Norwegian Development and Experience with Unlined Pressure Tunnels and Shafts

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1 Introduction

Unlined means that no steel or continuous concrete lining is installed in the shaft or tunnel with the result that the rock itself is under direct pressure from the water.

The application of unlined pressure tunnels and shafts in Norwegian hydropower construction started as early as 1919. The main reason was shortage of steel for penstocks during and after the First World War.

The benefits of the unlined design came more evident when Norwegian power houses were put underground in the 1950s, and from the mid of the 1960s the unlined pressure shaft solution became traditional.

Figure 1 shows the development of unlined pressure tunnels and shafts in hydropower. Before 1950s the penstock and power house was located in the surface. Then in the 1950s the penstock was placed in an inclined shaft and a horizontal tunnel leading to the power house at the surface.

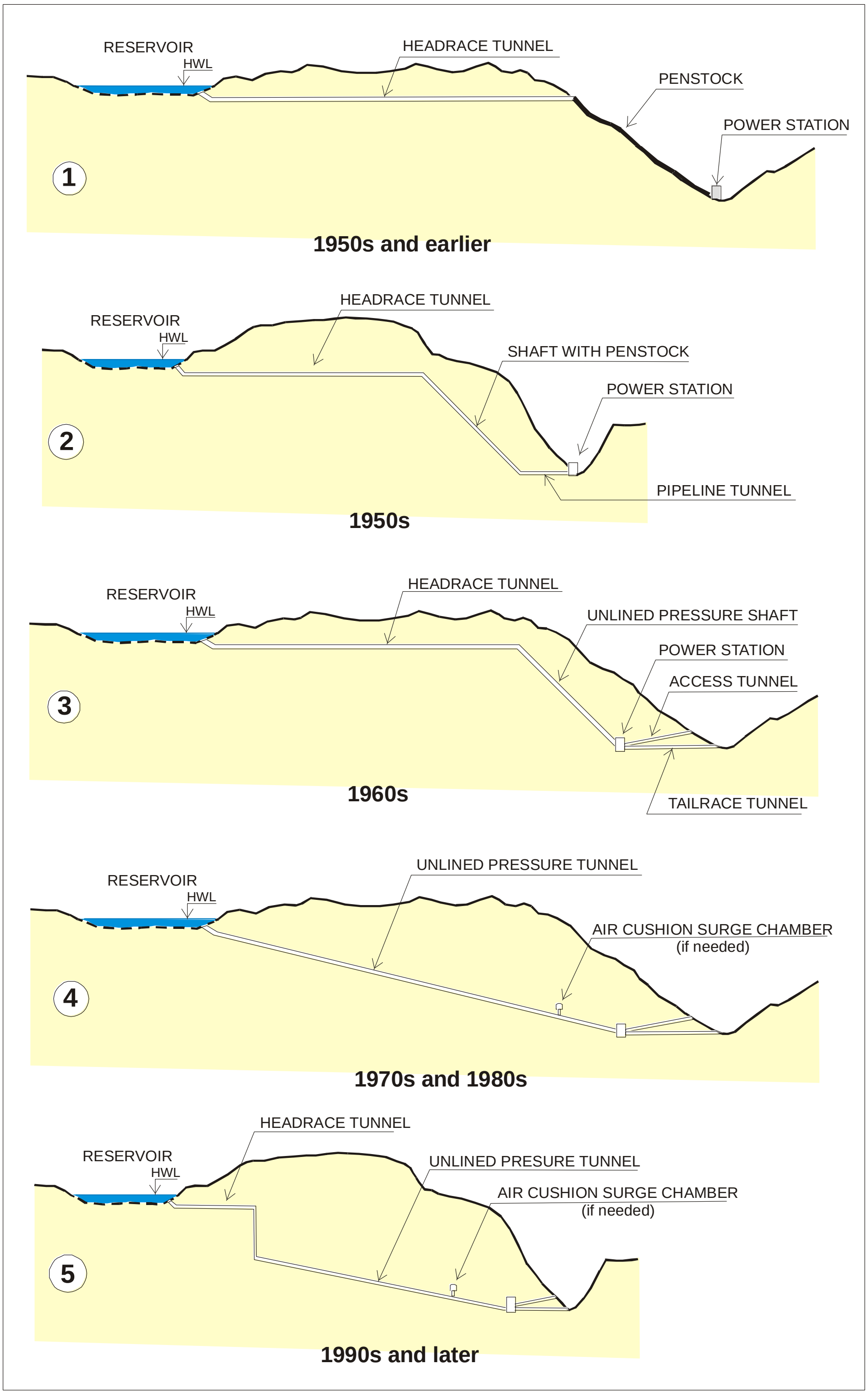


Figure 1. The development of unlined pressure conduits (simplified)

For some projects an underground location of the power house was chosen as it was found cheaper to excavate the power house cavern and the access tunnel compared with the long horizontal steel pipeline since the cost of such high pressure steel conduits and their installation is often very high. With the power house located underground, the distance with steel pipe from the turbine to the unlined tunnel/shaft portion can be made very short. Then in the 1960s the unlined pressure shaft was introduced applying underground power house. The in the 1970s the unlined pressure tunnel was taken into use. Instead of an extra shaft up to a surge chamber at reservoir or intake level the unlined air cushion surge chamber was introduced in late 1970s.

