SUB-SEA ROCK TUNNELS

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ABSTRACT

In many cases there are few differences between construction of sub-sea tunnels and ordinary "over land" tunnels, and much of the experience gained from the latter are therefore applicable for sub-sea tunnels. Of special importance is the use of an exploratory drilling program combined with sealing of possible water leakages by pre-grouting 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 paper concentrate on hardrock sub-sea tunnels and describes 9 tunnels constructed in Norway, the deepest being 253 m below sea level and the longest 4.7 km.

The geology has been the main uncertainty in sub-sea tunnelling, where the average costs for sealing and rock supporting works have varied from less than 50 % up to more than 200 % of the excavation (drill and blast) costs. The construction costs for a 50 m2 tunnel, where tunnel works (road etc.) and capital costs are excluded, have varied between 3,000 - 5,000 USD (1986) per meter tunnel. The excavation progress has been 17 - 40 meters per week.

Improvements in equipment and tunnelling techniques is also an important fact that contribute towards a successful construction in difficult rock mass tunnelling conditions. The trends to a decrease in the relative tunnelling costs make sub-sea rock tunnel an even more attractive alternative as compared to other strait crossings even for straits shorter than 1 km.

Tunnels down to depths of 500 - 600 m below sea level appear possible to construct within 10 - 15 years. There are also studies in progress evaluating 50 - 60 km long sub-sea tunnels for oil explortation in the North Sea within 8 - 10 years of construction time.

1. What is a Sub-sea Tunnel?

The break-through of the 54 km long Seikan tunnel after about 20 years of construction in poor rock condition made a significant contribution to the development of and interest for sub-sea rock tunnels. As will be delt with in the following, the construction of sub-sea tunnels may not be as challenging as many seem to believe today. The development in tunnelling combined with the experience gained from "over-land" tunnels make sub-sea tunnels an alternative much more attractive and which ought to be looked hits in many strait crossings.

Name	Location	Type of service	Length (km)	Year opened
Seikan (-260 m)	Japan	Railway	53.0	1983
Shin Kanmon	Japan	Railway	18.7	1973
Severn	U.K.	Railway	7.0	1886
Mersey	UK	Railway	4.9	1886
Karmsundet (-180 m)	Norway	Pipeline	4.7	1983
Mersey	U.K	Road	4.2	1934
Førlandsfjorden (-170 m)	Norway	Pipeline	3.9	1983
Kanmon	Japan	Railway	3.6	1942
Rafnes (-253 m)	Norway	Industry	3.6	1976
Førdesfjorden (-160 m)	Norway	Pipeline	3.4	1985
Kanmon Road	Japan	Road	3.6	1958
Vardø (-85 m)	Norway	Road	2.6	1982

Table 1. Some tunnels constructed under rivers/sea bed

Sub-sea tunnels, in contrast to other tunnels, pass under bodies of water that are inexhaustible and where drainage into the tunnel has no lowering effect whatever on the groundwater line. The downward excavation of such tunnels therefore include the possibility of having large inflows of water that will cause great problems to the excavation works or even drown the equipment and tunnel. A subsea tunnel project therefore require thorough planning of the works and included special safety measures.

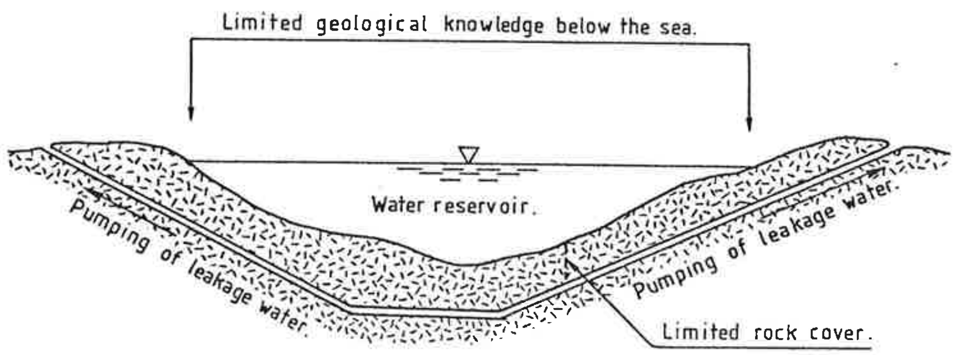

Fig. 1. Sub-sea tunnel aspects

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The special features in sub-sea tunnelling shown in the Fig. 1 are therefore:

- Short distance to the inexhaustible water reservoir
- Limited knowledge of the rock mass conditions
- All leakage water has to be pumped out both during construction and during the structures lifespan.

2. Differences between Land Tunnels and Sub-sea Tunnels

The sub-sea tunnelling is not as "hazardous" as many seem to believe, and there are many similarities with "over-land" tunnels. Except for the short leakage paths and the possibilities for large, never ending leakages, there are in fact small differences for many "over-land" tunnels excavated on declines as shown in Fig. 2.

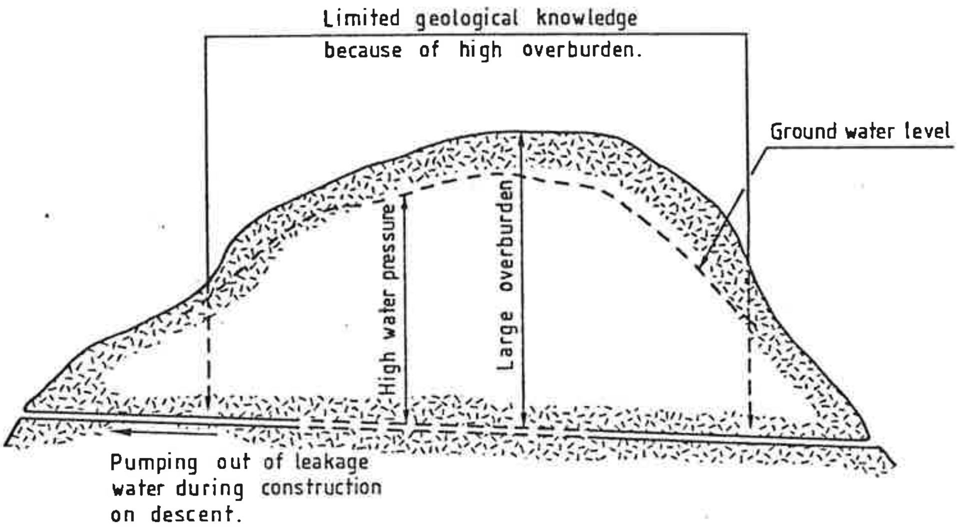

Fig. 2. Aspects of many land tunnels with high overburden

For many of the longer "over-land" tunnels having considerable rock cover there are in most cases also great uncertainties in predicting the rock mass tunnelling quality at tunnel level. In the author's opinion the construction of the tunnels through the Alps some 50 - 100 years ago was more challenging than most of the sub-sea tunnel plans of today considering the tunnelling equipment available at the time.

The ground conditions, construction methods and experience, price level, tunnel requirement and regulation etc. vary considerably around the world. It is therefore impossible to give a general opinion of sub-sea tunnels covering all these different aspects.

The author has therefore found it appropriate to concentrate on Norwegian sub-sea tunnelling experience. This results in a highlighting of hard rock sub-sea tunnelling techniques including more comprehensive and comparable descriptions of this.

3. Early Relevant Tunnelling Experience

Looking back on earlier constructions of "over-land" tunnels there are many projects which today would may be classified as sub-sea tunnels. In Norway for example, a common feature is the tunnelling of water conduits located below rivers and lakes for hydropower developments. Such tunnels generally serve as tailrace tunnels. Two of them are listed below:

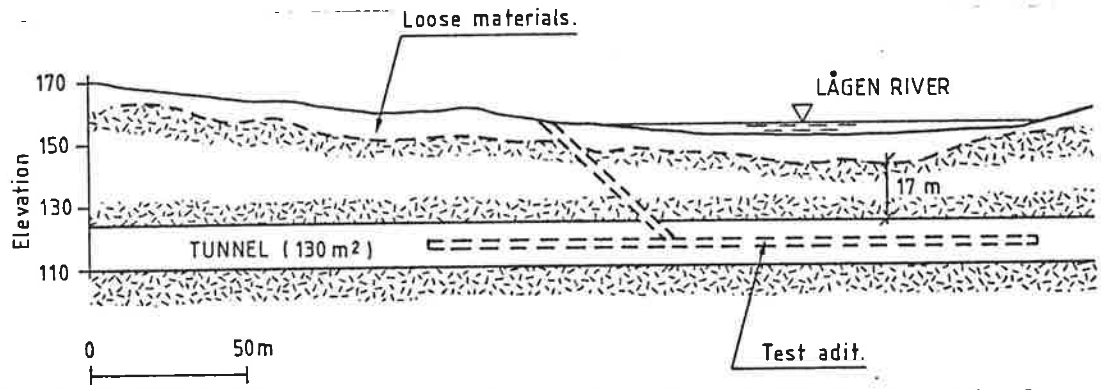

Fig. 3. At Hunderfoss power plant a 3.9 km long tailrace tunnel of cross-section 130 m2, was constructed in 1959-62. It involved the crossing under the Lågen river over a length of 200 m with a minimum rock cover of 17 m. Rock masses consisted of quartzite and gneiss.

