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NORWEGIAN DESIGN AND CONSTRUCTION EXPERIENCES OF UNLINED PRESSURE SHAFTS AND TUNNELS

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SUMMARY

The continuous development through 80 years of hydropower construction in Norway has lead to today's solutions of unlined waterways with up to 1000 m of hydrostatic head. Use of modern and more precise FEM design methods have resulted in safe locations of unlined pressure conduits. The increasingly common practice of checking the design values by in situ stress measurements and pore pressure measurements has contributed to the successful construction and operation of a number of high head conduits since the late seventies.

In Norway there are more than 80 unlined, high head pressure shafts and tunnels. The method gives both a lower construction cost and a reduced capital cost during construction due to a shorter construction period for the entire scheme. In addition a considerable bonus is often added for faster coming on stream of the plants.

Many other areas in the world have rock and topographical conditions suitable for a solution with unlined pressure waterway where considerable economical savings may be obtained.

1. INTRODUCTION

Unlined means that no steel piping 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 hydropower construction started as early as 1919. The main reason was shortage of steel during and after the First World War. Four Norwegian power plants of such kind were put into operation between 1919 - 21.

The benefits of the unlined design became more evident when Norwegian power houses were put underground in the 1950's, and from the middle 60's the unlined pressure shaft solution became traditional. From the late 60's the design with unlined pressure tunnels and unlined surge chamber with air cushion was introduced. Fig. 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 150m are in use. The total length of unlined pressure shafts/tunnels in operation in Norway today is not known exactly, but is estimated to exceed 2000 km.

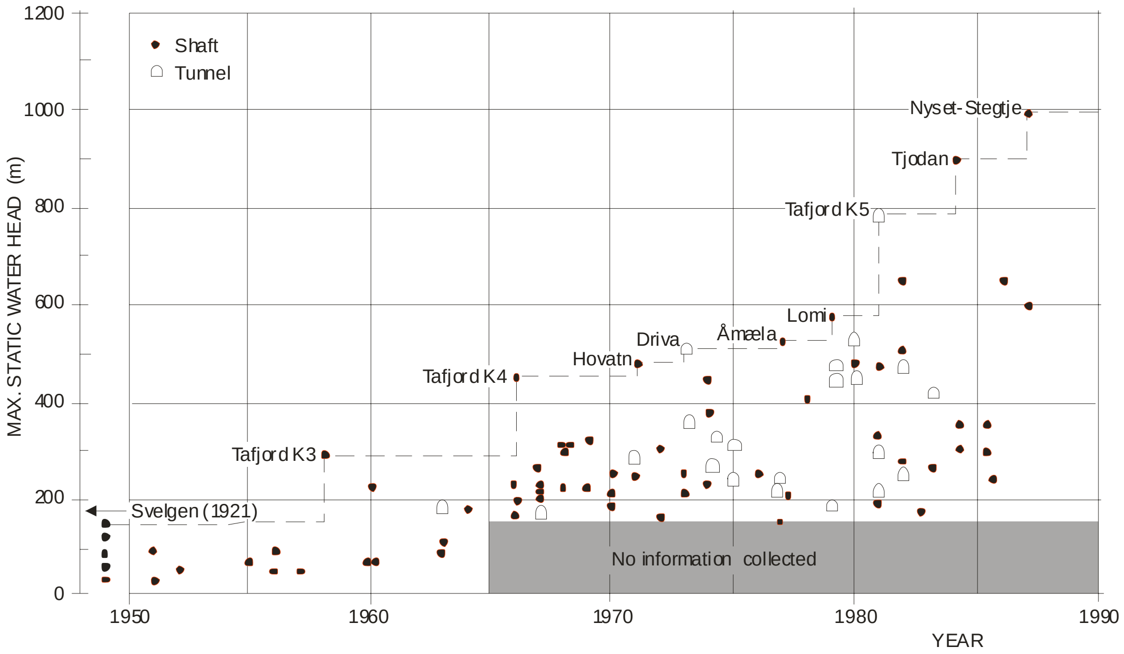

Fig. 1. Development of unlined pressure tunnels and shafts. Modified after ref. (7).

