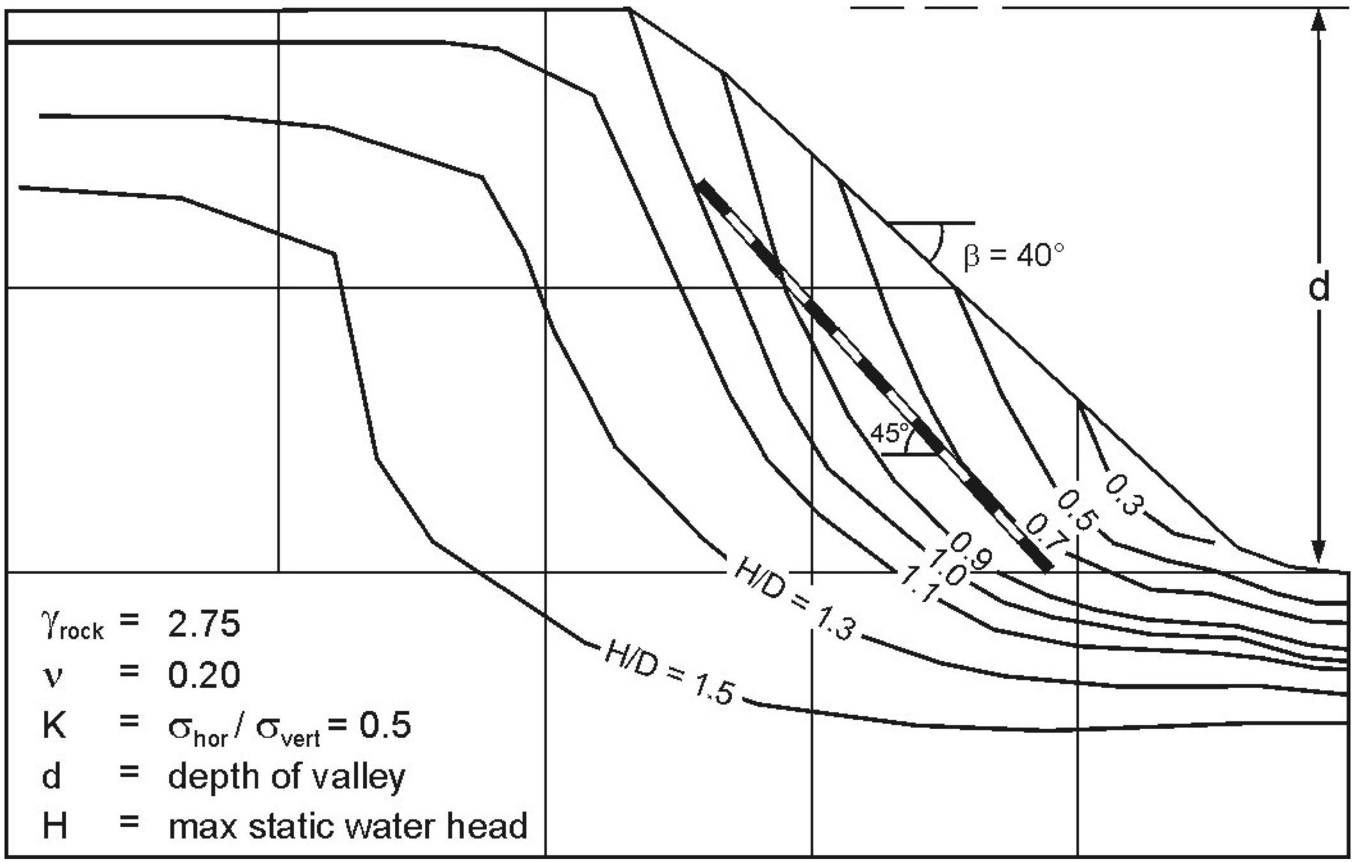
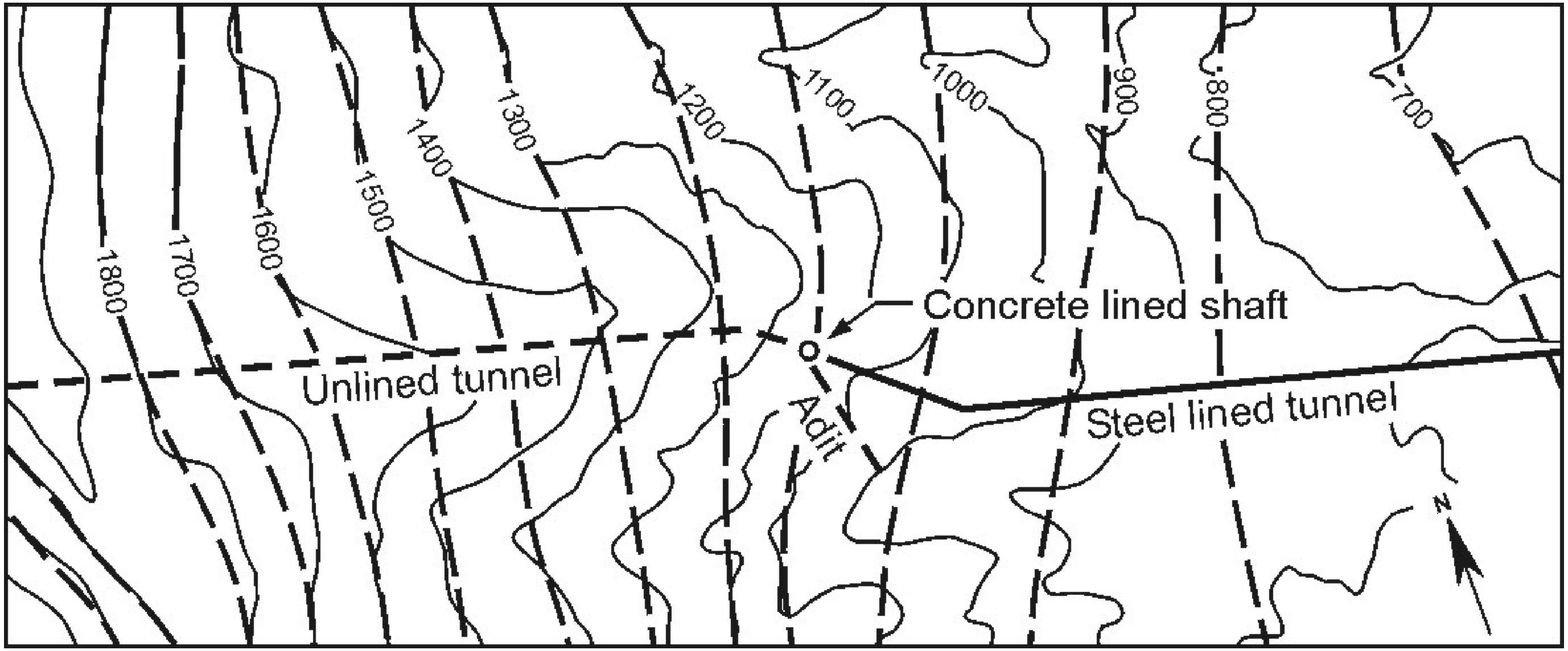
Unlined pressure shafts in valley sides with various inclinations



