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Norwegian experience with subsea rock tunnels

Arild Palmstrom
A.B.Berdal A/S, Sandvika, Norway

ABSTRACT: The paper describes Norwegian subsea tunnel development and gives details from eight such subsea tunnels in hard rocks, the deepest being 253 m below sea level and the longest 4.7 km. Of special importance for a subsea tunnel construction is the use of probeholes and pre-grouting of possible water leakages ahead of the tunnel face. This measure has been used for more than 50 years in the Norwegian lake taps made, as submerged tunnel piercings. The trends during the last ten years to a decrease in the relative tunnelling costs make subsea rock tunnel an even more attractive alternative as compared to other strait crossing connections.

I INTRODUCTION

Norway consists of old rocks of Precambrian and Paleozoic (Caledonian) age, Fig 1. This means that all rocks found onshore are hard rocks. The bedrocks are, however, often cut by faults and thrust zones where the rock mass conditions are of significantly poorer quality than elsewhere. There are also areas where more densily jointing results in poor excavation conditions over longer distances in a tunnel.

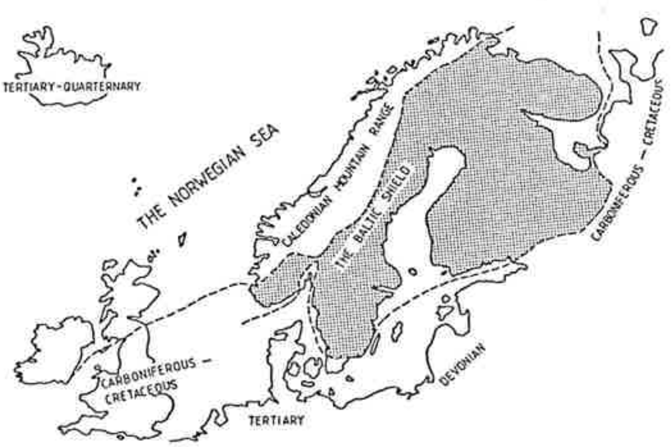


Fig. 1 The general geology of Scandinavia

The well exposed, mostly unweathered rocks in the surface offers good possibilities for evaluating the rock mass conditions underground, which have been an important feature in the tunnelling development during more than 75 years in Norway.

Up to the sixties most of the tunnelling was done in connection with hydropower exploitation where several improvements towards higher capacities and new design solutions were made. The lake tap method, includes tunnelling beneath a lake up to the lake bottom, has been most important for the later construction of subsea tunnels.

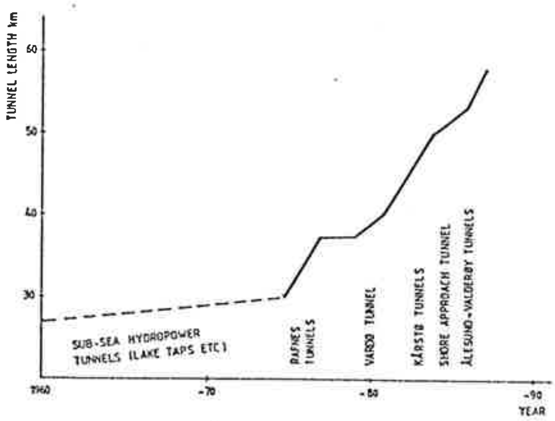


Fig. 2 Development of subsea tunnel construction in Norway

In the period 1975-87 five subsea tunnels for oil or gas pipelines were successfully constructed.

Construction of sub-sea road tunnels started in 1979. Today three tunnels of this kind has been finished and three more are under construction.

2 EARLIER SUBSEA TUNNEL EXPERIENCE

Subsea tunnels, in contrast to other tunnels, pass beneath the sea or the lake bottom where the geology is hidden by water. The downward excavation of such tunnels therefore meets higher geological risks including possibilities of having large inflows of water to cause great excavation problems or even cause drowning of the equipment and tunnel. A subsea tunnel project therefore requires thorough planning of the excavation works which should include special safety measures.

