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 layout 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
Unlined pressure shafts in valley sides with various inclinations
Design chart for unlined pressure shafts based on finite element model (FEM)

\[ \gamma_{\text{rock}} = 2.75 \]
\[ v = 0.20 \]
\[ K = \frac{\sigma_{\text{hor}}}{\sigma_{\text{vert}}} = 0.5 \]
\[ d = \text{depth of valley} \]
\[ H = \text{max static water head} \]
Tunnel system in topographically complicated area. Dashed lines are revised contour lines.
Vertical cross section with actual and revised topographical profile.

**Upper elbow**
- \( H_1 = 1277 - 967 = 310 \text{m} \)
- \( L_1 = 200 \text{m} \) \( L_1/H_1 = 0.65 \)
- \( L_2 = 120 \text{m} \) \( L_2/H_1 = 0.39 \)

**Start steel lining**
- \( H_2 = 1277 - 690 = 587 \text{m} \)
- \( L_3 = 430 \text{m} \) \( L_3/H_2 = 0.75 \)
- \( L_4 = 370 \text{m} \) \( L_4/H_2 = 0.63 \)
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 Palmstrøm\textsuperscript{1982}
Figure 12. Measured net water leakage from various unlined high pressure shafts and tunnels, from Palmstrøm1987
Development of the general layout of hydroelectric plants in Norway.
Figure 13. Plan and profile of the Ulset air cushion surge chamber
## Air cushion surge chambers

<table>
<thead>
<tr>
<th>Project</th>
<th>Year</th>
<th>Main rock type</th>
<th>Volume $\text{m}^3$</th>
<th>Cross section, $\text{m}^2$</th>
<th>Storage pressure MPa</th>
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Table 2 Air cushion features

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<tr>
<th>Site</th>
<th>Commissioning date</th>
<th>Powerplant capacity (MW)</th>
<th>Distance to turbine (m)</th>
<th>Conect. tunnel length (m)</th>
<th>Vertical cavern cross-sect. (m²)</th>
<th>Installed compressor capacity (Nm³/h)</th>
<th>Ratio between max. air cushion head and min. rock cover (m/m)</th>
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<tbody>
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<td>940</td>
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Figure 14. Plan of Kvilldal air cushion surge chamber with water curtain
Torpa air cushion surge chamber with water infiltration
Summary of experience – 1

• 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
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
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 ???