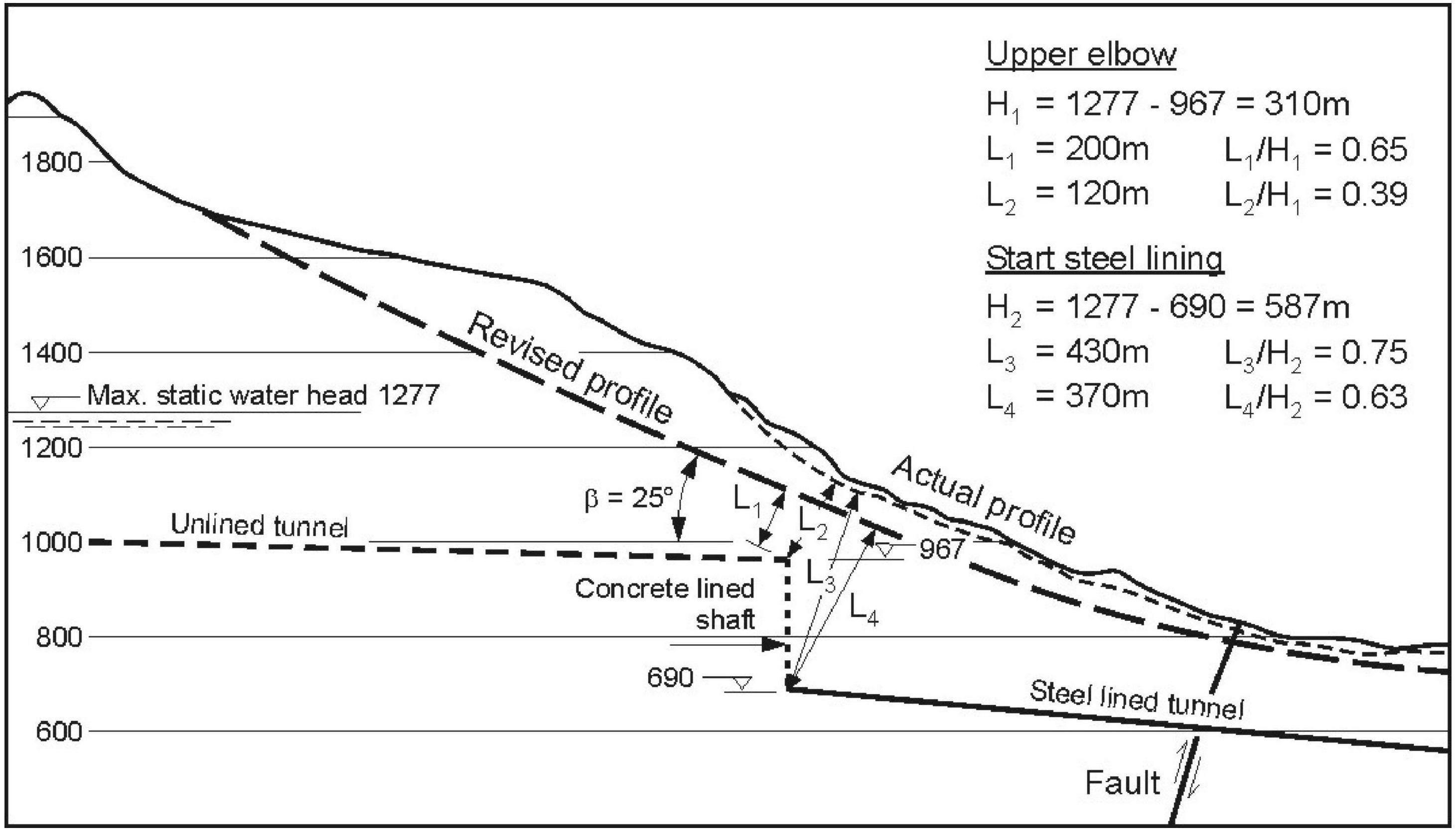
Design chart for unlined pressure shafts based on finite element model (FEM)