Looking back on earlier constructions of "over land" tunnels in Norway there are many projects which today may be classified as subsea tunnels. A common feature is the tunnelling of water conduits located below rivers and lakes for hydropower developments. Such tunnels generally serve as tailrace tunnels. One example of them is shown below:

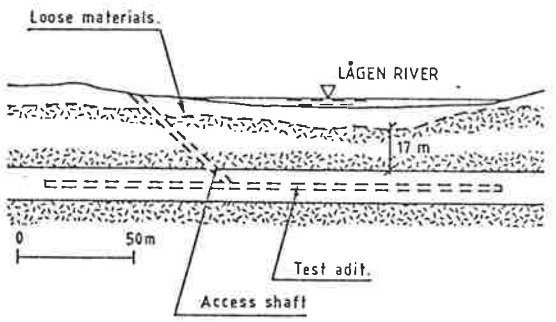


Fig. 3. At Hunderfossen power plant the 3.9 km long tailrace tunnel with a span of 13 m was constructed in 1959-62. It involved the crossing below the Lågen river over a length of 200 m with a minimum rock cover of 17 m. The bedrocks consist of quartzite and gneiss.

As mentioned earlier the most useful early experience in sub-sea tunnelling is the construction of submerged tunnel piercings, or lake taps, which is a Norwegian speciality in hydropower works. The piercing is effected by excavating a tunnel in the rocks under the lake bottom, up to a preselected point, from where a controlled hole through is made by a final round of blasting.

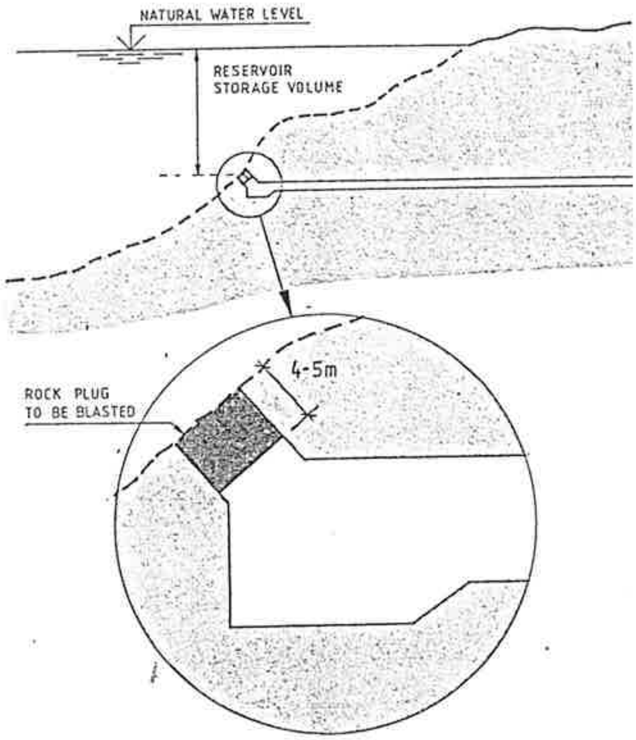


Fig. 4. Principles for the lake tap method

By such submerged piercing arrangements the lake is made accessible for hydropower exploitation using the storage volume available below the original water level.

The experience from more than 500 piercings is that the execution of probedrillings ahead of the tunnel excavation is the most important measure for a successful piercing construction. Where water leakages are detected in the drillholes, immediate sealing by cement grouting is carried out. With this procedure the experience shows that it is possible to approach as close as 4 - 6 m from the rock surface on the lake bottom.