2. IMPORTANT ROCK MASS PROPERTIES FOR UNLINED CONDUITS

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 material itself must therefore have a low permeability. This must also be the case for the rock masses with its joints and fractures. 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.

The main requirement is, however, that the rock mass conditions permit a steady, low leakage out of the unlined pressure conduit and that no deformations which may result in failures can develop. The main criteria for a possible unlined tunnel or shaft are therefore:

- low permeability of rock material
- low permeability of joints and fractures
- rock stresses high enough to prevent deformations and opening of joints (hydraulic splitting)
- durable rock masses (during the plant's lifetime)

As for all waterways in rock the rock mass conditions must be suitable for tunnelling. There are, however, no significant additional requirements for unlined conduits other than for ordinary waterways in rock. In most Norwegian hydropower projects there are portions of poorer rock mass conditions where comprehensive rock supporting works have to be carried out. In unlined pressure tunnels and shafts sealing works must often be applied in addition to reducing possible water leakages and possible washing out of soft gouge materials. It is of course important that the cases of such poor conditions are few in order to get the desired benefits out of the unlined design solution.

Table I. Important rock ground conditions for a beneficial application of unlined pressure waterways

Rocks
- rocks are suitable for tunnelling
- rocks are "impervious" (i.e. permeability coefficient is lower than approx. 10^{-8} m/s)
- rocks are durable

Joints/weakness zones
- possible to construct tunnel/shaft through the zone
- limited amount of water-conductive joints where leaks may occur

Rock stresses
- rock stresses are high enough to prevent failure caused by hydraulic splitting in rock masses adjacent to tunnel/shaft