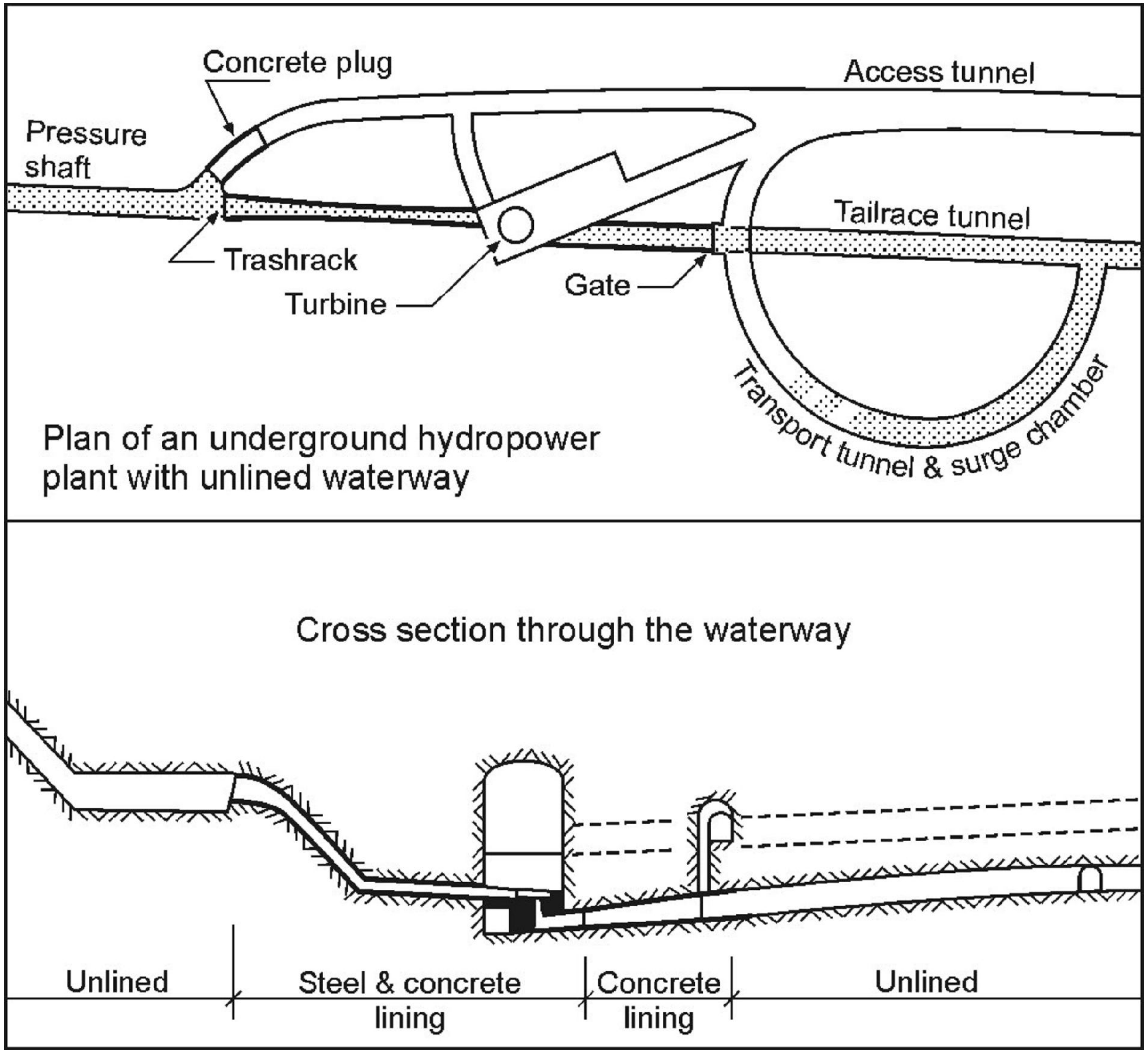


Tunnel system in topographically complicated area. Dashed lines are revised contour lines



Vertical cross section with actual and revised topographical profile.





Plan and cross section of an underground hydropower plant with unlined waterways.