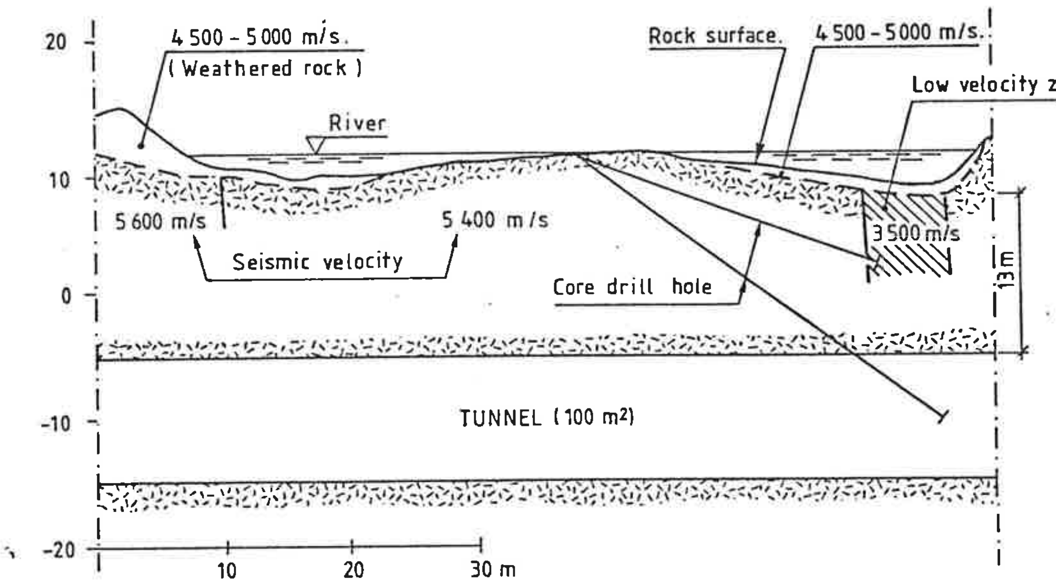

Fig. 4. Rygene power plant (1974 - 76): The 2 km long, 95 m2 tailrace tunnel crosses under the 100-200 m wide Nidelven river in two locations with a minimum rock cover of 13 m.

The most useful early experience from 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.

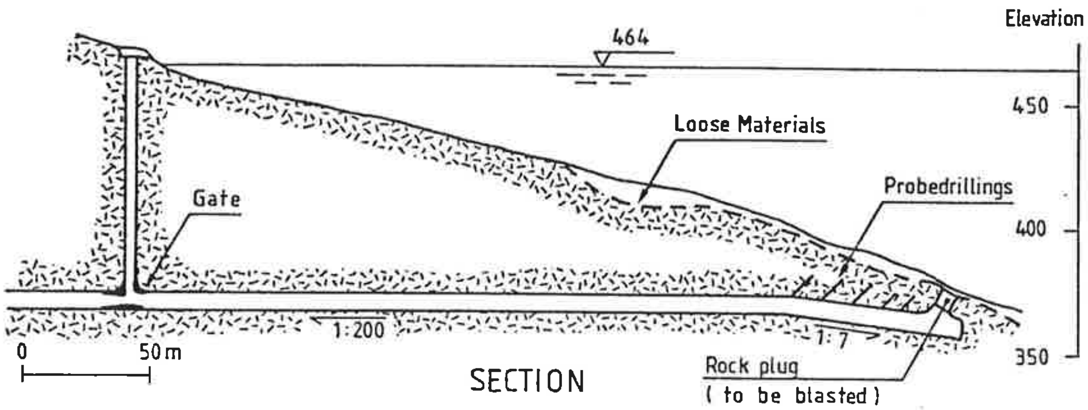

Fig. 5. Lake tap made at 80 m water dept

By such submerged piercing arrangements the lake is made accessible for hydropower exploitation using the storage volume available below the original water level. (If a similar storage volume should be provided above the natural water level, this would require heavy construction including dam etc. Such an alternative is generally much more expensive.)

The most important measure for a successful piercing construction is the carrying out of probedrilling ahead of the tunnel excavation. Where water leakages are detected, sealing by cement grouting is carried out. For this system experience shows that it is possible to approach as close as 4 - 6 m from the rock surface on lake bottom.

4. Norwegian Sub-sea Tunnels

4.1 General Experience

The field exploration work preceding the construction of the sub-sea tunnels, has mostly included geologic mapping, boomer-sparker profiling, seismic refraction measurements. In addition core drillings have been performed to verify the seismic results and to evaluate the permeabiliity of the rock masses.

The experience from 9 Norwegian sub-sea 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.

The experience of water leakage is that normally about 8 - 10 % and so far not more than 25 % of the tunnel length had to be pregrouted. The costs for the grouting have normally been between 1000 - 2000 USD per meter grouted. Compared to the whole tunnel length the sealing costs have therefore normally been only 100 - 200 USD per meter tunnel. Only in a very few cases it has been neccesary with grouting after excavation has been carried out. 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 being of the order $k = 10^{-7} - 10^{-8}$ m/s.

The construction costs for the tunnels described in the following are given in Table 5. The location of the tunnels is shown in Fig. 17

4.2 Sub-sea Gas Pipe Tunnel, Rafnes-Herøya (1975-76):

This is a 3600 m long gas pipe tunnel of 16 m2 cross-section built in 1975-76 designed to be waterfilled under normal operating condition. The basically unlined tunnel has a lowpoint 253 m below sea level, with a minimum rock cover of 50 m and loose materials approx. 100 m thick. The construction time for the tunnelling work was 1.1 years, working 112 hours per week from both headings, applying the drill and blast method.

The bedrocks consist of Precambrian granites and gneisses, and Cambrian shales and limestone. During the construction phase, drilling of 50 m long exploratory holes ahead of the tunnel face was made mandatory every weekend. The pre-grouting was carried out where the exploratory holes showed leakages. Inflow of leakage water was most pronounced in the gneisses, and required sealing by pre-grouting of rock masses in front of the heading over approx. 1000 m length. The permanent inflow of leakage water, in the drained-tunnel condition, was 1600 l/min.

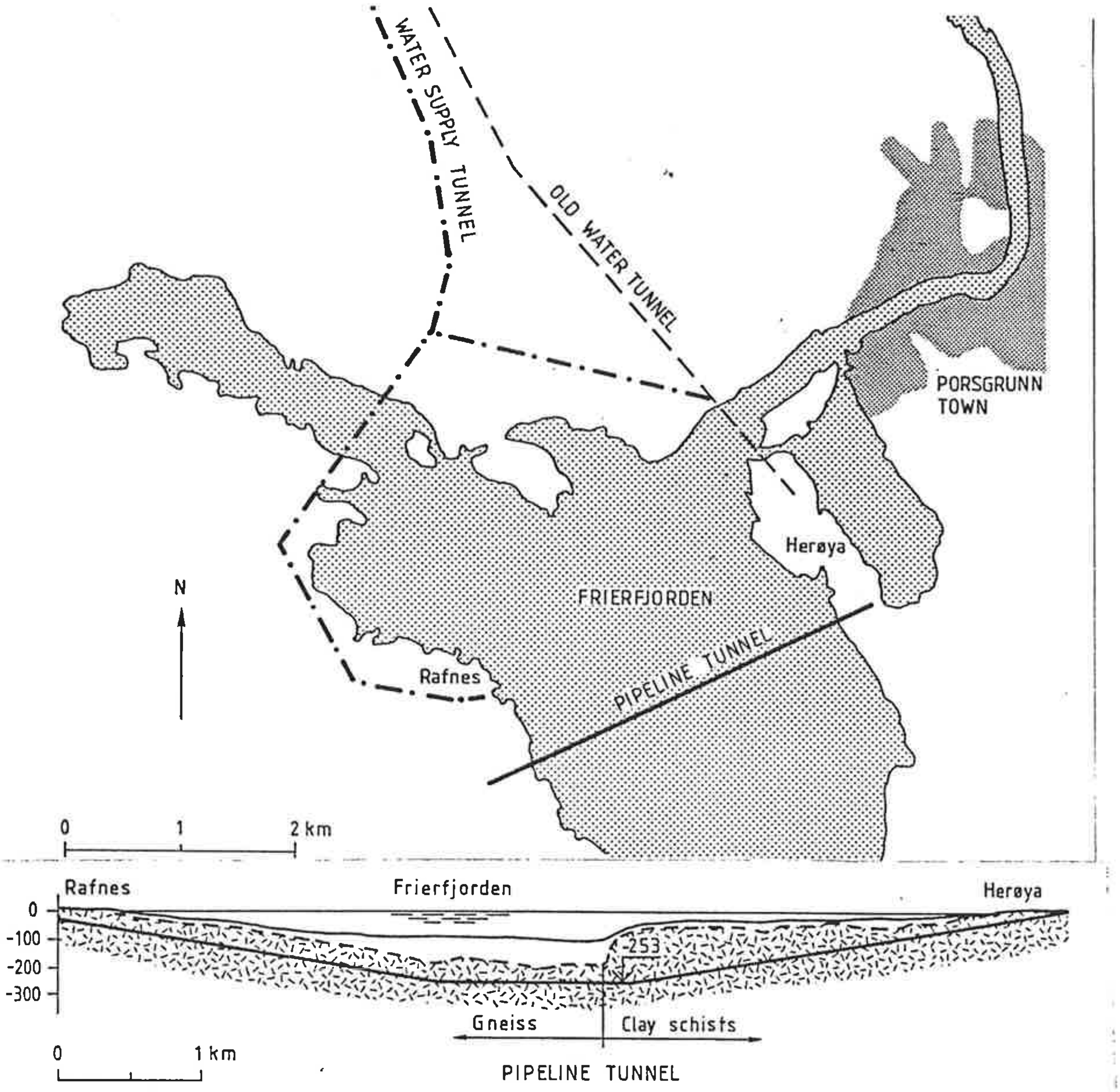

Fig. 6. Sub-sea tunnels in the Rafnes area

The amount of rock supporting work was moderate and included bolting, shotcrete and full concrete lining where required by the rock mass conditions.

4.3 Water Supply Tunnel Nordsjø-Rafnes (1974-77):

The trunk line of this tunnel is approximately 12 400 m long, including 4000 m at sub-sea level. Most of this latter part, with a tunnel cross-section of 8 m2, is located at 80 m below sea level. Over a total distance of 700 m, (between shorelines) the maximum water depth is 25 m and the minimum rock cover 40 m. The tunnel which is basically unlined was excavated by the drill-and-blast method. Cement grouting ahead of the tunnel face was occasionally used to seal the rock and prevent leakage.

The bedrocks are Precambrian granites and gneisses, with intersecting wide zones of swelling clay. After an initial completion in 1976, the tunnel collapsed in three locations shortly after being water-filled. The cave-ins occurred in swelling clay zones, where the shotcrete used as rock supporting measure during construction had not been strenghened by full concrete lining.