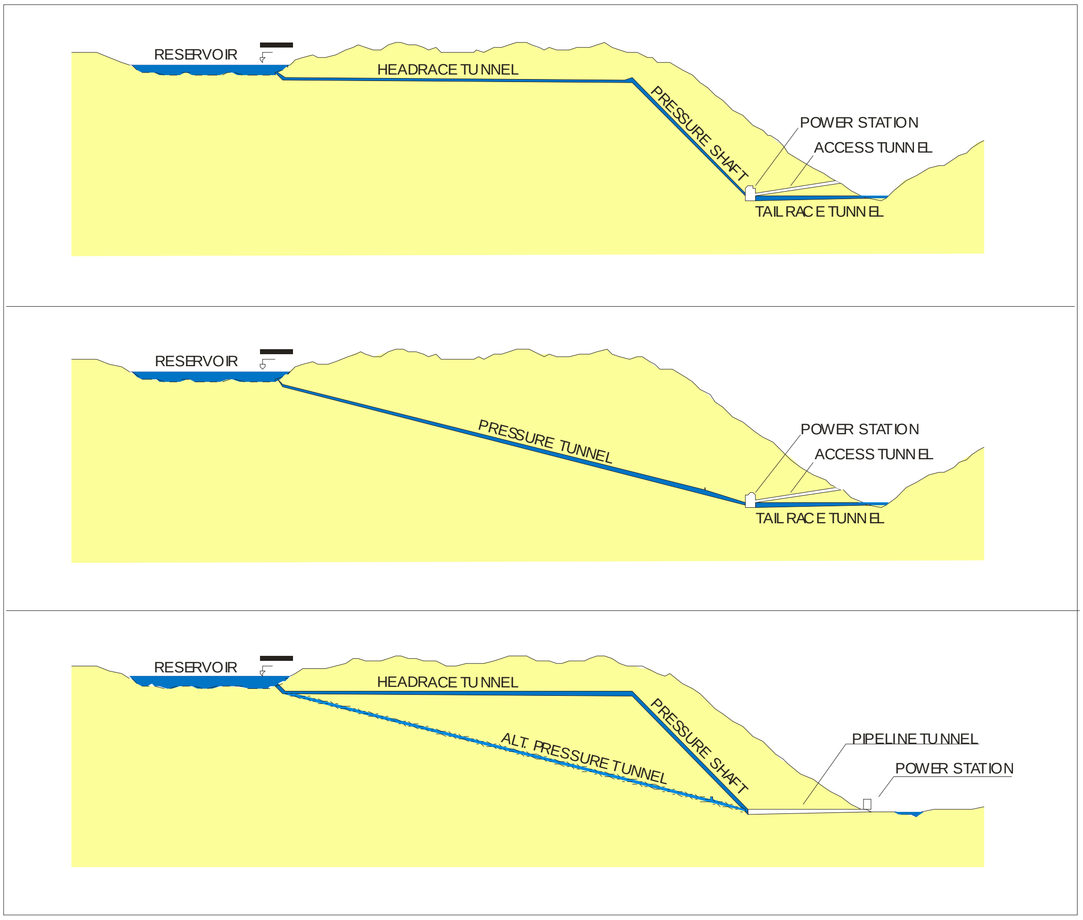

Fig. 2. Different design solutions with unlined pressure tunnels and shafts

3. COMMON DESIGN OF UNLINED PRESSURE CONDUITS

Fig. 2 shows the three main types of design solutions in current use. The pressure conduits have to be located deep enough to ensure sufficient rock pressure to withstand the internal water pressure. 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 costs of such high pressure steel conduits are often very high.