3 FIELD INVESTIGATIONS FOR SUBSEA TUNNELS

The ice erosion in Quarternary time (the last million years) removed all the weathered rocks in the surface and left behind a surface of unweathered, fresh rocks. Weaker rock masses like faults and weakness zones are often stronger eroded to form depressions and valleys. These features are therefore often easy to detect from surface mapping and aerial photo studies. With such conditions, which occur in many part of the country, the rock mass tunnelling conditions are easy to interpret. The costs for field investigations are therefore low, normally less than 1 % of the construction costs for "over land" tunnels.

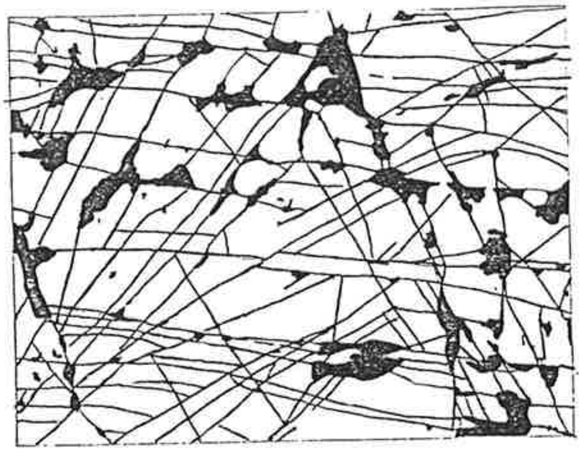


Fig. 5 Weakness zones and faults interpreted from air photos

Mapping of the bedrock conditions for subsea tunnels require, however, more sophisticated investigations since large parts of the geology is covered by water.

The first step in the investigations is to make a topographical map of the rock surface beneath the sea. For this reason acoustic measurements (boomer-sparker profiling and echo soundings) are carried out. The map produced is used to evaluate a possible preliminary tunnel alignment.

In addition to extrapolations of the geology onshore the geological conditions beneath the sea are found by means of refraction seismic profiling as well as core drillings, mainly carried out by inclined holes from the shore. The different seismic velocities in rocks is used as an indication of the rock mass qualities. In addition the thickness of loose materials is recorded. It has been found that good rock mass qualities normally have velocities higher than 5000 m/s. Weakness zones or faults have velocities lower than 3500 - 4000 m/s.

The costs of the investigations carried out for Norwegian subsea tunnels varies between 1 and 5 % of the total construction costs, refer to Table 2.

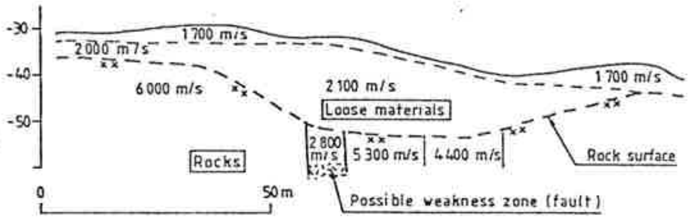


Fig. 6. Example of a refraction seismic profile of the sea bottom

In spite of comprehensive field investigations it is important to realize that detailed knowledge of the geology and the rock conditions prior to excavation can not be obtained for a subsea tunnel. To compensate for this ever present uncertainty, exploration ahead of the tunnel face during excavation is performed as a part of the preinvestigation program. The costs for this measure is about 1,5 - 2% of the construction costs, which must be considered as a reasonable insurance both regarding safe working conditions and a completion of the project as near on costs and schedule as possible.

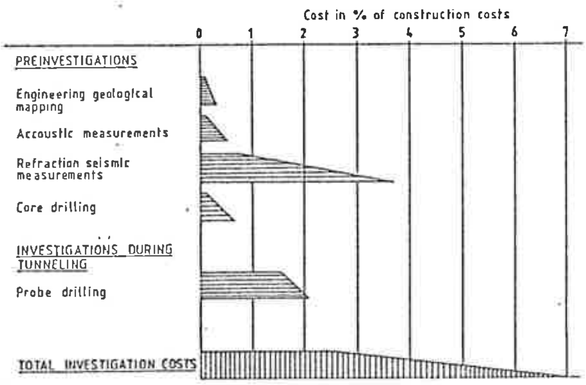


Fig. 7. Comparative costs in % between different investigation methods for a Norwegian subsea tunnel