Figure 2 shows the development of steadily increasing heads in Norwegian unlined pressure conduits with water head in excess of 150m are in use.

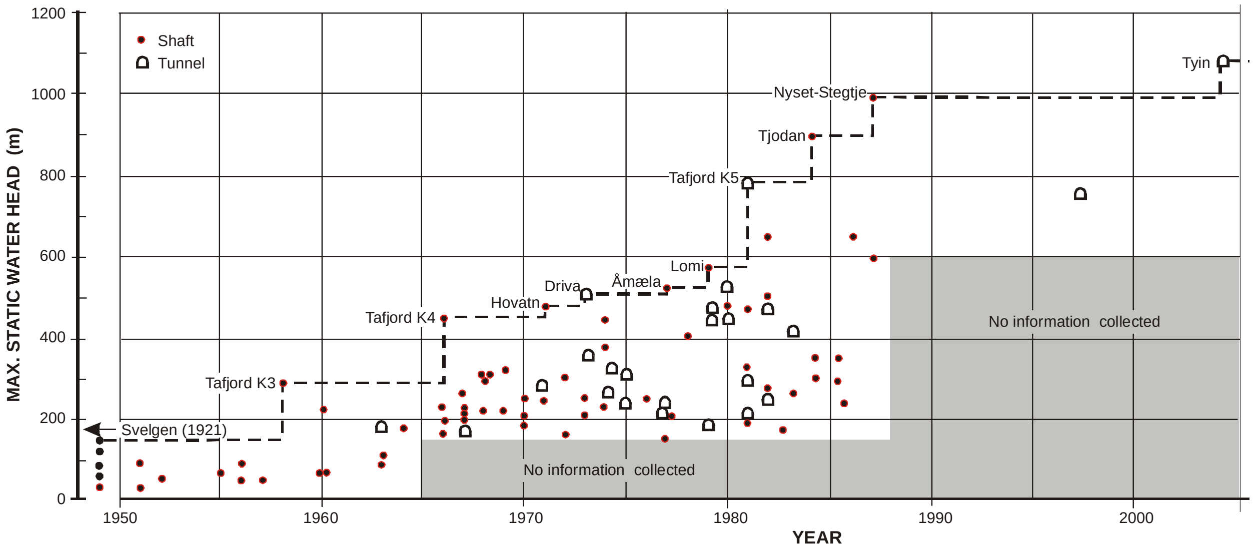


Figure 2. The increase in unlined pressure in Norwegian hydropower

The total length of unlined pressure shafts and tunnels in operation in Norway today is not known exactly, but is estimated to exceed 100km.

2 Rock conditions required

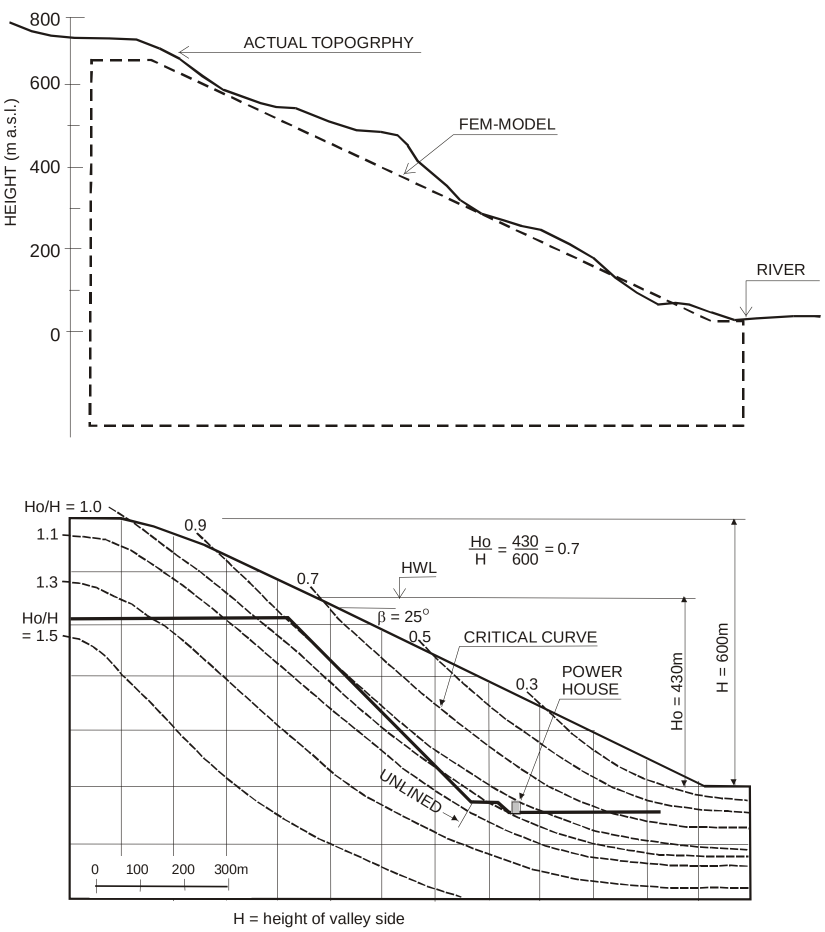
An unlined pressure conduit requires rock stresses high enough to withstand the internal water pressure both with regard to leakage and to deformation which can lead to failures.