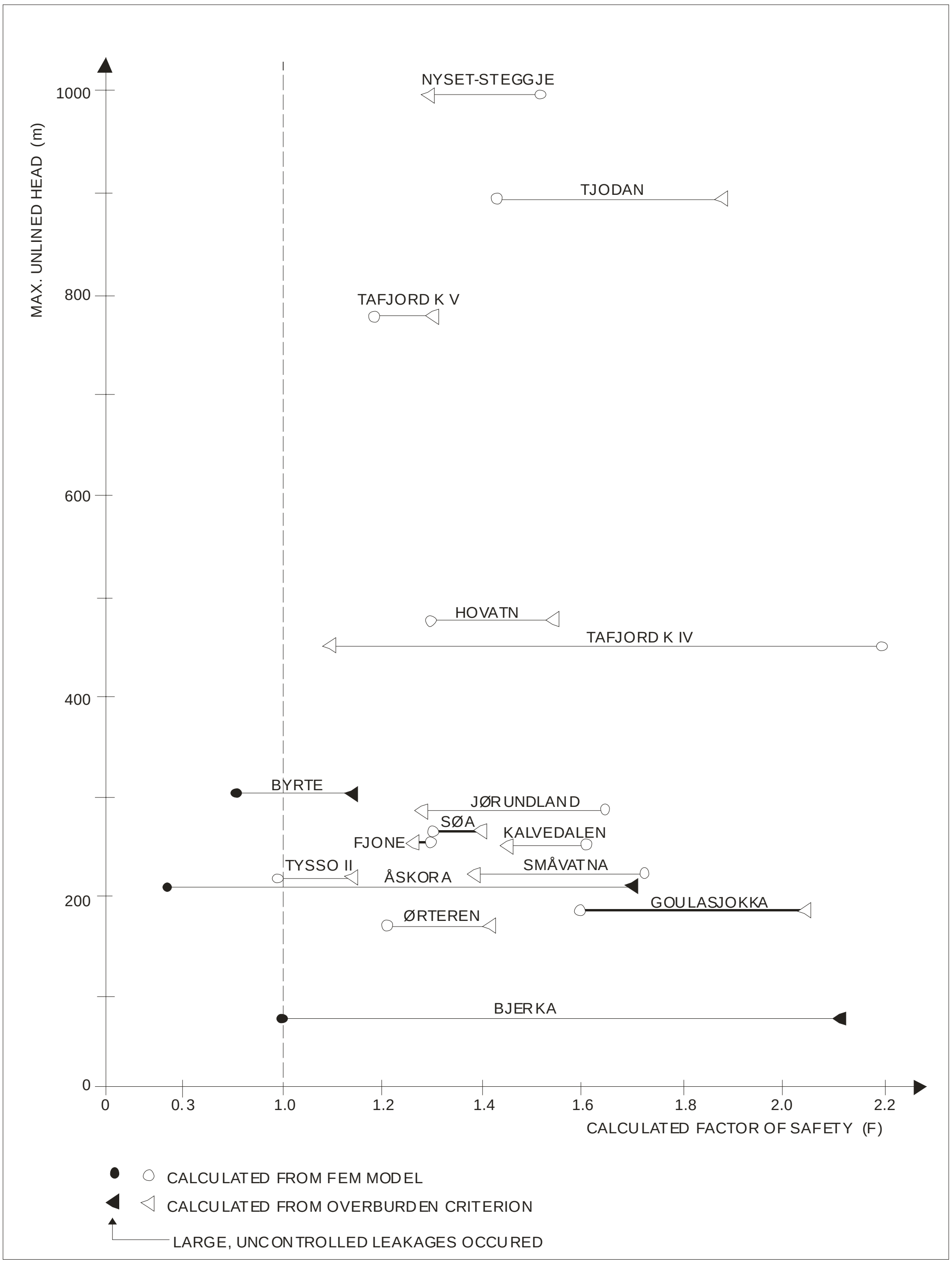

Fig. 3. Differences in factor of safety based on the overburden and the FEM criterion for some Norwegian pressure tunnels and shafts. Modified after ref. (12).

It should be mentioned here that the rock types encountered have mostly been as expected. Insufficient rock stresses, sometimes in connection with unfavourable fractures, have caused the failures mentioned, the reason being that the design principles used at that time did not provide for adequate rock cover and hence the stress conditions became critical.

Initiated by the experience gained from these failures, the design criteria have been further developed. This has gradually lead to today's design principles. Fig. 3 illustrates the difference in safety factors for the overburden design criterion compared with the FEM-analysis criterion. The FEM method gives a safety factor less than 1.0 for those unsuccessful projects. Had this design method been applied in those projects, the conduits would probably have been located differently and the failures would thus have been evaded.

It should be stated here that all the eight failed power plants have been repaired by extending the steel pipe, by a reasonable increase in cost, and that all of them are in use today.

The FEM design diagrams have been developed at the Norwegian Institute of Technology, Trondheim. This work was initiated by Prof. Rolf Selmer-Olsen. A set of standard two-dimensional FEM diagrams have been worked out. As most Norwegian power houses are located inside valley sides, these diagrams represent valley slopes varying from 14 – 75°. A conservative assumption of σ_h/σ_w = 0.5 and a Poisson's ratio = 0.2 has been applied. The principle of this method is that the minimum rock stress shall be higher than the operational interior water pressure at the same location.

These standard diagrams 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 has turned out to be the final one.

The topography at the actual site must often be ."transformed" to cover the standard valley side profile. An example of this is shown in fig. 4, and the location is chosen based on the values representing the valley side and the internal water pressure. The use of this method is further described by Selmer-Olsen (13) and Broch (7, 8).