4.4 Vardø Road Tunnel (1979-82)

A two-lane road tunnel 2,6 km long in rock, is linking the island city of Vardø with the mainland. 1700 m of the tunnel length is below seawater in a 25 m deep sound, where the minimum rock cover is 32 m. The lowest point of the tunnel is 87 m below sea level. The construction time for the tunnelling work was 2.2 years, working 75 hours per week, applying drill and blast excavation.

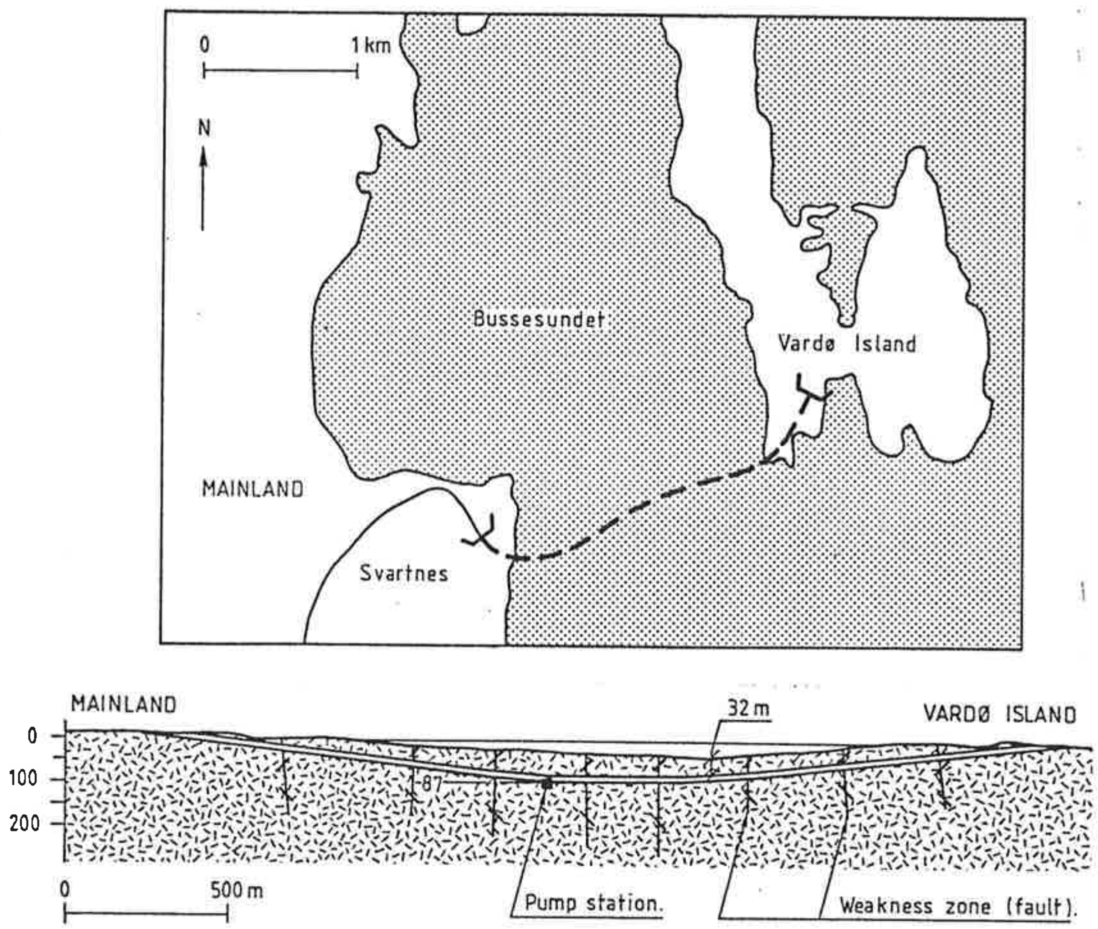

Fig. 7. The Vardø sub-sea road tunnel

The bedrocks of late Precambrian age consist of sandstones, siltstones and clay-schists. The rock mass quality for tunnelling was poor because of a pronounced bedding, but still surprisingly impervious. Leakage water was encountered only occasionally, requiring sealing measures by pre-grouting in 10 % of the length. The permanent inflow of leakage water, to be drained by pumping, is approximately 1000 l/min.

During construction of the tunnel between the shore-lines, drilling of an exploratory core-hole ahead of the tunnel face was made mandatory. The rock supporting work included bolting, shotcreting and full concrete lining. Full concrete lining was constructed in 21 % of the tunnel length.

4.5 The Kårstø Gas Pipe Tunnels (1981-84)

These three consequtive fjord crossings under seawater, basically unlined, were built to accommodate two high pressure continuously welded steel pipes of approx. 750 mm dia for the Statpipe Gas Transportation System. The common tunnel cross-section is 28 m2. Tunnel lengths vary between 3400 m and 4700 m, Fig. 8. The construction time for the tunnelling work was 1.4 years, working 108 hours per week on all six headings simultaneously, applying drill-and-blast method. The tunnel data and the excavation rates at the Kallstø-Kårstø tunnels are:

Tunnel	Length m	Lowest point m	Weekly progress rates in meters Max.	Average	Permanent water leakage l/min
Karmsundet	4700	-180	91.5	32.9	400
Førdesfjorden	3450	-160	63	26.0	300
Førlandsfjorden	3960	-170	85	35.6	300

More than 4 km of the total tunnel length of 12 km is below water (between shore-lines), where the minimum rock cover is 50 m.

The rock masses consist mainly of Precambrian gneisses, with some greenstone/ greenschist in the western and Cambro.Silurian phyllite in the middle and eastern part of the alignment. The overall tunnelling quality experienced was fair to poor. The rock supporting work included occasional bolting, shotcreting and full concrete lining. Full concrete lining was constructed in 30 % of the tunnel length.

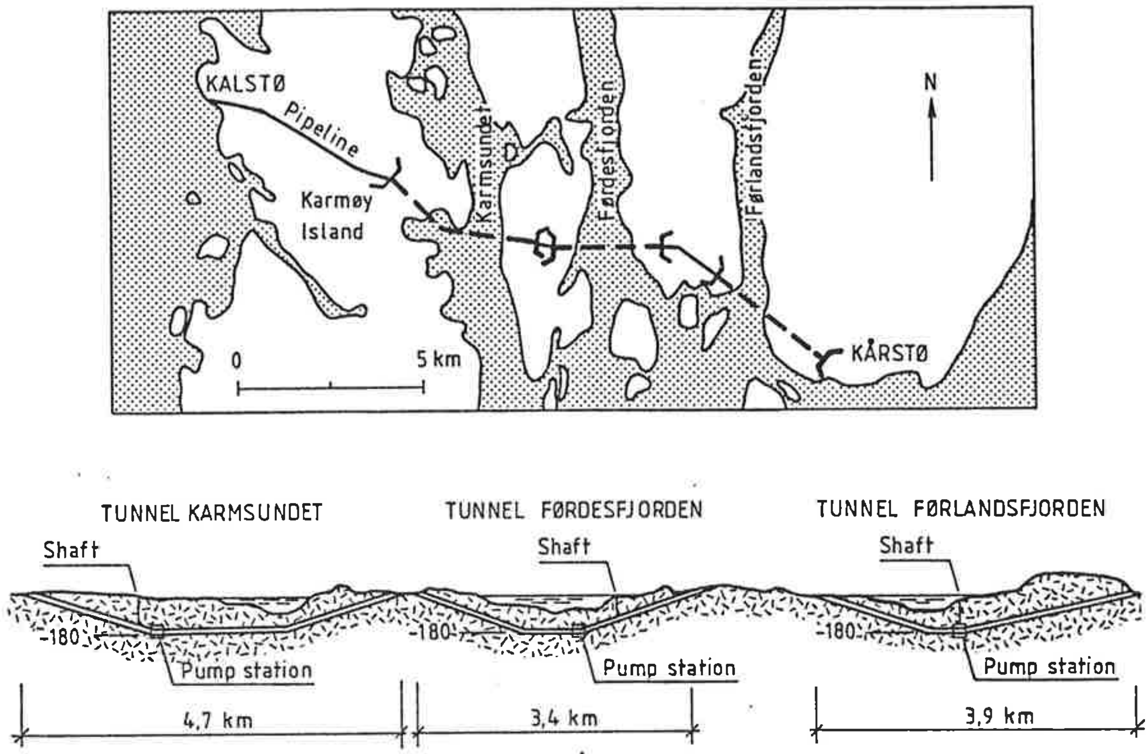

Fig. 8. The Kårstø tunnels

Inflow of leakage water was encountered occasionally, requiring grouting and sealing measures of approximately 8 % of the total tunnel length.

4.6 Shore Approach Tunnel, Hjartøy (under construction)

This is a landing tunnel for the oil pipeline from the Oseberg oil field in the North Sea. The subsea tunnel concept is used to provide protecting for the pipeline from the impact of heavy sea waves and currents that occur in this region.

The tunnel, 2320 m long and with a cross section of 26 m2, is located in Precambrian gneisses. In July 1986 the tunnel was excavated to within 10 m of the piercing at 80 m depth, Fig. 9. The piercing will be made similar to the Norwegian lake tap method, and the two concrete plugs close to the piercing point will keep the tunnel dry during installation of the pipeline from the sea side. Probedrilling was carried out by 3 - 4 holes of 30 m length. In addition core drillings were carried out in areas of expected, significant weakness zones.
The rock masses have given low water leakages (130 l/min) with pre-grouting only in 3% of the tunnel length.