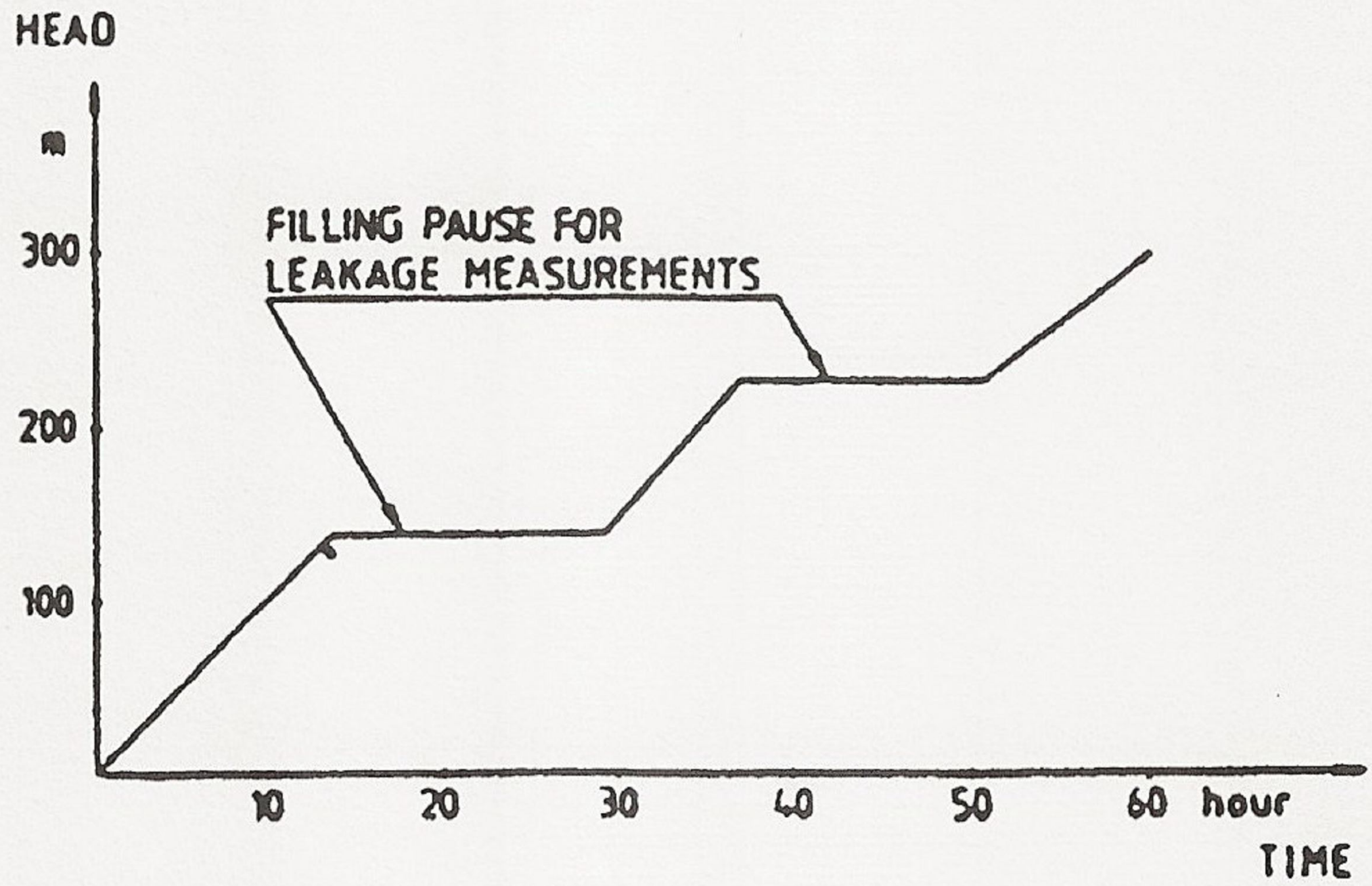


Figure 11. Example of controlled, slow filling of a pressure conduit, from Buen and Palmstrøm1982