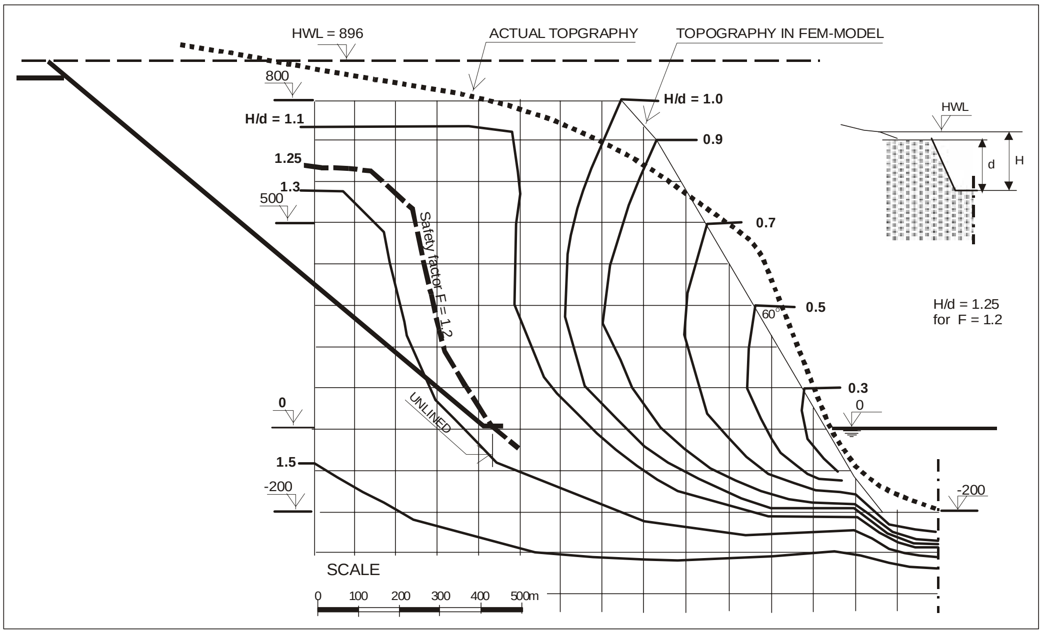

Fig. 4. Transformation of the actual valley side profile at Tjodan Power Plant to be applied in standard FEM diagrams. Modified after ref. (12).

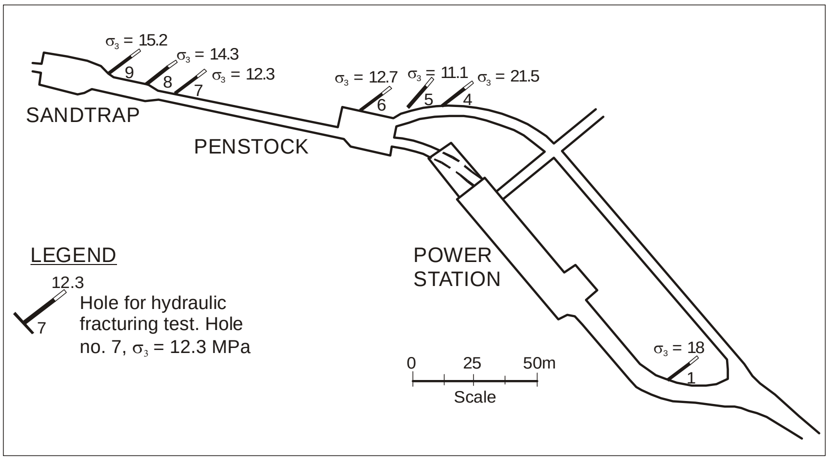

Fig. 5. Hydraulic splitting tests carried out for the Nyset-Steggje power plant. Max. head on unlined rock is 1000 meters (after ref. (4).