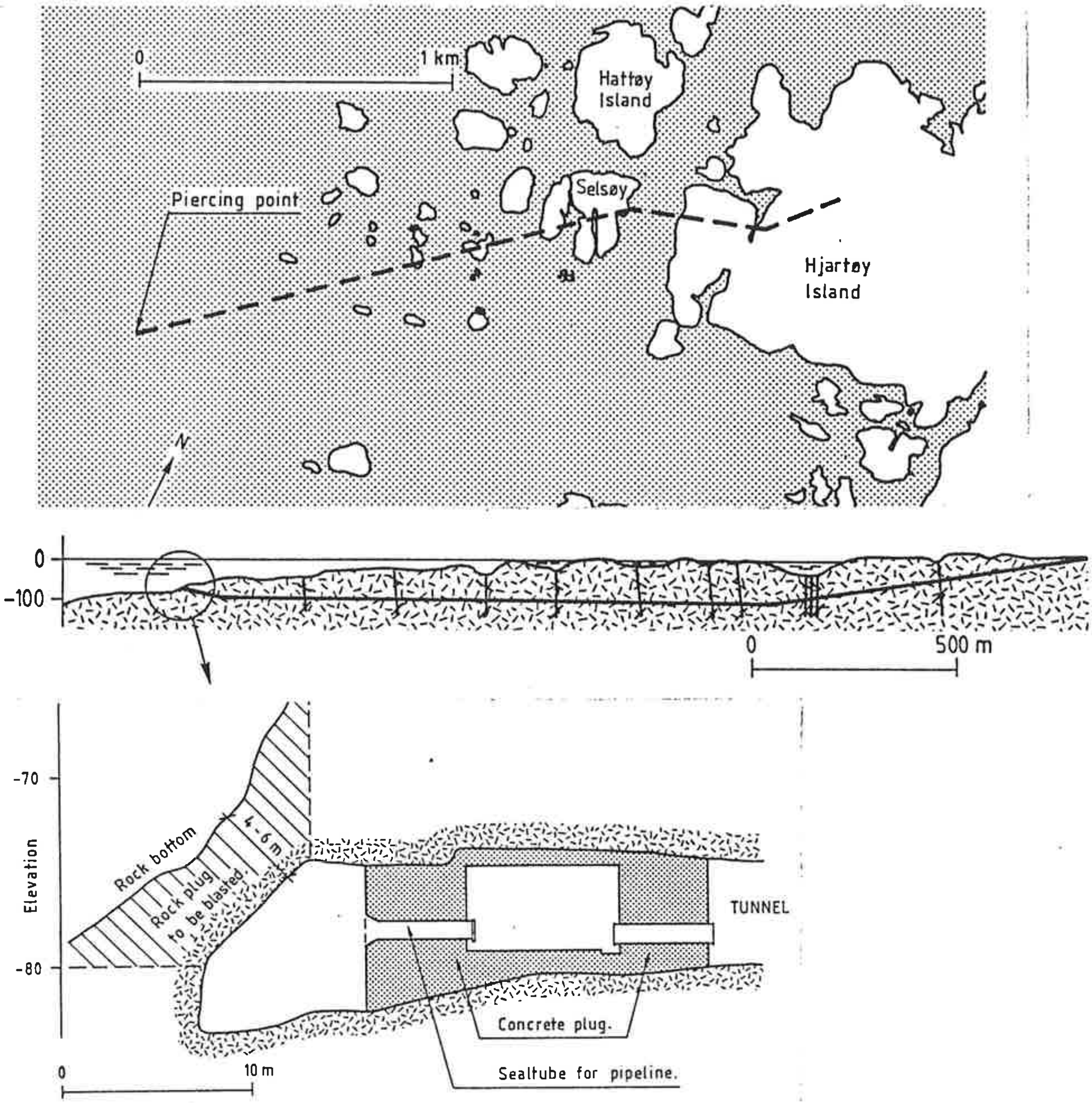

Fig. 9. Shore approach tunnel and piercing

4.7 Ålesund - Ellingsøy and Ellingsøy - Valderøy Road Tunnels under construction

The construction of these two road tunnels of 45 to 75 m2 cross section see Fig. 18, was started in January 1986. They will be finished in 1989. The total length of the tunnels to be excavated in Precambrian gneiss is 7.7 km with the lowest point 140 m below sea level. By July 1986 about 1800 m of tunnels have been excavated with overall good rock mass conditions. No water leakage zones have so far been encountered.

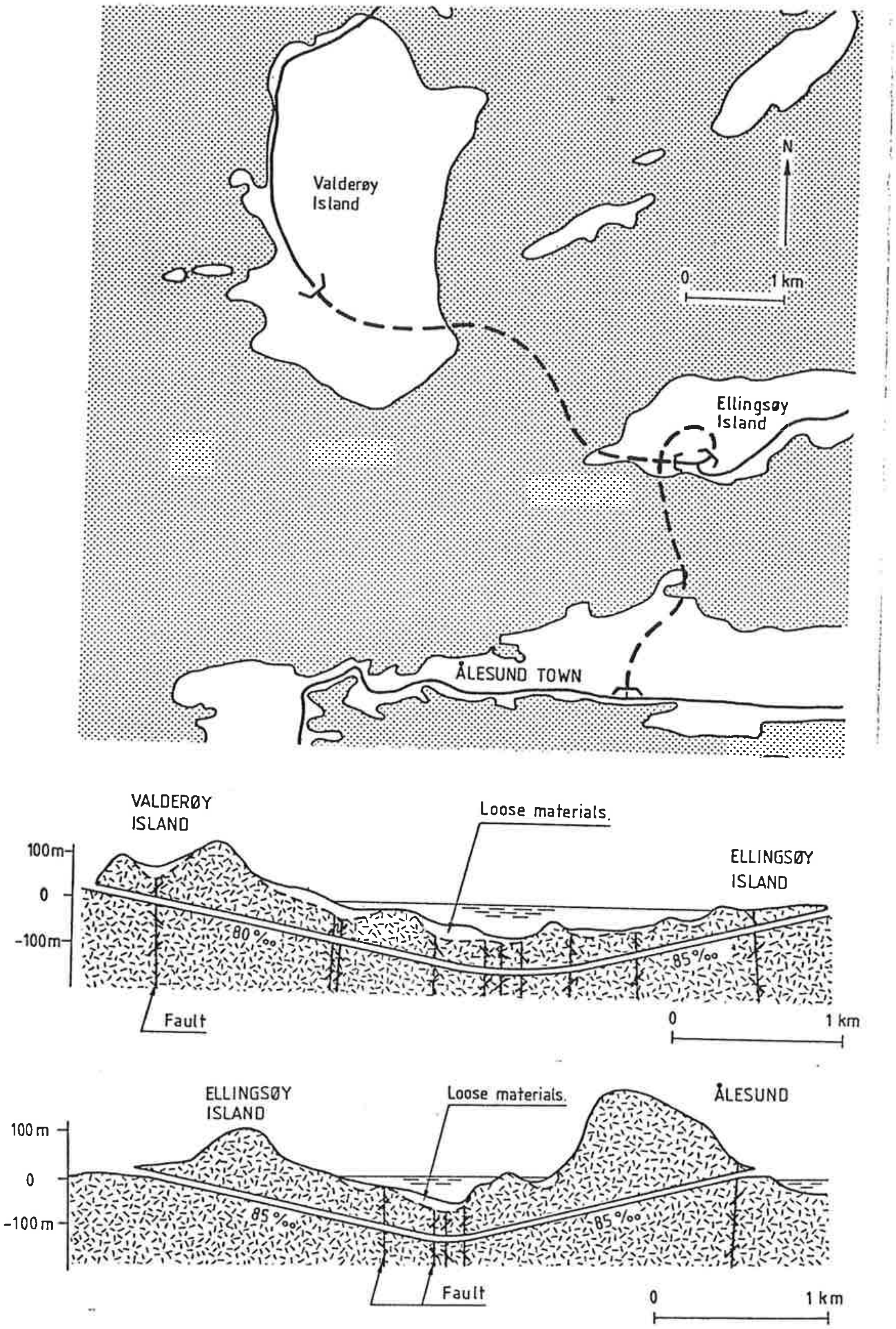

Fig. 10. The sub-sea road tunnels Ålesund - Valderøy

5. Governing Factors for a Sub-sea Tunnel Alignment

The alignment and length of a sub-sea tunnel is governed by three different parameters, namely the

- topography
- geology (rock mass conditions for tunnelling)
- project/construction requirements

These conditions are illustrated in Fig. 11.

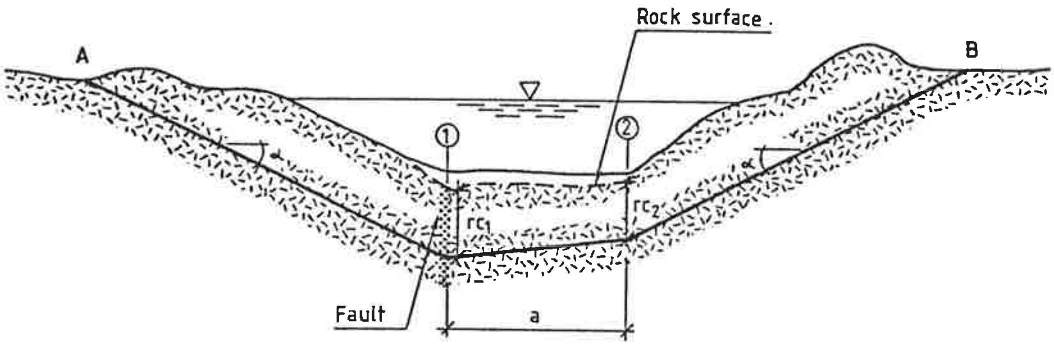

Fig. 11. Main parameters of a sub-sea tunnel

The topographical features of importance for a tunnel will be

a) elevation of the two portals (A & B)

b) water depth at the critical points (1 & 2) with minimum required rock cover (rc) above tunnel roof

c) the distance (a) between the (two) critical points.

The levels of the portals are in many cases only partly dependent upon the topography along the shore since the connection required to existing facilities (roads, railways etc.) often determine the location.

The critical points with minimum rock cover are partly determined by the geological conditions. The points are often located in the deepest part where the erosion has been strongest because of poor (weak) rock masses.

The geological conditions will have influence both on excavation and the rock cover required for a safe construction and operation of the tunnel. There are no existing requirements or standards for the minimum rock cover beneath the sea floor. Based on the author's experience from planning and construction of Norwegian tunnels in hard rocks the data in Table 2 has been used.