4 SOME DESIGN CRITERIAS USED

The design of the alignment and length of a subsea tunnel is governed by three different parameters, namely the:

- topography
- geology
- project/construction requirements

Important for the design of subsea tunnels is the thickness of the rock cover, i.e. the distance from the tunnel roof up to the rock surface beneath the sea. The geological conditions will influence on the rock cover required for a safe construction and operation of the tunnel. There are no existing Norwegian requirements or standards for this. The data in Table I have often been used as minimum requirements.

Table 1. Minimum rock cover used for a limited distance along subsea tunnels. Along longer parts of the tunnel the rock cover should be 10-20 m thicker.

	MINIMUM ROCK COVER		MAX GRADIENT
Water depth to rock surface	Good quality rock masses	Poor quality rock masses	
0 - 25 m	25 m	30 - 35 m	2
25 - 50 m	30 m	35 - 40 m	2.6
50 - 100 m	35 m	40 - 50 m	3.8
100 - 200 m	40 m	45 - 60 m	6

Also the inclination required for a subsea tunnel will influence on the actual tunnel length. Great cost savings can be achieved in using as steep tunnel as possible. For a road tunnel the inclination will vary from about 1:8 to 1:20 depending on the tunnel standard.

Subsea road tunnels are made with span 8 m for two lane and 11 m for three lane traffic. The tunnels are supported as required, i.e. the final decision of the amount and types of permanent support is taken after the tunnel has been excavated and the actual rock mass quality can be inspected and used in the support design. Rock bolts and shotcrete are the rock supporting types mostly used.

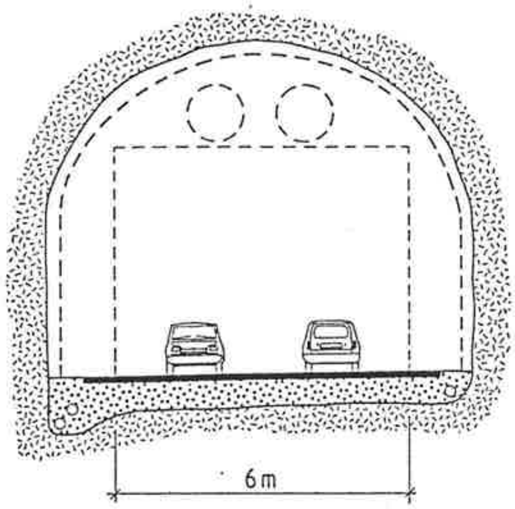


Fig. 8. The cross section for a two lane road tunnel is 50 m2

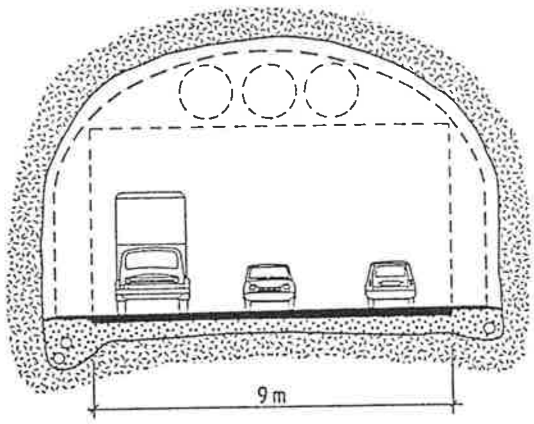


Fig. 9. The cross section is 70 m2 for a three lane road tunnel

5 EXCAVATION AND ROCK SUPPORT TECHNIQUE

5.1 Excavation

Excavation with tunnelling boring machine (TBM) seems immediately attractive due to high advance rates under suitable rock conditions. Average rates in the order of 125 m or more per week have been obtained even in hard rocks (gneiss, granite).