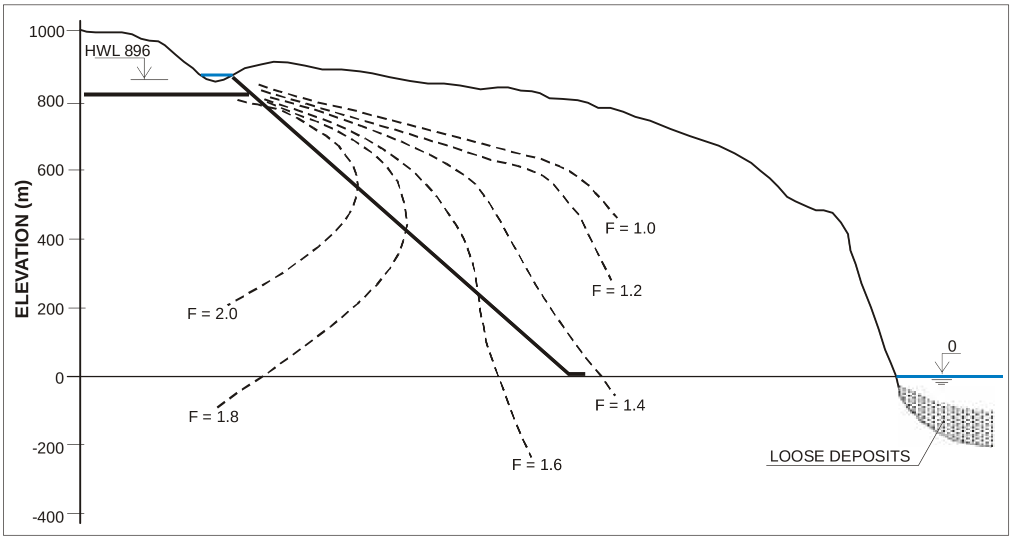

Fig. 6. From the FEM analysis and the measured in situ rock stresses it is possible to calculate the factor of safety along the unlined pressure shaft with regard to hydraulic splitting and failure. The example is from the Tjodan power plant. (after ref. (12))

For some projects a special FEM analysis have been performed where the actual topographical and geological conditions at the site have been put into the model. By this analysis it is also possible to carry out calculations for various magnitudes of the assumed stress levels or other changeable conditions.

As mentioned earlier there are always uncertainties regarding the true magnitude of the rock stresses occurring at the actual site. If the factor of safety used in the calculations is less than about 1.5, the rock stresses at the site should be verified by stress measurements. A relocation of the pressure conduit should be evaluated if the safety factor is less than about 1.15. Local conditions may, however, often play important role in these evaluations.

5. MEASURES DURING CONSTRUCTION AND FILLING UP OF THE SYSTEM

In *addition* to the possible measurements of rock stress it is important - at least for projects with high gradient from the pressure conduit - to carry out a conscientious registration of the rock conditions encountered during tunnelling, with special emphasis on water leakages. This information will form the basis for evaluating rock support and water sealing of possible leakages to be performed before the unlined tunnel/shaft is filled with water.

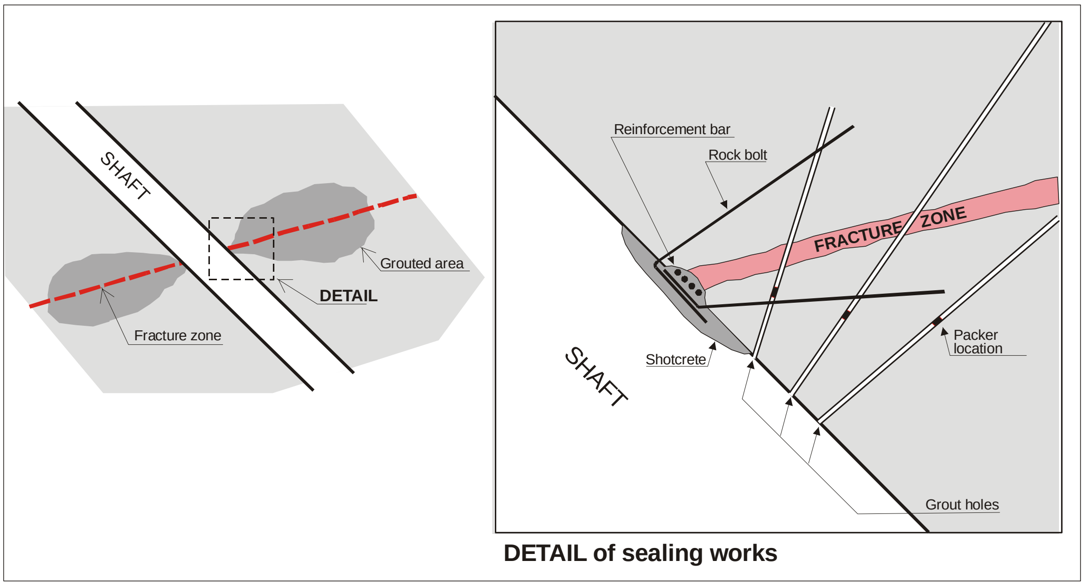

Fig. 7. Rock support and sealing of a fracture zone in a shaft.