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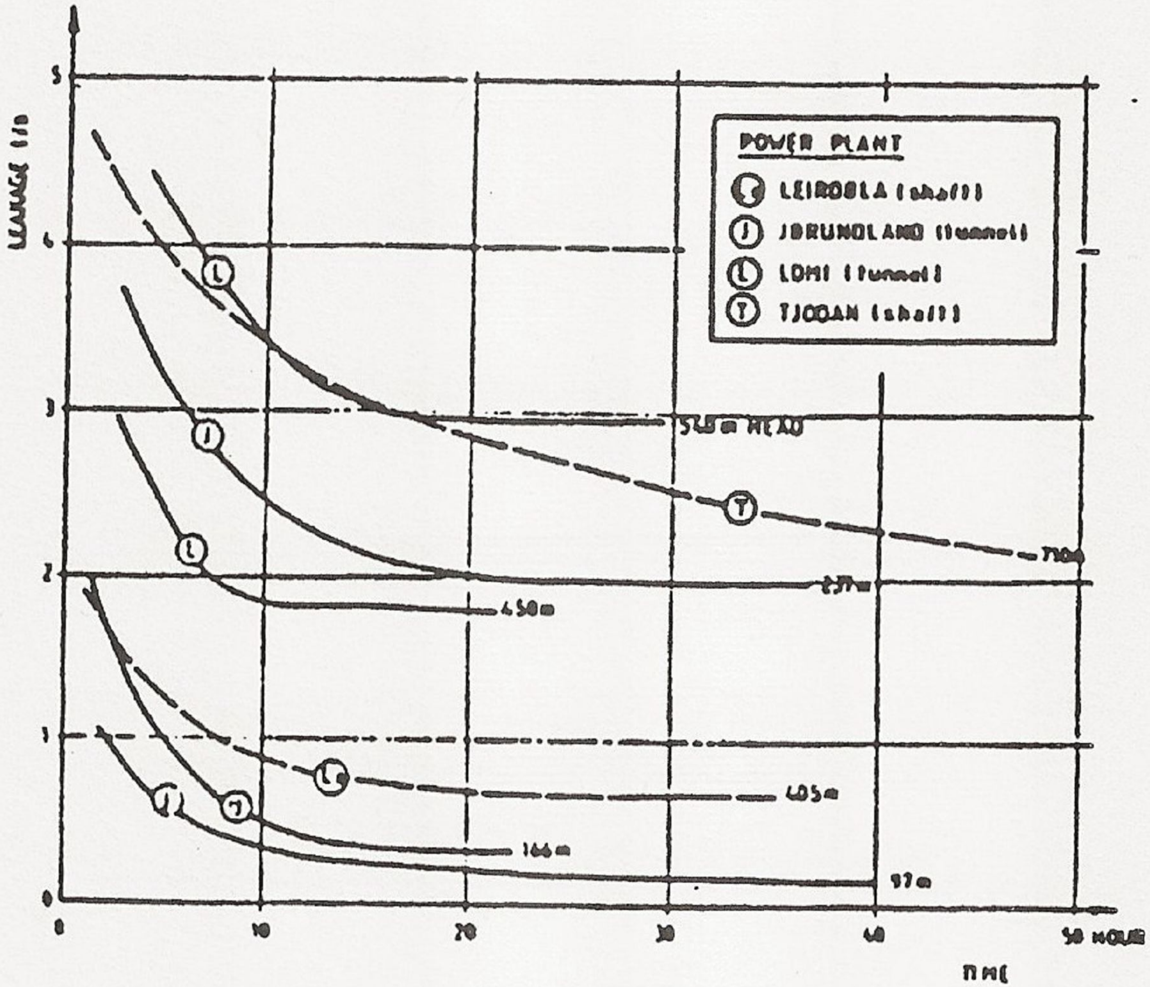
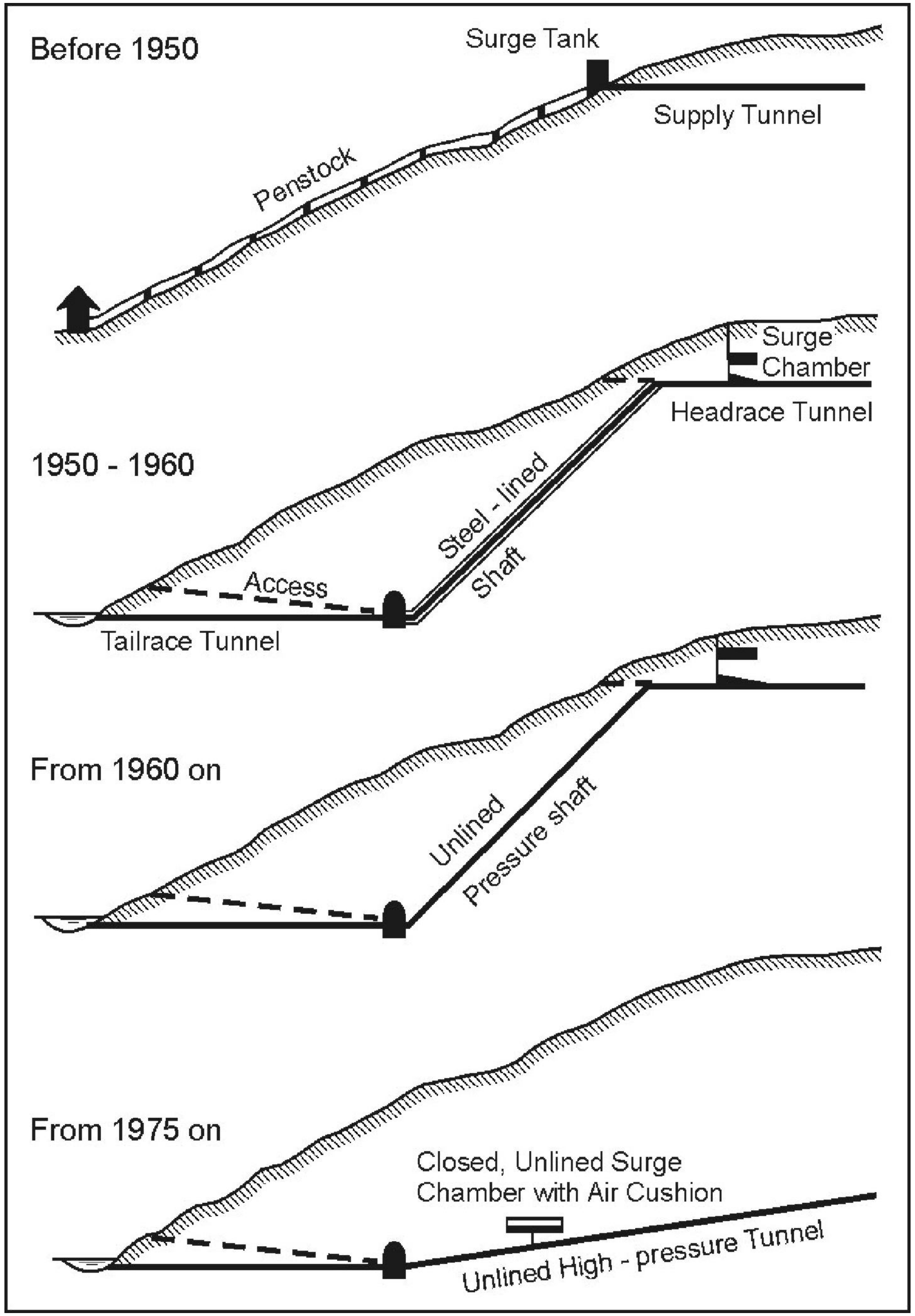