TBMs designed for hard rock provide, however, limited access to the face and to the area close behind. This restrict the use of rock support to be placed at the face. Under unstable rock conditions the TBM may consequently more easily get hampered or even get stuck before the tunnel is properly supported.

The traditional drill and blast method requires more rock support than the TBM method, and requires more ventilation. It has, however, a greater flexibility to changing rock conditions. The tunnel face is easily accessible for exploratory drilling, and the percussion probeholes can be performed by the tunnel jumbo used for drilling of blast holes. This method offers therefore a safer and more flexible excavation and has therefore been used for all Norwegian subsea tunnels.

The length of the blast rounds is mostly 4 m and the production 1.5 - 2 rounds per shift (7.5 hours). The rock supporting works and probedrillings, however, reduce the excavation rate normally to the half for subsea tunnels.

5.2 Probedrillings and sealing ahead of excavation

Probeholes and pre-grouting used in tunnel piercings has been fully applied in the Norwegian subsea tunnelling. Fig. 10 shows the principles for this technique.

The pre-grouting should preferably be included in the probedrilling programme. When a water-bearing zone has been detected by the probeholes, additional holes are drilled and grouting is done through all the holes showing water leakage. The number of grout holes varies normally between 10 to 20 for a 50 m2 tunnel and the length of the holes between 12 m and 30 m. After the grouting is completed and control holes performed, the tunnel can be further excavated by drill and blast through the sealed zone.

The required time for the grouting work will depend upon the rock and leakage conditions and may vary from less than one day to several weeks. Most often it takes 20-30 hours. This operation is presently being improved by the development of different chemical grouts and additives.

Extended probing has often been made by core drilling either carried out from specially made recesses or from the tunnel face. By this method more information is gained of the rock mass conditions in addition to the leakage recordings. A special advantage of this method is the possibility to detect leakages associated with poor or low stability rock mass conditions a long distance ahead of the tunnel. Thus the necessary precautions can be taken for the sealing of possible large leakages, and for preparing for required rock supporting works.

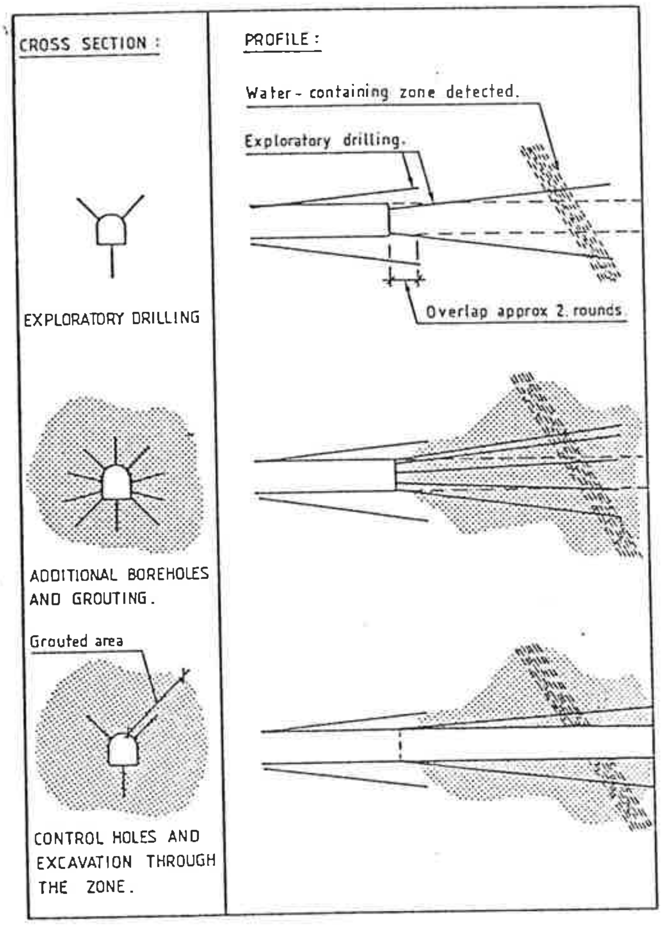


Fig. 10. Principles of probing by exploratory drilling and pre-grouting of leakages

Sealing by pre-grouting has two objectives. One is to prevent large water inflows into the tunnel during excavation and the other is to reduce the rate of permanent inflow into the tunnel after construction.