Water dept to rock surface	ROCK COVER	
	Good quality rock masses	Poor quality rock masses
0 - 25 m	25 m	30 - 35 m
25 - 50 m	30 m	35 - 40 m
50 - 100 m	40 m	45 - 50 m
100 - 300 m	50 m	55 - 65 m

Table 2. Minimum rock cover (rc) used for limited distance along sub-sea tunnels

The maximum inclination required for a sub-sea tunnel will to a great extent determine the actual tunnel length. As given in Table 3 the inclination will vary from about 1:8 to 1:80 depending on type of tunnel service. This means that there may be a difference in length for the whole tunnel in the order of 10 x 2 = 20 times between a high speed railway tunnel and a simple ("local") road tunnel.

Road tunnel	- highways	50 - 70 o/oo	ie.	1:20 - 1:14.3
	- main roads	70 - 100 o/oo	ie.	1:14.3 - 1:10
	- local roads	125 o/oo	ie.	1:8
Railway tunnel		12.5 - 25 o/oo	ie.	1:80 - 1:40

Table 3. Maximum descent of some traffic tunnels

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6. Field investigations for a Norwegian Sub-sea Tunnel

Norway consists of old rocks of Precambrian and Palaeozoic age, Fig 12. This means that all rock masses can be classified as hard rocks considering tunnelwork. The rock masses are, however, cut by faults and thrust zones where the rock conditions are of significantly poorer quality than elsewhere. There are also areas where more densily jointing results in poorer excavation conditions than normal.

The erosion of the ice in Quarternary times (the last million years) have caused unweathered, fresh rocks to be exposed at the surface and the weaker rock masses (faults, weakness zones) to form depressions (valleys, which are often easily detected on the surface). The rock mass tunneling conditions are most often relatively easy to interpret based on surface geological mapping and there are small amounts of loose deposits. The costs for preinvestigations are therefore low. For "over-land" tunnels these are normally less than 1 % of the construction costs.

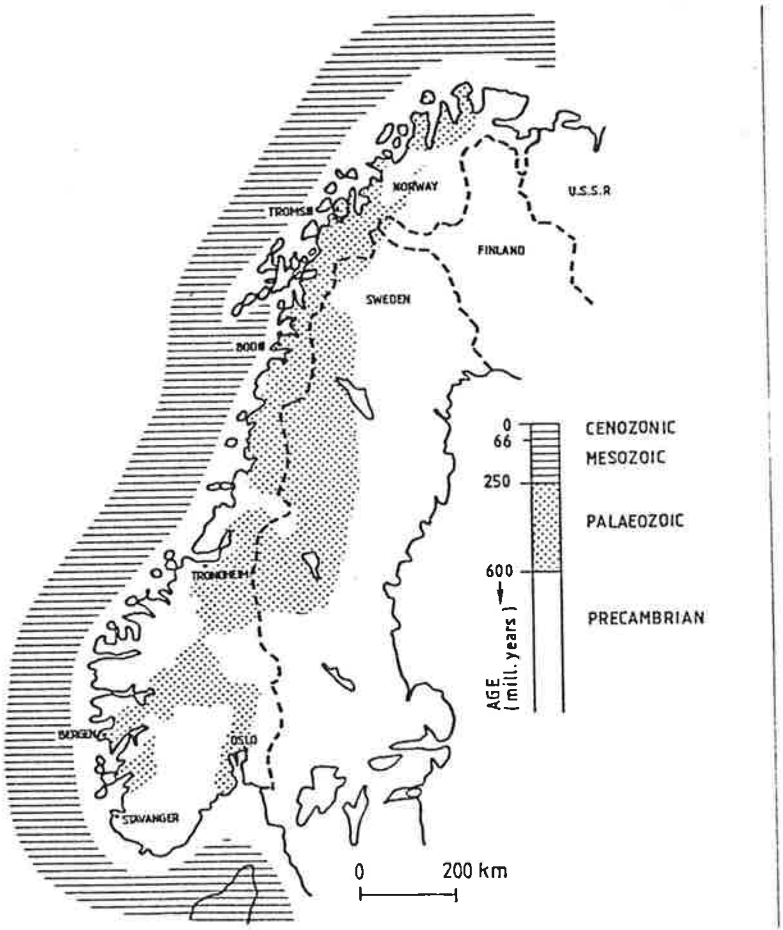

Fig. 12. Simplified geological map of Scandinavia

The mapping of the bedrock conditions for sub-sea tunnels require, however, more sophisticated investigations than for "over-land" tunnels since large parts of the area is covered by water. A common investigation program is started by collection of geological data supplied by studies of airial photos and sea-maps. When the most promising area for a possible tunnel has been evaluated, a program for boomer-sparker profiling and echo soundings is carried out. From the results of such investigations a map of the rock surface is worked out, and a possible tunnel alignment can be located.

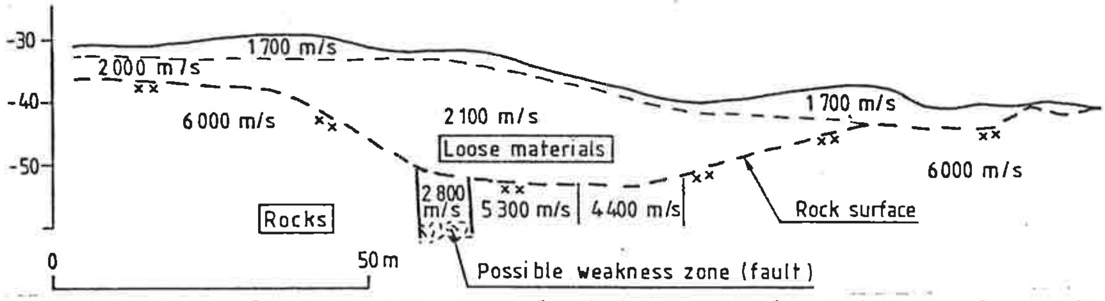

Fig. 13. The different seismic velocities in rocks indicate the rock mass qualities. In addition the position of loose materials is recorded

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 costs of the investigations carried out for Norwegian sub-sea tunnels varies between 1 - 5 % of the total construction costs, refer to Table 5.

It is, however, important to realize that detailed knowledge of geology prior to excavation can not be obtained for a subsea tunnel. To compensate for this ever present uncertainty, exploration ahead of the tunnel face should be 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 cheap insurance both regarding safe working conditions and the completion of the project as near on costs and schedule as possible.

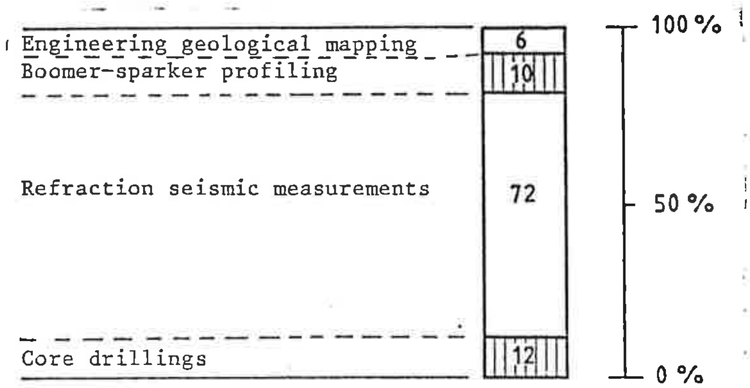

Fig. 14. Comparative costs in % between different pre-investigation methods for a sub-sea tunnel

7. Construction Methods

In addition to the actual rock excavation of the tunnel which can be executed by drilling, blasting and mucking out or by full-face boring machines (TBM), other works have to be carried out to safeguard working conditions and to reduce the leakage water. Progress rates and tunnelling costs will therefore depend on the types and amounts of the additional work, and where and when such work is being carried out in the tunnel. Table 4 shows the effect of the the various tunnelling works on the construction time.

As mentioned earlier much experience has been gained on the use, capacities and costs from earlier tunnelling works on the rock supporting and sealing methods to be used in sub-sea tunnels under different rock mass conditions.

7.1 Tunnel Excavation

The tunnelling boring machine (TBM) is immediately attractive due to high advance rates under suitable rock conditions. Average advance rates in the order of 125 m or more per week in hard rocks (gneiss, micaschist) have been obtained. Most TBM tunnels have been excavated on an incline or on a slight decline. TBM excavation on a decline in the range 50 - 100 o/oo requires modifications of the machine and the loading system.

TBMs designed for hard rock provide limited access to the face and to the area close behind. This means that only limited rock support can 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. It has in fact happened that a TBM had to be dismantled and the rest of the tunnel to be completed by drill and blast.

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 face is easily accessible for exploratory drilling, and the percussion drill holes can be performed by tunnel jumbos.
This method offers therefore a safer excavation for a declining sub-sea tunnel.

7.2 Rock Supporting Works

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

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

- Shotcrete. 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 aspecial advantage in difficult rock masses with short stand-up time.

- Concrete lining. Used under poor rock mass conditions where the stability of larger volumes of rocks may be involved.

7.3 Importance of Exploratory Drillings and Pre-grouting for Sub-sea Tunnels

The experience with probeholes and pre-grouting from the tunnel piercings has been fully applied in the Norwegian subsea tunnelling. Fig. 15 shows the principles for this technique.

There are great uncertainties associated with sub-sea tunnelling, as stated earlier, related to possible water inflow. Neither the number of waterbearing zones nor the maximum inflow rates can be predicted beforehand. The experience from other tunnel projects mentioned earlier is that the risk of large water inflows is greatly reduced when sealing of water-bearing zones is carried out as pre-grouting ahead of the tunnel face.

The pre-grouting should preferably be included in the exploratory drilling programme. When a water-bearing zone has been detected by the exploratory drilling, additional holes are drilled and grouting is done through all the boreholes showing water leakage. After the grouting is completed, the tunnel can be excavated by standard blasting methods through the sealed zone. The required time for the grouting work will depend upon the rock conditions and may vary from less than one day to several weeks. This operation is presently being improved by the development of different chemical grouts.

