10. UNLINED HIGH 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 became more evident when Norwegian power houses were put underground in the 1950s, and from the mid 1960s the unlined pressure shaft solution became traditional. From the late 1960s the design with unlined pressure tunnels and surge chambers with air cushion was introduced. Fig. 10.1 shows the development of steadily increasing heads in Norwegian unlined pressure conduits till today when more than 80 unlined pressure conduits with water head in excess of 150 m are in use.

Fig. 10.2 shows the three main types of design solutions in current use. When the power house is located underground, the distance with steel pipe from the turbine to the unlined tunnel/shaft portion can be made very short. This is highly beneficial since the cost of such high pressure steel conduits and their installations is often very high.

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

2. ROCK CONDITIONS REQUIRED

An unlined pressure conduit requires rock conditions able to withstand the internal water pressure both with regard to leakages and to deformations which can lead to failures. The rock must therefore have low permeability to ensure small leakages only. Even where the rock mass permeability is low, water will migrate into or out of a tunnel depending on the relation between natural ground water pressure and the pressure in the tunnel, i.e. the gradient.

As for all rock tunnel waterways the rock mass conditions must be suitable for tunnelling. In most Norwegian hydropower projects there are portions of poor rock mass conditions where comprehensive rock supporting has to be installed. In such rock masses also sealing works must often be carried out in the unlined conduits to reduce possible water leakages and prevent washing out of soft gouge materials.