5.3 Rock Supporting Works

The rock supporting methods, most commonly used in Norwegian tunnels are:

- Rock bolts is used to support unstable blocks or as an element in other supporting methods.

- Shotcrete is concrete sprayed on the tunnel roof and walls, often used in combination with rock bolts. The shotcrete can be strengthened by welded net or by steel fibre reinforcement. The fibre reinforced shotcrete offers a quick and very effective support and has therefore a special advantage in difficult rock masses with short stand-up time.

- Concrete lining is used under poor rock mass conditions which involve larger volumes of unstable rocks.

5.4 Safety Measures

The risks caused by the difficulty and uncertainty in predicting the geological conditions under the seabed can be offset by special safety measures during construction. Of these, the exploratory or probe-drilling and grouting ahead of the tunnel face is considered to be the most important. It is also of importance to chose a contractor with experience from similar projects who is able to work out plans and implement them quickly if unforeseen events take place.

A high pumping capacity and emergency generators during construction is another important measure.

A close supervision of the excavation works and the probedrillings at tunnel face by experienced engineering geologists is a must for a safe execution of the project.

The freezing technique offers the possibility of excavating even through zones with an exceptionally low degree of stability. Such a procedure is very time-consuming and expensive and can only be sucessfull if there are minor or no water leakages associated with the zone. So far it has not been used in Norwegian subsea tunnels.

6 NORWEGIAN SUBSEA TUNNELLING EXPERIENCE

The experience from 9 Norwegian subsea rock tunnels is that the rock quality has been fair to good for tunnelling. In weakness zones varying from 5 to 400 m in width the quality has been poor to very poor. In some occasions special rapid rock supporting concreting methods were succssfully used which made a safe advance possible even were the stand up time of the rock masses was very short. An experienced contractor is most important in such conditions.

The experience from sealing of water leakages is that normally about 8 - 10 % of the tunnel length has been pregrouted. The costs for the grouting have normally been between 1000 - 2500 USD per meter grouted (1 USD = 6.5 NOK). Compared to the whole tunnel length the sealing costs have therefore normally been only 100 - 250 USD per meter tunnel. Only in a very few cases it has been necessary to carry out grouting after hole through of the tunnel. The water leakages into the tunnels vary between 75-400 l/km tunnel. The corresponding permeability coefficient of the rock masses along the partly grouted tunnel is in the order $k = 10^{-7} - 10^{-8}$ m/s.

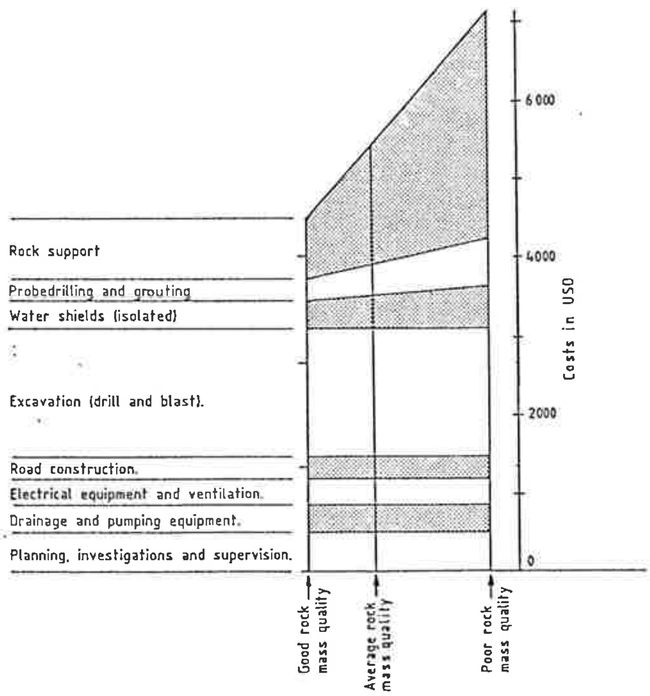


Fig. 11 Distribution of construction costs for Norwegian two lane subsea road tunnels