Figure 12. Measured net water leakage from various unlined high pressure shafts and tunnels, from Palmstrøm1987



Development of the general lay-out of hydroelectric plants in Norway.

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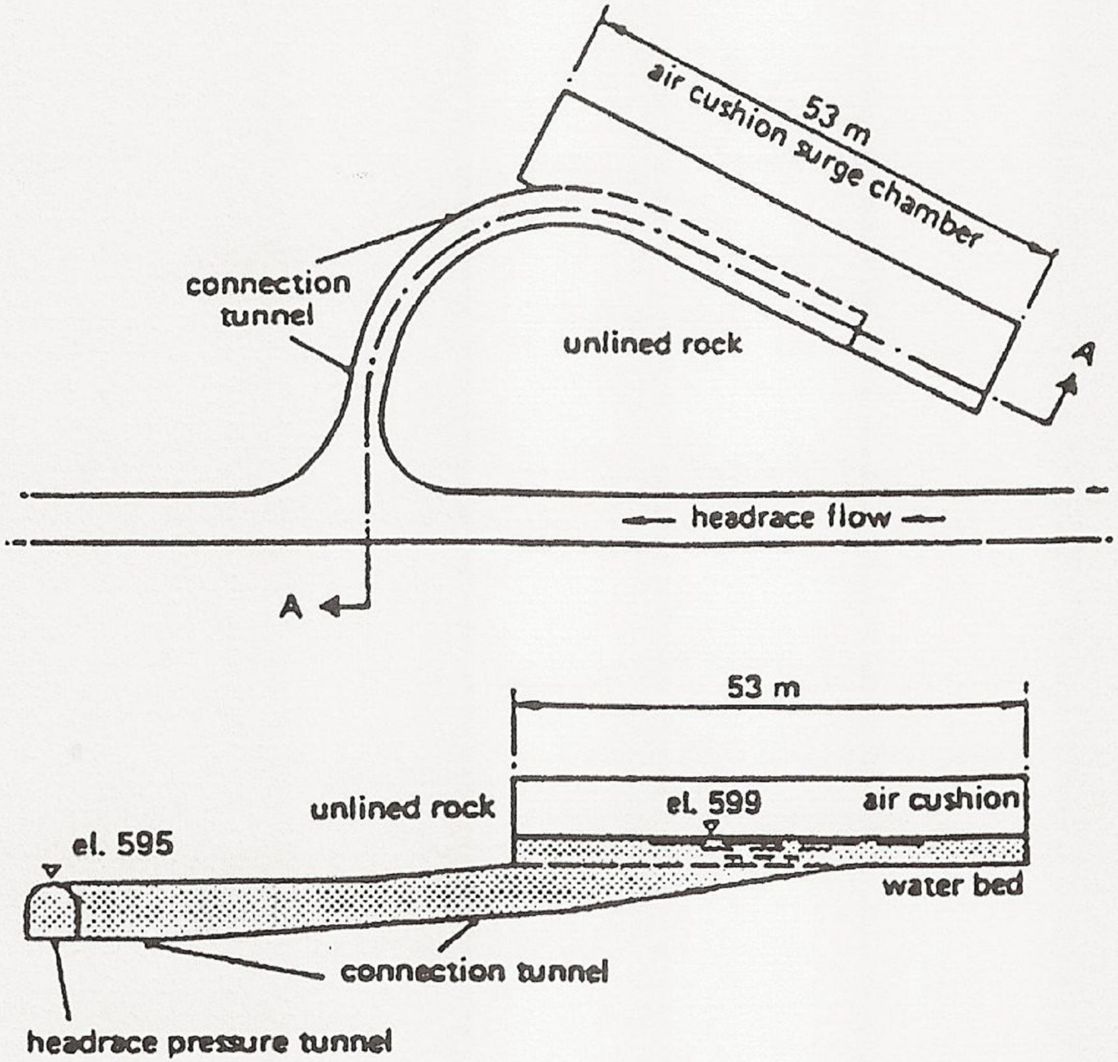