As for all rock tunnel waterways the rock mass conditions must be suitable for tunnelling. In addition, the rock must have low permeability to ensure small leakage only and the rocks must be durable. In most Norwegian hydropower projects there are portions of poor rock mass conditions (faults an weakness zones) where comprehensive rock supporting has to be installed. In such rock masses also water sealing works must often be carried out in the unlined tunnel or shaft to reduce possible water leakage and prevent washing out of soft gouge materials.

3 Design and construction principle

The construction of the many unlined waterways has provided a lot of experience which has served to improve the design criteria. The location of unlined pressure shafts was at first based on the simple theory that the weight of the rock above was greater than the pressure of the water in the shaft or tunnel. This somewhat conservative method was ascribable to the fact that rock is a non-homogeneous material intersected with joints and cracks which do much to weaken it. Along the lines of such cracks leaks tend to occur, and under insufficient stress condition these may attain considerable proportions.

In 1972 a better simulation model for location of the pressure shaft or tunnel was introduced, based on the finite element method. This work was initiated by Prof. Rolf Selmer-Olsen at the Norwegian University of Technology. The model makes use of the principle that the minimum main stress in the rock should not be exceeded by the water pressure. The requisite rock cover is arrived at by transferring the scheme to topographical models adapted local conditions, Figure 3.



A set of two-dimensional FEM diagrams that have been worked out, represent a useful tool in the early stage of the project. They make it possible to find a preliminary location of the pressure tunnel/shaft, a location which in many cases turns out to be the final one. As most power houses are located inside valley sides, these diagrams represent valley slopes varying from 14 - 75^{o}. From the 1990s computer FEM models (FLAC, FACE etc.) adopted to the local conditions have often been used to verify the simple FEM diagrams.

Figure 3. An example of the application of the FEM diagrams

In determining the final siting of the scheme, however, special attention has to be paid to any significant geological factors that may be present.

Later, during excavation, rock stress measurements have been common practise to ensure the stress situation assumed in the models. Most frequently, hydro-fracturing tests are applied as the measure the minimum rock stress, which is used in the calculations. A common experience is that the rock stresses estimated in the calculations are lower than those measured.

A controlled and slow filling up of the waterway is an important part of the safe construction of an unlined pressure system. Normally, a shaft or tunnel is filled in steps with intervals of 10-30 hours. During the pauses the water level is continuously and accurately monitored by an extra sensitive manometer. This makes it possible to calculate the net leakage out of the unlined pressure tunnel/shaft into the surrounding rock masses.

4 Experience

From the six pressure tunnels/shafts where leakage measurements have been carried out, a leakage of 0.5 - 5 l/s per km tunnel has been measured.

The benefits from the concept of unlined pressure shaft/tunnel are these:

- Cost savings in construction caused by the fact that the lining with concrete embedded steel penstock or penstock at the surface is omitted.
- Shorter construction time, meaning an earlier start-up of the power plant, and reduced capital costs.
- Simpler design of the waterways. In many cases it is possible to omit construction adits, which in areas with steep topography can be of substantial costs.

Table 1 shows data for some Norwegian unlined pressure tunnels and shafts.

Table 1. Some of the Norwegian unlined pressure tunnels/shafts

Hydropower project	**Date of commissioning**	**Max. static head** (m)	**Unlined section**	
			Type (inclin. - cross section - length)	**Rock type**
Svelgen I	1921	152	Shaft (45^o - $4.5m^2$)	quartzite
Balmi	1958	150	Shaft (45^o - $16m^2$)	phyllite
Tafjord III	1958	286	Shaft (45^o - $6.2m^2$)	gneiss
Byrte	1968	303	Shaft (60^o - $62m^2$) (failure occurred)	granite gneiss
Hovatn	1971	475	Shaft (45^o - $7m^2$) Tunnel (1:14 - $12m^2$)	granite and gneiss
Driva	1973	510	Tunnel(1:12 - $22m^2$) Shaft (45^o - $8m^2$) Tunnel(10‰ - $8m^2$)	gneiss
Tafjord IV	1981	780	Shaft (45^o - $8m^2$) Tunnel(1:10 - $15m^2$)	gneiss and dunite
Tjodan	1984	875	Shaft (41^o - $7.5m^2$) (TBM drilled)	gneiss
Nyset-Steggje	1986	964	Shaft (45^o - $8m^2$) (TBM drilled)	gneiss and granite
Flöyrli	1997	780	Tunnel (1:5 - $27.5m^2$) Shaft (vertical - $13.2m^2$ - 419m)	gneiss
Tyin	2004	1040	Tunnel (1:6 - $36m^2$) Tunnel (1: 11 - $27m^2$) Tunnel (1:32 - $27m^2$) Shaft (vertical - $12.6m^2$ - 430m)	gneiss