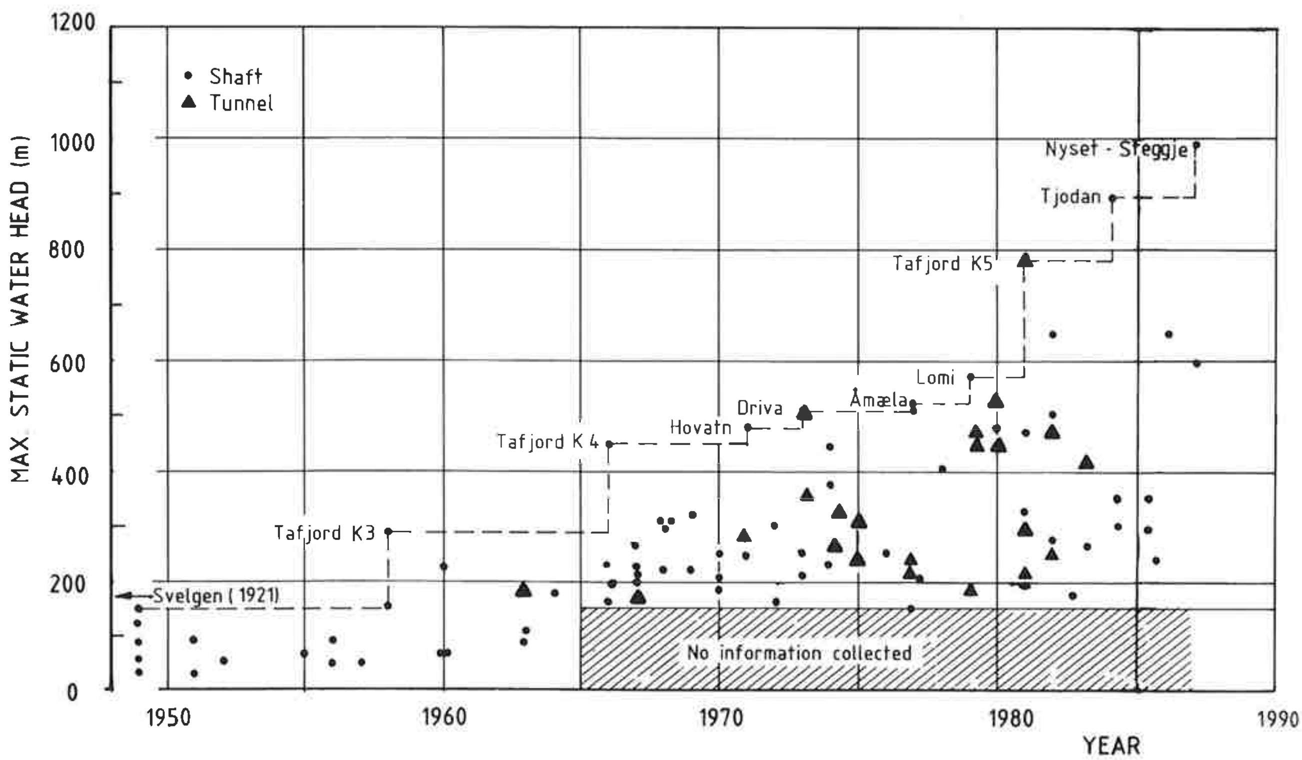


Fig. 10.1 Development of Norwegian unlined high pressure tunnels and shafts

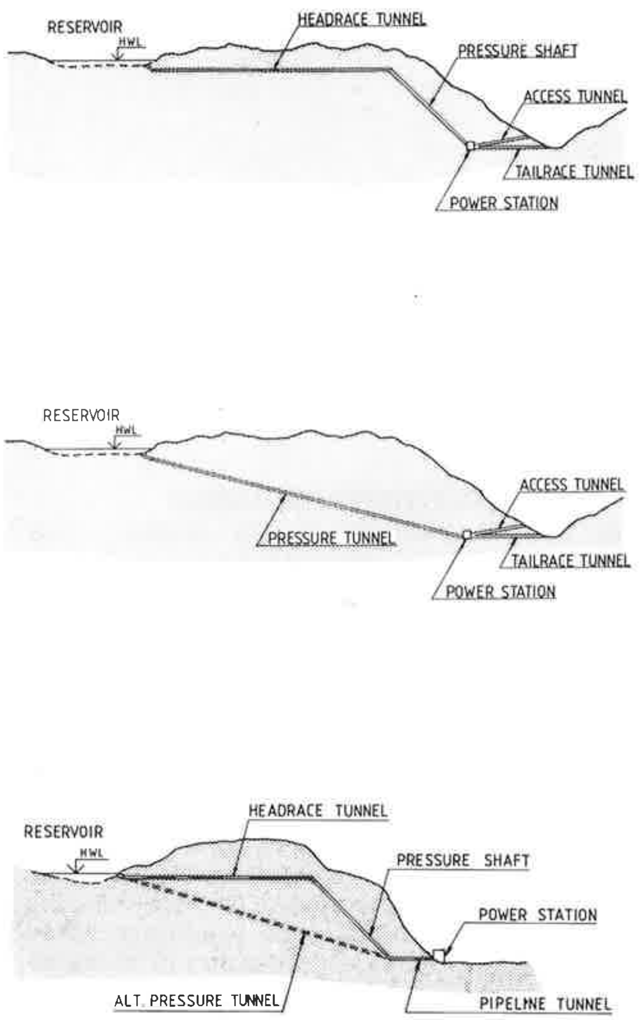


Fig. 10.2

Different design solutions with unlined pressure tunnels and shafts

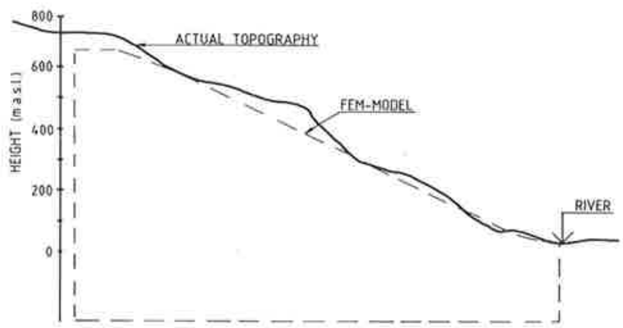
3. DESIGN AND CONSTRUCTION PRINCIPLE

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. 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 adverse conditions these may attain considerable proportions.

In 1972 a better simulation model was introduced, based on the finite element method. This work was initiated by Prof. Rolf Selmer-Olsen. 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 to local conditions. In determining the final siting of the scheme, however, special attention has to be paid to any significant geological factors that may be present.

A set of standard two-dimensional FEM diagrams that have been worked out represent a useful tool in the feasibility 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°.

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.