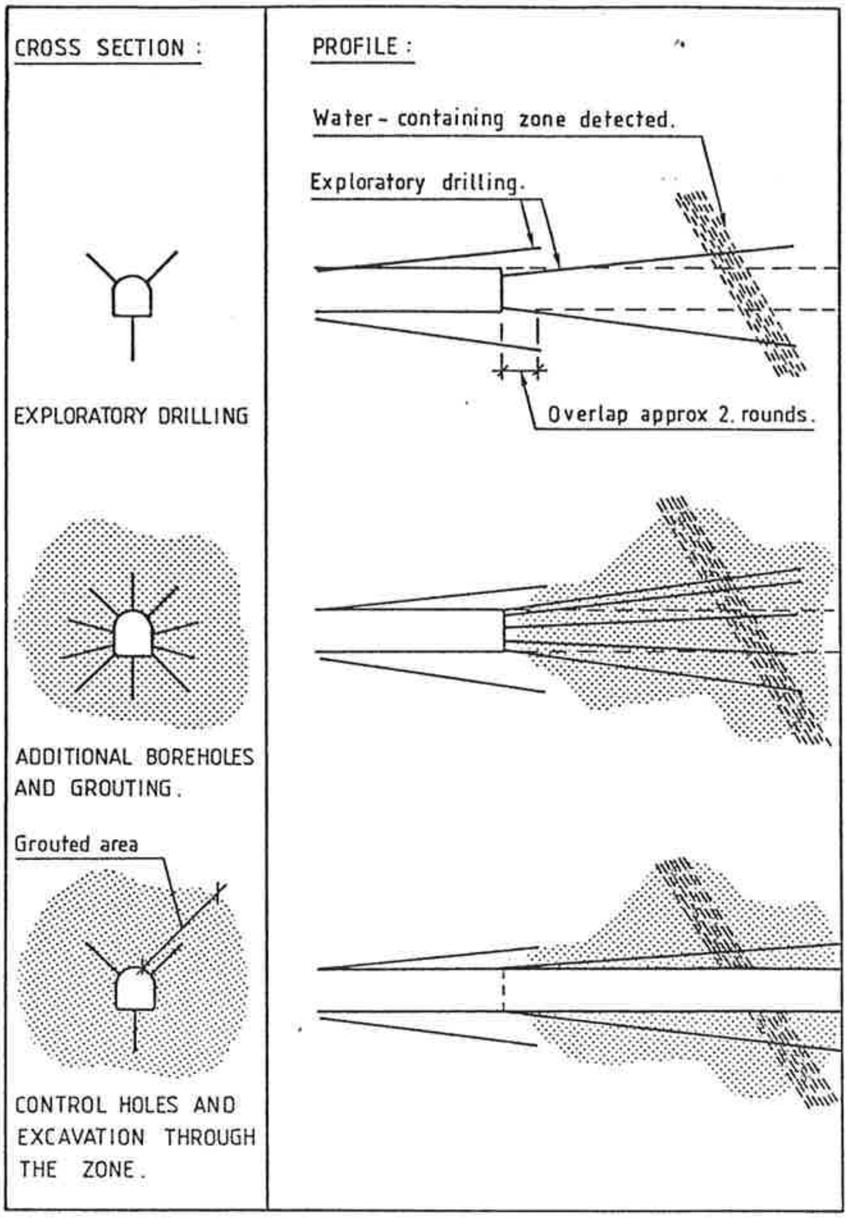

Fig. 15. Exploratory drilling and pre-grouting

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 (stability) condition in addition to leakage recordings. A special advantage of this method is the possibility to detect leakages associated with poor (low stability) rock mass conditions a long distance ahead of the tunnel. Thus the necessary precautions can be taken for the sealing of possible leakages, and for preparing for required rock supporting works, which is of vital importance to avoid the possibilities for running ground a drowning of the tunnel.

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The 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.

OPERATION	AT THE FACE	BEHIND THE FACE	AFTER BREAK-THROUGH
Exploratory drilling	(x)		
Grouting	(x)	( )	.
Excavation	(x)		
Rock support	(x)	( )	( )
Tunnel works		(x)	( )

(x) high influence on construction time
( ) little " " " "
. no " " " "

Table 4. Main tunnelling operations and their influence on construction time.

7.4 Safety Measures

The difficulty and uncertainty in predicting the existence and degree of possible leakage zones and zones with poor rock mass stability under the seabed can be offset by special safety measures during construction. Of these, the exploratory drilling ahead of the tunnel face together with a well planned grouting procedure 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 tunnel construction 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 successful if there are minor or no water leakages associated with the zone. So far it has not been used in Norwegian sub-sea tunnels.

8. Construction Costs

The main works involved in a sub-sea tunnel project is listed below together with the main factors influencing upon the costs for a given tunnel:

ITEM	VARYING WITH
Rock support	rock mass stability
Excavation (drill and blast)	partly with rock type(s)
Exploratory drilling and grouting	rock mass permability
Frost protection (water shields)	climate and water leakages
Tunnel works - Road surface, - Electr. equipment, - Drainage	small variations
Planning, investigations and supervision	small variations

For a given tunnel there are only small variations in the costs for the tunnel works or the planning costs compared with the construction costs. Also the excavation (drill and blast plus mucking out) costs have relatively small variations in costs per meter tunnel.

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The greatest uncertainties in costs stem from the required rock supporting and grouting works, caused by the actual rock mass conditions. This appear in Fig. 16 where the variations in the construction costs with different rock mass qualities are shown.

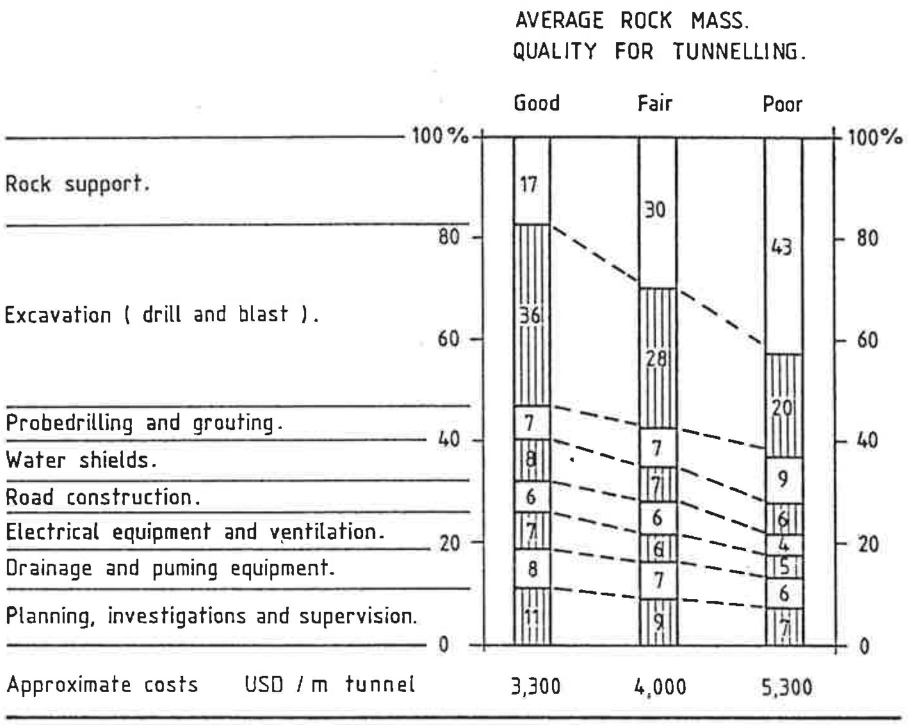

Fig. 16. Distribution of costs for a sub-sea rock tunnel with different rock mass tunneling conditions.

The variations in relative costs for tunnelling over the years (Fig. 22) makes it difficult to compare cost for tunnel projects constructed at different times. The figures in Table 5 are therefore not directly comparable. It can be seen, however, that the construction costs today for a 50 m2 tunnel in fair poor rock mass conditions (rock support and sealing 100 - 150% of excavation costs) amounts to about 3.000 - 3.500 USD per meter tunnel without tunnel works (road. ventilation etc.) and capital costs.

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YEAR OPENED	TUNNEL	LENGTH	CROSS SECTION	DEEPEST POINT	COSTS: ROCK SUPPORT AND WATER SEALING	COSTS: WATER SHIELDS	COSTS: PRE-INVES-TIGATIONS	COSTS: APPROCIMATE COSTS PER METER TUNNEL 1)	COSTS: COMPARATIVE COSTS 1) FOR 50m2 TUNNEL 2)
		km	m2	m	% of excavation costs		% of construction costs	USD(1986)	USD(1986)
1974	Rafnes - Herøya	3,6	16	-253	70	-	1,7	2,000	3,000
1982	Vardø	2,6	50	- 88	204	49	5,0	6,500 4)	5,000
1984	Karmsundet	4,7	26	-180	155	-	1,9	2,300	3,500
1984	Førdesfjord	3,4	26	-160	236	-	1,9	2,900	4,400
1984	Førlandsfjord	3,9	26	-170	107	-	1,5	2,300	3,500
1987	Shore Approach Hjartøy	2,3	26	-110	120	-	4,0	2,000	3,000
1988	Ålesund - Ellingsøy	3,5	70	-140			1,0	4,300 3)	3,000 3)
1988	Ellingsøy - Valderøy	4,3	70	-140					

1) Capital costs excluded
2) Without tunnel works
3) From tender prices
4) Only the rock tunnel part