Figure 13. Plan and profile of the Ulset air cushion surge chamber

Air cushion surge chambers

Project	Year	Main rock type	Volume m^3	Cross section, m^2	Storage pressure MPa
Driva	1973	Banded gneiss	6,600	111	4.2
Jukla	1974	Granitic gneiss	6,200	129	2.4
Oksla	1980	Granitic gneiss	18,100	235	4.4
Sima	1980	Granitic gneiss	10,500	173	4.8
Osa	1981	Gneissic granite	12,000	176	1.9
Kvilldal	1981	Migmatitic gneiss	120,000	260-370	4.1
Tafjord	1981	Banded gneiss	2,000	130	7.8
Brattset	1982	Phyllite	9,000	89	2.5
Ulset	1985	Mica gneiss	4,800	92	2.8
Torpa	1989	Meta siltstone	14,000	95	4.4

Table 2 Air cushion features

Site	Commissioning date	Powerplant capacity (MW)	Distance to turbine (m)	Conect. tunnel length (m)	Vertical cavern cross-sect. (m^2)	Installed compressor capacity (Nm^3/h)	Ratio between max. air cushion head and min. rock cover (m/m)
Driva	1973	140	1300	20	111	425	0.5
Jukla	1974	35	680	40	129	180	0.7
Oksla	1980	206	350	60	235	290	1.0
Sima	1980	500	1300	70	173	270	1.1
Osa	1981	90	1050	80	176	2320	1.3
Kvilldal	1981	1240	600	70	260–370	500	0.8
Tafjord	1982	82	150	50	130	260	1.8
Brattset	1982	80	400	25	89	700	1.6
Ulset	1985	37	360	40	92	360	1.1
Torpa	1989	150	350	70	95	940	2.0