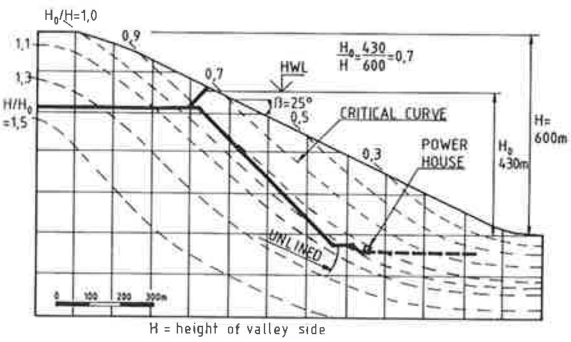


Fig. 10.3

Example of preliminary location of an unlined pressure shaft based on a standard FEM model. With a safety factor F = 1.4 the stress curve $\frac{Ho}{H}$ = 0.9 is applied

Table 10.1 Some of the Norwegian unlined shafts/tunnels

Name of hydropower project	**Date of commiss-ioning**	**Max static head (m)**	**Unlined section**	
			Type (inclin. -cross section)	**Rock type**
Svelgen I	1921	152	Shaft (45° –4,5m2)	quartzite
Balmi	1958	150	Shaft (45° –16 m2)	phyllite
Tafjord III	1958	286	Shaft (32° –6,2 m2)	gneiss
Byrte	1968	303	Shaft (60° –62 m2) (failure occured)	granite gneiss
Hovatn	1971	475	Shaft (45° –7 m2) Tunnel (1: 14-12 m2)	granite and gneiss
Driva	1973	510	Tunnel (1: 12-22 m2) Shaft (45° –8 m2) Tunnel (10 o/oo–8 m2)	gneiss
Tafjord V	1981	780	Shaft (45° –8 m2) Tunnel (1: 10-15 m2)	gneiss and dunite
Tjodan	1984	875	Shaft (41° –7,5 m2) (TBM-drilled)	gneiss
Nyset-Steggje	1986	964	Shaft (45° –8 m2) (TBM-drilled)	gneiss and granite

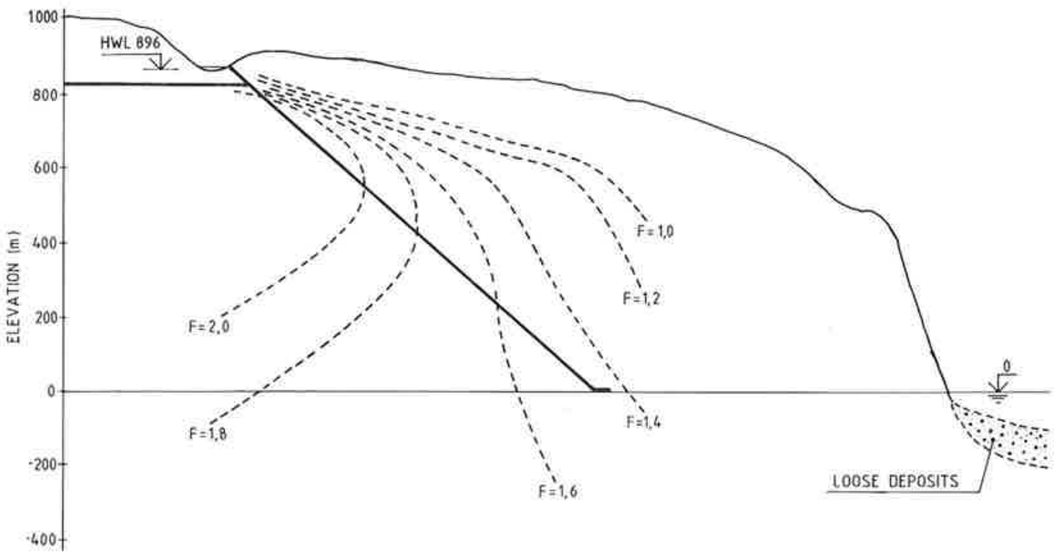


Fig. 10.4 From the FEM analysis and the measured in situ rock stresses it is possible to calculate the factor of safety along the unlined pressure shaft with regard to hydraulic splitting and failure. The example is from the Tjodan power plant with 880 m head on unlined rocks

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 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 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 constructions adits which in areas with steep topography can be of substantial costs.

Norwegian experience shows that up to 5% of the construction cost can be saved applying the unlined design. A high portion of this is gained from the possible earlier start-up of the power plant.