Table 5. Costs of some Norwegian sub-sea tunnels

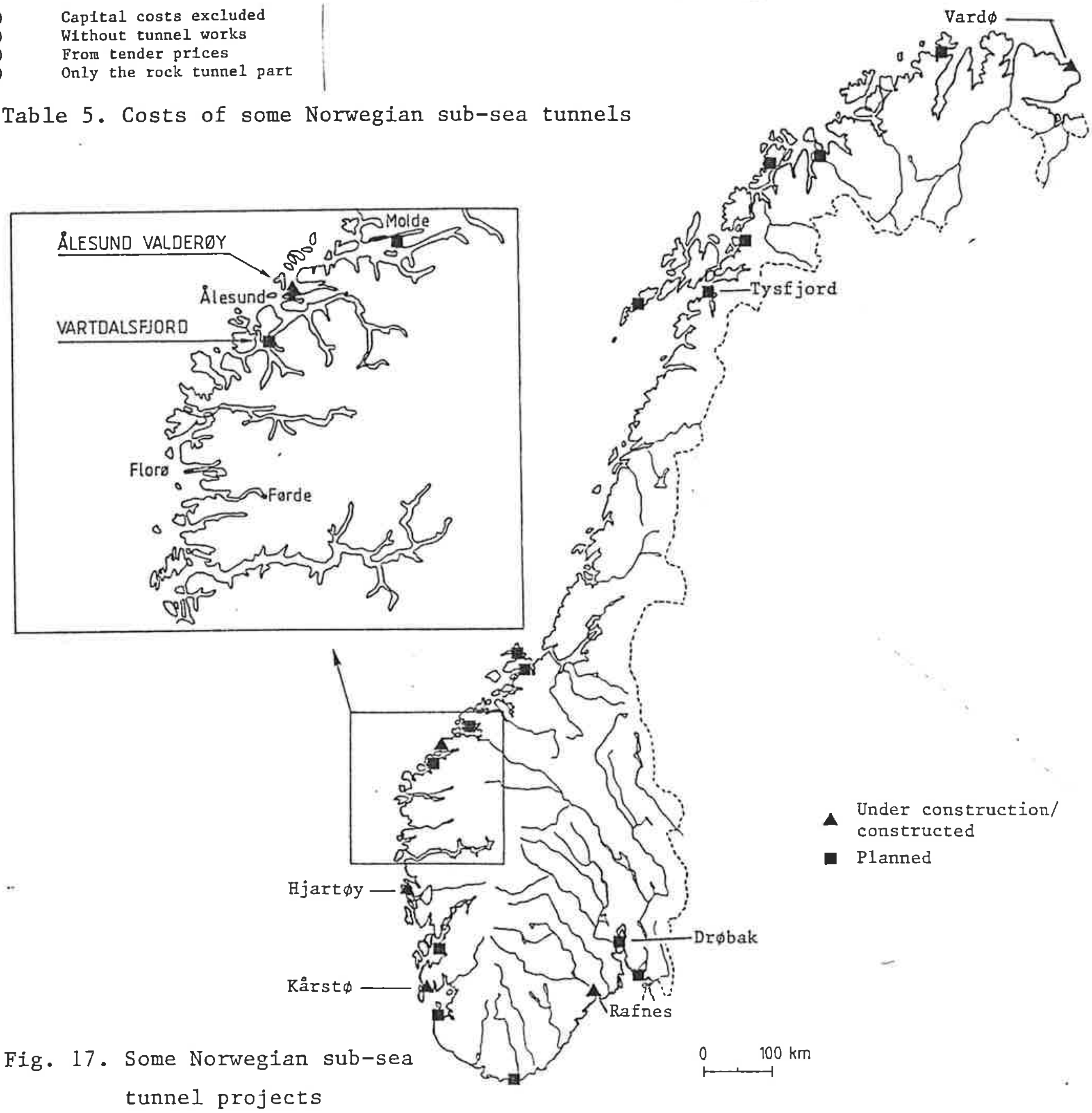

Fig. 17. Some Norwegian sub-sea tunnel projects

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9. Possible Future Norwegian Sub-sea Tunnel Projects

The more than 3000 km long coast of Norway with numerous fjords and islands (see detail in Fig. 17) has about 160 different connections served by ferries. (The yearly subsidies from the Government for these connections are about 50 mill. USD.) It is therefore a great need for permanent connections. As shown in Fig. 17 there are plans for several sub-sea tunnel projects. The main features for some of them are given in the following.

Tunnel Drøbak - Hurum is planned to start in 1987 and finished 1990. This is a 7.4 km long 3-lane tunnel of 75 m2 cross section in gneiss. The tunnel with a maximum descent of 70 o/oo will have its deepest point 125 m below sea level. Some larger low velocity zones (faults) have been registered beneath the sea bottom by refraction seismic measurements. The costs of this tunnel, with a traffic volume of 5000 - 6000 vehicles per day, is estimated at 50 mill. USD, capital costs excluded.

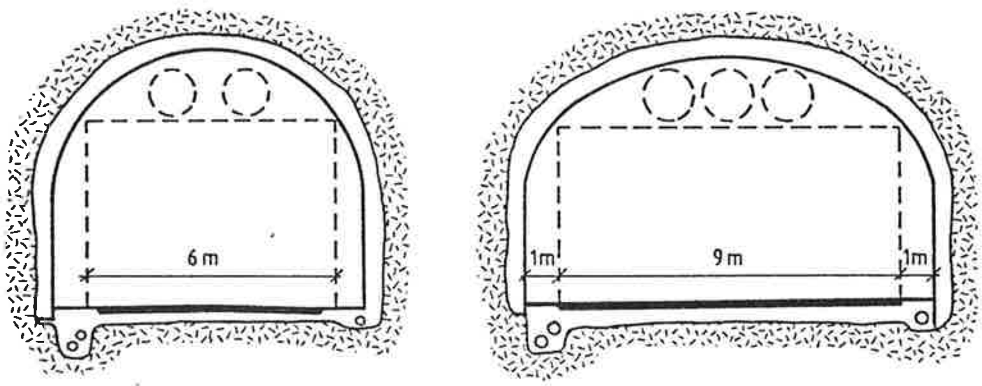
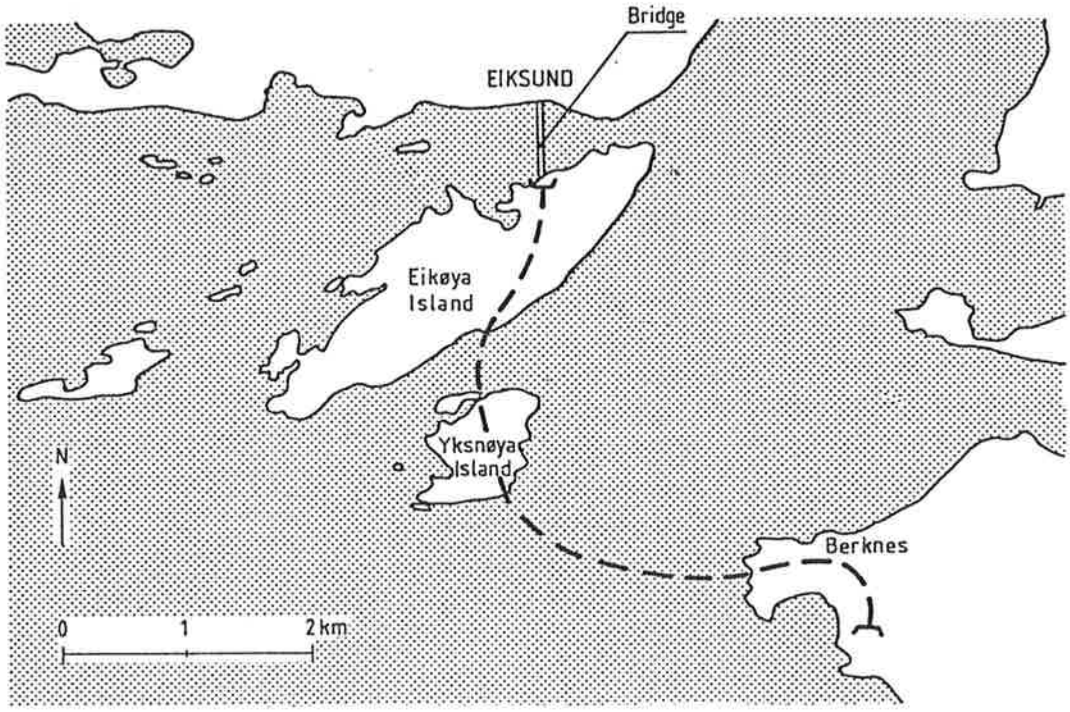


Fig. 18. Cross section of a two-lane (45 m2) and three-lane (75 m2) tunnel

The Vartdalsfjord tunnel is scheduled for construction 1988 - 91. The 6.7 km long two-lane (45 m2) tunnel will have its deepest point 315 m below sea level with a minimum rock cover 50 - 60 m, Fig. 19. The maximum descend is 100 o/oo.

The 11.6 km long and 350 m deep Tysfjord tunnel is probably the longest undersea road tunnel currently in the planning stage Fig. 20. By constructing this tunnel, the last ferry connection on the E6 road, will be ommitted. The costs for this two-lane tunnel is roughly estimated to 55 mill. USD.