The greatest uncertainties in construction costs stem from the required rock supporting and grouting works, caused by variations in rock mass conditions as shown in Fig. 11.

Some details of the Norwegian subsea tunnels are given in the following figures. Further information is given in Table 2.

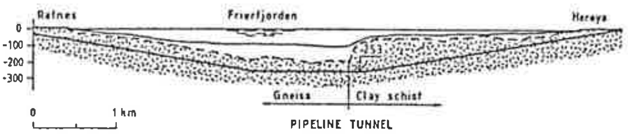
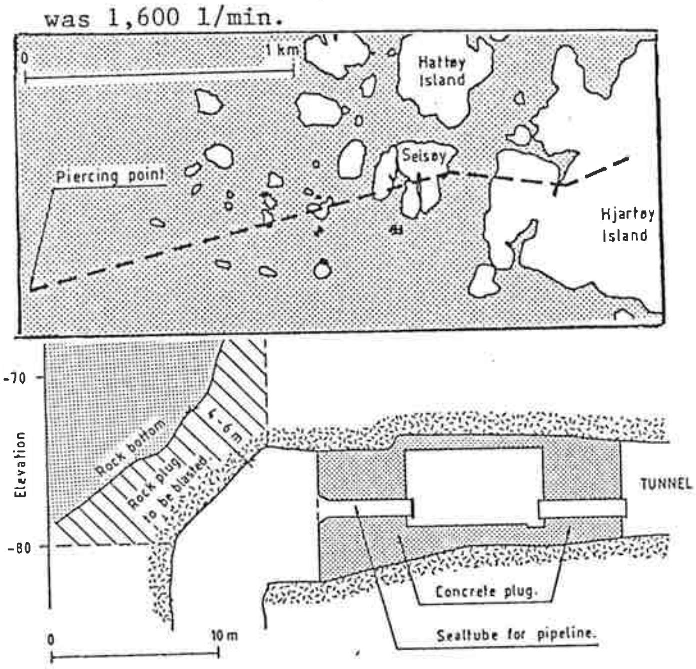


Fig. 12. The 253 m deep gas pipeline tunnel under the Frierfjord is 3.6 km long with a span of 4 m. The amount of rock supporting works was moderate and included bolting, shotcrete and full concrete lining where required by the rock mass conditions. The total water leakage into the tunnel was 1,600 l/min.



PIERCING POINT

Fig. 14. The 2320 m long Shore approach tunnel at Hjartøy was successfully constructed 1985-87. It has a cross section of 26 m2, and is located in Precambrian gneisses. The piercing was made similar to the Norwegian lake tap method, but it involved a larger rock plug to be blasted. The two concrete plugs located close to the piercing point which kept the tunnel dry during installation of the pipeline from the sea side, made the final blast most challenging.