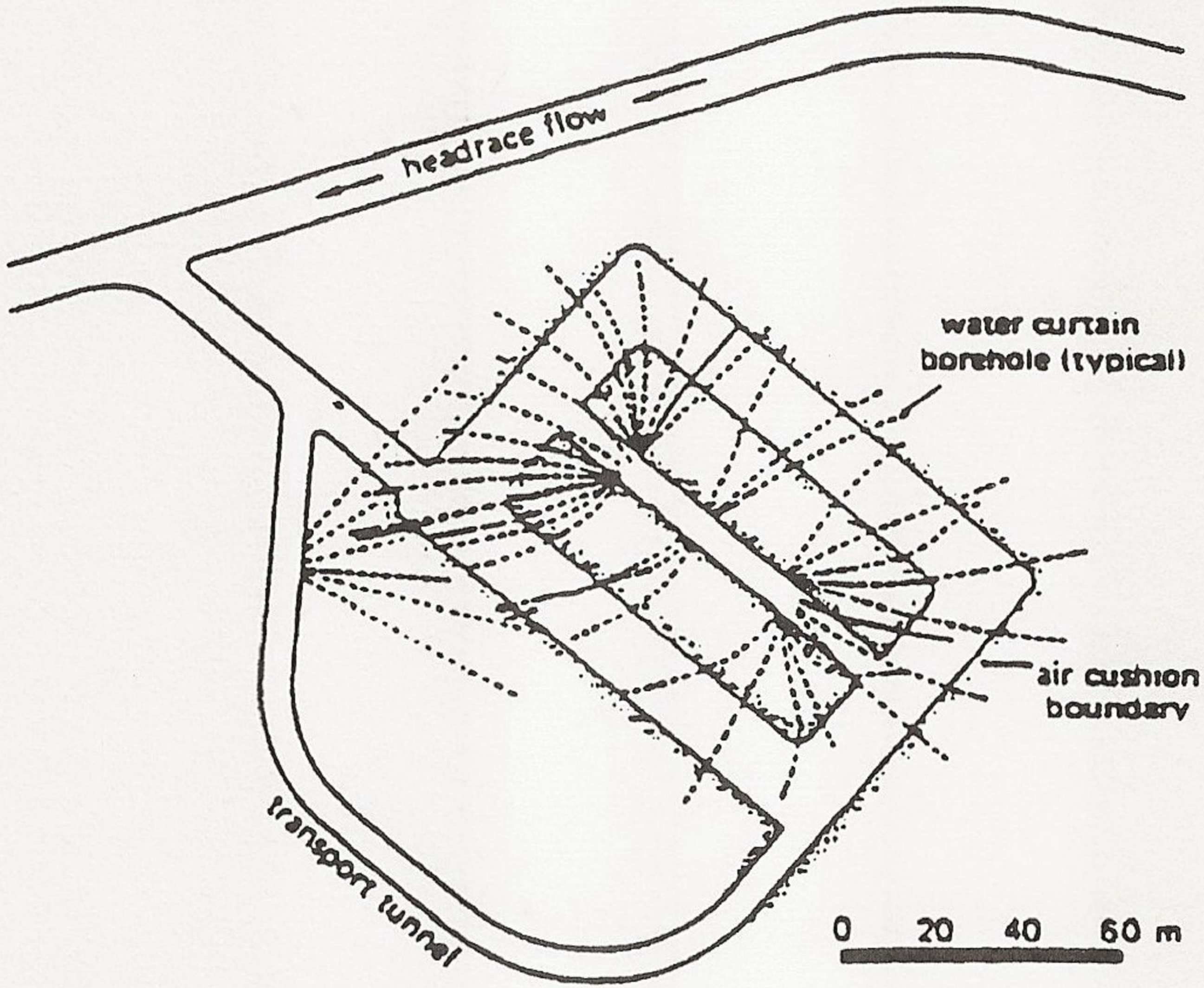
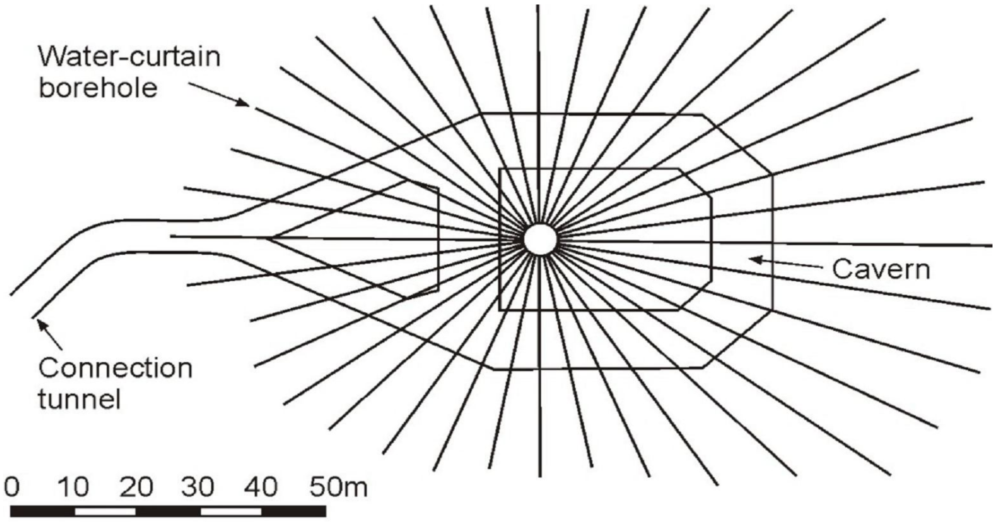
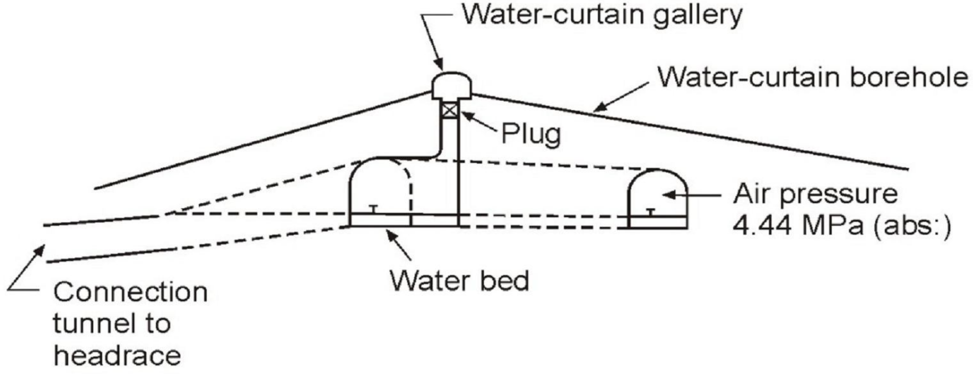


Figure 14. Plan of Kvilldal air cushion surge chamber with water curtain

Torpa air cushion surge chamber with water infiltration



Plan



Vertical section

Summary of experience – 1

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- Thorough geotechnical investigations required to obtain relevant information about:
  - the hydro-dynamical conditions
  - the rock mechanical conditions

Attention must be paid to rock mass permeability

Summary of experience – 2

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- The rock cover must provide sufficient rock stress to avoid hydraulic splitting of the rock masses by the air/gas pressure

Investigations are necessary to determine the necessary storage depth

Summary of experience – 3

- The groundwater level should be maintained during construction with the use of water infiltration curtains
- In very favourable rock mass and a high groundwater level, infiltration may not be necessary

Readiness for water infiltration should be kept

Summary of experience – 4

- Water infiltration is an effective measure of maintaining the ground water level
- The confining effect of the hydrostatic head (hydrodynamic control).
- In combination with pre-grouting, excessive water consumption can be avoided.
- Water infiltration curtains have successfully been installed in areas of groundwater drawdown

Summary of experience – 5

- Systematic pre-grouting is necessary if strict requirements to tightness shall be satisfied (permeability control)
- High pressure pre-grouting of the rock mass with micro- or ultra-fine cements can minimise the remaining water inflow
- Grouting of concrete plugs needs special attention

Unlined gas storage development in Norway

- Pressurised water tunnels up to 10 MPa
- LPG storage pressure up to 1 MPa at rock temperature
- Air cushion chambers up to 8 MPa
- Refrigerated LPG storage down to – 42 degrees C at atm. pressure
- Fully pressurised LNG within technology, not tested!!
- Fully refrigerated LNG at –162 degrees C ???