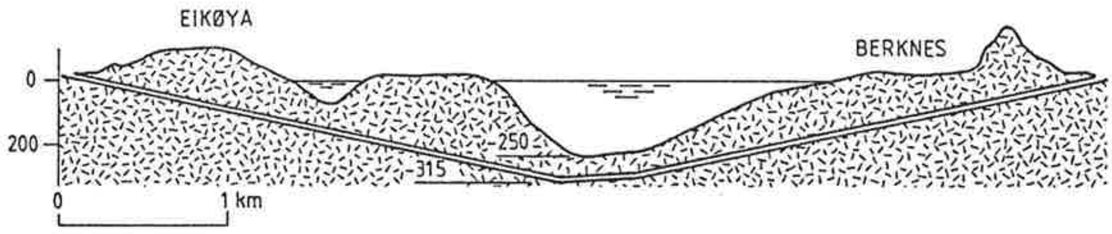


Fig. 19. The Vartdalsfjord sub-sea tunnel project

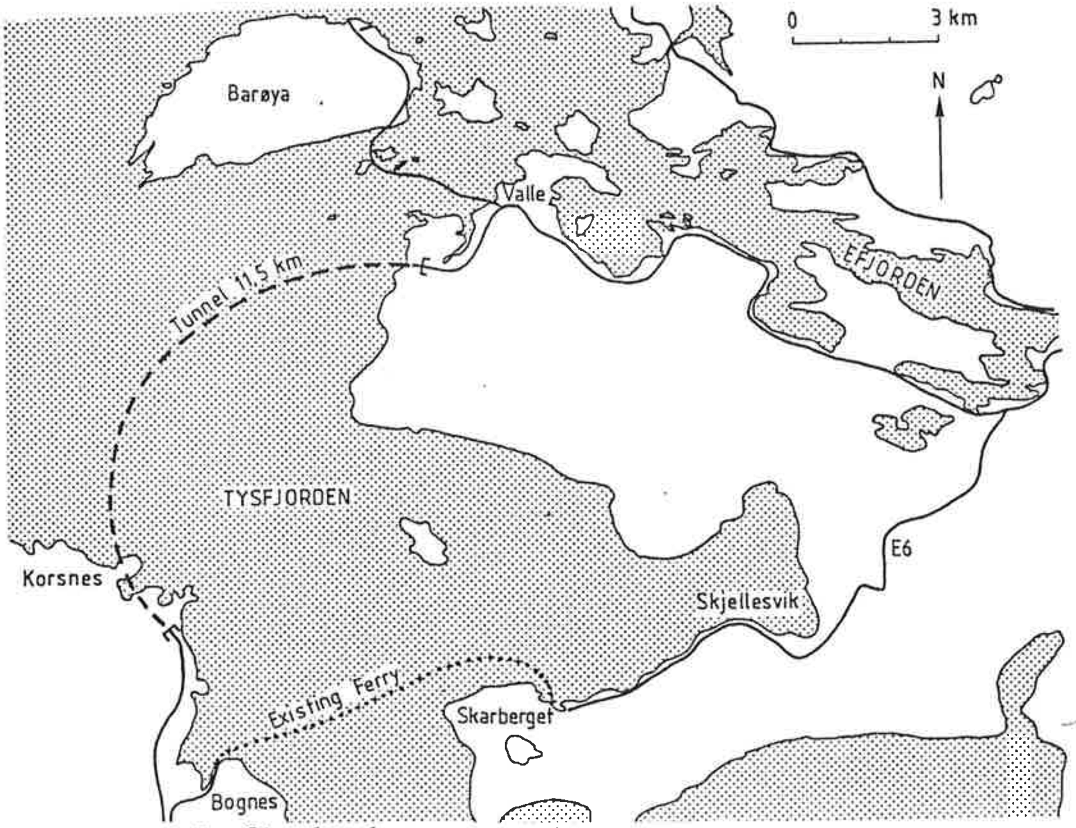


Fig. 20. The Tysfjord sub-sea tunnel project

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The most challenging Norwegian sub-sea tunnelling study of today is the development of oil fields in the North Sea by tunnels. The Petromine group has carried out studies which show that the tunnel can be constructed within 7 - 9 in soft rock masses of Cretaceous and Tertiary age along 75% of the 50 - 60 km long and 600 m deep tunnel. For this project it is found benefitial to use a specially designed TBM for both soft rocks and the hard rocks along the tunnel, Fig. 21. In the soft rocks containing possible pockets of shallow gas or water it is of utmost importance to carry out a well planned exploratory drilling and pre-grouting program to avoid the TBM boring into difficulties which could delay or even stop the tunnelling.

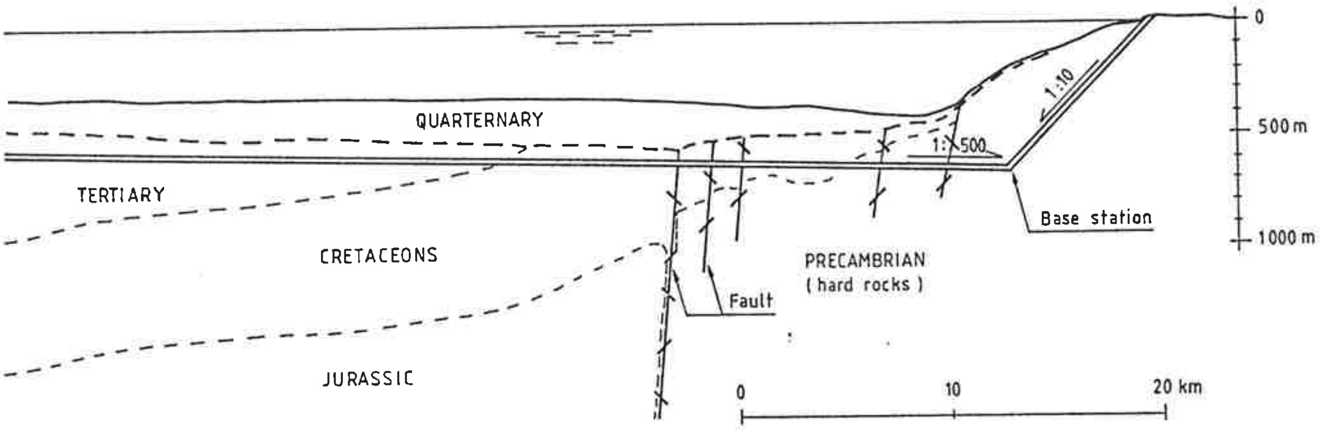

Fig. 21. The Petromine tunnel project for oil development

10. Why Sub-sea Rock Tunnels?

The skill of the contractors to tackle different rock masses is an important part of sub-sea tunnelling. During the last 5 - 10 years Norwegian contractors have taken into use more advanced rock supporting equipment and solutions. The practical development and use of shotcrete illustrates this. The quick and efficient use this method now offers, combined with short blasting rounds and quick concrete lining has been most important on at least two occasions involving tunnelling through low stability rock masses with very short stand-up time.

The development and improved experience in tunnelling over the last years has resulted in a general reduction of tunnel excavation costs, Fig. 22. This has made sub-sea rock tunnels an even more attractive alternative compared to bridges and other strait crossings.

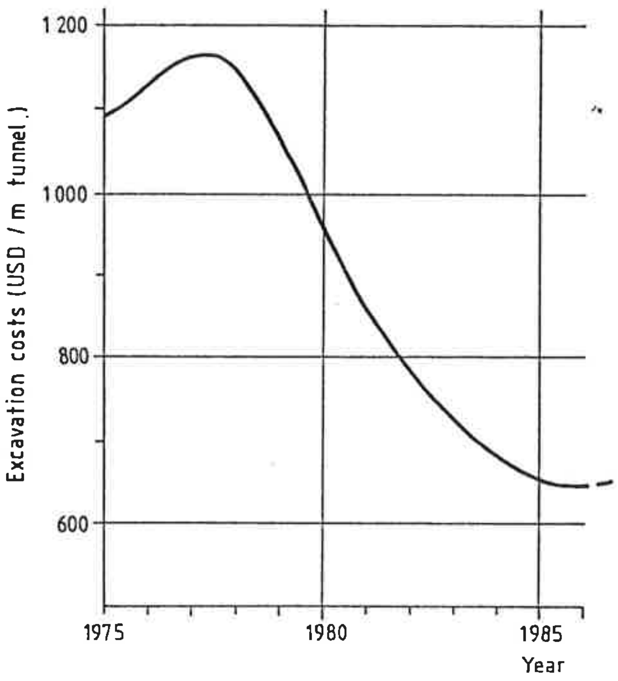

Fig. 22. Development of excavation costs (drill and blast) in Norway.

Fig. 23 shows approximate comparisons between different types of strait crossing methods. From this is clearly seen that under-sea road tunnels are the most economical alternative for most crossings with the present tunnelling costs.

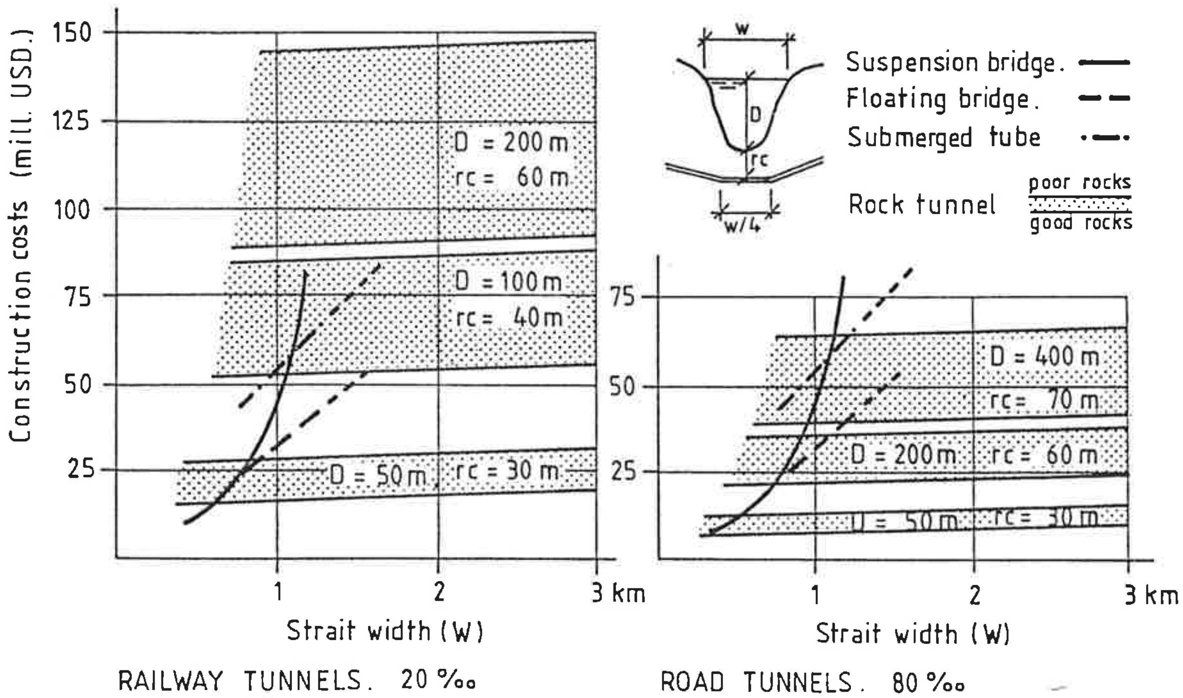

Fig. 23. Comparative costs for different strait crossing methods (modified after (9)).

Today we have experience of sub-sea tunnels down to 250 m and firm plans for 7 - 8 km long tunnels down to more than 300 m. With the experience from several long "over-land" tunnels with ground water heads up to 1000 m it is expected that sub-sea tunnels within 10 years may be constructed down to as much as 500 - 600 meters below sea level within reasonable costs and construction time.

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