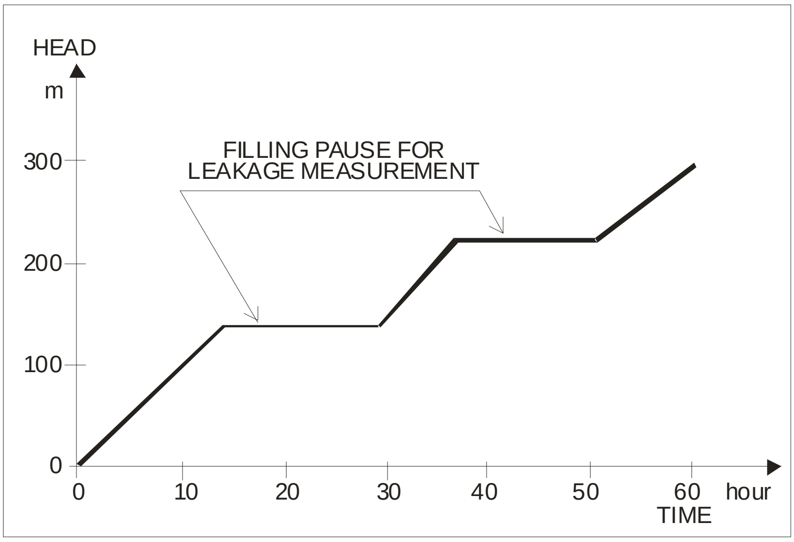

Fig. 8. Example of controlled, slow filling of a pressure conduit. (after ref. (9))

The last measure to be carried out to fulfil a safe construction of the unlined pressure waterway is a controlled and slow filling up of the system. The reason for this is explained in the following:

- While a shaft or tunnel is being excavated, and afterwards, joints and pores in the surrounding rocks are drained and often emptied, a situation observed in the fact that the leakage fed by the groundwater is often greatly reduced over time.
- When the system later is filled with water, the emptied joints and pores around the shaft become filled too. This generation of build-up of pressures may introduce a chance for deformations and a later possible washing-out of joints.
- If leakage measurements are done during first, slow filling, unforeseen leakages can be observed early so that the tunnel system can be emptied in time before flooding occurs and major damage is caused.