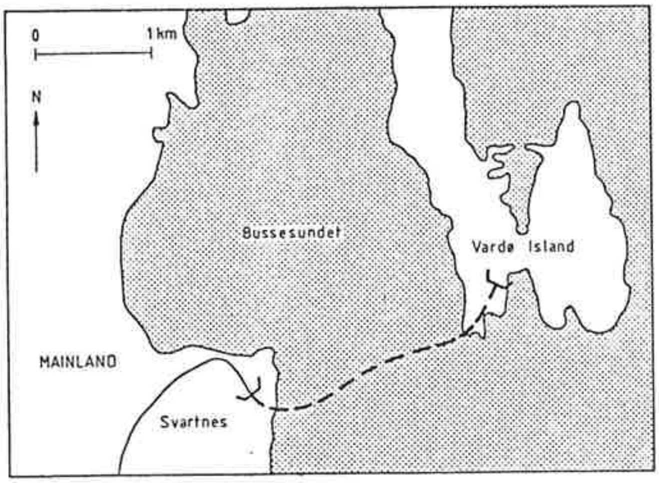


Fig. 13. The Vardø subsea road tunnel was constructed 1979-82. It is 2.6 km long with a cross section of 50 m2. The deepest point is 87 m below sea level and minimum rock cover 32 m. The rocks are late Precambrian siltstone, sandstone and clayschist. The permanent water inflow is 1000 l/min.

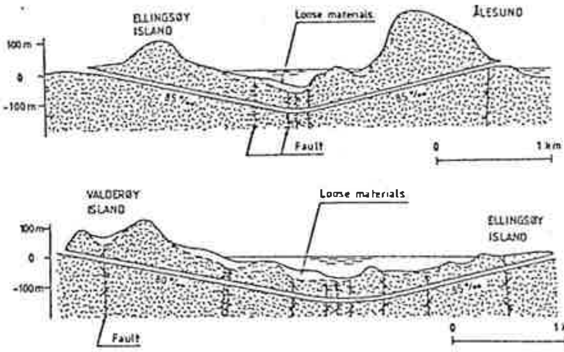


Fig. 15 The two Ålesund road tunnels of 75 m2 cross section opened in 1987, were constructed in 1.5 years. The total length of the tunnels excavated in Precambrian gneiss is 7.7 km with the lowest point 140 m below sea level.

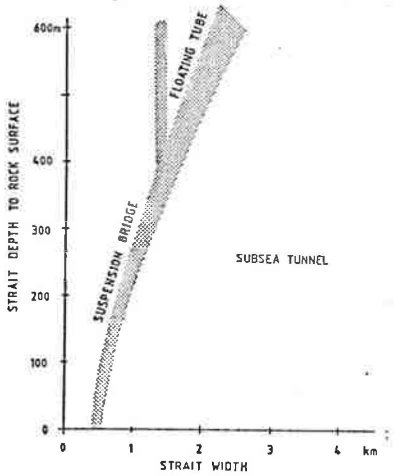


Fig. 16 Subsea road tunnel is often cheaper than other fjord connections in Norway.

Table 2. Data from eight Norwegian subsea tunnels

YEAR OPENED	PROJECT	PURPOSE	TUNNEL DATA			PRE-INVESTI GATIONS	WEEKLY PROGRESS RATES		WORKING HOURS PER WEEK
			LENGTH	CROSS SECTION	DEEPEST POINT	% of construction costs	Average	max	
			km	m2	m		m	m	
1974	Rafnes-Herøya	Gas pipeline	3,6	16	-253	1,7	37	97	130
1982	Vardø	Traffic	2,6	50	- 88	5,0	17	60	75
1984	Karmsundet	Gas pipeline	4,7	26	-180	1,9	33	92	105
1984	Førdesfjord	Gas pipeline	3,4	26	-160	1,9	26	63	105
1984	Førlandsfjord	Gas pipeline	3,9	26	-170	1,5	36	85	105
1987	Oseberg Shore Approach Hjartøy	Oil pipeline	2,3	26	-110	4,0	39	92	105
1988	Ålesund - Ellingsøy	Traffic	3,5	70	-140	1,0	35	55	105
1988	Ålesund - Valderøy	Traffic	4,3	70	-140		38	65	105

Looking at the 3000 km long Norwegian coastline with lots of island and long fjords, it is obvious that there is a great demand for permanent connections for the many people living in these regions. Subsea road tunnels are the most attractive solution for many of these, as can be seen on fig. 16.

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