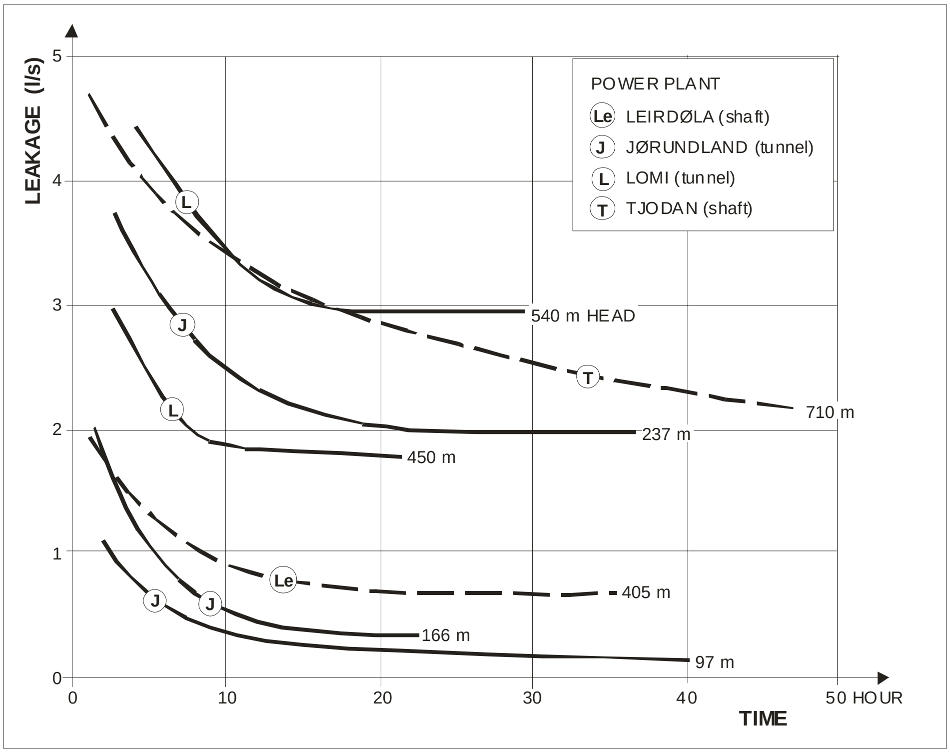

Fig. 9. Measured net water leakage out from various unlined high pressure shafts/tunnels. Modified after ref. (9) and (12).

It is normal procedure to fill a shaft in steps or intervals of 10 - 30 hours. During the intervals the water level in the shaft is continuously and accurately monitored by an extra-sensitive manometer. By deducting for the inflow of natural groundwater and the measured leakage through the plug cone, it is possible to calculate the net leakage out from the unlined pressure tunnel/ shaft to the surrounding rock masses.

From the about 5 - 6 pressure tunnels/shafts where leakage measurements have been carried out, an average permeability coefficient of $1 - 10 \times 10^{-9}$ m/s has been calculated. With this very low permeability a leakage of 0.5 - 5 1/s per km has been measured.

6. BENEFITS OF UNLINED PRESSURE TUNNELS/SHAFTS

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

- Cost savings during construction caused by the fact that the lining with steel penstock with concrete embedment is omitted.
- A normally reduced construction time meaning an earlier start-up of the power plant and reduced capital costs.
- A normally 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.

Finally it should be mentioned that the calculated cost savings at Tjodan power plant were about 6 mill. USD. The costs connected which geo-investigations, rock stress measurements and controlled filling up was 1 % of that saved amount.

7. CONCLUSION

The successful design of the unlined pressure tunnel/shaft is ensured by:

- a safe location with respect to the actual geology and topography (i.e. rock stress conditions)
- a well planned concrete plug both in connection with the cone and the possible adit
- a slow, controlled, first filling-up of the unlined waterway system
- possible later emptying of the conduit and the later refilling should be done slowly to avoid possible deformations.

Table II. Main evaluations during various design stages of an unlined pressure conduit.

STAGE	PROCEDURE/INVESTIGATION
CONCEPT STUDY	– study of topographical conditions; – main, rough geological (mapping) view; – estimate of possible location (overburden criteria or FEM standard diagrams).
FEASIBILITY	– geological mapping; – probable location based on FEM standard diagrams;
DETAILED DESIGN	– detailed geological mapping; – planned location based on special FEM analyses adapted to the topographical, geological and assumed rock stress conditions.
DURING CONSTRUCTION	– rock stress measurements in access tunnel at the planned location of the cone to verify the magnitude of the assumed rock stresses (a possible relocating of the cone may be done at this stage); – follow up of the geological conditions during construction of the pressure conduit; – rock supporting works; – sealing of fractures/zones where possible leakages may occur; – controlled, slow filling-up the first time of the pressure conduit together with leakage measurements.
DURING PRODUCTION	– slow filling or emptying of the pressure conduit.

The unlined pressure tunnel/shaft design has proved successful for many Norwegian hydro power projects. have made this possible, are not specific for Norway. The geological and topographical conditions which not specific for Norway. There exist lot of similar features in other parts of the world where the unlined pressure conduit design may be most beneficial to many future power plants.

8. ACKNOWLEDGEMENT

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